



Gluten-Free Ancient Grains

Cereals, Pseudocereals, and Legumes: Sustainable, Nutritious, and Health-Promoting Foods for the 21st Century

Edited by John R.N. Taylor and Joseph M. Awika

Gluten-Free Ancient Grains

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Gluten-Free Ancient Grains

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Sustainable, Nutritious, and Health-Promoting
Foods for the 21st Century

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Foreword

It is a great pleasure to write the foreword to this excellent and timely book *Gluten-free Ancient Grains: Cereals, Pseudocereals, and Legumes: Sustainable, Nutritious, and Health-Promoting Foods for the 21st Century*, edited by John Taylor of the University of Pretoria and Joseph Awika of Texas A&M University.

The book is a compendium of current knowledge on ancient grains and builds a case on why, despite the apparent neglect and underinvestment in research, as well as market development, these grains have persisted over the years, emerging recently as important sources for supply of critical foods for our nutrition and health in the 21st century.

Meeting the world's demand and choice for food and nutrition continues to be among the greatest challenges of human society. As the global population continues to increase, living standards are rising in parts of the world and the diets of people are shifting where more people want to eat meat in place of plant foods, raising the overall demand for grain. Our ability to produce more grain is constrained in parts of the world, and the global food system is at risk as a result of climate change and associated agronomic problems. This is particularly the case in third-world nations, especially sub-Saharan Africa, where the world's most chronically food-insecure reside, and penetrance of modern agricultural technology has been very limited.

Today, the world is also facing an additional food and nutrition challenge—the pandemic of noncommunicable, diet-related diseases, particularly obesity, type 2 diabetes, and a rise in cardiovascular diseases. Both high-income countries with their aging populations and the rapidly urbanizing middle- and low-income developing countries are affected. These so-called Western lifestyle diseases are, in part, a consequence of our shifting diet and changes in food habits from a predominantly plant-based diet rich in micronutrients, dietary supply of phytochemicals, to diets dominated by energy-dense, animal fat-, and sugar-rich foods. As a result, in a world endowed with great biodiversity and rich in genetic resources, only three major crops—wheat, rice, and maize—are counted upon to supply nearly two-thirds of the global dietary energy intake.

Most crops of the world originated and evolved in the old world. These old civilizations are responsible for the evolution, selection, and preservation of global crop biodiversity and many of the endowments of this planet that we cherish. Biodiversity is not a result of happenstance. Plants and animals exist where they do because of natural environmental adaptation and the powers of human selection that encouraged their survival and cultivation. The ancient

grains are those cereal grains, pseudocereals, and pulses that have been sustained as traditional staple food crops in rural areas of the old world, because they met the food and nutrition needs of people in those regions.

As major crops of the world are more seriously threatened by climate change, ancient grains thrive in many of these places because they have built-in adaptive traits that make them suitable for cultivation in harsh environments. Ancient grains are also crops of high premium potential and value. In addition to strong environmental stress tolerance, many of the ancient grains are sources of better nutrition as excellent sources of macronutrients and many micronutrients. They are notably rich in health-promoting phytochemicals with promising potential for prevention or alleviation of diet-related diseases.

This book, therefore is not simply a compendium of facts and tales about ancient grains. With its holistic coverage by expert authors from around the world, the book has wealth of information that imparts new insights on the global range of adaptation, stress tolerance, as well as nutritional and health potential of these indispensable crops of the poor. Eight-grain types from across the world are discussed: Sorghum, the Millets, Quinoa, Amaranth, Buckwheat, Lupin, African Legumes, and Wild rice. They represent the three different groups of grain staples: cereals, pseudocereals, and pulses (grain legumes) and all are characteristically gluten-free.

This book provides authoritative data on nutrient and phytochemical values of ancient grains in comparison with today's major food grains. It offers information on new developments in food processing technologies that enhance their food and nutrition potential, and offers a critical evaluation of the current research findings on their health-promoting properties. Additionally, the book portends the fundamental social and economic issues that currently constrain the supply of ancient grains, and suggests solutions required to make ancient grains major world staples so that far more people can benefit from their unique nutritional and health-promoting attributes.

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Chapter 1

Environmental, Nutritional, and Social Imperatives for Ancient Grains

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1 INTRODUCTION

This chapter focuses on the reasons why the Ancient Grains should be of interest to all those who are concerned about food: the world's food supply, our nutrition, and the role of foods in our long-term health and well-being. The chapter is three parts. The first section explains what ancient grains are and which particular grains are dealt with. The main section examines the societal and grain-specific trends, which are driving interest and activity in ancient grains. The concluding section gives an overview of the scope and content of the book.

2 WHAT ARE ANCIENT GRAINS

2.1 Definitions

Currently, there is no universally accepted definition as to what are ancient grains. According to the Whole Grains Council, a respected advocacy group working toward increasing whole grain consumption for improved consumer health, ancient grains can be loosely defined as “grains that are largely *genetically* (author's insertion) unchanged over the last several hundred years” ([Oldways Whole Grains Council, Undated](#)). A similar but more detailed definition comes from *Food Navigator.com* (2015) that “ancient grains is a category covering grains (*cereals*), pseudo-grains (*more properly pseudocereals*) and seeds that are “ancient” in the sense that they have remained largely unchanged over hundreds, even thousands of years, unlike, say modern wheat varieties.” Alternative terms for ancient grains include: specialty grains ([Abdel-Aal and Wood, 2005](#)), less common grains ([Belton and Taylor, 2002](#)), native grains ([National Research Council, 1996](#)), traditional grains ([Taylor and Stading, 2014](#)), and neglected and underutilized grains ([Padulosi et al., 2013](#)).

Another expression, which helps define ancient grains is “Lost Crops”. This was coined by the National Research Council of the US National Academies of Science. The concept of “Lost Crops” is that, these are plant foods, which are lost to the mainstream of international science and to people outside the less-developed rural regions of the world, where they are primarily cultivated. To enable the scientific community and the wider world to “find” these lost crops, in the late 1980s the Council, under the leadership of Dr. Noel Vietmeyer commenced publishing an on-going series of books, including *Lost Crops of the Incas* (1989), *Lost Crops of Africa: Vol. I Grains* (1996), *Vol. II Vegetables* (2006) (National Research Council, 1989, 1996, 2006). The “Lost Crop” books are literally a cornucopia of fascinating information about the ancient grains and other ancient food plants, and are a great introduction to the subject for the general reader.

Regarding consumer perceptions about ancient grains, these are apparently highly positive. According to the [Canadean Consumer \(2015\)](#), more than 80% of consumers worldwide are familiar with ancient grains as food ingredients. Furthermore, more than 50% of consumers consider that consumption of ancient grains has a positive impact on health and weight-conscience women in particular view ancient grains positively. A rather more conservative and probably realistic figure comes from a Health Focus International Survey of consumers in the Americas, Europe, and Asia, where 35% of respondents expressed an interest in ancient grains ([Webb, 2016](#)). The author also reported on a survey by Today’s Dietitian of 450 dietitians in the USA, which found that 50% of respondents stated that ancient grains would achieve “super food” status among consumers in 2016.

As to which particular grain species or varieties can be considered as ancient grains, the Whole Grains Councils limits the category to cereals and pseudocereals, and includes grains largely ignored by Western palates, that is, sorghum, teff and millet (*sic*), the pseudocereals quinoa, and amaranth, plus less common grains, such as wild rice and buckwheat (a pseudocereal). It also includes primitive wheats like einkorn, emmer/faro, Kamut (khorasan wheat), and spelt, and possibly heirloom varieties of other cereals, such as black barley, red and black rice, and blue corn (maize) ([Oldways Whole Grains Council, Undated](#)).

In view of the great interest in ancient grains by the both scientific community and the general public, there is clearly a need for better definition of what are ancient grains. This author is of the opinion that ancient grains should be primarily defined in terms of their properties.

Several properties are associated with the ancient grains:

- They are good sources of many macro- and micronutrients.
- They generally contain high levels of phytochemicals that have health-promoting actions.
- They are hardy crop plants that can be cultivated in environments with poor soils, high temperatures, and low rainfall.

- They are traditional staple food crops of communities in less technologically developed regions of the world.
- They have not undergone the substantial and deliberate genetic changes typical of the major grain crops.

Taking these together, the following is a working definition of ancient grains:

Ancient grains are species or particular varieties of cereal grains, pseudocereals, and pulses that have been cultivated and consumed for hundreds of years as traditional staple foods by communities outside the mainstream of technological development, and hence have undergone relatively limited genetic improvement. They are hardy crop plants enabling them to be cultivated in challenging agro-ecologies and in an environmentally sustainable manner. When consumed as substantially whole grain foods, ancient grains can provide significant levels of phytochemicals with evidence-based health-promoting activities.

On the basis that several pulses (grain legumes) have only undergone limited genetic improvement, are traditional staple food grains, good sources of many macro- and micronutrients and contain significant levels of phytochemicals, the author is strongly of the opinion that such pulses should also be considered as ancient grains, in addition to the cereals and pseudocereals aforementioned. Hence, some pulse types are the subjects of chapters in the book.

2.2 Grain Species Dealt With in This Book

This book is focused on a limited number of ancient grain species:

- *True cereals*: sorghum (*Sorghum bicolor* (L.) Moench); all the 11 economically significant cultivated millet species: Barnyard millet (also known as Indian barnyard millet) (*Echinochloa frumentacea* Link), Finger millet (*Eleusine coracana* (L.) Gaertn.), Foxtail millet (*Setaria italica* (L.) P. Beauv.), Japanese barnyard millet [*Echinochloa esculenta* (A. Braun) H. Scholz], Kodo millet (*Paspalum scrobiculatum* L.), Little millet (*Panicum sumatrense* Roth), Pearl millet (*Pennisetum glaucum* (L.) R. Br.), Proso millet (*Panicum miliaceum* L.), Fonio (*Digitaria exilis* (Kippist) Stapf and *D. iburua* (Stapf) and Teff [*Eragrostis tef* (Zucc.) Trotter], and Wild rice (*Zizania* spp.).
- *Pseudocereals* (starch seeds of cotyledonous plants): Amaranth (*Amaranthus* spp.); Buckwheat [*Fagopyrum esculentum* (Moench) and *F. tataricum* (L.) Gaertn.]; and Quinoa [*Chenopodium quinoa* (Willd)].
- *Pulses*: African yam bean [*Sphenostylis stenocarpa* (Hochst. ex A. Rich.) Harms]; Bambara groundnut (*Vigna subterranea* (L.) Verdc.; Cowpea (*Vigna unguiculata* (L.) Walp); Marama bean [*Tylosema esculentum* (Burch.) A. Schreib.]; West African locust-bean [*Parkia biglobosa* (Jacq.) R. Br. ex G. Don]; and Lupins (*Lupinus* spp.).

These grains contain either starch and/or protein as their major nutrients and normally high levels of B vitamins and minerals, and importantly all are rich in phytochemicals.

The major criterion for inclusion of these particular grains is that they have been, and largely staple are staple foods for local rural communities in less developed regions of the world and importantly, they have the potential to become significant sources of nutrients and health-promoting phytochemicals for the wider world. A second important criterion related to their nutrient composition is that all these grains are gluten-free and can be consumed by celiacs. Hence, primitive wheat and cereals related to wheat (members of the Pooideae subfamily) are excluded, such as barley, oats, and rye. Also excluded, in the interests of conforming to the definition of ancient grains as traditional staple foods and maintaining the book's focus, as well as keeping it to manageable proportions, are oil-rich seeds, such as chia, flax, and jobaba.

3 WHAT IS DRIVING INTEREST AND ACTIVITY IN ANCIENT GRAINS?

Today, there are many factors that are impacting on ancient grains as foods. The relative importance of the various factors and how they influence each other is almost impossible to quantify. However, for the sake of simplicity they are divided into drivers influencing production and consumption. Although, one directly affects the other.

3.1 Drivers Influencing Ancient Grain Production

[Table 1.1](#) summarizes the drivers of the ancient grain production—positive and negative. The most important is global food insecurity. According to the CGIAR institution Biodiversity International, to feed the predicted the world population of 9 billion people by 2050 and at the same time protect the environment and provide healthy and nutritious food, we need a more diverse agricultural and food systems than at present ([Padulosi et al., 2013](#)). Currently, just 103 crops provide 90% of the world's calories from starch. Furthermore, wheat, maize, rice, and potato account 60% of the starch caloric intake.

The continent most affected by food insecurity is Africa. In the past 50 years its population has increased by more than 400%, whereas, cereal production has only increased by 300% ([FAO, 2014](#)). The impact of this can be seen by the very high incidence of undernutrition. Data for 2011–13 reveal that 25% of Africa's people were undernourished compared with an overall figure, for developing countries, of 14% ([FAO, 2014](#)). This dire situation is likely to get worse. FAO's predictions is that the world's population will increase by 2 billion (a 14% increase) over the 40 year period from 2010 to 2050. Sub-Saharan Africa's population will be more than double, increasing alone by 1 billion people ([FAO, 2009](#)). The FAO furthermore predicts that, to meet the world's demand, global cereal production will have to increase from 2.1 to 3 billion tonnes over this 40 year period.

TABLE 1.1 Drivers Related to Ancient Grain Production	
Drivers	Ancient Grain Crop Characteristics
<i>Food Supply Issues</i>	
Promotion of production and consumption of ancient grains by international governmental and official organizations like the FAO and CGIAR institutions—driven by concerns over global food security	Ancient grains are a greatly underutilized food resource
Rapid population growth in developing countries—threat to food security	Yield potential of ancient grains currently lags behind the major grains
Climate change—adverse influence on crop production in tropical and subtropical regions	Ancient grains noted for ability to yield under harsh conditions
Genetic engineering breeding technology—short cut to increase in crop yields and grain quality	No genetically modified ancient grain is currently in commercial production—mitigates against cultivation in countries cultivating genetically modified (GM) maize
Hybrid cultivar technology—higher yield potential than open-pollinated varieties but higher inputs are generally required	Ancient grain hybrid cultivars increasingly developing
Improved varieties—higher yield than traditional landraces	Improved ancient grain varieties are rapidly and widely being implemented, even in small-holder agriculture
Biofortification—breeding of crop varieties with high levels of critical micronutrients	Considerable success has already been achieved with mineral biofortification of sorghum and pearl millet
Sustainable and conservation agriculture—reduced adverse effects on the environment	Ancient grains noted for their capacity to produce a crop with minimal inputs
Large-scale mechanized agriculture—reduced production costs	Improved open pollinated varieties and preferably hybrids are required
<i>Societal concerns</i>	Not applicable
Great resistance to genetic modification of ancient grains—concerns about environmental impacts and loss of genetic diversity—both uninformed and some informed concern	Ancient grains by their very nature are valued because they have great genetic diversity and perceived to be natural
Resistance to the implementation of ancient grain hybrid cultivars—concerns about viability and morality of hybrid seed systems in developing countries—both informed and uninformed concern	As aforementioned

The overarching concern is the impact of climate change on agriculture. The yearbook of [FAO \(2014\)](#), *Food and Agriculture Statistical Yearbook*, states that “the poorest and most food-insecure regions will be the most vulnerable under climate change. Scarce land and water resources will likely become even scarcer, and insufficient technical and financial means will make adaptation to the new climate very difficult.” There is evidence that the ancient grains are very well adapted to cultivate under harsh environment conditions (high temperatures, low and intermittent rainfall, and poor soils) and they can produce a moderate consistent crop yield with low agricultural inputs ([National Research Council, 1989, 1996, 2006](#)). One reason for their low requirement for agricultural inputs, such as agrochemicals is that many of their phytochemicals, especially the polyphenols, confer natural protection to the plants and seeds against biotic stresses like molds, insects, and birds ([Lattanzio et al., 2006; Waniska, 2000](#)).

With regards to water-use efficiency, a comparative yield study between maize and sorghum in a hot and dry type environment (North-East Spain), showed that maize out-yielded sorghum, when the crops were well irrigated, but sorghum out-yielded maize under conditions of moderate and severe water deficit ([Farré and Faci, 2006](#)). The ancient grains are also particularly well suited to sustainable, low-energy cultivation practices. For example, in an 8 year cultivation trial in the Sahel (Sahara desert margin region), crop rotation of sorghum and pearl millet (cereals) with cowpea (legume) increased sorghum and pearl millet yields by 18% and 23% on loamy sand and loam soils, respectively ([Kouyaté et al., 2000](#)). Additionally, with green manuring, cowpea yields were increased by 37% and 27%, respectively.

Concerning the implementation of modern plant breeding and cultivation technologies for ancient grains, as [Table 1.1](#) shows there is some conflict of interests. There is a clear need of considerable increase in the agricultural productivity of ancient grains if they are to become major food crops in the global food system. However, the implementation of newer technologies, such as hybrid cultivars and genetic modification in conjunction with high input and large-scale mechanized agriculture, is potentially at odds with the whole notion of the grains being ancient and sustainable.

3.2 Drivers Influencing Ancient Grain Consumption

[Table 1.2](#) summarizes the drivers of consumption of ancient grains—both positive and negative. As can be seen, many of the positive drivers for increased ancient grain consumption are nutrition and health related.

The study of the nutritional quality for foods is still a rapidly developing science. It started with the provision of basic food nutrient composition data, so-called food composition databases, such as the USDA’s National Nutrient Database for Standard Reference ([USDA NDL, 2016](#)). It has moved to the study of the bioavailability of these nutrients. In other words, when the food is digested, will the nutrients be absorbed, metabolized, and exert physiological effects?

TABLE 1.2 Drivers Related to Ancient Grain Consumption

Drivers	Grain Characteristics
<i>Nutrition and health issues</i>	
Gluten-free—both informed and uninformed concerns	Certain ancient grains, including all those dealt with in this book, are gluten-free. However, ancient and heirloom wheats and related cereals are not
Ultraprocessed foods—generally uninformed concern	Ancient grains, that are not highly refined to produce traditional food products, but can can be when used to produce modern food products
Whole grains—both informed and uninformed concerns	As aforementioned
Obesity pandemic—leading to type 2 diabetes and cardiovascular disease— informed concern	Some evidence of specific positive physiological effects of phytochemicals, such as reducing glycemic response, slow gastric emptying, reducing protein glycation, and hypertension
Cancer—increased risk of cancer with aging populations—general concern	Good evidence of specific phytochemical effects
General consumer in perception both developed and developing countries that ancient grains are more nutritious and healthy than common cereals, such as wheat and maize—generally uninformed perception	See aforementioned
GM—generally uninformed concern	Currently no ancient grains are genetically modified
<i>Social Issues</i>	
Food trending—demand for novelty in foods (unusual and exotic foods) in developed countries	Ancient grains generally have a more pronounced color, flavor, and texture than common wheat and maize
Ethnic foods—related to the aforementioned, but driven by mass movement of people from developing to developed countries	The ancient grains were and are still the traditional foodstuffs in developing countries
Fair trade—morality issue—feel good factor “helping poor people in developing countries”	Not applicable
Urbanization and its resulting changing lifestyle in developing countries—demand for convenience, ready-to-eat type foods	Ancient grains no more difficult to make into convenience foods than maize
Rising incomes in developing countries—demand for aspirational foods (i.e., media promoted food products that people in developed countries eat)	No intrinsic advantage or disadvantage-aspirational products, such as lager beer can be and are produced from ancient grains
Widespread perception in developing countries that their own ancient grains are a “poor man’s food”—related to the aforementioned	Not applicable

Probably the most well known measure of nutrient bioavailability is glycemic index (GI), which measures the bioavailability of α -glucan type carbohydrates in foods ([Glycemic Index Foundation, Undated](#)).

The next frontier is beyond nutrition, with the recognition of food-plant foods, and especially certain whole grains, are rich in health-promoting chemical components ([Liu, 2007](#)), referred to as phytochemicals, phytonutrients, or simply bioactive compounds. The thesis is that, regular consumption of foods rich in specific phytochemicals can exert specific physiological effects, which prevent or alleviate noncommunicable diseases, such as type 2 diabetes, cardiovascular disease, and certain cancers ([Belobrajdic and Bird, 2013](#); [Taylor and Duodu, 2015](#)). This has led to the associated concepts of functional foods and nutraceuticals. Where, the former can be defined as a true food product which has demonstrated physiological benefits and/or reduce the risk of chronic disease beyond basic nutritional functions, and the latter as a substance isolated from a foodstuff, often sold in a medicinal-type format, that has such physiological effects ([Health Canada, 1998](#)).

Another health-related driver of interest in, and consumption of ancient grains by consumers in high-income countries, which goes in tandem with the hype about supposed ill-effects resulting from wheat consumption ([Brouns et al., 2013](#)), is the gluten-free character of many ancient grains. Not surprisingly, among governmental organizations, the health interest in ancient grains are more concerned about their potential major role in combating undernutrition and in preventing and reversing the pandemic of obesity and its associated diseases, such as type 2 diabetes, cardiovascular disease, and certain cancers. For example, in a recent article of the Bulletin of World Health Organization (WHO), [Jones and Ejeta \(2016\)](#) identified ancient grains, pulses, fruits, and vegetables not only on account of their market potential for small-holder farmers, but also because they are essential for preventing malnutrition, undernutrition and obesity, and diet-related diseases. See also the Foreword to this book by Professor Gebisa Ejeta, who was awarded with the World Food Prize in 2009.

World Health Organization data, show that increasing overweight and obesity is a global crisis, which threatens the health of people worldwide. Worldwide obesity has doubled since 1980 and by 2014 more than 1.9 billion adults (39% of all adults) were overweight and 600 million (13%) were obese ([WHO, 2016](#)). With the exceptions of Asia and Africa, so-called overnutrition is now responsible for more deaths than undernutrition. However, obesity in low and middle-income countries is increasing rapidly ([Haggblade et al., 2016](#)). The most frightening fact is the growing number of young children in urban areas of developing countries, who are overweight and obese, with Asia accounting for nearly half the worldwide total. The consequences will be dire if the trend is not reversed. In South Africa (a rapidly urbanizing developing country), some 2.3 million adults (7% of the adult population) have diabetes with an annual healthcare cost of US \$900 per individual and nearly 60,000 people die each year due to this disease ([International Diabetes Federation, 2015](#)).

In relation to dietary habits, in the rapidly growing cities of developing countries, there is a dramatic nutrition transition, taking place in the diet of the youth (the so-called millennials). For example, across sub-Saharan Africa, the traditional predominant plant-based nutrient- and phytochemical-rich diet is giving way to a refined carbohydrate- and fat-rich diet of convenience-type food (Haggblade et al., 2016). The reason for this transition is that these Western-type products like hamburgers, french-fries, and carbonated sugar-sweetened soft drinks are considered by the young consumer as meeting their lifestyle and fulfilling their aspirations. Among those concerned by the health implication of this change in eating habits, such products have acquired the somewhat misleading label of ultraprocessed food (Monteiro et al., 2013).

A related driver impacting negatively on ancient grain consumption is that many young people in developing countries regard their traditional food crops as economically inferior food “the foods that poor people eat” (Padulosi et al., 2013). However, there is an ambivalence in attitude as these self-same foods, which “grandmother always used to make” are also regarded by these young urban consumers as being particularly nutritious and healthy. This is creating a new demand for ancient grains, as exemplified by the fact that a multinational food company recently introduced a pearl millet based line of its global instant weaning food product in West Africa (Nestlé, 2013).

Similarly, in middle- and high-income countries, the whole grain and ethnic food trends, and the artisan and craft food movement signal a positive development of expanding demand for traditional “more natural” and healthy food and beverage products. According to the Oldways Whole Grains Council (2016), the whole grain stamp is now on 11,000 food products worldwide. Specifically, regarding ancient grains, data from the USA indicate a dramatic rise in restaurant products containing these grains: sorghum (64% increase), millet (*sic*) (46%), quinoa (33%), and amaranth (29%).

4 BOOK SCOPE AND CONTENT

This book is divided in three parts—the first two chapters (Chapters 1 and 2) provide the background; the second and major part (Chapters 3–10) comprises chapters on each individual ancient grain type; and the third part (Chapter 11) looks at the research needs for the ancient grains along the value chain.

4.1 Chapter 2: Global Supply of Ancient Grains in the 21st Century

Following this present introductory chapter, which concerns the importance of ancient grains in nutrition and health and in a wider food security context, Chapter 2 addresses the critical issue of the supply of ancient grains to meet current and future demands. The author, Dr. Timothy Dalton, an agricultural

economist, is the Director of the USAID Sorghum and Millet Innovation Lab (SMIL) Feed the Future project based at Kansas State University.

The key conclusion is that the global supply of the various ancient grains is, with some exceptions, limited to a lack of crop improvement. A positive finding is that sustained consumer demand will improve ancient grain supply, driven in high-income countries by the healthy food image of these grains. However, he cautions that, ancient grains in low-income countries, where they are predominantly cultivated, as has been pointed out, regarded as economically inferior foods, and therefore the demand could fall with rising incomes. A last observation of overarching importance is the need for better and more easily accessible statistics that track ancient grain production and consumption. These data are necessary to determine ancient grain usage patterns and the factors that will influence agricultural productivity and their supply.

4.2 Chapters 3–10: The Ancient Grains Species Specific Chapters

The grain species-specific chapters, which deal with sorghum, millets, amaranth, quinoa, buckwheat, lupins, African legumes, and wild rice, follow essentially similar format. Each chapter is written by respected experts on the particular grains.

The topics covered in each chapter are:

- description of the grain specie(s),
- production data and cultivation practices,
- grain macro- and micronutrient content,
- detailed information on their particular composition of phytochemicals,
- a comparison of nutrient and phytochemical content with that of major food grains, such as wheat,
- information on any particular antinutrients and toxins present,
- food processing technologies,
- traditional, ethnic-type foods
- modern food products with an emphasis on the gluten-free market,
- effects of food processing on nutrients and phytochemicals, and their bio-availability,
- their health-enhancing (functional food) properties, especially with respect to combating diseases, such as obesity, type 2 diabetes, cardiovascular disease, and cancer,
- concluding remarks on future prospects for the particular grain.

4.3 Chapter 11: Future Research Needs for the Ancient Grains

This last chapter, written by the editors, critically evaluates the science and technology, research and development needs along the value chain that are required to make ancient grains, mainstream foods, globally. Throughout, are two

important crosscutting themes: the role that international collaborative research and support programs can play in achieving this goal and, second learning from past successes and failures. The chapter concludes with brief recommendations as to the research priorities for the ancient grains.

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Chapter 2

Global Supply of Ancient Grains in the 21st Century: Keys to Unlocking Their Full Potential

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1 INTRODUCTION

Ancient grains are often characterized by a lack of derivative breeding to improve intrinsic characteristics, such as yield, resistance to lodging, disease resistance, or adaptation to novel biotic environments. This implies that they have not evolved faster than the pace of natural selection and as such, most ancient grains are not cultivated on a wide scale but are more geographically associated with the location of their genetic origin. That is not to say that these grains are not grown outside of their origin but where so, these locations share many of the key agro-ecological factors associated with the location of their genetic origin. There are exceptions to this guideline with sorghum and some of the millets, and even with others, as their market appeal broadens to a wider set of consumers.

Initial demand for ancient grains was highly local and with several grains they were used in ritual practice or even held as something to be worshiped. However, over the time, demand grew out of these regions and through trade became global commodities used as whole grains or incorporated into processed products. Current demand for ancient grains varies by crop and also varies over time.

This chapter will examine some of the supply and demand dynamics associated with ancient grains. The aim is to determine what are the keys to unlocking the global food potential of these “climate-friendly” underutilized grains. This is a challenging topic because there is limited area, production, and consumption information on many of the grains. Because of the dearth of statistical information available for many ancient grains, this chapter is limited to a subset of crops where data is available from the United Nations Food and Agriculture Organization (FAO) (FAOSTAT, 2016).

2 SUPPLY AND DEMAND OF ANCIENT GRAINS

Supply and demand for ancient grains is heterogeneous and more is known about those that are widely traded, for example quinoa (*Chenopodium quinoa* Willd), sorghum (*Sorghum bicolor* (L.) Moench), some millets, and buckwheat (*Fagopyrum* species) than for those with limited global trade, for example fonio (*Digitaria* species), teff (*Eragrostis tef* (Zuccagni) Trotter), and amaranth (*Amaranthus* species). Those that are widely exchanged are captured in the accounts of global trade. However, even within the category of official trade, it is unclear what percentage of trade occurs in landrace varieties of, for example sorghum, which is commonly grown in low-income semiarid tropical nations versus what is grown from modern hybrid varieties. Sorghum adapted to temperate agro-ecologies does not fit the definition of an ancient grain yet it is this sorghum that is commonly grown in higher income nations and enters into global trade.

2.1 Sorghum

Global statistics on sorghum are the most complete of the ancient grains. Sorghum is grown in nearly 1/3 of all nations of the world with 90% of all area concentrated in 19 nations (Fig. 2.1). Production; however, is concentrated within 15 nations illustrating differences in illustrating the high heterogeneity of per hectare national yields ranging from more than 5.5 metric tonnes (MT)/ha to less than 0.20 MT/ha (Fig. 2.2).

The second defining characteristic of the global sorghum economy relates to utilization. There is a clear pattern of consumption of sorghum into two primary uses: the share consumed as human food and that consumed as an animal feed (Fig. 2.3). The distribution is bimodal with most middle- and high-income nations consuming sorghum primarily as an animal feed while low-income nations consume the grain as a staple food or processed food products. China

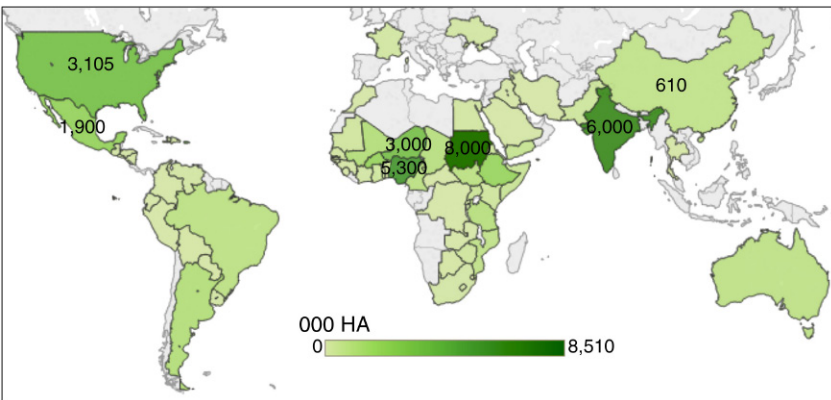


FIGURE 2.1 Estimated area of sorghum, harvested by country in 2015 (‘000 ha). (Author’s calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>)

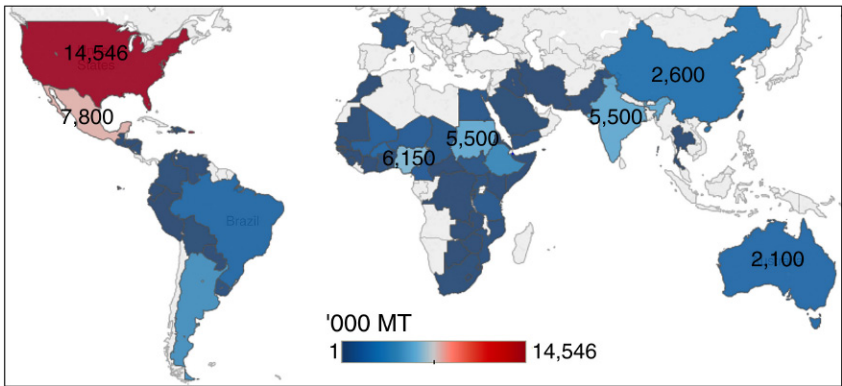


FIGURE 2.2 Estimated total production of sorghum by country in 2015 ('000 MT). (Author's calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>)

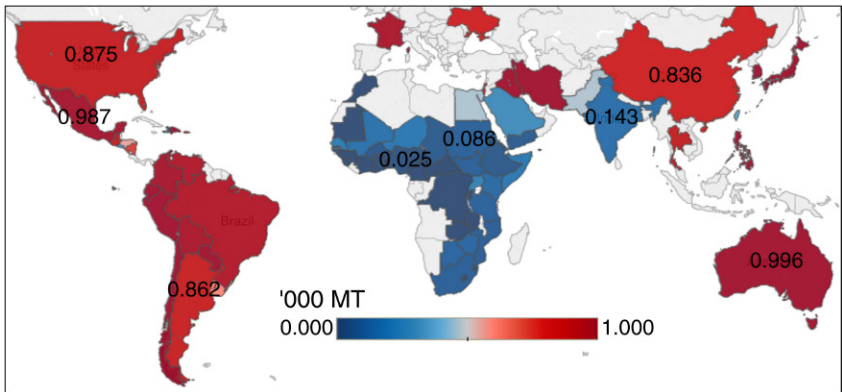


FIGURE 2.3 Share of total consumption of sorghum used as animal feed by country in 2015 (%). (Author's calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>)

consumes 20% of global production, which is double its nearest competitor, Mexico. Usage in ethanol production has been important in the recent past, but fluctuates according to the global supply of oil and substitute commodities used in ethanol production (Fig. 2.4). The demand for sorghum as a feedstock has largely shaped patterns of trade with surplus producing nations shipping to deficit nations (for both feed and food) and globally this translates to a nearly 86% of the global trade in sorghum being imported by China in 2015 (Fig. 2.5).

2.2 Millets

The category of “millets” refers to several specific species: pearl, finger, proso, fox-tail, little, kodo, barnyard (Indian barnyard) Japanese barnyard, and other millets. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT),

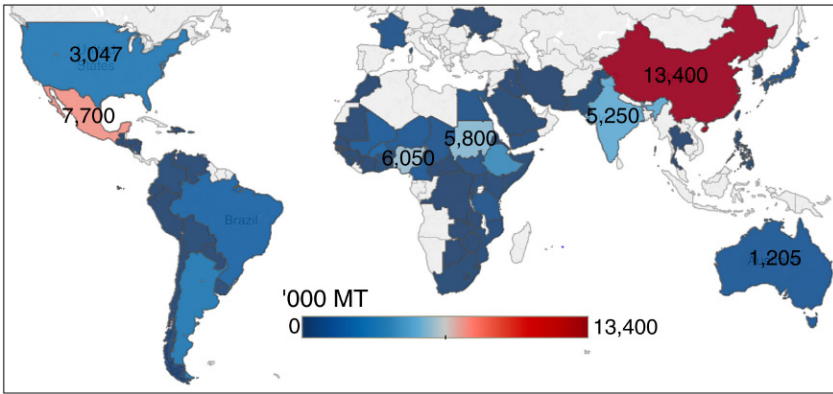


FIGURE 2.4 Estimated total consumption of sorghum by country in 2015 ('000 MT). (Author's calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>)

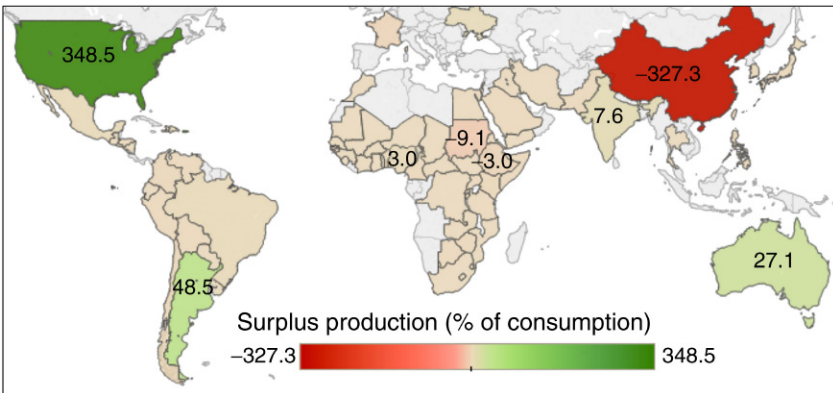


FIGURE 2.5 Surplus sorghum production as a percentage of consumption in 2015 (%). (Author's calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>)

the CGIAR (Consultative Group for International Agricultural Research) institute responsible for millets, argues that 50% of millet production is in pearl millet and that 90 million people depend upon this specie for food and income (ICRISAT, 2016).

Production and consumption statistics for each species are difficult to obtain but Fig. 2.6A illustrates that total area of combined millets is nearly equally split between Africa and Asia, while production is proportionately higher in Asia (Fig. 2.6B). Millets are produced in 84 nations but 90% of all production occurs in 13 nations. India dominates production of millets, mainly pearl millet and finger millet and produces 41% of global supply. Its production is some three and half times greater than Niger on just 25% additional land. This is largely due to the success of improved and hybrid varieties of pearl millet grown in India. Combined,

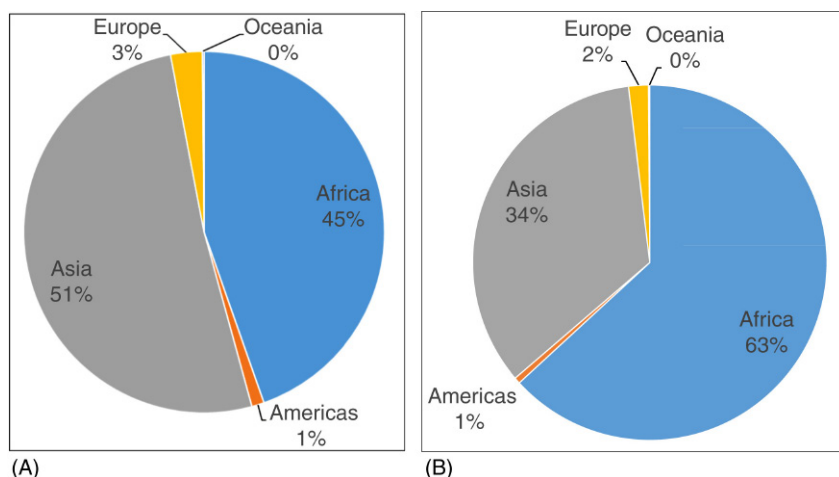


FIGURE 2.6A (A) Millet production by region (% of total production). (B) Millet area by region (% of total harvested area).

African Sahelian (Sahara desert margin) nations produce 38% of the world's millets and these nations primarily grow pearl millet as this region is the center of genetic origin for the crop. There is very limited global trade in pearl millet.

2.3 Quinoa

Global supply and demand of quinoa has risen dramatically in the past decade and in the past 5 years has increased by nearly 150%. Area under cultivation has increased exponentially (Fig. 2.7) and production has followed proportionately (Fig. 2.8). Three Andean nations, Bolivia, Ecuador, and Peru plant and produce most of the world's quinoa but the recent surge in demand has led to new plantings in the Pacific Northwest, Idaho, and California in the USA. Global demand for quinoa has contributed to increased welfare of Peruvian quinoa farmers through greater incomes and a reduction in income variability despite rising prices for consumers (Bellemare et al., 2016).

2.4 Buckwheat

Buckwheat production is concentrated in a very few temperate nations, with over two-thirds of global supply produced in China and the Russian Federation in 2014. Ukraine, France, Poland, and the USA produced 4%–8% of global supply each and combined these six nations' account for nearly 90% of global supply (Fig. 2.9).

Since 1961, the area under cultivation and production of buckwheat has evolved to the point that the average yield is approximately 1 MT/ha illustrating a doubling of productivity during a 20-year period. However, long-term trends in buckwheat production show an average annual decline in supply of nearly

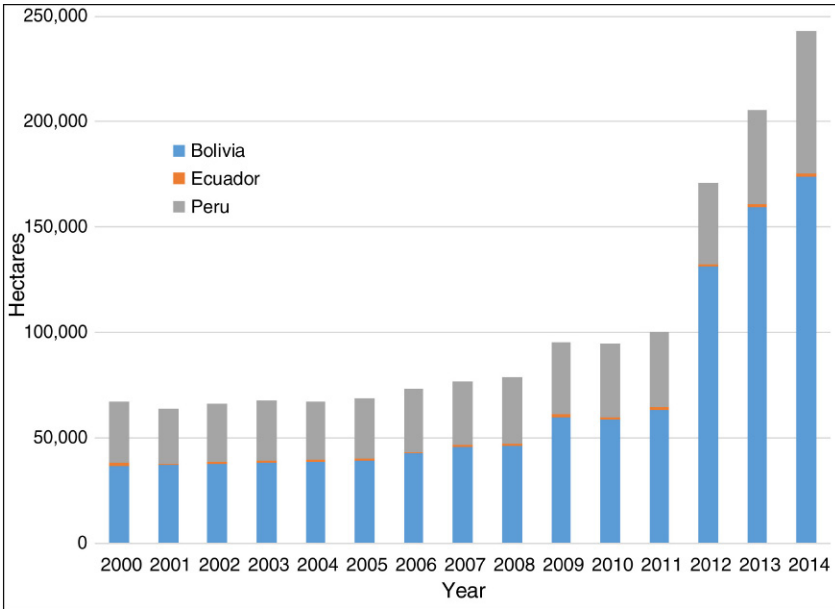


FIGURE 2.7 Area harvested of quinoa by country and year. (Author's calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>.)

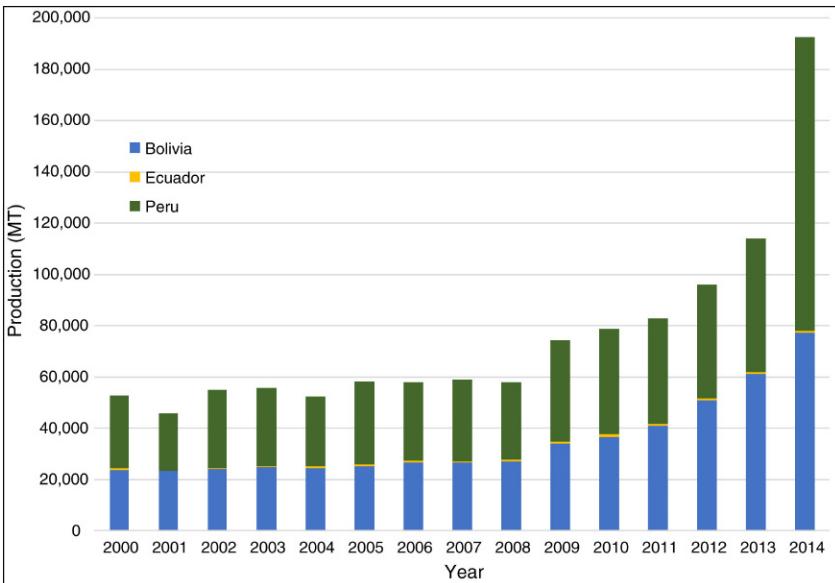


FIGURE 2.8 Total production of quinoa by country and year (MT). (Author's calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>.)

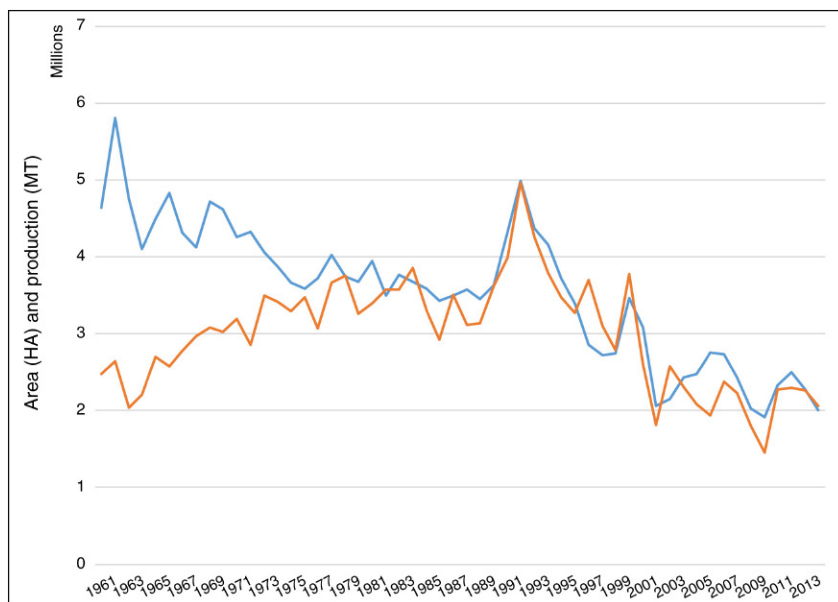


FIGURE 2.9 Global buckwheat area (blue) and production (brown) 1961–2014. (Author's calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>)

50,000 MT per year. But in the last 15 years, production trends are nearly flat, when annual variation is removed.

2.5 Fonio

Fonio production is geographically specific to West Africa. Seventy-six percent of global supply is produced in Guinea followed by Nigeria, Mali, and Côte d'Ivoire. The small size of the fonio grain, combined with its ease of shattering, produces yields that rarely exceed 1 MT/ha (Fig. 2.10). This is an example where limited research on improving crop productivity prevents expansion of supply to generate new opportunities for broader consumption.

3 CONCLUSIONS

- Global supply for ancient grains can be considered limited except for special cases where crop improvement, through plant breeding, has increased per hectare yields. This is the case with buckwheat, sorghum, and pearl millet, and to a lesser extent, with finger millet as well.
- Supply has also been increased through area expansion, as the case with quinoa in the Andes and more recently in other regions attempting to adapt the crop to similar growing conditions. A third trend, for example in buckwheat, is the long-term decline in total production as consumer preferences shift toward other products.

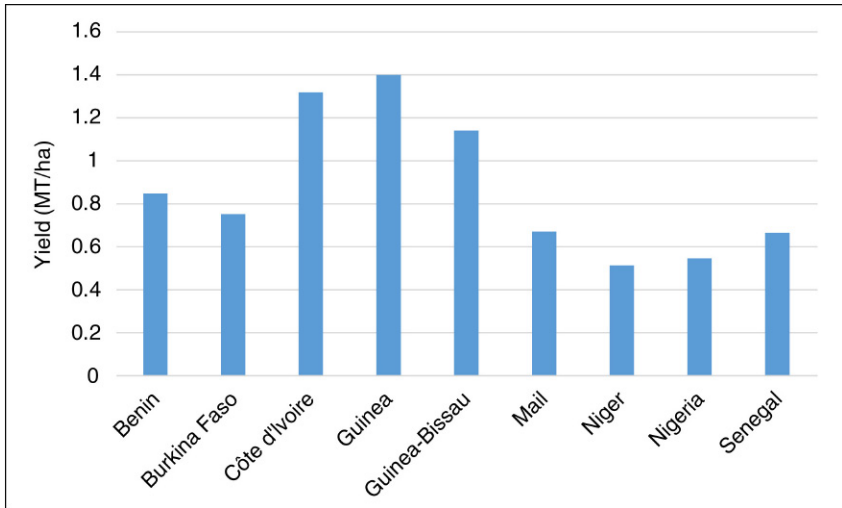


FIGURE 2.10 Comparative yields of fonio in 2014 (MT/ha). (Author’s calculation from FAOSTAT, 2016. Production: Crops. <http://faostat3.fao.org/beta/en/#data/QC>)

- Sustained consumer demand will trigger response in the supply of ancient grains and pseudocereals internationally, as it has with quinoa. Localized demand will remain stable, unless alternative crops with higher productivity, such as maize replace these grains.
- Current demand trends in high-income nations for “super-foods” or ancient grains may reflect health benefits or marketing claims since most increase in demand is occurring in those nations. In low-income nations, where many of these grains are produced, they may be considered economically “inferior” foods whose demand declines as income increases. Whether these labels are sufficiently strong to sustain a secondary demand-pull by high-income consumers, following the case of quinoa, remains to be seen.
- The third defining characteristic of ancient cereal grains and pseudocereals is that there are limited official and easily accessible statistics that track production and consumption. Some success has been made with the sorghum, millet, and a few of the region-specific cereals but more often than not, detailed statistics are found in national archives. Future research in this area will need to delve into this information to uncover usage patterns and the factors that affect productivity and supply.

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Chapter 3

Sorghum: Its Unique Nutritional and Health-Promoting Attributes

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1 INTRODUCTION

Sorghum is a drought-tolerant cereal grain that serves as the major staple for populations in many semiarid regions of Africa, including Niger, Burkina Faso, Mali, Ethiopia, the Sudan Region, among others. The grain is also a major food crop in some semiarid parts of India and Central America. Because the populations that consume sorghum as a staple are generally low income, sorghum has not experienced the dramatic genetic transformation geared toward increased productivity like the major cereal staples, for example, maize, have undergone. Global sorghum production is limited relative to the big three (maize, rice, and wheat); in 2013, world sorghum production was 55.5 million metric tons (MMT), compared to maize, rice, and wheat at 1018, 736, and 711 MMT, respectively (FAO, 2014). Despite the fact that overall production and productivity of the major cereal grains have grown tremendously over the past few decades (e.g., more than twofold for maize, 37% for rice, and 27% for wheat, between 1993 and 2013) driven largely by yield-based genetic enhancements, sorghum production has essentially stagnated over the same period, with declining trends in major producing countries like the USA, India, and Nigeria (FAO, 2014). The image of sorghum as a poor man's food may be a factor for the decline in some countries, which would not be strange because when economies improve, people tend to Westernize their diets around the world. However, in some countries in Africa where sorghum is considered an important food security crop, production has increased considerably, for example, in Ethiopia production has increased on an average of 10% per year from 0.63 MMT in 1993 to 3.8 MMT in 2013, largely driven by enhanced productivity (FAO, 2014).

In developed regions, like the USA, sorghum is produced mainly for feeding animals, with small amounts used for industrial alcohol production. Sorghum, thus remains a niche crop in the food chain in developed countries, and is mostly marketed for specialty applications, like gluten-free products and health-based

foods. Consequently, the overall incentive to increase sorghum productivity has been limited because of availability of alternative feed grains, especially maize, in the developed countries. However, the growing scarcity of fresh water for crop production, along with renewed consumer interest in alternative food sources like “ancient grains” is likely to benefit sorghum production for food use in the developed countries.

Sorghum has an incredible genetic diversity, with more than 40,000 accessions in the world collection (Rooney and Awika, 2005). The grain is generally spherical, and weighs 20–30 mg. It is an environmental-friendly crop to produce, because of its high water use efficiency and relatively low input (fertilizer, pesticides) requirements compared to other grains. Additionally, sorghum is heat tolerant and actually thrives (and mostly produced) in hot environments. Thus, the grain is well positioned as a climate-change friendly crop and is likely to be more relevant to world food supply in the future.

The most unique beneficial aspect of sorghum as human food is perhaps its composition of polyphenol compounds (Awika, 2011; Awika and Rooney, 2004; Dykes et al., 2005). Sorghum has a diverse array of phenolic compounds not commonly found in other cereal grains and some of these compounds, for example, 3-deoxyanthocyanins, are not known to exist in any other edible plants (Awika and Rooney, 2004). More importantly, the phenolics and other compounds in sorghum seem to have important and unique bioactive properties relevant to cancer prevention, cardiovascular health, and reduced chronic inflammation and oxidative stress, among others (Awika et al., 2009; Burdette et al., 2010; Carr et al., 2005; Chen et al., 1993; Yang et al., 2009, 2012, 2015). Recent evidence also suggests polymeric sorghum polyphenols (tannins) may be useful as natural ingredients to reduce the caloric impact of starch (Amoako and Awika, 2016a,b; Barros et al., 2012, 2014). The type of phenolic compounds accumulated by sorghum is controlled by a set of well-documented genes (Rooney, 2000; Boddu et al., 2005), and various sorghum phenotypes with different seed colors are commercially available (Fig. 3.1). Thus, selection and genetic improvement of sorghum for targeted health applications is possible. This will become increasingly relevant as more evidence is accumulated on the specific structure-activity mechanisms of the sorghum polyphenols on disease prevention. Sorghum offers exciting opportunities as a food ingredient and source of compounds that can be used to enhance health properties of foods. Available evidence and potential applications will be highlighted in this chapter.

2 NUTRITIONAL QUALITY OF SORGHUM

2.1 Proximate Composition

In terms of proximate composition, sorghum is generally similar to maize (Table 3.1), and their overall nutrient energy content is similar. However, from a nutritional perspective, sorghum may have distinct advantages and disadvantages depending on the nutritional status of the consumer. For example, cooked sorghum



FIGURE 3.1 Mature panicles of different types of sorghum in the field. Black (left), white (middle), and red (right) sorghum. (Images taken by author at Texas A&M University farm, College Station, TX, USA.)

endosperm has a slow digesting starch profile, believed to be due to crosslinked kafirin proteins hindering α -amylase access to starch (Zhang and Hamaker, 1998). This property is of benefit to diabetics, and may contribute to improved satiety, an important benefit in an increasingly over-fed world. On the other hand, sorghum protein generally has a lower digestibility, than other cereal proteins, which is a concern where protein-energy malnutrition (PEM) is a problem.

Starch is the major component of sorghum, like other cereal grains and pseudocereal grains, and constitutes about 72% of the whole grain, and about 86% of endosperm on a dry basis. The starch is mostly located in the endosperm; however, unlike other cereal grains, some sorghum varieties contain starch in the pericarp. This can make grains that contain a pigmented testa, and are genetically classified as tannin-sorghums, appear to be white in color. Sorghum starch is generally similar to maize starch in both shape and size, ranging from spherical to angular depending on location in the endosperm, and from 4 to 25 μm in size. Sorghum starch, however, tends to have a higher gelatinization temperature range (68–75°C) than maize (62–72°C), and other cereals (e.g., wheat, 51–72°C; and rice, 61–74°C). This is an important property that must be considered when designing optimal processing conditions for the grain, since higher energy may be required to achieve equivalent degree of cook for

TABLE 3.1 Typical Composition (%) of Whole Grain Sorghum Relative to Maize, Brown Rice, and Wheat

	Sorghum	Maize	Rice (brown)	Wheat
<i>Protein</i>	8.6–15.6 (11)	8.3–10.5 (10.1)	5.1–8.6 (6.5)	10–17 (12)
<i>Available carbohydrates</i>	60–75 (70)	68–75 (72)	78.5–83.3 (81)	70–76 (74)
<i>Lipids</i>	2.3–4.9 (3.3)	3.8–5.5 (4.5)	1.9–3.6 (2.8)	2.2–3.5 (2.8)
<i>Ash</i>	1.1–2.5 (2.0)	1.0–1.6 (1.4)	0.7–1.5 (1.0)	1.7–2.3
<i>Dietary fiber</i>	8.7–13.0 (11.0)	12.0–14.5 (13.0)	2.9–5.0 (4.0)	12.0–16.5 (14.0)

All values on a dry basis, typical average values in parentheses.

Source: Virupaksha, T.K., Sastry, L.V.S., 1968. Protein content and amino acid composition of some varieties of grain sorghum. *J. Agri. Food Chem.* 16, 199–203; Bressani, R., Benavides, V., Acevedo, E., Ortiz, M., 1990. Changes in selected nutrient contents and in protein quality of common and quality protein maize during rural tortilla preparation. *Cereal Chem.* 67, 515–518; Ramulu, P. Rao, P.U., 1997. Effect of processing on dietary fiber content of cereals and pulses. *Plant Foods Human Nutr.* 50, 249–257; Awika, J.M., McDonough, C.M., Rooney, L.W., 2005. Decorticating sorghum to concentrate healthy phytochemicals. *J. Agri. Food Chem.* 53, 6230–6234; Ohtsubo, K.I., Suzuki, K., Yasui, Y., Kasumi, T., 2005. Bio-functional components in the processed pre-germinated brown rice by a twin-screw extruder. *J. Food Comp. Anal.* 18, 303–316; Da Silva, L.P., De Lourdes Santorio Ciocca, M. 2005. Total, insoluble and soluble dietary fiber values measured by enzymatic-gravimetric method in cereal grains. *J. Food Comp. Anal.* 18, 113–120; Awika, J.M., 2011b. Sorghum flavonoids: unusual compounds with promising implications for health. *Advances in Cereal Science: Implications to Food Processing and Health Promotion*. American Chemical Society, TX, pp. 171–200; Thomas, R., Wan-Nadiah, W.A., Bhat, R., 2013. Physiochemical properties, proximate composition, and cooking qualities of locally grown and imported rice varieties marketed in Penang, Malaysia. *Int. Food Res. J.* 20, 1345–1351.

sorghum as for other cereals. The dietary fiber of sorghum is mostly derived from cellulosic cell wall carbohydrates; more than 90% of the sorghum dietary fiber is insoluble.

Like other cereal grains, sorghum proteins comprise the water-soluble albumins, salt soluble globulins, alcohol soluble prolamins, and acid-alkali soluble glutelins. From a nutritional perspective, the albumins and globulins are the most desirable, owing to their high lysine content (5.5%–7%) (Taylor and Schüssler, 1986). Most of the globulin and albumin proteins fractions are found in the germ. The glutenins are poorly studied, but appear to be minor components of sorghum proteins. The sorghum prolamins (called kafirins) make up the majority of sorghum storage proteins, and are only present in the endosperm. These proteins make up about 70% of whole grain sorghum proteins, and about 80% of the endosperm proteins (Hamaker et al., 1995). Unfortunately, the prolamins are low in lysine, resulting in an overall low protein lysine content (averaging 2.0%) in sorghum grain (Table 3.2). However, it should be mentioned that all cereal grains that are deficient in lysine. High lysine sorghum mutants (about 3.0% of protein) are available, though not yet commercially produced to any great extent. The prolamins are high in glutamine and proline, and are exclusively found in distinct protein bodies, that have a relatively hydrophobic

TABLE 3.2 Essential Amino Acid and Selected Important Micronutrient Content of Sorghum

Essential Amino Acid	Average (Range) mg/g Protein	Micronutrient	Average (Range) mg/100 g Grain
Cysteine	13 (23–43)	Thiamin (B1)	0.60 (0.35–0.73)
Histidine	21 (14–31)	Riboflavin (B2)	0.14 (0.12–0.16)
Isoleucine	40 (23–43)	Niacin (B3)	3.1 (2.6–5.1)
Leucine	135 (90–148)	Vitamin B6	0.43 (0.40–0.50)
Lysine	21 (13–27)	Iron	5.7 (2.6–11.3)
Methionine	13 (09–36)	Zinc	2.8 (1.1–5.7)
Phenylalanine	49 (30–64)	Magnesium	140 (54–188)
Threonine	33 (20–43)	Potassium	320 (220–460)
Tryptophan	10 (8–22)	Calcium	21 (15–27)
Valine	50 (36–76)	Phosphorus	337 (301–350)

Source: Vietmeyer, N.D., Ruskin, F., 1996. Sorghum. In: Vietmeyer, N.D., Ruskin, F. (eds.), *Lost Crops of Africa Volume I: Grains*. National Academy of Sciences, Washington, DC; Verbree, C., Aitkenhead-Peterson, J., Loeppert, R., Awika, J., Payne, W., 2014. Shea (*Vitellaria paradoxa*) tree and soil parent material effects on soil properties and intercropped sorghum grain-Zn in southern Mali, West Africa. *Plant Soil* 386, 21; Bean, S.R., Wilson, J.D., Moreau, R.A., Galant, A., Awika, J.M., Kaufman, R.C., Adrianos, S.L., Ioerger, B.P., 2016. Structure and composition of the sorghum grain. In: Ciampitti, I., Prasad, V. (eds.), *Sorghum: State of the Art and Future Perspectives*, Agronomy Monographs, vol. 58. ASA and CSSA, Madison, WI.

surface (recently reviewed in depth by [Bean et al., 2016](#)). These aspects have important impact on sorghum protein functionality during processing, and its nutritional quality (reviewed in [Section 2.2](#)). Also, it is important to note that sorghum does not contain the gliadin proteins, which are responsible for gluten allergies, are commonly associated with wheat and related grains. Thus, sorghum is “gluten-free.”

The sorghum lipids are similar to maize in fatty acid profile, with linoleic acid and oleic acid constituting 80% of fatty acids, although sorghum is lower in lipids ([Table 3.1](#)). Sorghum tends to be relatively high in lipid waxes (fatty alcohols, wax esters, fatty aldehydes, etc.) compared to maize or other grains. For example, the content of wax is approximately 2.0 mg/g grain ([Weller et al., 1998](#)), which is about 50-fold higher than maize. Among the waxes, evidence suggests that polycosanols (fatty alcohols) may be beneficial in providing protection against cardiovascular disease ([Carr et al., 2005](#); [Gouni-Berthold and Berthold, 2002](#)). Sorghum contains about 75 mg policosanols/100 g grain.

Micronutrient composition of sorghum is unremarkable, relative to other cereal grains ([Table 3.2](#)). However, sorghum contains an average of twofold higher iron than maize. Most of these micronutrients are found in the pericarp and germ, thus grain processing has a major impact on the amount of the

nutrients consumed from the grain (see [Section 2.2](#)). Recognizing the important role of sorghum as a source of key micronutrients, various efforts to increase the content and bioavailability of key micronutrients in the grain (especially iron, zinc, and vitamin A), especially through biofortification via genetic, biotechnological, and agronomic practices, are underway.

2.2 Effect of Processing on Sorghum Nutritional Quality

Sorghum is traditionally used in diverse products, including various forms of thin and thick porridges in East and West Africa, flatbreads, like roti in India, injera in Ethiopia, and kiswa in the Sudan, along with alcoholic beverages. Such products often require processing that includes various combinations of mechanical (decortication, size reduction), biochemical (fermentation, malting), and hydrothermal (wet cooking) processes. Depending on the combination of processes used, the impact on nutritional profile of sorghum will be different.

2.2.1 *Decortication*

The decortication process also referred to as dehulling, although in fact the sorghum grain threshes free from its hull (the glumes) used in many traditional sorghum-based products involves mechanically peeling-off outer layers of sorghum grain with the primary aim of removing the pericarp. This is done to improve the sensory appeal of the grain, because the pericarp is high in cellulose and hemicellulose derivatives and secondary plant metabolites like polyphenols which impart undesirable texture, flavor, and color to products ([Fig. 3.1](#)). The decortication process, depending on the extent, can also increase shelf stability (reducing susceptibility to oxidative rancidity) of subsequently obtained flour by removing large portion of the germ that is high in lipids and lipolytic enzymes. Thus, sorghum decortication essentially accomplishes the same effect as the wheat-refining process during roller milling, where obtaining a pure endosperm is the ultimate goal.

A positive nutritional benefit of decortication is the reduction in levels of “antinutrients” like tannins (where present), which are concentrated in the outer layers of the grain. The tannins (discussed later) are large polyphenol polymers, present in a small subset of sorghum varieties, which can inhibit digestive enzymes and/or complex with food macropolymers, especially proteins, to reduce their overall digestibility and biological value. The polyphenols, in general, can also chelate divalent metal ions, reducing bioavailability of key micronutrients like iron and zinc. Thus, decortication, which can reduce polyphenol and tannin content of sorghum by 80%–95% ([Awika et al., 2005](#); [Dlamini et al., 2007](#)), should theoretically improve bioavailability of these minerals.

However, a paradox is that the decortication process, just like wheat flour refining, also strips the grain of most of these micronutrients ([Hama et al., 2011](#)). For example, iron, a major nutritionally deficient micronutrient in regions that consume sorghum as a staple, is reduced by as much as 70% in the decorticated grain, since most iron is located in the bran (the removed portion of decorticated

grain). This presents a particular challenge to sorghum biofortification efforts meant to combat micronutrient malnutrition. With modern food processing, opportunities to efficiently exploit the sorghum bran for targeted fortified food applications, or as a source of functional food ingredients or bioactive compounds should be exploited. The decorticated bran is high in dietary fiber (more than 40%), polyphenols, and other valuable compounds (Awika et al., 2005; Carr et al., 2005; Dlamini et al., 2007). Due to the recognized benefits, sorghum bran, traditionally, a waste product of decortication process (Fig. 3.1) is currently finding use in health foods, and is, for example, commercially available from diverse sorghums in the USA market.

Besides, losses of essential micronutrients, sorghum decortication will also lead to a loss of most of the grain dietary fiber, as well as the bioactive secondary metabolites, like polyphenols and lipid waxes. In the developing countries where malnutrition is traditionally the major concern, such losses of nutritionally nonessential grain components has been regarded as almost irrelevant. However, as evidence becomes clear on the important role of these nonessential constituents to the nutritional health of these populations, such a perspective should be revised. For example, the grain polyphenols, as well as dietary fiber components have been shown to contribute positively to overall gut health, by a direct interaction with gut epithelial cells (Ojwang et al., 2015; Tuohy et al., 2012; Yang et al., 2015), or influencing proliferation and metabolic activity of desirable microbiota in the colon (Etzeberria et al., 2013; Tuohy et al., 2012). A healthy gut is fundamentally essential for efficient uptake of nutrients and immune function (Tuohy et al., 2012), which in turn is critical in curbing malnutrition.

2.2.2 Hydrothermal Processing

The majority of traditional and modern sorghum products require some form of processing using moist heat. In general, the most prominent effect of wet cooking is to increase digestibility of starch through gelatinization, thus improving efficiency of dietary energy uptake from the grain. This is important because the primary reason cereal grains are traditionally produced is as a source of dietary glucose in the form of starch. Wet heat also inactivates compounds, that can inhibit starch and protein digestion (α -amylase and protease inhibitors).

An unusual effect of wet heat on sorghum (when compared to other grains) is the extensive crosslinking of the kafirin proteins in the endosperm. During cooking, the β - and γ -kafirins at the periphery of the protein bodies, the organelles of kafirin prolamin storage, extensively crosslink, and become less digestible. The crosslinking of kafirins is especially extensive in the hard endosperm (Ezeogu et al., 2008). The overall effect is that sorghum protein digestibility can reduce by 20%–50% after wet cooking (Axtell et al., 1981). This is in sharp contrast to the other cereal grains, where protein digestibility, either remains the same or slightly increases with cooking (Duodu et al., 2003). This property is a considerable negative nutritional attribute in areas where PEM is a major concern, which tends to characterize regions where sorghum is a staple.

On the other hand, the nondigested sorghum protein has been shown to be a source of nitrogen for colon microbiota (Bach Knudsen et al., 1988), and may be indirectly contributing to colon health. The sorghum protein crosslinking is a redox reaction mainly mediated by disulfide linkages (Ezeogu et al., 2008). Consequently, reducing agents inhibit the ability of sorghum proteins to cross-link, and this restores their digestibility after cooking (Hamaker et al., 1987). Traditional food processes, like lactic acid fermentation have also been shown to improve cooked sorghum protein digestibility (Axtell et al., 1981; Taylor and Taylor, 2002), likely by disrupting native protein structure through the action of endogenous seed or microbial enzymes.

Sorghum mutants with a high protein digestibility trait (similar to other cereal grains) that is less negatively impacted by wet cooking have been identified (Weaver et al., 1998). These sorghums also have improved protein functionality that may be useful in gluten-free products (Goodall et al., 2012). As the proteins in these sorghum mutants do not envelope starch and restrict its swelling, like normal sorghum proteins during cooking, they are also likely to enhance quality of traditional products that rely on starch functionality, like porridges, injera, kiswa, roti etc. The high protein digestibility sorghum mutants are, however, not yet available commercially due to various agronomic limitations (e.g., soft endosperm). These sorghums are under genetic improvement (Jampala et al., 2012) and are likely to play an important role in improving protein availability in regions where PEM is a major problem, especially given that they also tend to be higher in lysine. This will also open opportunities for new food applications, and industrial uses for sorghum (Wu et al., 2010).

An important consequence of the sorghum protein crosslinking that is relevant to calorie control is the overall impact on starch digestibility. When the proteins crosslink, they envelop starch granules and restrict the ability of starch to swell in the endosperm (Hamaker et al., 1987), and consequently restrict enzyme access to the starch, thus slowing starch digestion (Ezeogu et al., 2008; Rooney and Pflugfelder, 1986). Increasing the level of slow-digesting starch in meals, recognized as an effective way, not only to prevent rapid spike in blood glucose, but also to lengthen overall satiety therefore reduce frequent food cravings. This is an attribute that is likely to be more valuable for calorie control in an increasingly overnourished world, where more people are obese than undernourished (Fig. 3.2).

2.2.3 Fermentation and Partial Germination (Malting)

Both processes of lactic acid bacteria fermentation and partial germination (as accomplished during malting) improve the overall digestibility of sorghum proteins, as well as starch. As mentioned earlier, this effect is mainly due to the activation of the endogenous seed enzymes (malting) and microbial enzymes (fermentations) that initiate the hydrolysis of the macromolecules making them more accessible to human digestive enzymes. However, fermentation is also known to result in reduced levels of protease and α -amylase inhibitors,

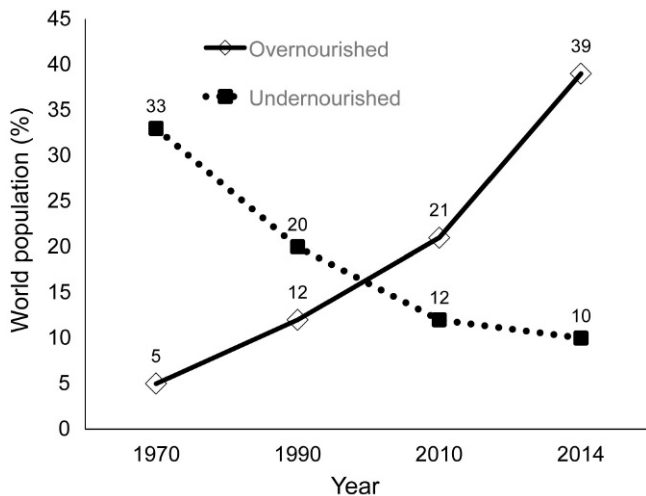


FIGURE 3.2 The changing roles of hunger and obesity as global health challenges. ((Data derived from FAO, WHO Statistics, 2014; FAO, 2014. Food & Agriculture Organization of the United Nations, Statistical Database. Available from: <http://faostat3.fao.org>.)

as well as measurable tannin content in sorghum (Hassan and Tinay, 1995; Osman, 2004), all of which would increase digestibility of macronutrients. The processes of fermentation and partial germination are also known to increase bioaccessibility of micronutrients. This effect is partially related to activation of endogenous phytase enzymes, as well as partial removal of tannins (if present), probably through leaching or microbial action. Phytate and tannins are known metal chelators, that significantly reduce bioaccessibility of micronutrients in sorghum-based products (Kruger et al., 2012).

The combination of partial germination and fermentation results in an enhanced positive effect on mineral bioaccessibility, by interactively decreasing the levels of key metal chelators, tannins, and phytate in sorghum (Kayodé et al., 2013). Fermentation is widely used in many African regions as a traditional way to make various types of sorghum-based porridge and other products; perhaps such preferences evolved as a result of the inherent nutritional benefits these fermented products were observed to provide. In developed regions, such processes are still nutritionally relevant, especially with increased interest in “natural foods”; micronutrients like iron, remain deficient in the diets of many people in these regions. People on plant-based diets (vegetarians, vegans, etc.) are especially vulnerable. It is important to highlight that fermentation can also improve functionality of the sorghum in gluten-free bread production, via partial hydrolysis of the proteins and starch (Schober et al., 2007). For example, Schober et al. (2007) demonstrated that fermentation of sorghum batter using the sourdough bread-making method eliminated the collapsed top, and irregular crumb cell-structure observed in gluten-free bread made from unfermented sorghum batter.

3 MAJOR POLYPHENOLS FOUND IN SORGHUM

Polyphenols are ubiquitous in plants and are widely studied for their presumed health benefits related primarily to their ability to scavenge free radicals and modulate various signaling pathways relevant to disease prevention. Like other cereal grains, phenolic compounds in sorghum are mostly concentrated in the outer part of the grain (bran). This is because, among other roles, these compounds serve as components of the plant's natural defense against pathogens and pests. In fact in sorghum, the protective role of polyphenols has been clearly demonstrated, for example, lower preference of tannin-containing sorghums by bird pests.

The polyphenols in sorghum are very interesting, if not intriguing, due to their relative abundance compared to those found in other cereal grains, as well as their unique composition. The sorghum phenolics have also been reported to possess unique bioactive (Shih et al., 2007; Yang et al., 2009, 2014a) and functional properties in foods (Awika et al., 2004; Ojwang and Awika, 2010). For example, sorghum is among the very few cereal grains with reliably documented presence of condensed tannins (proanthocyanidins); barley ear and finger millet also contain these compounds (Brandon et al., 1980). Other compounds uniquely found in sorghum are the 3-deoxyanthocyanin pigments. These compounds are responsible for the coloration of sorghum seeds (ranging from red to black) and secondary plant color. They are distinguishable from their anthocyanin analogs found in other cereal grains and most food plants, by their lack of a substitution at position 3 of the heterocyclic ring (Fig. 3.3 mentions the flavonoid skeletal structure).

In general, sorghum contains a higher proportion of flavonoids than other cereal grains, which, with the exception of some millets, tend to contain phenolic acids. Another important difference is that compared to other cereals, sorghum also has a relatively high proportion of extractable phenolic acids, which primarily exist as monomeric and dimeric glycerol esters (Svensson et al., 2010; Yang et al., 2012). In all, the composition of the specific phenolics in sorghum is highly variety-dependent with well-characterized genes controlling their synthesis (Rooney, 2000). As the structure and composition of the phenolics have a major impact on their bioactive properties, the knowledge of genetic factors that control the composition of sorghum phenolics, has led to the on-going efforts to develop sorghum varieties, targeting specific applications in food for health and quality.

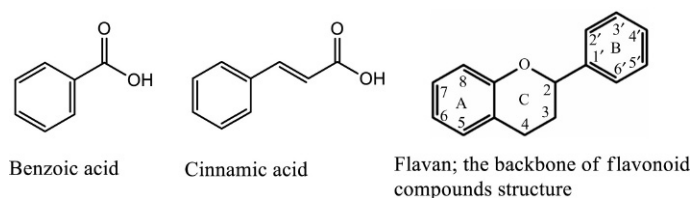


FIGURE 3.3 Basic structures of major phenolic compounds found in sorghum.

3.1 Phenolic Acids in Sorghum

In cereal grains, phenolic acids are the most abundant and by far the most well characterized group of polyphenols. Both benzoic and cinnamic acid (Fig. 3.3) derivatives are present in sorghum, with cinnamic acid derivatives dominating. Typically, ferulic acid derivatives dominate cereal grain phenolic acid profile; most of these exist as components of cell-wall structure (esterified to hemicelluloses) thus are not readily extractable without cell-wall hydrolysis. These bound phenolates have been postulated as major contributors to health benefits associated with whole grain intake. They are thought to act via positive direct interaction with gut microbiota, as well as being partially hydrolyzed and released in the colon for absorption.

The composition of phenolic acids in sorghum has traditionally been reported to follow similar patterns reported for other cereal grains (Awika and Rooney, 2004; Chandrasekara and Shahidi, 2011; Dykes and Rooney, 2006; Subba Rao and Muralikrishna, 2002). However, this appears to only hold true for bound phenolic acids. Among the bound phenolic acids of sorghum, ferulic acid derivatives typically account for close to 90% or more. As the bound phenolic acids are cell-wall components, grain hardness affects their content in sorghum, with harder grains having higher content (Chiremba et al., 2012).

A pioneering report by Svensson et al. (2010), demonstrated for the first time, the presence of extractable phenolic acid aldehydes and glycerol mono- and diesters in a red sorghum (Fig. 3.4). Our own investigations have confirmed the presence of large quantities of phenolic acid esters as the major extractable (organic solvent) phenolic compounds in red and white sorghum varieties, and their prominent presence in all sorghum varieties we have analyzed (Yang et al., 2012). The compounds are higher in bright red sorghum, accounting for about 2000 µg/g of the grain. Interestingly, the most abundant phenolic acid

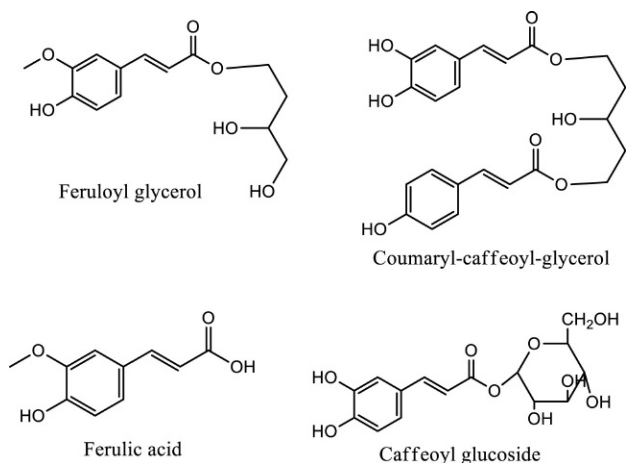


FIGURE 3.4 Some of the common extractable phenolic acids found in sorghum grain.

constituent of these esters was caffeic acid (as monoglyceride, diglyceride, and coumaric and ferulic diglyceride esters). Granted, we have analyzed only a limited number of sorghum lines, but the ubiquity of these compounds suggests their universal presence in sorghum as significant component of phenolic compounds. So far, we are not aware of any studies investigating the potential contribution of these phenolic acid derivatives to bioactive properties of sorghum. Their ease of extraction implies they are likely to be available for absorption in the upper gastrointestinal tract. These compounds also interact with and affect functionality of other polyphenols in sorghum, for example, 3-deoxyanthocyanin pigments stability (Awika, 2008) (Table 3.3).

TABLE 3.3 Major Phenolic Compound Groups Identified in Sorghum		
Compounds	Content (µg/g)	Comments
<i>Phenolic Acids</i>		
Extractable phenolic acids	15–1,650	Mostly as caffeoyl glycerides, also some feruloyl and coumaroyl esters. Bright red sorghums have highest values; black sorghums from purple secondary plant have lowest.
Bound phenolic acids	430–1,200	Mostly ferulic acid derivatives. Harder endosperm grains have higher values.
<i>Flavonoids</i>		
3-Deoxyanthocyanins	200–4,500 (grain) 20,000–90,000 (glume, sheath)	Highest in black grains; leaf/sheath of purple plants. Mainly apigeninidin and luteolinidin, and their derivatives.
Flavones	20–390	Red and lemon yellow grains from tan secondary plant color. Mostly apigenin and luteolin derivatives.
Flavanones	10–2,000	Highest in lemon yellow sorghums. Mainly naringenin and eriodictyol derivatives.
Proanthocyanidins (HPLC method)	0–3,100	Exclusively found only in sorghum genotypes with a pigmented testa.
Source: Awika, J.M., Dykes, L., Gu, L.W., Rooney, L.W., Prior, R.L., 2003a. Processing of sorghum (<i>Sorghum bicolor</i>) and sorghum products alters procyanidin oligomer and polymer distribution and content. J. Agri. Food Chem. 51, 5516–5521; Awika, J.M., Rooney, L.W., 2004. Sorghum phytochemicals and their potential impact on human health. Phytochemistry 65, 1199–221; Dykes, L., Seitz, L.M., Rooney, W.L., Rooney, L.W., 2009. Flavonoid composition of red sorghum genotypes. Food Chem. 116, 313–317; Dykes, L., Peterson, G.C., Rooney, W.L., Rooney, L.W., 2011. Flavonoid composition of lemon-yellow sorghum genotypes. Food Chem. 128, 173–179; Chiremba, C., Taylor, J.R.N., Rooney, L.W., Beta, T., 2012. Phenolic acid content of sorghum and maize cultivars varying in hardness. Food Chem. 134, 81–88; Yang, L., Allred, K.F., Geera, B., Allred, C.D., Awika, J.M., 2012. Sorghum phenolics demonstrate estrogenic action and induce apoptosis in nonmalignant colonocytes. Nutr. Cancer 64, 419–427; Yang, L., Allred, K., Dykes, L., Allred, C., Awika, J. 2015. Enhanced action of apigenin and naringenin combination on estrogen receptor activation in non-malignant colonocytes: implications on sorghum-derived phytoestrogens. Food Funct. 6, 749–755.		

3.2 Flavonoids in Sorghum

Flavonoids in sorghum are perhaps the most uniquely interesting group of phenolic compounds in relation to other cereal grains; they are responsible for the diverse coloration seen in sorghum grains (Fig. 3.5). Flavonoids are the most abundant and diverse group of phenolics in plants. The flavonoid backbone is characterized by the flavan structure, with classification largely based on substitutions around the heterocyclic (C) ring (Fig. 3.3). In most cereal grains (like rice, wheat, maize, oats, etc.), flavonoids are minor phenolic constituents, with the exception of pigmented varieties of these grains that are not commonly used for food. Sorghum is unique as it contains a wide array of flavonoids at relatively high levels; many of these are not commonly found in other cereal grains, or even most food plants. Thus, in terms of opportunities to uniquely impact health and nutrition, the sorghum flavonoids are of most interest, and are most widely investigated.

Sorghum flavonoids can be grouped into monomeric and polymeric (condensed). The monomeric forms identified in sorghum include 3-deoxyanthocyanins (pigments), flavones, flavanones, and flavan-4-ols. An interesting feature of the monomeric sorghum flavonoids is that they are almost exclusively 3-deoxyflavonoids (i.e., lack a substitution at position 3 of the heterocyclic (C) ring; see Fig. 3.3 for flavan carbon numbering). This feature produces important chemical and biochemical properties relevant to food processing and human health (Ojwang and Awika, 2008; Yang et al., 2009, 2012, 2014b). The polymeric flavonoids of sorghum (tannins) are mainly condensed polymers of flavan-3-ols with a mean degree of polymerization of about 15. The interflavan linkages are exclusively 4→8, making for relatively organized linear structures. Sorghum tannins have received a lot of attention due to their ability to bind principally to proteins and form poorly digestible complexes. On the other hand, the tannins have also been associated with various health benefits. It is important to note, that most cultivated sorghum varieties do not contain tannins, due to deliberate genetic selection against these compounds by breeders. This is because sorghum tannins have a negative impact on feed value when present at high concentrations. A brief overview of the major flavonoid groups in sorghum follows below.



FIGURE 3.5 Examples of different sorghum grain pericarp colorations induced by differences in flavonoid composition.

3.2.1 3-Deoxyanthocyanins

The 3-deoxyanthocyanins (Fig. 3.6A) are derivatives of the anthocyanins (Fig. 3.6B); anthocyanins are ubiquitous in plants and are responsible for colors of flowers, leaves, fruits, and other plant tissue that range in hues from orange to blue-black. A common feature of the anthocyanins is that they almost always have a glycosyl substitute at C-3 (Fig. 3.3 describes the flavonoid carbon numbering). This helps stabilize the compounds that are otherwise relatively unstable. In sorghum, the pigments are unsubstituted at the C-3 position, thus the name 3-deoxyanthocyanins. This small structural difference is highly relevant for food processing (Ojwang and Awika, 2008, 2010; Yang et al., 2014b) and potential bioactive properties of the sorghum pigments (Shih et al., 2007; Yang et al., 2009). Even though sorghum does have anthocyanin synthesizing enzymes, the pathway for anthocyanin synthesis appears to be almost completely suppressed in the mature plants and grain in favor of the 3-deoxyanthocyanins, unless the plant grows in a sterile (biotic stress-free) environment (Lo and Nicholson, 1998).

The 3-deoxyanthocyanins exist in nature mainly as aglycones, that is, without sugar substituents, and almost always as derivatives of luteolinidin or apigeninidin (Fig. 3.6A). The most common derivatives include O-methylated forms, as well as dimers (Geera et al., 2012). This is in contrast to the anthocyanins that are always glycosylated. Part of the reason for existence of sorghum pigments as aglycones is probably due to the inherent stability of the 3-deoxyanthocyanidins, thus reducing the need for stabilization via glycosylation. The lack of substitution at C-3 results in a region between C-5 and C-4' that has greater hydrophobicity than their anthocyanin analogs and is less reactive with hydrophilic molecules. This region causes 3-deoxyanthocyanidins to be less susceptible to nucleophilic attack and hydration, which is a primary mechanism for structural transformation of anthocyanins in solution to colorless forms. Consequently, the 3-deoxyanthocyanins have a relatively stable color profile over a broad pH range (Fig. 3.7), which is an advantage in providing predictable color hues in foods. An additional advantage of the 3-deoxyanthocyanins is that they provide red hues at near neutral pH, which would complement the

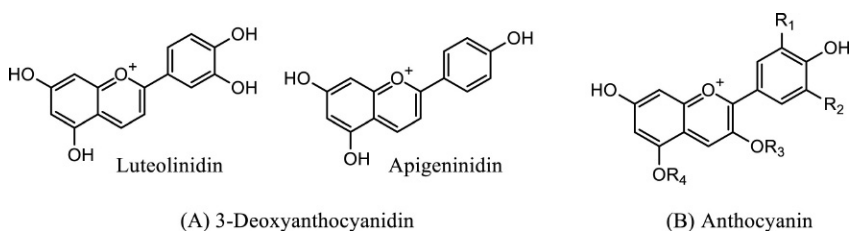


FIGURE 3.6 The major 3-deoxyanthocyanin aglycones in sorghum (A) compared to their anthocyanins analogs found in other plants (B) the R_x are commonly H, CH₃, sugars, or phenolic acid esters.



FIGURE 3.7 Effect of pH on sorghum 3-deoxyanthocyanin pigment hue compared to anthocyanin pigments from fruits. Color stability and predictable hue over a broad pH range is a distinct advantage of the 3-deoxyanthocyanins. ((Image taken by author).)

anthocyanins that tend to be blue at neutral pH. The compounds are also accumulated in plant tissue (grain, glumes, sheath, etc.) that are easy to dry and store for a longer period. This is in contrast to fruits and vegetable sources of anthocyanins, which are generally high in moisture and enzyme activity and are thus expensive to store and concentrate pigments from.

Among sorghum varieties, black sorghum grains contain the highest levels of these compounds (4–16 mg/g bran) (Awika et al., 2004, 2005). Some sorghum plant tissue (glumes, sheath, leaves) accumulates much higher levels (up

to 90 mg/g) of these pigments (Geera et al., 2012; Kayodé et al., 2011; Petti et al., 2014) (Table 3.2). As these nongrain tissues are much the larger part of the plant biomass, there is opportunity to exploit them as commercial source of the pigments. Due to their advantages, there is growing interest in using the sorghum 3-deoxyanthocyanins as natural food colorants, and many companies are at various stages of testing the pigments.

However, two important challenges that limit the use of 3-deoxyanthocyanins, include poor extractability from plant tissue and tendency to self-associate in aqueous systems. The pigments are located in cell vacuoles within the pericarp cells, high in cellulosic cell-wall material. Thus, disruption of the cell-wall is essential to improve their extractability. Acidified organic solvents, especially methanol, are most efficient at extracting these pigments in laboratory conditions. However, evidence suggests that due to their thermal stability (Yang et al., 2014b), high temperature and pressure systems can be exploited to enhance extractability of these compounds in aqueous systems (Barros et al., 2013). Microwave assisted extraction is also likely to increase efficiency of the 3-deoxyanthocyanins removal from plant tissue.

The self-association of 3-deoxyanthocyanins in aqueous systems is largely due to their reduced hydrophilicity relative to anthocyanins. The fact that they exist mainly as aglycones further exacerbates this problem. From our experience, the composition of the 3-deoxyanthocyanins affects their aqueous stability, with pigments higher in the more hydrophilic luteolinidin derivatives remaining in solution longer. However, encapsulation with emulsion stabilizers that have appropriate HLB (hydrophilic–lipophilic balance) values appears to be the most practical mechanism to retain the pigments in aqueous solution for long periods of time. The 3-deoxyanthocyanins can meanwhile be used in liquid systems with reduced water content, for example, alcoholic beverages, as well as in various nonliquid food applications, that is, bakery, candy manufacture, and so forth.

3.2.2 Flavones

Flavones are a group of pale yellow flavonoids found in many cereal grains in small quantities. The most relevant food source of these compounds are herbs, such as parsley and celery (Yao et al., 2004). However, some sorghum varieties, as well as pearl millet and fonio, accumulate rather high levels flavones, primarily as derivatives of luteolin and apigenin (Fig. 3.8A) (Awika, 2011; Salunkhe et al., 1983). It appears that red and lemon yellow sorghum genotypes with a tan secondary plant color accumulate the highest levels of these compounds (Dykes et al., 2009, 2011). For example, tan-plant sorghums with a pigmented pericarp contain 60–386 $\mu\text{g/g}$ flavones (Dykes et al., 2009). Fonio (*Digitaria exilis*) was also reported to contain relatively high levels of luteolin and apigenin (150 and 350 $\mu\text{g/g}$, respectively) (Sartelet et al., 1996).

Interestingly, in contrast to the 3-deoxyanthocyanins, the sorghum flavones exist naturally as glycosides. However, the glycosidic linkage is quite unstable

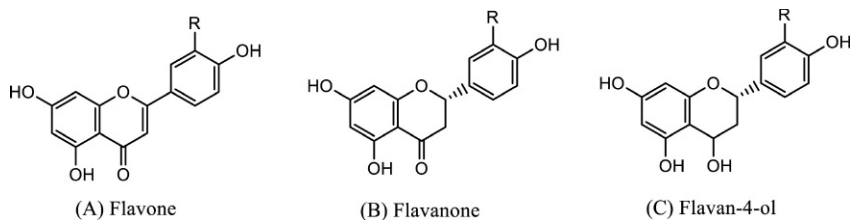


FIGURE 3.8 Backbone structures of major classes of nonpigment monomeric flavonoid aglycones found in sorghum. Note the common lack of substitution at C-3 on these compounds, R = H, OH.

in an acidic environment and readily hydrolyzes into the aglycone (Dykes et al., 2011). In fact, flavone glycosides are easily hydrolyzed by the pH conditions in the stomach (Lefort and Blay, 2013), which may increase their absorption. In general, the levels of flavones in sorghum are nutritionally relevant to prevent the various diseases, based on their observed bioactivity at relatively low levels (Yang et al., 2012, 2015). Furthermore, their activity is enhanced in the presence of structurally complementary flavonoids, such as flavanones and flavonols (Yang et al., 2015).

3.2.3 Flavanones

Flavanones are structurally distinguishable from flavones only by the lack of a double bond between C-2 and C-3; this gives them a chiral center at the C-2 position (Fig. 3.8B). They are widely distributed in nature, with the most well known (and studied) being naringenin and its derivatives. The most relevant dietary source of these compounds is citrus fruits, for example naringenin is relatively abundant in grapefruit. Among cereal grains, some sorghum varieties contain high amounts of flavanones; for example, some lemon-yellow sorghum varieties contain in excess of 2000 $\mu\text{g/g}$ (Dykes et al., 2011; USDA, 2007; Yang et al., 2015). The major flavanones in sorghum are primarily eriodictyol and naringenin glycosides, as well as their aglycones and O-methylated derivatives (Gujer et al., 1986; Kambal and Bate-Smith, 1976; Yasumatsu et al., 1965).

Interestingly, sorghum varieties that accumulate the majority of luteolin-based flavones, also accumulate eriodictyol-based flavanones. Likewise, varieties that accumulate apigenin-based flavones also contain mainly naringenin-derived flavanones (Dykes et al., 2011; Yang et al., 2015). Furthermore, the purple secondary plant colors is associated with higher levels of the luteolin family of flavonoids (e.g., luteolinidin, eriodictyol), whereas the tan and red secondary plant colors are associated with higher levels of the apigenin family (e.g., apigeninidin, naringenin). In addition, the combination of pericarp color and secondary plant color further influences the class of flavonoids accumulated in sorghum. Thus, using genetics, sorghum can be readily exploited as a vehicle to accumulate a specific group of flavonoids that can be used for targeted applications to benefit human health.

3.2.4 Flavan-3-ols and Condensed Tannins (Proanthocyanidins)

The flavan-3-ols are a subclass of flavonoids that is highly abundant in nature, with catechin and gallic acid and their isomers and derivatives (e.g., epicatechin, epigallocatechin gallate) being the most well known. In some plants, for example, tea, and various legumes like cowpea, the flavan-3-ols mainly exist as monomers or low molecular weight condensed polymers (Roberts and Wood, 1951; Ojwang et al., 2013). However, in sorghum, the vast majority of these compounds exist as high molecular weight condensed polymers (with a mean degree of polymerization of around 15), and the monomeric forms tend to be trivial (Awika et al., 2003a; Gu et al., 2002). Thus, in sorghum, it appears that the flavan-3-ols mainly serve as intermediates in the biosynthesis of condensed tannins (also called proanthocyanidins).

Besides the flavan-3-ols, other 3-deoxyflavans are also involved in the polymeric structure of sorghum tannins. For example, glycosylated 3-deoxyflavan polymers (proluteolinidin and proagigeninidin) with flavanones (eriodictyol or naringenin) and their glycosides as the terminal units have been reported in sorghum (Brandon et al., 1980; Krueger et al., 2003). Given the dominant presence of the 3-deoxyflavonoids as monomeric flavonoids in sorghum, it would be expected that they play a dominant role in polymeric sorghum tannin synthesis. However, these types of polymeric flavonoids appear to be a minor component of the sorghum tannins, suggesting the 3-deoxyflavans play a lesser role in flavonoid polymerization in sorghum. Also, besides the classical 4→8 B-type flavan linkages, the A-type interflavan linkages (Fig. 3.9) have also been

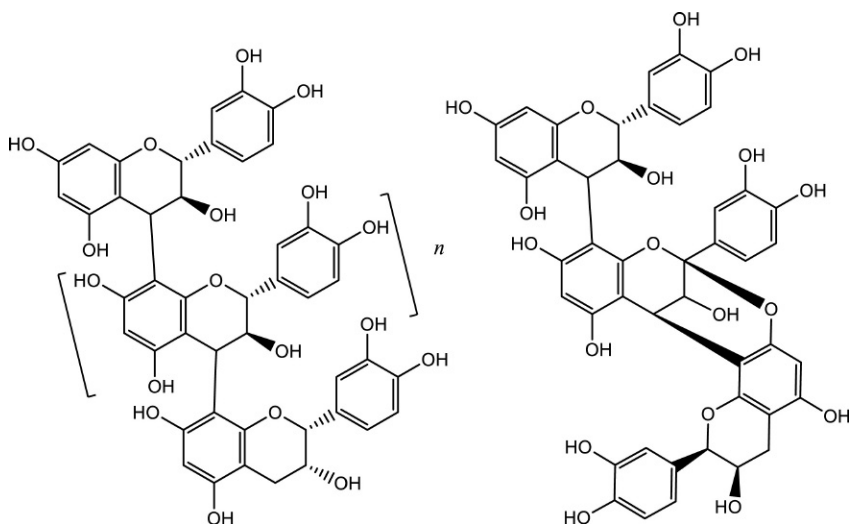


FIGURE 3.9 Left: idealized sorghum tannin structure with B-type interflavan linkages ($n = 10\text{--}18$, on average), right: A-type interflavan linkage also identified in sorghum.

reported in sorghum (Krueger et al., 2003). Thus, the overall body of evidence suggests significant heterogeneity in sorghum tannin structure.

In sorghum, the condensed tannins have been the most widely investigated group of flavonoids. As stated earlier, the main reason they have been such a subject of scientific curiosity, is their observed negative impact on feed value of sorghum. Tannins are well known to bind strongly to proteins, a property that has been used for thousands of years to convert hide into leather. When a high-tannin sorghum is cooked, the tannins complex with the proteins enough to significantly restrict protein digestibility. This negative effect of tannins on protein digestibility can be as high as 70% or more (Mitaru et al., 1984). In addition, the tannins can also complex with micronutrients, specifically divalent minerals like iron and zinc, further negatively impacting nutritional profile of sorghum. In free form (not complexed with other food macronutrients), the tannins can also impact nutritional profile of sorghum by directly complexing with and inhibiting the digestive enzymes (themselves proteins). However, these effects are strongly dependent on the content of tannins in sorghum, with type III high tannin sorghums having the most obvious impact (Awika and Rooney, 2004; Mitaru et al., 1984).

On a positive note, tannins appear to significantly reduce bird pest predation of sorghum grain during maturity. When tannin and nontannin sorghum are present in the same vicinity, the observed bird preference for the nontannin sorghums is dramatic. This clearly indicates that tannins serve an important protective role against predation. Consequently, in regions where bird pest pressure is a major problem (e.g., parts of Eastern and Southern Africa), the majority of sorghum grown for local use is almost always the tannin type.

4 OPPORTUNITIES FOR USING SORGHUM TO PROMOTE HUMAN HEALTH AND WELL BEING

4.1 Antioxidant and Antiinflammatory Related Mechanisms

Oxidative stress plays a central role in chronic disease development (Fig. 3.10). The recognition of this fact has led to an explosion of in vitro method and food commodity-based investigations aimed at predicting ability of foods, and food components to reduce oxidative stress in vivo. A Google Scholar search for “antioxidant capacity” reveals more than 1.6 million hits (as of April, 2016). Since the 1990s, the most cited literature in food science and nutrition areas are based on antioxidant-related testing and “antioxidant capacity” of various food components. Due to the redox chemistry of polyphenols, they have been the most widely investigated dietary antioxidants.

The erroneous assumption that antioxidant capacity measured in vitro can be directly correlated with antioxidant effect in vivo led to a plethora of studies comparing the phenolic content (and by extension antioxidant capacity) of various food commodities, a majority being fruits and vegetables naturally high in polyphenols. The inferences drawn by consumers, and used by marketing firms,

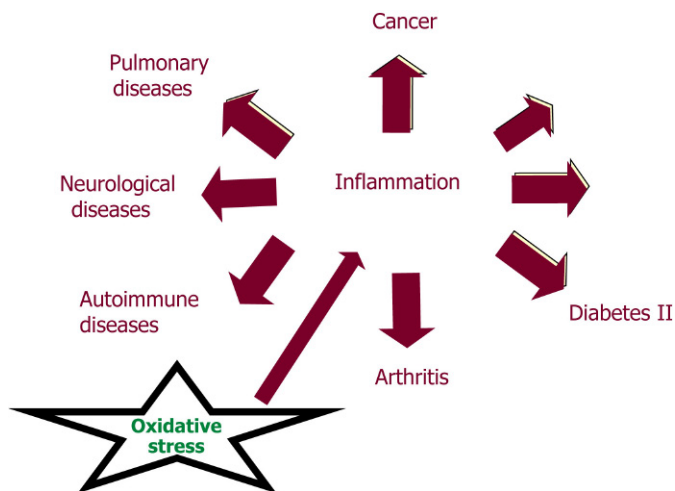


FIGURE 3.10 Interrelated nature of oxidative stress, inflammation and various chronic diseases.

has been that higher polyphenol and in vitro antioxidant capacity equals better health benefits. However, it is now recognized that there is no direct correlation between in vitro antioxidant capacity and the ability of the targeted compounds to influence or reduce oxidative stress in vivo (Li et al., 2010; Niki, 2010). This is because the ability of dietary antioxidants to scavenge free radicals in vivo is limited by their poor absorption, as well as the generally far more robust endogenous antioxidant system. However, many dietary polyphenols, depending on their structure, can indirectly influence endogenous redox enzymes (e.g., phase II enzymes), by modulating their expression and activity. Consequently, antioxidant capacity of a specific food or commodity is less relevant than the composition of the specific active components.

Sorghum polyphenols have been shown to express high-antioxidant capacity in vitro relative to other grains (Awika et al., 2003b; Dykes et al., 2005). This is expected due to the high polyphenol content in them (Awika and Rooney, 2004). However, as aforementioned, this by itself does not imply better health benefits. Our data, along with other investigators, have shown that the unique polyphenols found in sorghum do indeed exert important bioactive properties not related to their direct antioxidant activity that may provide superior health benefits. For example, the sorghum 3-deoxyanthocyanidins are strong phase II enzyme inducers, a property not reported for their anthocyanin analogs (Awika et al., 2009; Yang et al., 2009). Such indirect effect on endogenous detoxifying enzymes is highly relevant, because it indicates these compounds can exert properties with important consequences on oxidative stress and cancer prevention at low levels of intake. In addition, the structure of the 3-deoxyanthocyanins has a major impact on their ability to influence the phase II enzymes; O-methyl substitution significantly enhances their activity (Awika et al., 2009; Yang et al., 2009) (Fig. 3.11). Interestingly,

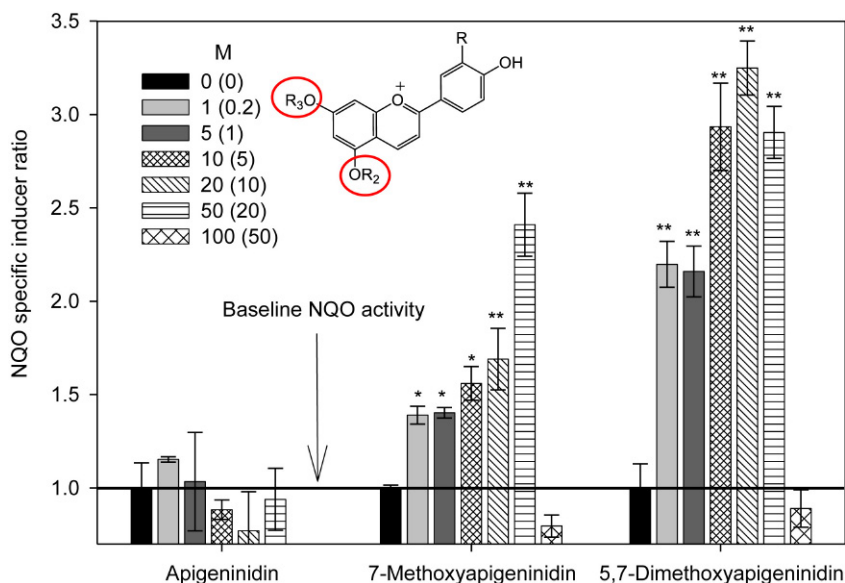


FIGURE 3.11 Quinone oxidoreductase (NQO) specific inducer capacity of apigeninidin and its methoxylated derivative found in black sorghum. Hepa1c1c7 murine hepatoma cell lines were used for the assay. Error bars represent \pm sd from three separate experiments. *, $P < 0.05$; **, $P < 0.01$, compared to control (Bonferroni multiple-comparison test). ((Reproduced from Yang, L.Y., Browning, J.D., Awika, J.M., 2009. Sorghum 3-deoxyanthocyanins possess strong phase II enzyme inducer activity and cancer cell growth inhibition properties. *J. Agri. Food Chem.* 57, 1797–1804.))

O-methyl substitution actually reduces in vitro antioxidant capacity of polyphenols; this highlights the risk of extrapolating in vitro antioxidant capacity to in vivo effects. Other evidence showed that pigments extracted from sorghum stem eliminated oxidative stress in rat brain induced by cyclophosphamide, which may suggest protective effect from oxidative stress-related neurodegenerative diseases (Obboh et al., 2010). Thus, sorghum 3-deoxyanthocyanins, depending on their composition, can have important indirect benefits against oxidative stress in vivo.

Among different sorghum types, tannin-containing varieties have the strongest in vitro antioxidant capacity, which is attributed to higher free radical scavenging power of tannins relative to simple flavonoids (Hagerman et al., 1998; Awika et al., 2005). Condensed tannins have more hydroxyl groups in close proximity to each other and are thus more effective at quenching peroxy radicals than simple phenolics, and are not capable of acting as prooxidants via redox cycling (which is sometimes the case for simple phenolics) (Hagerman et al., 1998). The high in vitro antioxidant properties of the tannins may be directly relevant to oxidative stress in vivo, particularly in the gastrointestinal tract, partly because the tannins typically form complexes with proteins and other macromolecules that are nonabsorbable (Tian et al., 2012). In this regard, the bound whole grain phenolic compounds that are not extractable by standard

chemical assays (typically covalently bound to cell-wall material) are also thought to exert antioxidant effect by direct interaction with GI epithelium, or upon partial release via microbial hydrolysis in the colon.

Besides oxidative stress, chronic inflammation (which is related to oxidative stress), is a common pathway to various chronic diseases (Fig. 3.10). Thus, measuring the effect of phenolic and other bioactive compounds against inflammatory markers has become one of the most popular research areas in the recent past, and is believed to be directly important to disease prevention. In fact antiinflammatory testing has been nicknamed “antioxidant 2.0.” As the effect of polyphenols against inflammatory biomarkers is dependent on their structure and target marker (specific), these studies may provide better insight on overall potential contribution of the polyphenols to health. Furthermore, in vitro and in vivo data on antiinflammatory effects of specific polyphenols do generally seem to agree (Smolinski and Pestka, 2003).

Among the most well-recognized antiinflammatory compounds are the flavones, apigenin, and luteolin (Funakoshi-Tago et al., 2011; Hougee et al., 2005; Smolinski and Pestka, 2003; Wölfle et al., 2011). The other monomeric flavonoids in sorghum have also been shown to have varying levels of antiinflammatory activity. Thus, it is not surprising that direct evidence on the antiinflammatory effect of sorghum in vitro and in vivo is promising (Moraes et al., 2012). Moraes et al. (2012) demonstrated effectiveness of various sorghum genotypes differing in phenolic composition against low grade inflammation in adult Wistar rats when fed at 21%–26% of diet; the overall effects were independent of phenol content of the grains, indicating the composition was more relevant (Moraes et al., 2012). Bran extracts from various sorghum varieties, including tannin sorghum, and nontannin sorghums with red, black, and white pericarp inhibited the activity of hyaluronidase; overexpression of hyaluronidase can lead to chronic inflammatory responses in macrophages and dendritic cells (Bralley et al., 2008). Brans from tannin and black (nontannin) sorghum also reduced the release of cytokines after LPS (lipopolysaccharide) irritation in vitro, and reduced infection induced by TPA (12-O-tetradecanoylphorbol acetate) in rats (Burdette et al., 2010). Interestingly, wheat and rice brans did not show antiinflammatory properties in each of the two studies. This suggests that the unique flavonoids in sorghum may be driving the observations. Another study (Sugahara et al., 2009) demonstrated that white sorghum bran extract suppressed IgE production by U266 cells, whereas wheat bran extract did not. Our recent findings confirm the effectiveness of sorghum against inflammation, with the strongest effect associated with sorghum flavones (Agah et al., 2017).

4.2 Sorghum in Cancer Prevention

In general whole grains consumption is strongly associated with prevention of different types of cancer, especially of the gastrointestinal tract. For example, Larsson et al. (2005) reported that colon cancer risk was reduced 33% in women

who consumed 4.5 servings of whole grain per day compared to those who consumed less than 1.5 servings per day. Whole grain consumption was also associated with a 50% reduced risk for cancers of upper digestive tract (esophagus, oral cavity, and pharynx) (Levi et al., 2000). The antioxidant activity and other cellular regulatory mechanisms (e.g., phase II enzyme activation and estrogenic activity) of whole grain polyphenols contribute to these benefits.

Among cereal grains, sorghum seems to stand out for its potential to benefit chemoprevention. Van Rensburg (1981) reported, reduced incidences esophageal cancer in various parts of the world (Africa and Asia) where sorghum consumption was high, whereas consumption of maize and wheat correlated with elevated incidences. An epidemiological study by Chen et al. (1993) revealed similar findings for Sachxi Province, China. This study found that regions that consumed highest amounts of sorghum had 1.4–3.2 times lower mortality from esophageal cancer than areas that primarily consumed wheat or maize. Growing incidences of squamous carcinoma of the esophagus among black people in South Africa has been attributed to the change in diet from sorghum to maize (Isaacson, 2005).

In vitro and in vivo experiments confirm the unique benefits of sorghum polyphenols observed in epidemiological studies. For example, the sorghum 3-deoxyanthocyanidins luteolinidin and apigeninidin were much more effective against HL-60 leukemia and HepG2 cancer cell proliferation than their analogs, cyanidin and pelargonidin, at various concentrations (Shih et al., 2007). We also found that sorghum tannins were more potent than grape seed tannin at inhibiting the HT-29 cancer cell growth, whereas black sorghum pigments were much more effective than red cabbage anthocyanin pigments (Awika, 2011). The evidence indicates that sorghum polyphenols have higher potential to suppress cancer cell proliferation than their analogs found in other food sources, and may thus be relevant for dietary applications at low use levels. Possible reasons for these observations are not clear, but may be partly related to better bioavailability of the sorghum flavonoids due to their relatively lower hydrophilicity compared to their analogs from other food sources (Figs. 3.6 and 3.8). The sorghum flavonoids generally have fewer hydroxyl groups and lower frequency of glycosylation.

We also recently found that the composition of flavones and flavanones in specific sorghum varieties enhances their ability to activate estrogen receptor β (ER- β) in nonmalignant colonocytes at low concentrations, and the content of apigenin was the strongest predictor of ER- β activation (Yang et al., 2012, 2015). Activation of ER- β is a well-recognized mechanism for colon cancer prevention. We further demonstrated that the sorghum flavonoids were able to reduce azoxymethane-induced aberrant crypt foci formation in the colon of ovariectomized mice (Yang et al., 2014a), confirming protective estrogenic action in vivo. Thus, estrogenic activity is a mechanisms by which sorghum flavonoids may contribute to chemoprevention, particularly those high in flavones (Yang et al., 2012).

4.3 Obesity, Glycemic Response and Related Mechanisms

Consequences of overconsumption of calories is currently a bigger global health problem than hunger (Fig. 3.2). Obesity (and related health problems) has become one of the greatest health challenges facing humankind today. Even more worrisome is the fact that cases of obesity and diabetes are increasingly inflicting developing world at rates that rival those in the developed world. For example, overweight and starvation coexist side by side in many countries in Africa. Challenges related to excess calorie intake are expected to dominate global health concerns in the coming decades. Sorghum is well positioned to contribute positively in combating excess calorie intake for several reasons, the most important are highlighted further.

4.3.1 *Sorghum Endosperm Properties*

Sorghum endosperm has a relatively slow digesting starch compared to other cereal or starchy foods. As explained, this is mainly due to the extensive cross-linking of the γ -kafirin proteins that surround the starch in the endosperm during hydrothermal processing (cooking in presence of moisture). Disulfide bond formation is largely responsible for the sorghum protein crosslinking (Duodu et al., 2003; Ezeogu et al., 2008), and it appears extent of cooking affects the degree of crosslinking, with longer cooking leading to more extensive polymerization (Ezeogu et al., 2005). The crosslinked proteins restrict amylase enzyme access to the starch and thus slows the rate of glucose release from the starch. Zhang and Hamaker (1998) reported, that cooked sorghum endosperm had 15%–25% lower starch digestibility relative to maize, and this effect disappeared when pure starches were compared, or a reducing agent (sodium metabisulfite) was used to prehydrolyze the crosslinked sorghum endosperm proteins. These results were largely confirmed by Ezeogu et al. (2005), who observed a 30 min in vitro starch digestibility of about 75% in a cooked hard sorghum endosperm, compared to about 90% for a cooked hard maize endosperm.

The slow digesting starch has important consequences on the feeling of satiety, and reduced food cravings, as well as producing a favorable glycemic response for diabetics (Zhang and Hamaker, 2009). In fact sorghum porridge is traditionally preferred over maize or other cereals in some African cultures during physically demanding labor due to its perceived lasting power in the stomach (Awika and Rooney, 2004). Additionally, the crosslinked sorghum proteins are poorly digestible (e.g., 30%–55% digestibility compared to cooked maize or wheat proteins that are more than 80% digestible) (Duodu et al., 2003), which would further reduce overall caloric impact of sorghum-based products. Even though this is highly beneficial in overnourished populations, the impact on protein deficient populations must be considered.

Thus, sorghum can actually contribute to alleviating some of the concerns consumers have with mainstream starchy food commodities like wheat, maize, or potatoes as major contributors to weight gain. Even though human studies on effect of sorghum on glycemic response and satiety are limited, a few animal

and human studies confirm various in vitro data that show sorghum endosperm is slow digesting. For example [Carciofi et al. \(2008\)](#) showed that sorghum produced a slow glycemic response, and did not produce the rapid spike in blood glucose and insulin observed for rice, maize, or cassava flour in dogs. The authors reported that sorghum behaved more like a legume, and produced a postprandial blood glucose response similar to that of lentil and pea, with a higher proportion of slow digesting carbohydrates than cassava, maize, or rice.

Recently, [Stefoska-Needham et al. \(2016\)](#) reported that human subjects fed flaked sorghum biscuits (from different sorghum types) reported higher subjective satiety than those fed wheat biscuits for breakfast. They also found that the net postprandial glucose response over a 4 h period (reported as incremental area under the plasma concentration–time curve) was lower for all sorghum types (47–55 mmol/L min) compared to wheat biscuit (67 mmol/L min). More of this type of data is critically needed to establish credible benefits of sorghum to glucose metabolism and possible weight management.

4.3.2 Sorghum Tannins

Sorghum tannins also present an interesting opportunity to modify starch digestion and calorie impact of foods in general. Besides the known crosslinking with proteins discussed earlier, a growing body of evidence indicates sorghum tannins can also directly complex with starch and make them less digestible or completely nondigestible ([Amoako and Awika, 2016a,b](#); [Barros et al., 2012](#)). Thus beyond their ability to inhibit starch-digesting enzymes, the tannins also appear to make the starch itself less digestible. The binding of tannins with starch appears to be specific, as is the case for proteins. High molecular weight fractions of sorghum tannins are most effective at complexing with starch, whereas monomeric flavonoids like catechin do not bind with starch ([Amoako and Awika, 2016a](#)). Furthermore, as tannin degree of polymerization increases, its binding efficiency with starch increases ([Barros et al., 2014](#)). The fact that amylose component of starch interacts more readily with the tannins than amylopectin further suggests the specificity of the starch–tannin complexes.

Starch–tannin binding mechanisms were proposed to involve mainly hydrogen bonding, stabilized by hydrophobic interactions, similar to the mechanisms observed for proteins ([Amoako and Awika, 2016a](#)). The linear nature of sorghum tannin affords orderly sites for hydrogen bonding, whereas the “open” and helical nature of amylose also provides hydrophobic core to facilitate partial interaction with tannin aromatic rings. This also mirrors other observations of tannin complexation with nonstarch polysaccharides, where the polysaccharide structural conformation and its hydrophobic nature were shown to dictate its binding efficiency with tannins ([Soares et al., 2012](#)). The authors found that, polysaccharides with hydrophobic regions and an open structure bound most efficiently to tannins.

A diverse body of research reporting on polyphenol interaction with starch have found only modest to no impact on starch digestibility. This is because the polyphenols used in most of these studies are monomeric, which we have

found to have no meaningful direct interaction with starch (Amoako and Awika, 2016b). For example tea catechins were found to reduce starch digestibility only at relatively high levels of 100 mg/g starch (Liu et al., 2011); which suggests enzyme inhibition as the mechanism. On the other hand we have found that sorghum tannins, even at low levels of 3.4 mg/g starch can almost completely block starch digestion (>90% resistant starch) when complexed with partially gelatinized intact starch granule. Furthermore, depending on the degree of starch gelatinization, the tannins can significantly increase slow digesting starch. For example, we observed a tripling of slow digesting starch from 97 to 274 mg/g in normal maize starch when tannins were reacted with partially gelatinized starch in a high moisture environment (Amoako and Awika, 2016b). In the same experiment, rapidly digesting starch was reduced by 46%. Furthermore, the sorghum tannins were also shown to increase slow digesting starch in a complex baked tortilla matrix (Dunn et al., 2015). This type of evidence is highly relevant to food processing and human health, because it indicates that sorghum tannins can be feasibly used as ingredients to naturally make starch more nutritionally favorable for weight management and type II diabetes prevention.

4.4 Sorghum as an Important Food Security Crop

In general, sorghum use for food has tended to decline as societies that consume it as a staple become more affluent. This has been the story in countries like South Africa, Kenya, Nigeria, India, Central America, and so on, where consumers have shifted to more “acceptable” grains, such as maize, rice, and wheat. A contributing factor to this trend is related to the perception of sorghum as a low status crop, that is, poor man’s food. Unfortunately the shift to crops like maize has exacerbated food security problems in some of these regions. For example, in Kenya, maize has been used by subsistence farmers to replace sorghum in low rainfall, hot, marginal areas that are far more suitable for sorghum production (e.g., the Eastern Province). The consequence is chronic crop failure and famine in such regions. In addition, the well-publicized aflatoxin related deaths in the Eastern Province of Kenya from contaminated maize (Lewis et al., 2005; Ngindu et al., 1982) could be traced to the shift from sorghum to maize. Maize produced under such abiotic stress is more susceptible to the aflatoxin fungus.

Another problem that contributes to reduced demand for sorghum as a food crop is its difficult processability. As mentioned earlier, sorghum protein cross-linking during cooking restricts ability of starch in the endosperm to swell and form the matrix necessary for desirable textural profile in most cereal-based products. Sorghum starch also gelatinizes at a higher temperature, thus requiring more energy to produce desirable texture. Consequently, sorghum tends to produce gritty, dry, weepy (due to syneresis), or crumbly products, depending on product moisture content and processing conditions. The reduced functionality of the grain is a major impediment that must be addressed if sorghum use is to sustainably increase in both the developing and the developed regions.

Raising the “status” of sorghum through reliable research on its superior or unique benefits to humans will not only increase its use in modern foods, but also be a major step in ensuring the decline of the crop among populations that need it the most for survival is reversed. Technologies that overcome the suboptimal processability of the grain will also go a long way in ensuring high-quality products that consumers would use repeatedly.

5 CONCLUSIONS

Although sorghum is nutritionally similar to maize in many respects, sorghum has some unique properties that can be exploited to improve nutritional status of different populations. It appears that sorghum can be processed differently to either enhance its overall nutritional energy content or reduce it. Processes that use dry heat or limited moisture and high shear (like extrusion or popping) do not seem to reduce sorghum protein digestibility, and actually appear to enhance both protein and starch digestibility to be equivalent to other grains (Duodu et al., 2001; Fapojuwo et al., 1987). Such processes could be used to make products that target enhanced nutrition among children and other vulnerable groups in developing and developed regions, while providing other health benefits associated with sorghum. On the other hand, thermal processes that involve significant amount of moisture (as is the case for most products) can be used to produce sorghum-based products that target attenuated glycemic response, as well as management of calorie intake, along with the additional benefits associated with the unique sorghum polyphenols. Additionally, the strong evidence on the effect of sorghum-derived tannins on reduced starch digestion implies these compounds could be used to produce new types of naturally modified starches or as food ingredients targeting calorie reduction.

Sorghum contains a diverse array of phenolic compounds, many of which are not found in other cereal grains. The high levels of compounds like 3-deoxyanthocyanins, proanthocyanidins, flavones, and flavanones in certain sorghum varieties is especially of interest both from a commercial and health perspective. Most of these compound are stable to thermal processing (de Morais Cardoso et al., 2015; Yang et al., 2014b), thus their benefits are likely to be retained in products. Evidence suggests that the unusual compounds in sorghum and the high levels at which they are present in the grain may produce specific health benefits that are not observed for other grains, such as corn, rice, or wheat. However, more credible data is sorely needed. The fact that sorghum food used as a staple is largely restricted to some of the poorest regions of the world and has been somewhat a drawback in terms of stimulating widespread research into the specific health benefits of the grains. However, with the growing number of “Western” health problems linked to obesity in developing countries, there is great opportunity for sorghum to make an impact on population health in these regions.

Documenting specific health benefits of sorghum-based products in humans will be essential to sway consumer perceptions. Other opportunities to innovate with sorghum that take advantage of the unique functionality of its polyphenol



FIGURE 3.12 Samples of sorghum-based products increasingly available on grocery shelves in Western countries. (Part A: Garden Spot Foods used with permission. Part B: Used with permission from Nature2Kitchen. Part C: Used with permission from Sanitarium Health and Wellbeing. Part D: Used with permission from Kashi Company. Part E: Silver Palate Kitchens, Inc. used with permission.)

profile abound. For example, innovative products, including all natural sorghum ice cream, multicolored sorghum snacks, and sorghum “tea” have won product development competitions at the American Association of Cereal Chemists International meetings. The growing demand for “ancient grains” and healthy whole grain products in the Western food markets is already encouraging new innovative sorghum-based product offerings in grocery stores (Fig. 3.12). Products that take full advantage of the potential of sorghum to positively impact human health will have the highest chance for long-term success.

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Chapter 4

Millet: Their Unique Nutritional and Health-Promoting Attributes

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1 INTRODUCTION

Millet is the collective term for cereal species that have small/tiny grains, approximately one quarter to one tenth the size of wheat kernels. They are not a single species or even species in a single genus. In fact, some millet species are more distantly related to each other than, wheat and barley. There are some 11 cultivated-millet species (Table 4.1). They vary greatly in economic importance but all millets are of considerable nutritional security importance in food insecure countries. This is due to the fact that the millets are notably hardy. They can be cultivated with low agricultural inputs and can withstand conditions of high temperature and drought.

In this chapter, on the basis of economic importance, fonio (white and black fonio), finger millet, foxtail millet, proso millet, pearl millet, and teff will be referred to as the major millets and barnyard millet, Japanese barnyard millet, kodo millet, and little millet as minor millets.

The study of millets is complex and even basic information about the composition of the various millets is still incomplete and sometimes contradictory. This is primarily because millets are largely cultivated by small-holder farmers in developing countries and globally most millets are very minor crops. Hence, they have not been studied to near the same extent as the major cereals. A contributing factor is that it can be difficult to distinguish between the different species, especially after they have been “dehulled” to remove the hulls or bran.

The millets, like maize and sorghum, are C4 tropical grasses (Brown, 1999), unlike the temperate cereals: wheat, barley, rye, rice, and oats. Millets belong to two botanical subfamilies and tribes, the Choridoideae subfamily and Eragrostideae tribe (finger millet and teff), and the Panicoideae subfamily and Paniceae tribe (all the other millets) (Morrison and Wrigley, 2004). Maize and sorghum are also members of the latter subfamily. However, millets are only distantly related to the temperate cereals (Pooideae subfamily) and rice (Bambusoideae

TABLE 4.1 The Millet Species

Generally Used English Name	Other Common and Vernacular Names	Taxonomy [Tribe, Genus, Species, Subspecies where Applicable, Authority(s)]	Grain Description [Type, Approximately Grain Size (mm), Approximately 1000 Kernel Weight (g), Shape, Color	Major Producing Regions/Countries	Approximate Percentage of World Millet Production
<i>Finger millet</i>	Ragi, Wimbi	Tribe Eragrostideae <i>Eleusine coracana</i> L. Gaertn.	Utricle, 1.7 mm, 2.5 g, round or globose, white, red or brown	Eastern and Southern Africa (Uganda, Kenya, Zimbabwe) and Asia-Near East to Far East (India, Nepal, China),	11
<i>Teff</i>	Tef, teff grass Abyssinian lovegrass	Tribe Eragrostideae <i>Eragrostis tef</i> (Zuccagni) Trotter	Tiny naked caryopsis, 0.9 × 0.7 mm, oval, 0.3–0.4 g, whitish or brown	Ethiopia, Eritrea, South Africa, USA, Australia	9
<i>Barnyard millet</i> (also known as <i>Indian barnyard millet</i>)	Sama/Shama, Sawa millet, Billion dollar grass	Tribe Paniceae <i>Echinochloa frumentacea</i> Link	Hulled grain, elliptical	India	Very minor cultivation
<i>White fonio</i>	Fonio, Acha Fonio millet Hungry rice	Tribe Paniceae <i>Digitaria exilis</i> (Kippist) Stapf	Both fonio species—hulled caryopsis, elliptical, 1.3 × 0.8 mm (black fonio slightly larger), 0.5 g whitish, white fonio; darkish, black fonio	Both fonio species, Africa-Sahel region (Guinea, Nigeria) (both species)	Both fonio species—1
<i>Black fonio</i>	Black acha hungry rice	Tribe Paniceae <i>Digitaria iburua</i> Stapf			
<i>Foxtail millet</i>	Italian millet Foxtail bristle grass German millet Hungarian millet	Tribe Paniceae <i>Setaria italica</i> (L.) <i>P. beauv.</i> subsp. <i>italica</i>	Utricle, <2 mm, 1.9 g, creamy with ridges	Eurasia, Southern Europe, tropical and subtropical Asia (China, India, Korea), USA, Australia	19

<i>Japanese barnyard millet</i>	Japanese millet, Siberian millet, White millet, Marsh millet	Tribe Paniceae <i>Echinochloa esculenta</i> (A. Braun) H. Scholz, (also classified as <i>E. crus-gali</i> (L.) P. Beauv)	Hulled grain, whitish to light brown	China, India, Japan, Korea	Minor cultivation
<i>Kodo millet</i>	Kodo, Kodra	Tribe Paniceae <i>Paspalum scrobiculatum</i> L.	2.5 × 2.0 mm, 4 g, oval, light brown to dark gray	India	Minor cultivation
<i>Little millet</i>	Blue panic, Kutki, Sama	Tribe Paniceae <i>Panicum sumatrense</i> Roth	2.5 × 1.5 mm, 1.9 g, oval, creamy and shiny	China, Indian subcontinent, Myanmar, Malaysia, Philippines	Minor cultivation
<i>Pearl millet</i>	Bulrush millet Cattail millet Babala Bajra/Bajira	Tribe Paniceae <i>Pennisetum glaucum</i> (L.) R. Br.	Naked caryopsis, 3.5 × 3.7 mm, 8 g, tear shape, creamy, gray, purplish (individual grains often multicolored), often shiny	West and Central Africa (Niger, Mali, Burkina Faso, Nigeria), India, East and Southern Africa (Namibia, Botswana), USA, Brazil	50
<i>Proso millet</i>	Common millet Broom millet Hog millet Panic millet	Tribe Paniceae <i>Panicum miliaceum</i> L. subsp. <i>miliaceum</i>	Hulled type utricle, 2.7 × 2.5, 2.5 g, oval and flattened, cream to brown and shiny	Eurasia (China, Kazakhstan, Afghanistan, India, Turkey, Romania), USA, Australia	8

Source: Information from FAO, 1995. Sorghum and Millets in Human Nutrition. Available from: www.fao.org; Serna-Saldivar, S., Rooney, L.W., 1995. Structure and chemistry of sorghum and millets. In: Dendy, D.A.V. (Ed.), Sorghum and Millets: Chemistry and Technology. American Association of Cereal Chemists, St. Paul, MN, pp. 69–124; FAOSTAT, 2014. Production Crops. Available from: <http://faostat3.fao.org>, GRIN, Undated. Germplasm Resources Information Network. Available from: <http://www.ars-grin.gov>, ICRISAT (undated) and own unpublished data.

subfamily). Due to the genetic distance between the millets and wheat and its near relatives, the millets are suitable food for people suffering from celiac disease and other intolerances and allergies to wheat and related cereals.

Millets are widely cultivated in warm and tropical regions throughout the world. In developing regions and countries (Africa and across Asia, particularly India and China, and Eastern and Southern Europe) millets are widely consumed in the form of traditional staple foods and used to produce traditional alcoholic and nonalcoholic beverages. In Africa and Asia, the minor millets are used as food crops of last resort in the event of droughts. In more developed countries, such as USA, Argentina, Brazil, Australia, and South Africa, millets are widely cultivated for forage, and there is growing production for the use in specialty foods, particularly gluten-free products. In both developing and more developed countries, millets are produced in abundance as bird food, for both companion birds and game birds. In the USA and South America, there is also an expanding production of pearl millet in particular for poultry feed.

This chapter provides basic information about the production and cultivation of millets. Then it briefly describes the grains of the various millet species. The composition in terms of nutrients, phytochemicals, and antinutrients in the various millet species is then examined. Following this, the processing technologies used to produce traditional and modern millet food and beverage products are described in brief. Further, their impacts on nutrients, phytochemicals, and antinutrients are explained. Then, findings of research into the nutritional quality and health-promoting properties of millet foods are explored and evaluated, with emphasis on animal and human studies examining nutrient and phytochemical bioavailability. The chapter's concluding remarks primarily concern the status of knowledge and research needs, into the nutritional and health promoting attributes of millets, and the prospects for millets as staple and specialty foods.

2 PRODUCTION AND CULTIVATION

Millets truly are ancient grains. There is clear evidence of widespread cultivation of proso millet in Kazakhstan more than 7000 years ago ([Frachetti et al., 2010](#)) and probable cultivation of pearl millet in Ghana more than 5000 years ago ([D'Andrea et al., 2001](#)). It is probable that pearl millet, fonio, finger millet, and teff all originated in Africa, south of the Sahara, pearl millet and fonio in West Africa and finger millet and teff in Northeast Africa. Finger millet and pearl millet were brought to the Indian subcontinent around 2000 BP ([Fuller et al., 2011](#)). The other millets probably all originated in Eurasia. There is evidence of proso millet across Asia and Europe prior to 7000 BP and of foxtail millet in northern China at this time ([Hunt et al., 2008](#)).

Today, the millets are collectively assumed to be the sixth most important cereal grain in terms of production after maize, rice, wheat, barley, and sorghum. However, data on millet production seem to be contradictory. The FAO ([FAOSTAT, 2014](#)) gives an average millet annual production (millet plus fonio, which are listed separately) of 28.3 million tonnes, with an average yield of 0.9 tonnes/ha. This

production seems to be a considerable underestimate as ICRISAT (the International Crops Research Institute for the Semi-Arid Tropics) the CGIAR organization responsible for millets, gives a world crop area for pearl millet alone, quantitatively the most important millet accounting for some 46% of world millet production, of 31 million hectares (ICRISAT, Undated a). At a yield of 0.9 tonnes/hectare this would mean a production of pearl millet of 27.9 million tonnes. Assuming this yield for all the millets, this would translate to a world millet production of some 60 million tons, the same as that of sorghum. As stated, pearl millet accounts for nearly half of world production. The other major cultivated millets are in descending order of production: foxtail millet (some 19% of world production), teff (9%), finger millet (11%), proso millet (8%), and fonio (1%) (Table 4.1).

The great potential of millets as staple food crops under conditions of climate change induced rising temperatures and more frequent droughts is that they are generally very hardy. Pearl millet is probably the most water-efficient cereal plant and can be grown in areas with an annual rainfall as low as 250–400 mm (National Research Council, 1996; USDA, Undated). Proso millet is a short season crop (60–90 days) and hence can be grown in more temperature zones and at high altitude (up to 3500 m) (ICRISAT, Undated b). Foxtail millet has only two-thirds the water requirement of maize and has high tolerance to differing soil fertility (ICRISAT, Undated b). Finger millet requires slightly more water than the other millets (annual rainfall 500–1000 mm) (Obilana and Manyasa, 2002) but can be grown at elevations up to 2000 m. Teff can also be grown at high altitude (1700–2800 m) and under widely varying rainfall conditions (300–2500 mm) (Obilana and Manyasa, 2002). Fonio can be cultivated on poor soils, which are unsuitable for other cereals (National Research Council, 1996) and under a wide range of rainfall conditions (Obilana and Manyasa, 2002).

As indicated, millets are mostly cultivated by small-holder farmers in developing countries. Traditional manual agricultural practices, hand or animal traction ploughing, hand sowing, hand weeding, and hand or animal threshing are the norm. Typically in Africa, there is no, or minimal fertilizer application because of the relative cost of fertilizer versus the commercial value of millets as a crop. As consequence, millet yields are invariably very low. Further, open-pollinated varieties, which enable the farmer to keep the seed for planting in the next season, are almost always used. Today, improved varieties with better yield potential and disease resistance, and larger more easily processed grains are rapidly replacing the local landraces. For example, in Ethiopia teff yields, although still low (2011–1.26 tonnes/ha), have increased dramatically, by 33% in 6 years, as a result of cultivation of improved varieties and more intensification of production in response to rapidly rising demand (Demeke and Di Marcantonio, 2013). In more developed countries, there is cultivation of high yielding hybrid cultivars and millet production is generally mechanized, resulting in higher yields. Pearl millet and foxtail millet hybrid cultivars are now also being released in countries, such as India and China, respectively (ICRISAT, Undated a) (Fig. 4.1). Notwithstanding these developments, overall millet yields (0.9 tonnes/ha) still lag considerably behind that of comparable cereals



FIGURE 4.1 Hybrid foxtail millet bred in China compared to a traditional variety.

(maize 5.2 tonnes/ha and sorghum 1.5 tonnes/ha). Genetic engineering has been applied to produce disease resistant millets. For example, transgenic pearl millet with resistance to downy mildew has been developed (Girgi et al., 2006) but as yet genetically modified millets are not in commercial cultivation.

3 DESCRIPTION AND STRUCTURES OF MILLET GRAINS

Millet grains vary greatly in size between species (Table 4.1). The largest is pearl millet, which has a thousand kernel weight of approximately 8–10 g (about one fourth that of wheat) and the smallest is teff, with a thousand kernel weight of only 0.3–0.4 g. However, there is considerable variation in grain size within species and intensive breeding programs have resulted in varieties with much larger grain size, for example, foxtail millet (Fig. 4.1). The difference in grain size can be dramatic. We have found that an improved pearl millet line from India had twice the thousand kernel weight of the most popular variety grown in Senegal, 14.9 g as against 6.9 g.

In addition to variation in grain size, millet kernels differ in botanical structure between species (Fig. 4.2). Some are naked grains, for example, pearl millet that

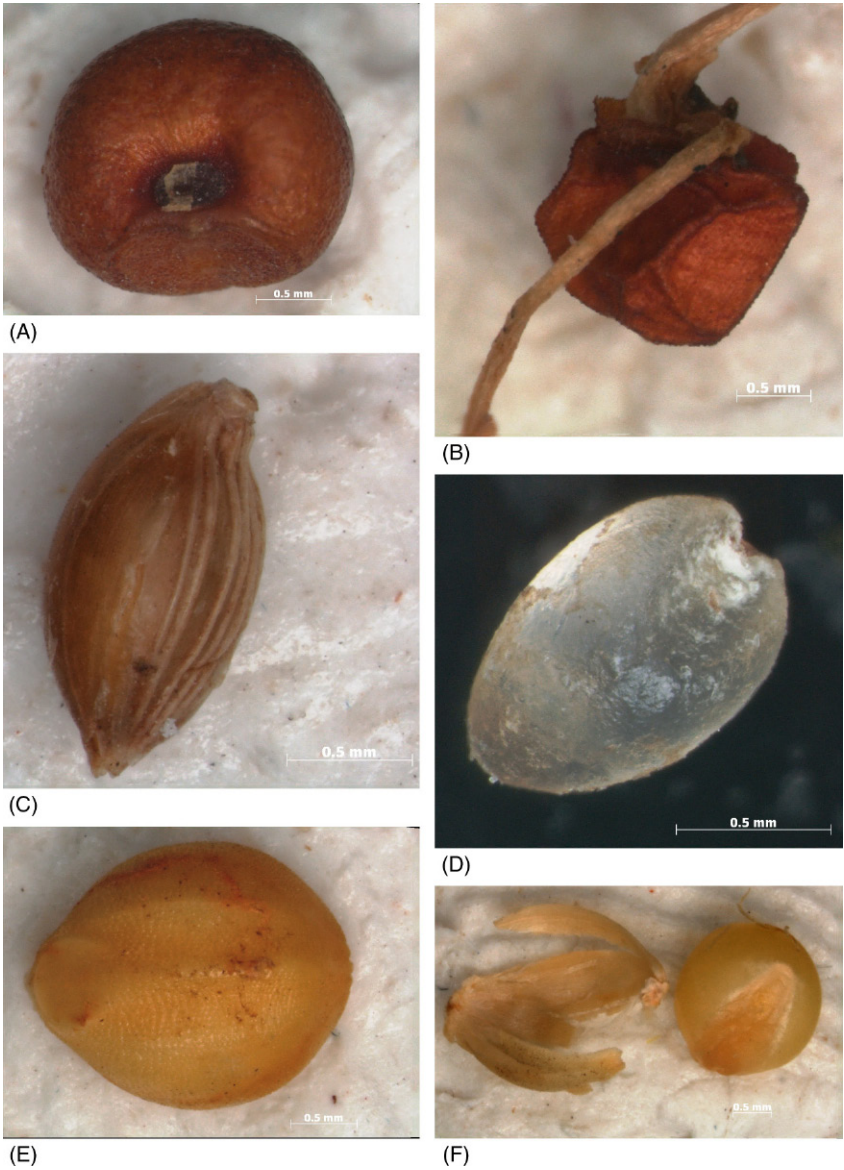


FIGURE 4.2 Grains of various millet species. (A) Finger millet, red variety; (B) malted finger millet grain; (C) black fonio, wholegrain; (D) white fonio, dehulled; (E) foxtail millet, whole grain; (F) foxtail millet, dehulled;

(Continued)

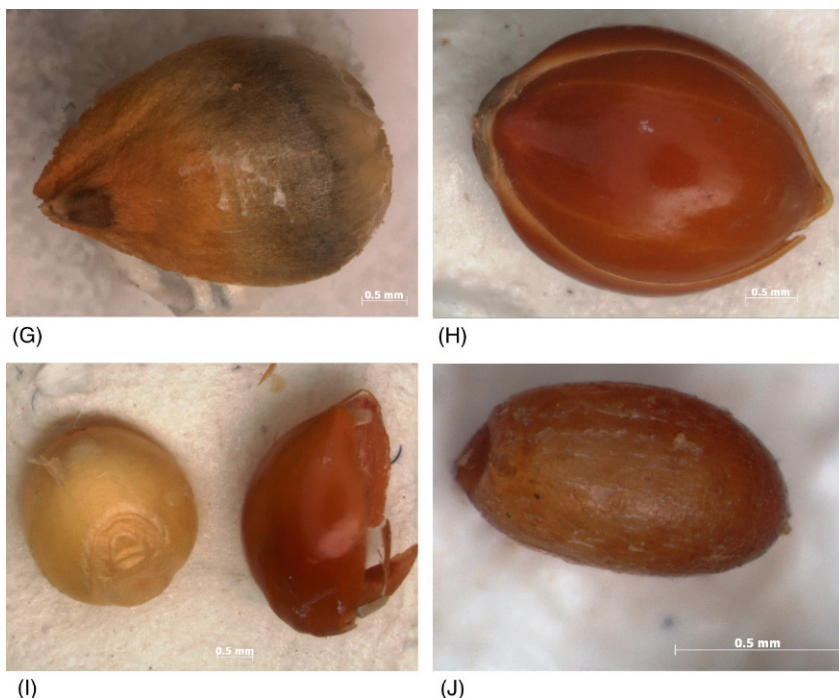


FIGURE 4.2 (cont.) (G) pearl millet, whole grain; (H) proso millet, whole grain; (I) proso millet, dehulled; (J) teff, brown variety, whole grain.

thresh free from the husk like wheat, whereas others, for example, fonio do not and are hulled grains like oats. Some are caryopses with a normal grain structure, for example, pearl millet, like all the major cereals; whereas others are utricles, for example, finger millet, where the pericarp is not completely fused to the seed coat and can be removed by threshing. The overall grain color varies both between and within species. For example, there are both black (actually brown) and white species of fonio and there are both brown and white colored varieties of finger millet and teff (Fig. 4.2). The grain color is related to their content of polyphenolic phytochemicals since anthocyanin type pigments are responsible for the dark grain colors (Dykes and Rooney, 2006). All these factors greatly influence the nutrient and phytochemical contents of the millets. Furthermore, published data; however, do not distinguish as to whether the edible portion of the grain was analyzed or it was including husk/hull or detachable pericarp (if present). Hence, statements on websites and even in some scientific literature to the effect that millet (*sic*) is very nutritious and healthy are at best an oversimplification.

4 NUTRIENTS AND PHYTOCHEMICALS

Notwithstanding the differences in grain size and structure between millet species and their small size relatively to other cereal grains, it is clear that the proximate macronutrient composition of the millets does not differ vastly between species and is generally in the same range as that of other cereals (Table 4.2).

TABLE 4.2 Energy and Proximate Composition (g/100 g db, Except Where Stated Otherwise) of the Millet Species With Wheat for Comparison^a

Species	Energy (kJ/100 g)	Protein	Lysine (g/100 g Protein)	Carbohydrate (Essentially Starch)	Dietary Fiber	Ash	Total Lipids	Palmitic (16:0)	Stearic (18:0)	Oleic (18:1)	Linoleic (18:2)	Linolenic (18:3)
								Total Fatty Acids (%)				
Finger millet	1396 (1392–1405)	8.5 (4.9–11.3)	2.9 (2.5–5.5)	75 (73–82)	15.2 (11.7–18.6)	2.7 (2.0–5.0)	1.4 (1.3–1.6)	23 (20–35)	2	51 (46–62)	21 (8–27)	4
Teff	1441 (1388–1536)	10.0 (7.9–12.6)	2.7 (2.0–4.0)	74 (73–77)	8.0	2.6 (2.2–2.9)	2.1 (2.0–2.4)	14	4	24	39	6
Barnyard millet	1877	15.0	1.4	74	2.0?	1.3	5.2 (4.7–5.7)	11 6–17	1	27 (24–30)	58 (48–68)	1
Fonio	1409 (1300–1529)	8.4 (5.1–10.4)	2.2 (1.9–2.5)	75	18.2 (15.7–20.7)	3.4 (1.0–6.0)	2.6 (1.8–4.5)	No data				
Foxtail millet	1467	9.6 (6.0–17.0)	1.9 (1.5–2.8)	69 (63–73)	9.4	2.6 (1.5–4.3)	4.5 (1.6–9.3)	9 (7–10)	3 (1–7)	14 (11–16)	69 (65–72)	3 (2–4)
Japanese barnyard millet	No data	11.8 (11.2–12.7)	1.7 (1.6–1.8)	60 (59–62)	14.7	4.9 (4.7–5.0)	4.9 (2.5–6.3)	No data				
Kodo millet	1661 (1476–1846)	10.4 (6.2–13.1)	2.4 (1.3–4.0)	76 72–79	10.4	2.7 (1.7–3.6)	3.7 (3.2–4.9)	19 (18–20)	2	38 (37–39)	41 (40–43)	1
Little millet	1910	15.0	1.1	76	2.5?	1.1	4.5 (3.5–5.4)	16	5	35	41	1
Pearl millet	1499 (1442–1517)	12.4 (6.9–20.9)	2.8 (1.7–6.5)	70 (67–72)	13.8 (8.5–15.3)	2.8 (0.3–5.1)	5.1 (3.1–8.8)	14 (9–24)	3 (1–8)	25 (20–30)	54 (37–64)	2 (1–7)

(Continued)

TABLE 4.2 Energy and Proximate Composition (g/100 g db, Except Where Stated Otherwise) of the Millet Species With Wheat for Comparison (*cont.*)

Species	Energy (kJ/100 g)	Protein	Lysine (g/100 g Protein)	Carbohydrate (Essentially Starch)	Dietary Fiber	Ash	Total Lipids	Palmitic (16:0)	Stearic (18:0)	Oleic (18:1)	Linoleic (18:2)	Linolenic (18:3)
								Total Fatty Acids (%)				
Proso millet	1522	12.6 (6.4–16.0)	1.5 (0.8–4.3)	71 (64–76)	13.1	2.7 (0.8–8.8)	2.6 (1.7–4.1)	108 (7–11)	2 (2–3)	21 (18–24)	65 (62–70)	2 (1–3)
Wheat (hard red winter)	1574	14.5	2.7	82	14.0	1.6	1.8	21	1	18	55	2

^aValues are the average (range) of reliable published data.

Source: Adapted from Taylor, J.R.N., Kruger, J., 2016. Millets. In: Caballero, B., Finglas, P., Toldrá, F. (Eds.), *The Encyclopedia of Food and Health*, vol. 3. Academic Press, Oxford, pp. 748–757; with additional data from Mahadevappa, V.G., Raina, P.L., 1978. Lipid profile and fatty acid composition of finger millet (*Eleusine coracana*). *J. Food Sci. Technol.* India 15, 100–102; Geervani, P., Eggum, B.O., 1989. Nutrient composition and protein quality of minor millets. *Plant Foods Hum. Nutr.* 39, 201–208; Sridhar, R., Lakshminarayana, G., 1992. Lipid class contents and fatty acid composition of small millets: little (*Panicum sumatrense*), kodo (*Paspalum scrobiculatum*), and barnyard (*Echinochloa colona*). *J. Agri. Food Chem.* 40, 2131–2134; Serna-Saldivar, S., Rooney, L.W., 1995. Structure and chemistry of sorghum and millets. In: Dendy, D.A.V. (Ed.), *Sorghum and Millets: Chemistry and Technology*. American Association of Cereal Chemists, St. Paul, MN, pp. 69–124; National Research Council, 1996. *Lost Crops of Africa*, vol. 1, Grains. National Academies Press, Washington, DC, pp. 381; Léder, I. 2004. Sorghum and millets. In: Füleky, G. (Ed.). *Cultivated Plants, Primarily as Food Sources*, Encyclopedia of Life Support Systems. Eolss Publishers, Oxford; Kim, J.Y., Jang, K.C., Park, B.R., Han, S.I., Choi, K.J., Kim, S.Y., Oh, S.H., Ra, J.E., Ha, T.J., Lee, J.H., Hwang, J., 2011. Physicochemical and antioxidative properties of selected barnyard millet (*Echinochloa utilis*) species in Korea. *Food Sci. Biotechnol.* 20, 461–469; USDA, Undated. Plants Database. Available form: <http://plants.usda.gov>

As with other cereals, carbohydrates, essentially starch (approximately 60%–75%) is the major component, followed by dietary fiber (10%–15%) and protein (8%–15%), and lipid (oil/fat) (1%–5%) and ash (total minerals) (1%–3%). With exception of carbohydrates which are lower, these values fall within the range of those of hard red bread wheat.

4.1 Carbohydrates

As stated, the major edible carbohydrate of millet is starch. Data from finger millet and foxtail millet indicate that the other carbohydrates in millets are mainly sucrose plus a little glucose and fructose, and comprise approximately 1% of millet grain weight (Malleshi et al., 1986). The starch in millets generally has the normal approximately 3–4:1 ratio of amylopectin to amylose (Emmambux and Taylor, 2013; Kumari and Thayumanavan, 1998). However, there are waxy (high-amylopectin) varieties of foxtail and proso millets (Taylor et al., 2014). The gelatinization temperatures of millet starches are similar to that of maize and sorghum and typical of starches from tropical cereals. Mean values ranging from 65°C for pearl millet (Beleia et al., 1980) to 84.9°C for Japanese barnyard millet (Kumari and Thayumanavan, 1998) have been reported. By comparison, the gelatinization temperature of hard winter wheat starch is approximately 59°C (Yoo and Jane, 2002).

Interestingly, there is great variation in starch granule morphology between millet species and several species contain more than one type of starch granule. Pearl millets, like maize and sorghum contains just large, simple granules (8–13 µm) (Emmambux and Taylor, 2013). Fonio contains small, simple granules (approximately 7 µm), whereas other species including finger, kodo, little, and proso millets generally contain two types, fairly large polygonal and small polygonal and/or round granules, in the approximate size range of 1–10 µm (Emmambux and Taylor, 2013; Kumari and Thayumanavan, 1998). In the case of finger millet some of these granules are compound granules (McDonough et al., 1986), that is, large starch granules made up of many closely packed small granules. This is probably also the case with some of the other millets. With teff, it appears that all the granules are compound, where the small granules (2–6 µm) are polygonal shaped (Bultosa et al., 2002). The small starch granules in millets are similar in size to those of the pseudocereals amaranth, buckwheat, and quinoa, and also to rice, which is noted for its compound granules (Wei et al., 2010). Perhaps due to their relatively larger surface area, small starch granules seem to impact positively on the quality of dough-based products. For example, injera (the fermented flatbread of Ethiopia) made from teff and finger millet is more resistant to staling than that made from sorghum. In fact, when teff or finger millets are not available, rice is the preferred flour for injera making (Gebey et al., 2012).

4.2 Proteins

As with other cereals, lysine is the first limiting indispensable (essential) amino acid in all millets. It is probable that among the millets, pearl millet has the highest levels of lysine, notwithstanding the range of values shown in [Table 4.2](#). This is on account of its proportionally large protein-rich (approximately 31% protein) germ ([Abdelrahman et al., 1984](#)), which contains the lysine-rich albumin and globulin proteins.

As with most cereals, with exception of rice and oats, the prolamin storage proteins are the major protein fraction in the major millet species ([Shewry, 2002](#)). Values for prolamins as a percentage of total grain protein for finger, foxtail, pearl, and proso millets and teff of approximately 42, 76, 43, 58, and 41%, respectively, are given in the literature ([Taylor and Taylor, 2017](#)). Prolamins are by definition rich in proline and glutamine and very low in lysine. Hence, it is for this reason that lysine is the first limiting amino acid in most cereals. An exception seems to be fonio where the major proteins are apparently glutelins ([Carcea and Salvatorelli, 1999](#)), which are richer in lysine, as is the case in rice, and comprise some 60% of grain protein. Data on the proteins of minor millets, although incomplete, suggest that glutelins are also the major protein fraction in barnyard millet, Japanese barnyard millet, kodo millet, and little millet ([Monteiro et al., 1988](#); [Parameswaran and Thayumanavan, 1995](#); [Sudharshana et al., 1988](#)). However, because most millets are closely related to maize and sorghum and the lysine content of their protein is very low, it is the author's opinion that this is probably not correct.

The millet prolamins have not been studied in any details. It has been shown that antibodies to the kafirin, the sorghum prolamin, react with the prolamins of barnyard, finger, foxtail, kodo, little, and proso millets ([Mazhar et al., 1993](#)). Thus, there must be a high degree of homology. There is also a high degree of homology between the pearl millet and teff prolamins and those of maize and sorghum ([Shewry, 2002](#); [Tatham et al., 1996](#)). Interestingly, it has been found that the teff prolamins have a lower degree of polymerization, are less hydrophobic and have a lower denaturation temperature than kafirin ([Adebowale et al., 2011](#)). These properties suggest that the teff prolamins may be more functional in dough systems than the notably inert sorghum kafirin prolamin protein.

4.3 Lipids

Lipids are the only major component that differs substantially between millet species. Pearl millet and foxtail millet clearly have higher lipid contents than the other major millets, and of the minor millets, Japanese barnyard millet, and little millet are also apparently high in lipids ([Table 4.2](#)). The higher levels of lipids in pearl millet and foxtail millet are due to their relatively large germs as lipids are concentrated in the germ tissue. The germ of pearl millet comprises some 32% lipid and contains approximately 88% of the total fat in the grain ([Abdelrahman et al., 1984](#)).

Concerning the fatty acid composition of millet lipids, this is the same as other cereals. They are rich in the unsaturated fatty acids, oleic (C18:1), and linoleic acid (C18:2), with the linoleic acid predominating. Finger millet seems to be an exception with the monounsaturated oleic acid predominating. This factor, and its low fat content (approximately 1.4%), probably account for the well-known excellent storability of finger millet grain (Obilana and Manyasa, 2002).

4.4 Dietary Fiber

Although, there are apparently some large differences in the dietary fiber contents of the millet species (Table 4.2), the data are actually not clear. This is because of the aforementioned issue of whether the analysis were performed on hulled or dehulled grains, and because of ongoing advances in dietary fiber analysis, whereby soluble dietary fiber and resistant starch are considered as dietary fiber in addition to the traditional insoluble (crude) dietary fiber. Hence, the very high (approximately 18%) and low (2%–3%) values for dietary fiber probably do not relate to the total dietary fiber content of edible whole grain.

4.5 Micronutrients

The contents of minerals and vitamins in the millets generally do not differ vastly between the species and are essentially the same as that of other cereals (Table 4.3). However, the micronutrient and antinutrient data are less comprehensive than for macronutrients and there are some gaps in the data, especially for the minor millets.

With regard to minerals, finger millet contains a notably high level of calcium (approximately 240–410 mg/100 g). Its distribution is also interesting in that the calcium is concentrated in the seedcoat (the pericarp is removed during threshing of finger millet), with some in the endosperm and none in the germ (Kruger et al., 2014). Concerning pearl millet, ICRISAT has developed lines that are high in iron and zinc using conventional breeding. Hybrid cultivars of these biofortified pearl millet lines contain >75 mg/100 g iron and >55 mg/100 g zinc (Rai et al., 2013), that is, >60% and >30% higher, respectively than the average iron and zinc content of pearl millet (Table 4.3).

Concerning vitamins, like all cereals the millets are rich in B vitamins (vitamin B₁—thiamin, vitamin B₂—riboflavin, and vitamin B₃—niacin) (Table 4.3), which are concentrated in the bran layers. Like all cereals, they are very low in provitamin A (β-carotene). Foxtail millet has a yellow endosperm due to the presence of carotenoids (Fig. 4.2). However, *trans*-lutein and *trans*-zeaxanthin, the primary carotenoids (Shen et al., 2015), have very little provitamin A activity. Although incomplete, the available data suggest that the millets are not exceptional sources of vitamin E (tocopherols), with the contents being lower than that of wheat.

TABLE 4.3 Major Dietary Mineral, Vitamin, and Antinutrient Contents (per 100 g db) of the Major Millet Species With Wheat for Comparison

Millet Species	Fe	Zn	Ca	Mg	K	Na	P	Vitamin B ₁	Vitamin B ₂	Vitamin B ₃	β-Carotene (μg ^a RE)	Vitamin E (μg ^b α-TE)	Phytate (mg)	Oxalate (mg)
	(mg)													
Finger millet	8.7 (3.9–18.2)	2.0 (1.5–2)	343 (240–410)	127 (110–140)	438 (314–580)	46 (20–90)	243 (200–280)	0.38 (0.24–0.48)	0.14 (0.11–0.19)	1.1 (1.0–1.3)	No data	2.2	590 (450–700)	29 (29–30)
Teff	11.6 (1.5–30)	2.1 (0.7–4.0)	161 (157–180)	177 (168–184)	378 (310–427)	26 (12–46)	384 (350–429)	0.38 (0.30–0.45)	0.18 (0.10–0.27)	2.6 (2.0–3.4)	0.8	0.1	682 (528–842)	No data
Barnyard millet	7.6 (2.3–12.9)	0.9 (0.4–1.4)	210 58–361)	190 (167–213)	No data		240	0.30	0.09	No data				
Fonio	11.4 (1.0–55.0)	2.3 (1.3–3.6)	38 (30–44)	415 (400–430)	160	20	195 (160–234)	0.24 (0.08–0.30)	0.14 (0.10–0.26)	2 (0.9–3.0)	0.0	No data	514 (413–448)	No data
Foxtail millet	8.4 (2.8–24)	1.9 (2.1–5.1)	24 (10–40)	115 (70–140)	335 270–580)	45 (10–130)	290 (70–360)	0.54 (0.48–0.59)	0.12 (0.11–0.12)	3.5 (3.2–3.7)	No data	3.1	660 (650–700)	27 (25–28)
Japanese barnyard millet	No data		2	No data										
Kodo millet	8 2–13	No data	25 (10–40)	13	170	10	256 (180–332)	0.34 (0.17–0.50)	0.10	No data				

Little millet	15	No data	33	No data			299	0.41	0.28	No data				
Pearl millet	3.1–6.1	3.2–5.4	31 (10–42)	121 (111–30)	468 (440–495)	13 (10–15)	341 (332–350)	0.35 (0.30–0.38)	0.21 (0.19–0.22)	2.7 (2.5–2.8)	0.9 (0.8–1.2)	1.1 (0.2–1.9)	585 (180–990)	No data
Proso millet	9.4 (2.9–31)	2.1 (10) (1.7–6.8)	19 (8–40)	130 (60–180)	345 (200–590)	35 (10–100)	245 (210–340)	0.52 (0.41–0.63)	0.25 (0.22–0.28)	3.2 (1.8–4.5)	No data	No data	1140 (500–1670)	23 (21–23)
Wheat (hard red winter) ^b	3.7	3.0	33	145	418	2	331	0.44	0.13	6.3	0.0	5.0	1167 (1080–1350) ^{a,b}	59 (53–71) ^c

Values are the average (range) of reliable published data.

^aRetinol equivalent (RE), 1 µg β-carotene = 0.167 µg RE.

^bα-Tocopherol equivalents.

^cWheat type not specified.

Source: Adapted from Taylor, J.R.N., Kruger, J., 2016. Millets. In: Caballero, B., Finglas, P., Toldrá, F. (Eds.), The Encyclopedia of Food and Health, vol. 3. Academic Press, Oxford, pp. 748–757; with additional data from Lolas, G.M., Palamidis, N., Markakis, P., 1976. The phytic acid-total phosphorus relationship in barley, oats, soybeans, and wheat. Cereal Chemistry 53, 867–871; Geervani, P., Eggum, B.O. 1989. Nutrient composition and protein quality of minor millets. Plant Foods Hum. Nutr. 39, 201–208; Sridhar, R., Lakshminarayana, G., 1992. Lipid class contents and fatty acid composition of small millets: little (*Panicum sumatrense*), kodo (*Paspalum scrobiculatum*), and barnyard (*Echinochloa colona*). J. Agri. Food Chem. 40, 2131–2134; Serna-Saldivar, S., Rooney, L.W., 1995. Structure and chemistry of sorghum and millets. In: Dendy, D.A.V. (Ed.), Sorghum and Millets: Chemistry and Technology. American Association of Cereal Chemists, St. Paul, MN, pp. 69–124; National Research Council. 1996. Lost Crops of Africa, vol. 1, Grains. National Academies Press, Washington, DC, pp. 381; Léder, I. 2004. Sorghum and millets. In: Füleky, G. (Ed.), Cultivated Plants, Primarily as Food Sources, Encyclopedia of Life Support Systems. Eolss Publishers, Oxford; Siener, R., Hönow, R., Voss, S., Seidler, A., Hesse, A., 2006. Oxalate content of cereals and cereal products. J. Agri. Food Chem. 54, 3008–3011; Kim, J.Y., Jang, K.C., Park, B.R., Han, S.I., Choi, K.J., Kim, S.Y., Oh, S.H., Ra, J.E., Ha, T.J., Lee, J.H., Hwang, J., 2011. Physicochemical and antioxidative properties of selected barnyard millet (*Echinochloa utilis*) species in Korea. Food Sci. Biotechnol. 20, 461–469; Rai, K.N., Yadav, O.P., Rajpurohit, B.S., Patil, H.T., Govindaraj, M., Khairwal, I.S., Rao, A.S., 2013. Breeding pearl millet cultivars for high iron density with zinc density as an associated trait. Journal of SAT Agricultural Research 11, 1–7; USDA, Undated. Plants Database. Available from: <http://plants.usda.gov>; Muthamilarasan, M., Dhaka, A., Yadav, R., Prasad, M., 2016. Exploration of millet models for developing nutrient rich graminaceous crops. Plant Sci. 242, 89–97.

4.6 Phytochemical Compounds

Generally, millet grains contain considerably higher levels of phenolic phytochemical compounds compared to the major cereals (Taylor and Duodu, 2015), such as red wheat (Table 4.4). As in all cereal grains, the major phenolics in the millets are phenolic acids and flavonoids. Some brown colored varieties of finger millet additionally contain condensed tannins (proanthocyanidins/procyanidins) (Dykes and Rooney, 2006), like the tannin-type sorghum varieties. There have been reports of other types of phytochemicals in millets, for example, γ -amino butyric acid has been found in foxtail millet (Bai et al., 2009) and barnyard millet (Sharma et al., 2016), particularly in germinated grains.

Concerning the phenolic acids in millets, both hydroxybenzoic acids (e.g., protocatechuric acid and vanillic acid) and hydroxycinnamic acids (e.g., ferulic acid, caffeic, coumaric acid, and sinapic acid) and their derivatives are found in the different species of millets in varying proportions (Shahidi and Chandrasekara, 2013). Although data are very incomplete and sometimes contradictory, it appears that teff, kodo millet, and foxtail millet contain high levels of phenolic acids (Table 4.4). Comparing data from different researchers is; however, problematic as phenolic acids exist in several different forms: free, esterified, etherified, and bound (Chandrasekara and Shahidi, 2011a). In the different millet species, as in other cereal grains, the majority of phenolic acids exist in the bound form (Acosta-Estrada et al., 2014; Chandrasekara and Shahidi, 2011b). The bound forms are invariably dimers or oligomers particularly of ferulic acid, for example, diferulic acid, which are crosslinked to the cell wall nonstarch polysaccharides (Acosta-Estrada et al., 2014) and hence very difficult to quantify accurately.

Concerning the flavonoid-type phenolics, it appears that finger millet generally contains the highest levels (Table 4.4) with several different compounds and derivatives having been identified, including catechin, gallic catechin, epicatechin, epigallocatechin, taxifolin, vitexin tricin, luteolin, myricetin, quercetin, kaemferol, narigenin, and diadzein (Shahidi and Chandrasekara, 2013). As with the phenolic acids, the flavonoids also exist in the free, esterified, etherified, and bounds forms, but with probably the majority being in the free form.

4.7 Antinutrients

Phytate (myoinositol hexaphosphate) and oxalate are antinutrients, which occur widely in plant foods (Akande et al., 2010). They bind to divalent metal ions, such as iron, zinc, and calcium and can severely adversely affect their bioavailability. Phytate is located in the cereal aleurone layer and to a lesser extent the germ (Serna-Saldivar and Rooney, 1995) and oxalate is concentrated in the seedcoat. Again, although incomplete, the data show that the levels of these antinutrients in the millets (Table 4.3) are no higher than those in other cereals. Hence, statements in the literature that single out particular millets as containing these antinutrients (Sripriya et al., 1997) can be misleading.

TABLE 4.4 Phenolic Phytochemicals and Health Related Aspects of the Millets

Millet Species	Tannins	Flavonoids (mg/100 g)	Phenolic acids (mg/100 g)	Some Significant Phenolics	Health Related Aspects
<i>Finger millet</i>	White and red, none Brown, some varieties—(600–2100 mg/100 g)	High levels Soluble: 210 Insoluble: 1	Low levels Soluble: 17 Insoluble: 52	<i>trans</i> -Ferulic acid, procatechuric acid Catechin, gallocatechin, epicatechin, epigallocatechin, taxifolin, vitexin, tricetin, luteolin, myricetin, quercetin, kaempferol, narigenin, diadzein Procyanidins B1 and B2 (some brown varieties)	Antihyperglycemic effects Antiinflammatory
<i>Teff</i>	None	High in brown varieties, intermediate in white varieties Brown varieties: 106–116 White varieties: 62–67	Apparently high levels Brown varieties: 186–219 White varieties: 142	Ferulic acid, Protocatechuric, <i>p</i> -Coumaric acid Catechin, Rutin, Quercetin, Resveratrol	
<i>Barnyard millet</i>	None	Low 29–58	Total phenolics: 29–80	Ferulic acid, Vanillic acid, Sinapic acid Kaempferol, Naringenin, Apegenin	Antihyperglycemic and hypolipidemic effects?
<i>Fonio</i>	None	Low levels? White fonio: total flavonoids: <1 Black fonio: no data but should be higher	White fonio: low levels Soluble: 2 Insoluble: 4	<i>trans</i> -Ferulic acid, Procatechuric acid Luteolin, Epigenin	
<i>Foxtail millet</i>	None	Generally low levels 25–88 Soluble: 25 Insoluble: 2	High levels Soluble - 63 Insoluble- 181	<i>p</i> -Coumaric acid, <i>trans</i> -Ferulic acid Catechin, Quercetin, Apigenin, Kaempferol	Antihyperglycemic and hypolipidemic effects
<i>Japanese barnyard millet</i>		No data	No data	<i>N</i> -(<i>p</i> -coumaroyl)serotonin, luteolin, tricetin, Kaempferol, Biochanin A	
<i>Kodo millet</i>	None	Low levels? Soluble: 13 Insoluble: 38	High levels Soluble: 95 Insoluble: 379	<i>trans</i> -Ferulic acid, <i>p</i> -coumaric acid, Caffeic acid, Kaempferol, Apigenin, Vitexin, Isovitexin, Luteolin, Quercetin	

(Continued)

TABLE 4.4 Phenolic Phytochemicals and Health Related Aspects of the Millets (cont.)

Millet Species	Tannins	Flavonoids (mg/100 g)	Phenolic acids (mg/100 g)	Some Significant Phenolics	Health Related Aspects
<i>Little millet</i>	Essentially none	Both low and high levels: 87 and 335 Soluble: 87 Insoluble: 0	Intermediate levels Soluble: 67 Insoluble: 136 Total phenolics: 430	<i>p</i> -coumaric acid, <i>trans</i> -ferulic acid, Vanillic acid, Apigenin	
<i>Pearl millet</i>	Probably absent in all varieties	Low levels Soluble: 6 Insoluble: 1	Intermediate levels Soluble: 58 Insoluble: 100	<i>trans</i> -Ferulic acid C-glycosyl flavones (Vitexin), Epigenin, Myricetin	Goiterogenic effects
<i>Proso millet</i>	Essentially none	Generally low levels 8-51 Soluble: 5 Insoluble: 3	High levels Soluble: 50 Insoluble: 208	<i>p</i> -Coumaric acid, <i>trans</i> -Ferulic acid Kaemferol, Apigenin, Myricetin	Serum cholesterol improvement
<i>Red Wheat</i>	None	Generally Low levels Soluble: 2 Insoluble: 33 Total 11	Low levels Total: 68–78	Ferulic acid, diferulic acid, <i>o</i> -Coumaric acid	

Source: Adapted from Taylor, J.R.N., Kruger, J., 2016. Millets. In: Caballero, B., Finglas, P., Toldrá, F. (Eds.), The Encyclopedia of Food and Health, vol. 3. Academic Press, Oxford, pp. 748–757; with additional data from: Watanabe, M., 1999. Antioxidative phenolic compounds from Japanese barnyard millet (*Echinochloa utilis*) grains. J. Agric. Food Chem. 47, 4500–4505; Mpofu, A., Sapirstein, H.D., Beta, T., 2006. Genotype and environmental variation in phenolic content, phenolic acid composition, and antioxidant activity of hard spring wheat. J. Agric. Food Chem. 54, 1265–1270; Siwela, M., Taylor, J.R.N., de Milliano, W.A.J., Duodu, K.G., 2007. Occurrence and location of tannins in finger millet grain and antioxidant activity of different grain types. Cereal Chem. 84, 169–174; Liu, Q., Qiu, Y., Beta, T., 2010. Comparison of antioxidant activities of different colored wheat grains and analysis of phenolic compounds. J. Agri. Food Chem. 58, 9235–9241; Pradeep, S.R., Guha, M., 2011. Effect of processing methods on the nutraceutical and antioxidant properties of little millet (*Panicum sumatrense*) extracts. Food Chem. 126, 1643–1647; Shahidi, F., Chandrasekara, A., 2013. Millet grain phenolics and their role in disease risk reduction and health promotion: a review. J. Funct. Foods 5, 570–581; Baye, K., 2014. Tef: Nutrient Composition and Health Benefits. Ethiopian Development Research Institute, Addis Ababa and International Food Policy Research Institute, Washington, DC, 20 pp; Inglett, G.E., Chen, D., Liu, S.X., 2015. Antioxidant activities of selective gluten free ancient grains. Food Nutr. Sci. 6, 612–21; Pradeep, P.M., Sreerama, Y.N., 2015. Impact of processing on the phenolic profiles of small millets: evaluation of their antioxidant and enzyme inhibitory properties associated with hyperglycemia. Food Chem. 169, 455–463; Kotásková, E., Sumczynski, D., Mlc'ek, J., Valášek, P., 2016. Determination of free and bound phenolics using HPLC-DAD, antioxidant activity and in vitro digestibility of Eragrostis tef. J. Food Comp. Anal. 46, 15–21; Sharma, S., Saxena, D.C., Riar, C.S., 2016. Analysing the effect of germination on phenolics, dietary fibres, minerals and γ -amino butyric acid contents of barnyard millet (*Echinochloa frumentaceae*). Food Biosci. 13, 60–68; Ugare, R., Chimmad, B., Naik, R., Bharati, P., Itagi, S., 2014. Glycemic index and significance of barnyard millet (*Echinochloa frumentaceae*) in type II diabetics. J. Food Sci. Technol. 51, 392–395.

As mentioned, finger millet seems to be unique among the millets in which the brown colored varieties contain condensed tannins. The condensed tannins in sorghum are well-known to act as antinutrients as a result of their binding with dietary proteins (Butler et al., 1984) and digestive enzymes. The tannins in sorghum also reduce the bioavailability of dietary minerals (Kruger et al., 2012). As with sorghum, the tannins in finger millet grain are located in the testa layer (Siwela et al., 2007). However, the level of condensed tannins in the brown varieties of finger millet (1–2 g catechin equivalent/100 g) seems to be generally lower than in tannin sorghum varieties. Despite the relatively low levels of tannins in brown finger millet varieties, they could have negative nutritional effects. Fermentation of finger millet both substantially reduces assayable tannin content and at the same time probably improves protein, starch, and mineral availability, as indicated by in vitro assay (Antony and Chandra, 1998).

There is some evidence that pearl millet can cause goiter when it is consumed as a staple by communities that have a very restricted diet, for example, in areas of Sudan and South Sudan (Elnour et al., 2000). Pearl millet contains C-glycosyl flavone-type phenolic compounds, in particular vitexin, glucosyl vitexin, and glucosyl orientin, which have been implicated as the causal agents (Gaitan et al., 1989). These C-glycosyl flavones can inhibit the deiodination of the hormone thyroxine to its more active form triiodothyronine.

5 PROCESSING AND FOOD APPLICATIONS

5.1 Primary processing technologies

5.1.1 Milling

Although it is difficult to generalize across the world and across all millet species, it seems that millets are traditionally not eaten as a milled whole grain food. Rather, the grain is refined to a limited extent. The hull if present (as in fonio), the loose "pericarp" in the utricule type millets (such as finger, foxtail, and proso millet) or the outer parts of the pericarp and germ (the bran) are removed in caryopsis-type millets (such as pearl millet). An exception seems to be teff, which is normally milled into whole grain flour. This is presumably as a consequence of its very small grain size. However, even teff flour is often refined to some degree by sifting out coarse particles.

The grain refining process, which is called dehulling or decortication, was traditionally achieved as part of the process of grain milling by hand pounding using a pestle and mortar or with a simple stone quern type mill, which has two horizontal mill-stones. From the 1970s, mechanical decortication, followed by mechanical milling, have progressively displaced the manual milling processes (Bassey and Schmidt, 1989). Fig. 4.3A shows a pearl millet decorticator manufactured in Senegal and widely used in the Sahel (Sahara desert margin region) and the decorticated grain kernels. The decorticator removes the bran by means of abrasion using angle grinder-type abrasive disks mounted on an axle (top

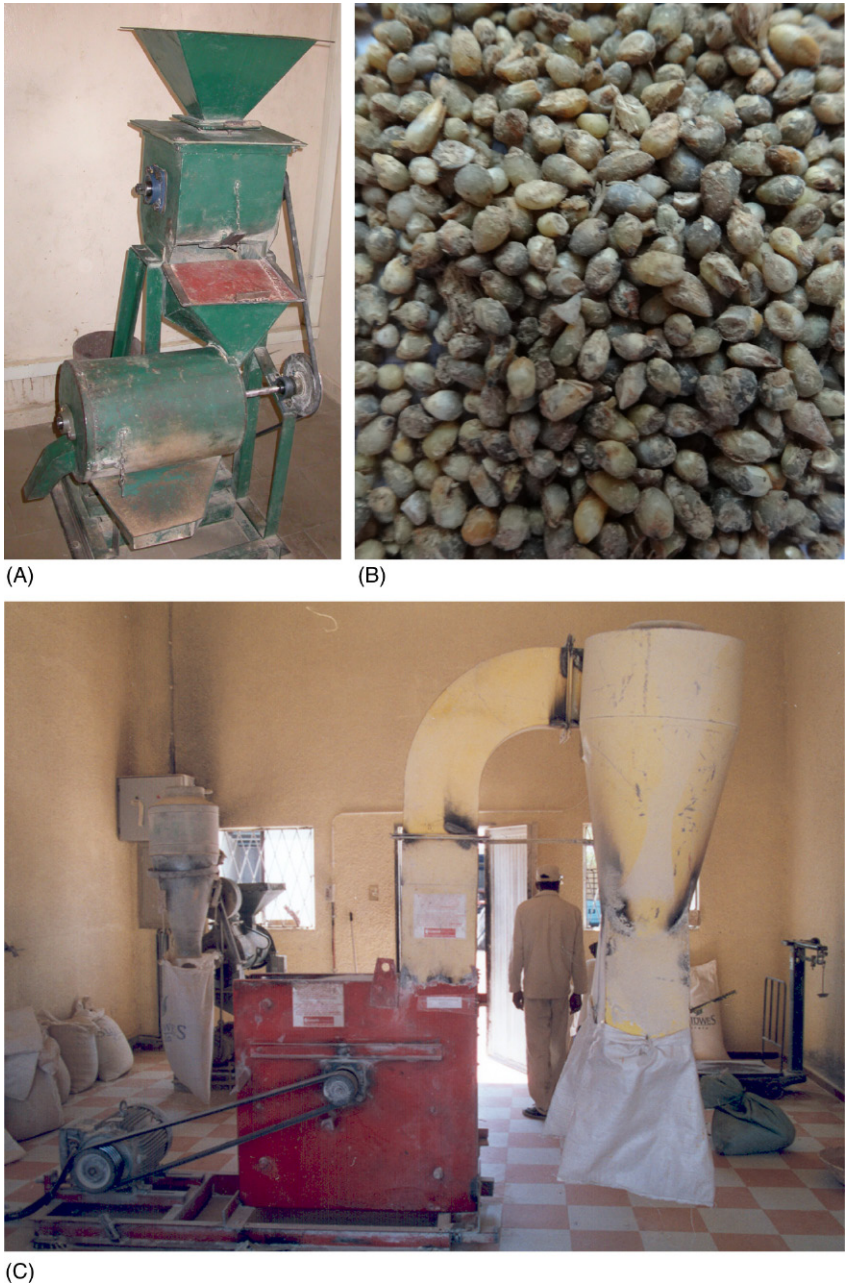


FIGURE 4.3 Milling of millets. (A) Pearl millet dehuller from Senegal; (B) decorticated pearl millet; (C) pearl millet dehuller with cyclone and hammer mill in Namibia.

chamber). The abrasion principle is common to virtually all types of mechanical decorticators. In the pearl millet decorticator from Senegal the fine bran is then separated by means of a revolving bar (which may be fitted with brushes) within a cylindrical sieve. The decorticated grain (Fig. 4.3B) exits from within the cylindrical sieve and the bran is pushed through the sieve and collected. In some other types of decorticators the bran is removed by a suction fan and collected via a cyclone (Fig. 4.3C). The mechanically decorticated grain is then milled into flour, using a hammer mill or a vertical steel plate mill.

5.1.2 Lactic Acid Fermentation

Across Africa, whole grain millet, decorticated grain, or flour is traditionally widely fermented by lactic acid bacteria fermentation (Taylor, 2016), often referred to as a souring process. Well-known examples of such soured foods are the uji finger millet-based porridge of East Africa, injera the sour leavened flatbread of Ethiopia and Eritrea, which is generally made from teff, and the opaque and cloudy beers produced across sub-Saharan Africa which are made with pearl millet or finger millet. Repeatable, rapid, and safe fermentation is achieved by the process of back-slopping, whereby a small portion of the previous successful fermentation liquid is used to inoculate a new batch of grain or flour. Hence, specific microorganisms are progressively selected, although it is not a defined culture and generally comprises both lactic acid bacteria, such as *Lactobacilli*, and yeasts (Owusu-Kwarteng et al., 2012). Thus, it is a form of sourdough fermentation as used in wheat bread making. The lactic acid fermentation gives the millet food products an attractive sour taste. It also extends their shelf life as the pH is generally below pH 4.0 and hence the growth of spoilage microorganisms is discouraged. Most importantly, the low pH in particular, renders the products safe as the growth of pathogenic bacteria is prevented (Svanberg et al., 1992). Further, some of the fermentative microorganisms have been found to be probiotics (Pedersen et al., 2012; Turpin et al., 2011). The fermentation process also improves the nutritional quality of the food by making nutrients more bioavailable and reducing some antinutrients, and it also impacts on the quantity and availability of phytochemicals (Section 5.4).

5.1.3 Malting

Across Africa and India, millets, in particular finger millet and pearl millets are malted (sprouted). This is generally done at small scale (a few kilograms), although large industrial-scale (several tonnes) millet malting is carried out in Zimbabwe. Millet malts (pearl millet and finger millet) are used in traditional opaque beer brewing across sub-Saharan Africa and in porridges in East and West Africa (Murty and Kumar, 1995). Malting involves soaking, which hydrates the grains, followed by limited germination for approximately 4–5 days. The “green malt” is then dried to produce a shelf-stable product (Fig. 4.2B). During malting, endogenous enzymes, particularly amylases and proteases are mobilized, which hydrolyze some of the grain starch and proteins into their component sugars and amino

acids, respectively (Taylor et al., 2013). As with lactic acid fermentation, malting generally improves the nutritional quality of the foods by making nutrients more bioavailable and reducing some antinutrients, and impacting on phytochemicals (Section 5.4). In addition, the amylase activity of the malt reduces the viscosity of porridges, which are used as a complementary food for infants and for the elderly and infirm (Thaoge et al., 2003). The reduction in viscosity renders the porridges more palatable and enables porridges of high solids (nutrient) content, that is lower water content, to be made without them having excessive viscosity, which would render them inedible. A difficulty with the malting process is that the warm, moist conditions of germination can cause the proliferation of fungi. These not only spoil the malt product, but can lead to contamination of the malt with mycotoxins, rendering it unfit for consumption (Nkwe et al., 2005). Hence, malting, although deceptively simple, demands considerable operator experience to obtain a safe and consistently good quality product.

5.2 Traditional Food and Beverage Products

Despite the absence of gluten in the millets, around the world a very wide range of traditional food and beverage products are produced from them. Examples are given in Table 4.5 and some products are shown in Fig. 4.4. The food product types comprise: whole grain products—rice and gruels, flour-based semiliquid products—porridges (included malted porridges) and dumplings, agglomerated flour products—couscous and arraw, and flatbreads—unleavened and leavened, and biscuits. Both nonalcoholic (often soured) and opaque-type beers and “wines” are made from millets.

Injera, fermented leavened flatbread, is probably the most well-known traditional millet product, internationally. The injera making process, which enables a leavened pancake-like bread to be produced from flour, that does not form gluten is complex and technically ingenious (Yetneberk et al., 2004). The flour is first subjected to a sourdough type fermentation, which produces carbon dioxide. In some case, a portion of the flour is then cooked to pregelatinize the starch. This is then added back to the fermented flour, diluted to a batter, and allowed to ferment further. The batter is poured onto a hot clay griddle and the lid on the griddle is closed, trapping the steam released during baking. The carbon dioxide, which comes out of solution, creates a texture of small cells referred to as “eyes” as the starch in the batter gelatinizes and sets into a pancake. The formation of this foam-like texture is aided by the increased viscosity provide by the pregelatinized starch.

The taste and flavor of many traditional millet food products are stronger than is normally the case in Western-type cereal foods. Also, the textures of some of millet foods can be rather unexpected when first consumed. Foods products made from red and brown millets, such as most finger millet varieties and some teff varieties, tend to be somewhat bitter and astringent due to the high levels of polyphenols. Pearl millet products have an earthy and acid odor and flavor, sometimes described as “mousy like”, which is probably caused by

TABLE 4.5 Examples of Traditional Millet Food and Beverage Products

Products	Millet Species	Region/Country	Vernacular/ Common Name
<i>Popcorn</i>	Finger millet	India	
<i>Rice</i>	Fonio	West Africa Sahel— Burkina faso	
<i>Gruel</i>	Foxtail millet	China	Xiao mi zhou
<i>Gel type porridge</i>	Pearl millet	West Africa Sahel— Mali	Tô
<i>Dumplings</i>	Pearl millet	Northern South Africa	Dingwa tsa bupi bja leotsa
<i>Thick porridge</i>	Pearl millet	West Africa Sahel— Senegal	Lakh
<i>Fermented soft porridge</i>	Finger millet	Kenya	Uji
<i>Malted porridge</i>	Finger millet	India	
<i>Dried agglomerated flour for porridge making</i>	Pearl millet	West Africa Sahel region—Senegal	Arraw
<i>Couscous</i>	Pearl millet	West Africa—Sahel	
<i>Fermented leavened flatbread</i>	Teff	Ethiopia	Injera
<i>Unleavened flatbread</i>	Finger millet, pearl millet and other millets in combination with black gram (mung bean)	India	Dosa
<i>Biscuits</i>	Foxtail millet	China	
<i>Fermented beverage</i>	Pearl millet	Namibia	Oshikundu
<i>Millet and milk beverage</i>	Pearl millet	Zimbabwe	
<i>Opaque beer</i>	Finger millet and teff	Ethiopia	Tella
	Proso millet	Turkey	Boza
<i>Wine</i>	Foxtail millet	Taiwan	Xiao mi jiao
<i>Distilled spirit</i>	Other cereals plus finger millet and teff	Ethiopia	Katikala



FIGURE 4.4 Traditional millet products. (A) Fonio rice, Burkina Faso; (B) foxtail millet gruel, Taiwan; (C) finger millet porridge, Zimbabwe; (D) pearl millet porridge, Senegal; (E) teff injera, Ethiopia; (F) foxtail millet biscuits, China; (G) foxtail millet wine, Taiwan.

the C-glycosyl flavone polyphenols (Reddy et al., 1986). However, 3-acetyl-1-pyrroline has also been implicated (Seitz et al., 1993), which is the compound responsible for the flavor of aromatic rice types. As explained, many traditional millet foods are subjected a lactic acid fermentation. The acidity is generally similar to that of yogurt but can be particularly pronounced in injera teff flatbread. In the Sahel region, pearl millet porridge is often flavored with tamarind giving it a sweet and sour taste as tamarind contains tartaric acid. In Mali, the gel-like tô porridge is strongly alkaline due to the addition of wood ash and hence similar in flavor to traditional nixtamalized corn tortillas. Regarding texture, finger millet porridges can be remarkably sticky (Fig. 4.4), possibly due

to swelling of its small granule starch. Injera has a soft spongy rubbery-like texture, perhaps similarly due to swelling of the small granule teff starch.

Foxtail millet and proso millet products tend to be quite bland. This combined with the relatively large grain size of proso millet probably accounts for why it is often used to produce gluten-free flours in Western countries.

5.3 Modern Food and Beverage Products

Millet flours, in particular from white teff and proso millet, are being increasingly produced in Western countries as gluten-free flours for baked goods and pasta manufacture. Puffed whole grain proso millet is produced as breakfast cereal using the technology of gun puffing. Millets are also puffed and then milled into pregelatinized flours for gluten-free baked products. Millet rice is produced from foxtail millet and proso millet. [Fig. 4.5](#) shows a number of modern-type millet food products. Millets are also malted to a limited extent for use in gluten-free beers.

In Africa, there is expanding small-scale manufacture of convenience-type versions of traditional millet-based foods ([Taylor et al., 2010](#)). These products cater for the needs of the growing numbers of urban middle class consumers who are prepared to pay a considerable price premium of convenience and nutrition. They are also exported to African expatriates residing in Western countries. For example, in Senegal, there is considerable manufacture of dried pearl millet couscous and arraw (agglomerated flour balls for porridge making). Finger millet flour fortified with minerals and soy is produced in Kenya and Tanzania, respectively, for soft breakfast porridge making. There is also great interest in producing precooked instant porridge flours using the technology of extrusion cooking. Such products, based on pearl millet, have been manufactured in Nigeria and are under development in Senegal. [Fig. 4.6](#) shows some convenience type versions of traditional African millet products and their manufacture. Most notably, pearl millet is now being used in West Africa as an ingredient in the manufacture of an instant-infant porridge by a major international food company.

5.4 Effects of Food Processing on Nutrients and Phytochemicals

5.4.1 Starch

Although limited, there is no conclusive evidence that processing of millets results in them having unusually high levels of resistant starch. Resistant starch is a starch that is not hydrolyzed into glucose in the upper gastrointestinal tract, and would therefore contribute to a food product having a low glycemic index (GI) ([Taylor et al., 2014](#)). Processing finger millet into foods using a variety methods including baking into traditional foods, such as roti (flatbread), did not substantially elevate levels of resistant starch ([Mangala et al., 1999](#); [Roopa and Premavalli, 2008](#)). Although low moisture treatment was found to decrease



FIGURE 4.5 Modern millet products. (A) Foxtail millet rice, South Africa; (B) puffed proso millet, USA; (C) rice and millet pasta, Australia.



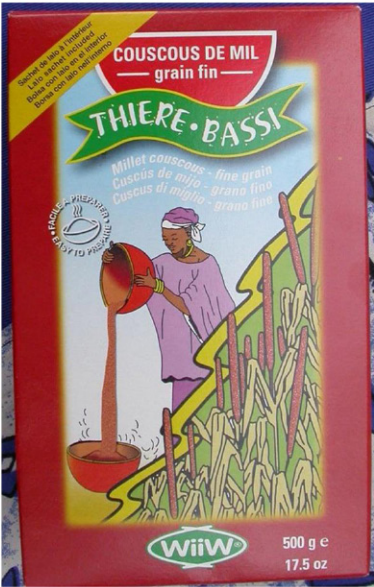
(A)



(B)



(C)



(D)

FIGURE 4.6 Modern products based on traditional African millet foods. (A) Finger millet based porridge powder, Kenya; (B) finger millet-soy composite porridge powder, Tanzania; (C) pearl millet-cowpea composite infant porridge powder, Senegal; (D) pearl millet couscous, Senegal;



FIGURE 4.6 (cont.) (E) agglomerating pearl millet to make couscous in a small factory, Senegal; (F) pearl millet arraw for porridge making, Mali; (G) pearl millet and tamarind instant porridge powder, Nigeria; (H) extrusion cooking pearl millet to make instant porridge powder, Senegal.

foxtail millet starch digestibility (Amadou et al., 2004), a similar effect was previously found with rice (Chung et al., 2012).

5.4.2 *Proteins*

As explained, all millets, as with other cereals, are deficient in lysine. The traditional food processing technologies of lactic fermentation and malting generally improve millet protein quality somewhat (Table 4.6). Lysine is increased by approximately 12%, due to hydrolysis of the lysine-poor prolamins storage

TABLE 4.6 Effects of Lactic Acid Fermentation and Malting on the Protein Quality of Finger Millet, Foxtail Millet, and Pearl Millet

	Finger Millet				Foxtail millet				Pearl millet			
	Fermentation		Malting		Fermentation		Malting		Fermentation		Malting	
	Grain	Fermented Product	Grain	Malt	Grain	Fermented Product	Grain	Malt	Grain	Fermented Product	Grain	Malt
<i>Protein</i> (g/100 g db)	8.1 ^d	8.3 ^d (48 h)	6.1 ^b	7.9 ^b (4 day)	10.2 ^c	10.5 ^c (48 h)	11.4 ^e (2 day)	10.7 ^e	10.8 ^f	12.8 ^f (1 day)	12.6 ^e	12.6 ^e (2 day)
			8.2 ^e	7.5 ^e (2 day) 6.8 ^e (4 day)								
<i>Lysine</i> (g/100 g protein)	2.58 ^b	2.75 ^b (48 h)	3.5 ^e	4.0 ^e (2 day) 5.3 (4 day)			3.0 ^e	3.3 ^e			3.7 ^e	4.3 ^e (2 day)
<i>In vitro</i> protein digestibility (%)	59.9 ^d (protein extract- ability)	76.2 ^d (48 h) (protein extractability)	33.9 ^b	55.4 ^b (4 day)	68.5 ^c (protein extractability)	76.9 ^c (48 h) (protein extractability)			61.2 ^a	81.0 ^a (36 h)		

^aElyas et al. (2002)—average of two cultivars.^bMbithi-Mwikya et al. (2000)—values of malt with external roots and shoots, average of two cultivars.^cAntony et al. (1996a).^dAntony et al. (1996b).^eMalleshi and Desikachar (1986)—values for malt after removal of external roots and shoots.^fAli et al. (2003).

proteins and synthesis of new proteins (Taylor and Taylor, 2017). Protein digestibility is also improved to a greater extent, approximately 30%, by the same process. A downside of malting is that there is a significant loss of carbohydrate in the grain as a result of respiration.

In traditional diets, legumes are widely consumed together with millets in an approximate proportion of 30% legume to 70% millet. Importantly, such cereal-legume composite meals can provide all the indispensable amino acids in the required proportions that can meet the requirements of infants, the most nutritionally at-risk group. As a result, there has been much research into developing cereal–legume composite products in the form of instant and ready-to-eat porridges for infant feeding and as snack foods for older children using extrusion-cooking technology. For example, Sumathi et al. (2007) investigated pearl millet-soy (85:15 ratio) and pearl millet-Bengal gram and green gram (mung bean) (70:30 ratio) composite porridges. In small animal trials these products had approximately 70% of the protein quality of milk powder and gave approximately 80% of the weight gain at similar food and protein intakes.

With regard to the digestibility of the proteins (protein bioavailability) in millets, although the data are limited, the evidence is that processing by wet cooking does not adversely affect protein digestibility, unlike the case in sorghum (Duodu et al., 2003). Ejeta et al. (1987) observed a minimal reduction in pearl millet-protein digestibility when wet cooked and Ravindran (1992) found that protein digestibility was substantially improved in finger, foxtail, and proso millets on cooking.

5.4.3 Lipids

The lipid content of millet foods is somewhat reduced by decortication, depending on the level of debranning. For example, using laboratory equipment, a 20% decortication reduced the lipid content of pearl millet grain by a greater proportion, approximately 30% (Hama et al., 2011). However, lipid losses with decortication are liable to be greater with pearl millet than with other millets, such as foxtail and proso millet as its kernel is tear-shaped, rather than round. Fat rancidity is also a particular problem with pearl millet flour due to its high fat content. Research has shown that this can be largely prevented by wet heating the grain prior to milling (Nantanga et al., 2008).

5.4.4 Minerals

As indicated, whole grain millets contain substantial amounts of most essential minerals. However, significant losses can occur as a result of decortication and their availability may be poor due to the presence of antinutrients. It should be noted that these are issues common to all cereal grains, not just millets. With regard to the effects of decortication on mineral content, as iron is concentrated in the bran, the reduction in its content, in particular, is directly related to the degree of debranning. For example, Hama et al. (2011) found that removal of 5% and 10% of the outer layers of pearl millet grain resulted in an approximately 38% and 50% reduction in iron, respectively, but only an approximately 5% and 10% reduction in zinc.

There is a large body of data that indicates the traditional processing technologies of lactic acid fermentation and malting, can improve mineral bioavailability. For example, [Antony and Chandra \(1998\)](#) showed that fermentation of finger millet increased calcium, phosphorus, and iron extractability (an in vitro measure to predict bioavailability) by 20%–30%. This was attributed to the concomitant reduction in phytate, total phenolics, and tannins. The reduction in phytate paralleled the phytase activity of the fermenting flour. Similarly, [Jha et al. \(2015\)](#) found that the dialyzability (another in vitro measure to predict bioavailability) of iron and zinc in the bran fraction of pearl millet was increased by some 150% and 63%, respectively, after malting for 48 h. However, the total contents of the minerals were reduced somewhat, presumably as a result of them leaching from the grain. In this work, there was a concomitant reduction in phytate but no reduction in polyphenols or flavonoids.

However, some workers consider that the reduction in phytate brought about by endogenous phytases may be insufficient to significantly improve mineral bioavailability in whole grain millet foods. [Lestienne et al. \(2005\)](#) working with pearl millet found that when decorticated grain was steeped endogenous phytase improved iron and zinc bioaccessibility (in vitro assessment of bioavailability) but with the bran fraction, even with the addition of exogenous phytase, mineral bioaccessibility was not improved. They attributed the latter result to binding of the minerals to fiber and tannins, presumably by nontannin polyphenols.

Parboiling, whereby the whole grain is steamed, is commonly applied to rice and can result in minerals migrating from the bran to endosperm, and hence reduce their losses when the grain is decorticated ([Da Silva et al., 2013](#)). However, work on fonio indicated the parboiling did not reduce physical mineral losses resulting from milling or leaching losses during cooking ([Koreissi-Dembélé et al., 2013a](#)). This finding is perhaps a consequence of the very small size of the fonio grain.

Prevention of mineral losses during processing and alleviating the adverse effects of phytate, fiber, and polyphenols on mineral bioavailability in these small grain cereals is challenging. One promising novel approach to improve iron bioavailability is to treat the porridge made from decorticated grain (i.e., a product with reduced levels of phytate, fiber, and polyphenols but also minerals, such as iron) with exogenous phytase. [Koreissi-Dembélé et al. \(2013b\)](#) investigated incubating fonio porridge with wheat flour, a rich source of phytase. They found that young women subjects who consumed the porridge and a ferrous iron fortificant had a threefold increase in fractional iron absorption compared to those who consumed the iron fortificant and fonio porridge without phytase treatment.

5.4.5 *Vitamins*

There is much less research into the effects of processing on the vitamins in millets. [Ochanda et al. \(2010\)](#) found that spontaneous lactic fermentation of pearl millet for 1 week increased the contents of vitamins B₁, B₃, and B₅ 8–9-fold and of vitamins B₂ and B₆ by 2- and 3.6-fold, respectively. They attributed this to vitamin synthesis by the microorganisms. [Malleshi and Klopfenstein](#)

(1998) found that malting for 4 days increased the vitamin B₂ content of pearl millet by 4-fold and that of finger millet by 2.5-fold. However, vitamin B₁ and B₃ levels were not substantially affected. Similar results were found by [Ochanda et al. \(2010\)](#), working with pearl millet. These latter authors suggested that the smaller effect of malting compared to fermentation was due to the fact that the seed is providing nutrients for growth and there is little synthesis of new products.

5.4.6 Phenolic Phytochemicals

As indicated, millet grains generally contain much higher levels of phenolics than the major cereals ([Taylor and Duodu, 2015](#)). With regard to processing, because the phenolics are concentrated in the bran layers, decortication substantially reduces the levels of phenolics ([Table 4.7](#)), particularly the polyphenols (flavonoids and the tannins in finger millet) ([Shobana and Malleshi, 2007](#)). Notwithstanding this, the levels generally remain substantially higher than in refined products from the major cereals.

Although there are limited data, traditional lactic acid fermentation also seems to substantially reduce the levels of phenolics. In the case of sorghum, it has been shown that the bacteria responsible for the fermentation can metabolize some phenolics (phenolic acids, phenolic acid esters, and flavonoid glycosides), to reduce their antimicrobial action ([Sánchez-Maldonado et al., 2011](#); [Svensson et al., 2010](#)).

The effects of malting on phenolic levels are at first sight contradictory with both decreases and increases in levels being reported ([Table 4.7](#)). The reductions are primarily due to leaching out of unbound water-soluble phenolics. A major reason for the contradictory findings is that some workers analyze the whole malt complete with external roots and shoots, whereas others just measure the malt “berry” after removal of the roots and shoots. For the brewing of lager-type of beers, it is normal to remove the external roots and shoots, but for traditional African beers and nonalcoholic beverages, they are retained. The measured increases in phenolics are probably due to anthocyanin-type pigments in the roots and shoots ([Fig. 4.2](#)), which are produced as a response mechanism to moisture stress and microbial infection ([Glennie, 1983](#)).

Thermal processing technologies are applied in the production of virtually all cereal foods to gelatinize the starch. Thermal technologies are divided into, hydrothermal (wet heat) and dry thermal. The former include boiling, steaming and extrusion cooking, and the latter baking and roasting. The effects on the levels and composition of phenolics are highly complex and incompletely understood. The mechanisms involved, include release of bound phenolics and binding to other food components, polymerization, oxidation, thermal degradation, depolymerization, and Maillard-type reactions ([Taylor and Duodu, 2015](#)). Hence, it is not surprising that both increases and decreases in total phenolics and specific phenolic groups, as well as compounds have been variously reported when millets are thermally processed ([Table 4.7](#)).

TABLE 4.7 Summary of Recent Research Into the Effects of Processing Technologies on the Phenolics in Millets

Processing Technology	Millet Species	Details of Processing	Effects on Phenolics
<i>Decortication/whole grain milling followed by separation of bran from flour</i>	Finger millet	Tempering with water, mill, and sieve to remove seedcoat	Whole grain flour: 2.3% TP Refined flour: 0.8% TP Seedcoat: 6.2% TP
		Hydration, steaming and decortication	Refined flour: P reduced by 75%
		Tempering with water milling then sieving to remove seedcoat	Refined flour: 3%–4% TP Seedcoat: 13% TP
	Finger millet Foxtail millet Kodo millet Little millet Pearl millet Proso millet Pearl millet	Decortication and separation of bran by air classification	Decorticated grain
			Finger millet: TP reduced by 12%–21%
			Foxtail millet: TP reduced by 65%
			Kodo millet: TP reduced by 79%
			Little millet: TP reduced by 31%
			Pearl millet: TP reduced by 2%
			Proso millet: TP reduced by 72%
		Mechanical dehulling	Refined flour: TP reduced by 50%
		Milling and separation of bran by air classification	Reduced TP content Ferulic acid reduced by 39% <i>p</i> -Coumaric acid reduced by 52%
<i>Fermentation</i>	Finger millet	Natural fermentation at 37°C for 48 h	CT reduced by 44%–52% TP reduced by 26%–29%
	Pearl millet	Natural fermentation at 30°C for 14 h	P reduced by 31%–60%

(Continued)

TABLE 4.7 Summary of Recent Research Into the Effects of Processing Technologies on the Phenolics in Millets (*cont.*)

Processing Technology	Millet Species	Details of Processing	Effects on Phenolics
<i>Malting</i>	Finger millet	Steeping then germination for 96 h	Reduction in major phenolic acids Caffeic acid reduced by 45% Coumaric acid reduced by 42% Ferulic acid reduced by 48%
		Steeping then germination at 25°C	TP reduced by 21% Catechols reduced by 46% Resorcinols reduced by 32%
		Steeping then germination for 120 h	P reduced by 44% after 24 h P reduced by 88% after 72 h
	Barnyard millet	Steeping then germination at 33°C for 36 h (roots and shoots retained)	TP increased by 168% Free TP increased by 180% Bound TP increased by 45% F increased by 148% Free F increased by 380% Bound F increased by 35%
	Barnyard millet	Germination at 25°C for 48 h (roots and shoots retained)	Barnyard millet TP increased by 209% F increased by 22%
	Foxtail millet		Foxtail millet TP increased by 135% F increased by 80%
	Proso millet		Proso millet TP increased by 220% F increased by 79%

Thermal processing	Little millet	Steeping then germination at 25°C for 48 h (roots and shoots retained)	TP increased by 5% F increased by 5% CT increased by 17%
	Pearl millet	Steeping then germination for 48 h	TP reduced by 15% by steeping TP reduced by further 73% by germination
	Finger millet	Boiling whole grain	TP reduced by 40% Catechols reduced by 40% Resorcinols reduced by 53%
	Finger millet	Boiling decorticated grains	Finger millet: TP reduced by 11%–36%
	Foxtail millet		Foxtail millet: TP reduced by 3%
	Kodo millet		Kodo millet: TP reduced by 12%
	Little millet		Little millet: TP reduced by 2%
	Pearl millet		Pearl millet: TP reduced by 4%
	Proso millet		Proso millet: TP recuded by 4%
	Barnyard millet	Whole grain steeped in autoclave for 20 min	Barnyard millet TP reduced by 5% F reduced by 22%
	Foxtail millet		Foxtail millet TP increased by 5% F reduced by 34%
	Proso millet		Proso millet TP increased by 7% F reduced by 23%
	Barnyard millet	Dry whole grain microwaved at 700 W for 3 min	Barnyard millet TP reduced by 8% F increased by 4%

(Continued)

Table 4.7 Summary of Recent Research Into the Effects of Processing Technologies on the Phenolics in Millets (*cont.*)

Processing Technology	Millet Species	Details of Processing	Effects on Phenolics
	Foxtail millet		Foxtail millet TP increased by 44% F reduced by 15%
	Proso millet		Proso millet TP increased by 17% F reduced by 5%
	Little millet	Soaked whole grains autoclaved for 15 min	TP increased by 13% F increased by 22% CT increased by 9%
	Little millet	Soaked whole grains roasted 165°C for 75 s	TP increased by 21% F increased by 25% CT increased by 19%
	Pearl millet	Wet cooking of decorticated flour	TP reduced by 8%–13%
		Heating of whole grains in hot air at 110°C	TP reduced by 24%

CT, Condensed tannins; P, polyphenols; T, flavonoids; TP, total phenolics.

Source: Table adapted from Taylor, J.R.N., Duodu, K.G. 2015. Effects of processing sorghum and millets on their phenolic phytochemicals and the implications of this to the health-enhancing properties of sorghum and millet food and beverage products. *J. Sci. Food Agri.* 95, 225–237; with additional data from Pradeep, S.R., Guha, M., 2011. Effect of processing methods on the nutraceutical and antioxidant properties of little millet (*Panicum sumatrense*) extracts. *Food Chem.* 126, 1643–1647; Pradeep, P.M., Sreerama, Y.N., 2015. Impact of processing on the phenolic profiles of small millets: evaluation of their antioxidant and enzyme inhibitory properties associated with hyperglycemia. *Food Chem.* 169, 455–463; Sharma, S., Saxena, D.C., Riar, C.S., 2016. Analysing the effect of germination on phenolics, dietary fibres, minerals and γ -amino butyric acid contents of barnyard millet (*Echinochloa frumentaceae*). *Food Biosci.* 13, 60–68.

A related critical issue is whether the phenolics in the millet food products are bioavailable, in other words, whether when the food is digested, will the phenolics exert physiological effects. More specifically, bioavailability can be defined by the percentage of a compound in a food that passes through the intestine cell membrane, and is available for action. [Shahidi and Chandrasekara \(2013\)](#) were of the opinion that millet-grain phenolics are bioaccessible. However, they stated that there are very few studies on the bioavailability of hydroxycinnamic acids (abundant phenolics in cereals). [Acosta-Estrada et al. \(2014\)](#) observed that the majority of phenolics in cereals are in the insoluble bound form. They reviewed research that indicates the release of bound ferulic acid (a major hydroxycinnamic acid in millets and other cereals) takes place due to microbial fermentation in the colon and that only a small percentage is released in the stomach and small intestine. Their review also indicated that flavonoids are extensively degraded in the colon. In vitro digestion of millets, which had been decorticated, wet cooked, freeze dried, and milled showed that in general, in five millet species (finger, foxtail, kodo, pearl, and proso) the contents of soluble total phenolics and total flavonoids substantially increased in the gastric digestion phase, intestinal digestion phase, and colonic fermentation phase ([Chandrasekara and Shahidi, 2012](#)). On the basis that the phenolics were solubilized during these phases, the authors considered that they would be bioaccessible and that they may exhibit bioactivity.

6 HEALTH-ENHANCING PROPERTIES OF MILLET FOOD PRODUCTS

The potential health-enhancing effects of millet foods can be categorized into antidiabetic, antiinflammatory, and cardiovascular disease (CVD) prevention, and prebiotic and probiotic effects.

6.1 Antidiabetic-Related Effects

There is great interest, as to whether millet foods have low GI and are protective against diabetes. Most of the research has been carried out on finger millet in India, as there is a very strong cultural belief in its efficacy in that country ([Pradhan et al., 2010; Shobana et al., 2013](#)). Unfortunately, according to a review by [Shobana et al. \(2013\)](#) much of the work has been and continues to be experimentally flawed, for example, in terms of the protocols of the GI studies. Hence, here only some apparently better designed studies will be reviewed. These have yielded contradictory results.

It has been found that composite flour noodles made from finger millet and refined wheat gave a lower GI (45) than refined wheat noodles (63) when consumed by healthy young female adults ([Shukla and Srivastava, 2014](#)). Similarly, finger millet–wheat composite breads when consumed by healthy subjects had a lower GI (41–43) compared to wheat bread (68) ([Chhavi and Sarita, 2012](#)).

In contrast, when noninsulin dependent diabetic subjects consumed roti (flat-bread) and dumplings made from finger millet, rice, and sorghum, the finger millet rotis and dumplings generally elicited a higher glycemic response than those made from the other cereals (Urooj et al., 2006). In other work, when porridges prepared from wheat, decorticated finger millet, popped and expanded rice were given to healthy subjects, the wheat porridge elicited by far the lowest GI (55 ± 9) and that of the finger porridge (93 ± 7) was only slightly less than that of the rice products (Shobana et al., 2007).

Some research has also indicated that foxtail millet products have low GI. For example, with healthy subjects, finger millet–wheat composite biscuits had somewhat lower GI than the wheat biscuits, 51 versus 68 (Anju and Sarita, 2010). Similarly foxtail millet–wheat composite bread was shown to have a lower GI than wheat bread (Chhavi and Sarita, 2012). In a crossover randomized clinical trial, foxtail millet–wheat composite biscuits and a foxtail millet–chickpea composite sweet (burfi) were fed to type 2 diabetic patients (Thathola et al., 2011). Notably, both foxtail millet products resulted in significant reductions in serum glucose, cholesterol, low-density lipoproteins (LDL) and glycosylated hemoglobin and an increase in high-density lipoproteins (HDL). Concerning pearl millet, in a study in Sudan where subjects with type 2 diabetes received various traditional foods, it was found that pearl millet porridge and wheat pancake gave the lowest glucose and insulin responses, whereas maize porridge gave the highest (Abdelgadir et al., 2005). There is little published work on the minor millets. In one study, healthy and type 2 diabetics consumed foods made from dehulled and roasted barnyard millet (Ugare et al., 2014). In the 28-day trial both groups showed slight reductions in serum glucose and triglycerides and an increase in HDL. However, the work also showed that the roasting treatment substantially reduced the GI of the barnyard millet. This suggests that the process formed resistant starch, and hence was probably not an intrinsic property of barnyard millet.

Recently, research has provided strong evidence that traditional African food products prepared from pearl millet and sorghum have much slower gastric emptying than Western-type cereal food products (Cisse et al., 2015). In a study conducted in rural Mali, healthy subjects consumed thick porridges prepared from sorghum and pearl millet, thin porridges and couscous prepared from pearl millet, white rice, wheat pasta, and cooked potato. Using a ^{13}C -labelled octanoic acid breath test method, all the sorghum and pearl millet foods had approximately double the time for half gastric emptying (some 5 h) compared to the other foods. Somewhat curiously, the subjective data from the subjects revealed that the white rice and the pearl millet couscous meals gave a higher feeling fullness and lower hunger scores compared to other meals.

Undoubtedly, phenolic phytochemicals are involved to a considerable extent in the observed antidiabetic-related effects of millets. Shobana et al. (2009) showed that extracts from finger millet seed coat that were rich in a range of phenolics, including simple phenolics, anthocyanins, and tannins, were powerful

inhibitors of the α -glucosidase and α -amylase, the major human starch digestive enzymes. Similar results have been found with phenolic-rich extracts from barnyard, foxtail, and proso millets (Pradeep and Sreerama, 2015). There are also indications that phenolics in millets exert for more subtle effects, probably related to their antioxidant activities. In a rat study, finger millet seedcoat was found to reduce lens aldose reductase activity, serum advanced glycation, glycosylated hemoglobin levels and reduce the incidence of cataracts (Shobana et al., 2010). These are all indicators of reduced serum glucose-protein reactions. Additionally, the test group showed some reversal of kidney damage.

In other work, strong antihyperglycemic effects have also been observed with an aqueous extract from foxtail millet in a rat study (Sireesha et al., 2011). Similarly, in a mouse model, white fonio flour was found to improve insulin tolerance compared to rice flour (Traore et al., 2011). It was suggested that fonio might modulate diabetes severity by reducing inflammatory cytokines. However, in these studies the effects cannot be clearly attributed to phenolics.

6.2 Antiinflammatory and CVD Prevention Effects

It is well-proven that the dietary intake of whole grain foods, including millets, is inversely associated with several disease risk factors and disease outcomes, including CVD (Mellen et al., 2008). Unfortunately, specific data on the role of millets specifically in ameliorating risk factors associated with CVD are scarce. Lee et al. (2010) examined the effects of whole grain foxtail millet, proso millet, and sorghum versus white rice in rats fed a high-fat diet. Serum triglyceride levels were lower in the foxtail and proso millet groups compared to the sorghum and white rice group. However, levels of C-reactive protein (a marker for inflammation) were significantly lower in only the finger millet group. Using a mouse model, Park et al. (2011) showed that an aqueous extract of proso millet (which is likely to contain soluble phenolics) reduced serum triglyceride levels, liver lipid accumulation and total cholesterol. Evidence was presented that the effects were related to regulation of hepatic lipogenesis and lipolytic gene expression, inhibition of cytokine and chemokine release. Choi et al. (2005) found that foxtail millet protein substantially increased HDL-cholesterol and adiponectin levels in a mice model compared to a casein control. Since adiponectin is involved in regulating lipid breakdown, they speculated, that the protein was involved in increasing its concentration. Similarly, Shimanuki et al. (2006) found that a protein concentrate from proso millet raised plasma HDL in a rat model. In view of these findings, and since Lee et al. (2010) showed that sorghum increased lipid markers for CVD, it would appear that the positive effects of millets on CVD markers are not primarily due to phenolics.

6.3 Anticancer Effects

There do not seem be any specific data that indicate the consumption of millets is protective against cancer, although there is circumstantial evidence (Chen

et al., 1993; Van Rensburg, 1981). However, several studies have shown that phenolic extracts from millets have powerful antioxidant activity. Notably, Chandrasekara and Shahidi (2012) who studied five different species of millet (finger, foxtail, kodo, pearl, and proso) found that simulated digestion resulted in substantially increased antioxidant activity as measured by the oxygen radical absorbance capacity (ORAC), DPPH (1,1-diphenyl-2-picryl-hydrazyl radical scavenging activity), and hydroxyl radical scavenging activity assays. High-antioxidant activities have also been associated with phenolics in white fonio (N'Dri et al., 2013), Japanese barnyard millet (Watanabe, 1999), little millet (Pradeep and Guha, 2011), and teff (Kotásková et al. 2016).

Oxidative damage to DNA caused by free radicals has been identified as a cause of cancer (Valko et al., 2006). Chandrasekara and Shahidi (2011c) investigated the inhibition of lipid peroxidation, DNA scission, and colorectal cancer cell proliferation by whole grain extracts from six species of millet (finger, foxtail, kodo, little, pearl, and proso). All millet species exhibited powerful inhibition of lipids in liposomes and singlet oxygen quenching, and some inhibition of DNA scission. Further, the millet extracts inhibited colorectal cancer cell proliferation, with kodo and pearl millet extracts giving up to 100% inhibition. The authors concluded that millet phenolics might be effective, preventing cancer initiation and progression.

6.4 Prebiotic and Probiotic Effects

Prebiotics are a type of dietary fiber, which is fermentable and also selectively stimulates the growth of specific types of bacteria in the colon that are beneficial to the human host (Holzapfel and Schillinger, 2002). Probiotics are those bacteria, which are beneficial to the human host as they promote or support a healthy balance in the indigenous microbial population in the gastrointestinal tract. Dietary fiber fractions from both foxtail millet and pearl millet have been found to be excellent substrates for several probiotic bacteria *Lactobacillus acidophilus*, *Lactobacillus rhamnensis*, *Bifidobacterium bifidum*, and *Bifidobacterium longum* (Farooq et al., 2013). Through fermentation of fiber fractions, these bacteria produce the short-chained fatty acids acetate, propionate, which themselves are well-known to have important gastrointestinal health promoting attributes (Rose and Hamaker, 2011).

Regarding fermented millet products, *Lactobacillus fermentum* strains isolated from ben-saalga, a pearl millet gruel from Burkina Faso, been found to have probiotic potential as they had genes associated with both bile salt tolerance and the ability to tolerate low pH (Turpin et al. 2011). Also, yeast strains isolated from fermented pearl millet dough from Ghana indicated probiotic properties in terms of improvement in gastrointestinal cell barrier properties (Pedersen et al., 2012). Some work shows that the bacteria associated with traditional fermented millet foods can produce bacteriocins, antibacterial proteins. A strain of *Enterococcus faecium* isolated from a fermented finger millet food

from India, koozh, was found to produce a bacteriocin, which inhibited the growth of food-borne pathogens (Rajesh et al., 2009). However, to date there is no clear evidence that such traditional fermented millet foods can actually promote improved gastrointestinal health in practice, despite the fact that they contain probiotic bacteria (Lei et al., 2006).

7 CONCLUSIONS AND FUTURE DIRECTIONS

7.1 The Nutritional and Health-Promoting Attributes of Millets

Regarding general macro- and micronutrient composition, currently there is no firm evidence that any of the millet species are truly exceptional in terms of any nutrient. The problem is that we do not have adequate basic data on the nutrient composition of the various millet species. This is exemplified by the fact that the latest USDA National Nutrient Database food list gives data on just six millet products: millet raw; millet cooked; millet flour; teff uncooked and teff cooked (USDA, 2014). Notably, the name(s) of the millet species is not provided. Further, it is not stated whether the data are for whole grain or refined grain products. Clearly, there is a great need for better basic nutritional data on millets and their food products.

With regard to health-enhancing properties, it is evident that some (but not all) studies clearly show that millet products (both traditional and modern) have a low glycemic response and traditional millet foods can have substantially slower gastric emptying than Western-type foods. However, a key question that still needs to be answered is whether findings of lower GI and gastric emptying for millet products are due to intrinsic differences in grain composition and structure between millets and other cereals, or are the differences related to processing? For example, whole grain or slightly refined cereal products will contain higher levels of nonstarch polysaccharides, lipids, B vitamins, certain minerals, phytate, and notably flavonoid-type phenolics than highly refined grains, irrespective of the species of cereal. Further, there are several other food processing factors that greatly influence the starch availability in cereal foods, notably grain particle size, thermal, and shear processing treatments and temperature of food serving (Taylor et al., 2015).

Notwithstanding these issues, this author's opinion is that the generally higher levels of flavonoid-type phenolics in millets compared to the major cereals contribute to regular consumption of millet foods being somewhat protective against the development of certain noncommunicable diseases, notably type 2 diabetes and CVD. However, there is a chronic need for in vivo and clinical studies where comparisons are made with directly equivalent foods prepared from other cereals and that the grains and food products are far better characterized in terms of the composition. At the more fundamental level, the bio-availability of phenolics from food products themselves (not extracts) and the physiological actions of particularly phenolic compounds needs to be far more fully elucidated.

7.2 Future Prospects for Millets as Staple and Specialty Foods

As has been seen, millets have many positive attributes. They are better adapted to cultivation in harsh climatic conditions than most other cereals and therefore have great potential to become worldwide staple foods as result of the influence of climate change on agriculture. They continue to play an important role in the traditional food culture of many developing countries. They are gluten-free and there is evidence (although limited) that they are protective against so-called Western life-style diseases. Thus, the prospects for millets as major staple foods in developing countries and as a regular food items in more developed countries would appear to be excellent. However, millets and their products also have drawbacks that need to be addressed. Millet foods and beverages generally have a stronger flavor than those of the major cereals. This is almost certainly due to their higher levels of flavonoid-type phenolics. These have been bred out in modern wheat, maize, and rice cultivars. Thus, the challenge for millet breeders, food scientists, nutritionalists, and food manufacturers is to improve palatability of the millets and their products; however, at the same time maintain functional levels of these health-promoting phytochemicals.

Another challenge is that millets are generally much more expensive than the major cereals. For example, in the author's local supermarket foxtail millet rice is three times the cost of regular rice. Thus, in developing countries the rapidly increasing numbers of people who purchase their food (as opposed to subsistence farming families) generally consume the major cereal grains. Likewise, in Western countries millet-foods are almost exclusively consumed by people with high income. The price differential can be considerably reduced if the demand for millet products increases substantially. This will provide breeders with greater incentive to improve varieties and farmers to increase cultivation inputs, thus increasing yields. Also, also greater economies of scale will apply in the food value chain.

Probably, the most urgent area that needs to be addressed to support increased demand for millets and other ancient grains is the development of internationally accepted grain-quality management systems. Millet-specific quality management systems would improve the efficiency of millet grain handling, the quality of millet-grains as commodities and promote worldwide trade in millets for food and beverage applications.

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Chapter 5

Quinoa: Its Unique Nutritional and Health-Promoting Attributes

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1 INTRODUCTION

The origin of quinoa (*Chenopodium quinoa* Willd.) is considered to be in the Andean region of South America. Several varieties were grown by the pre-Hispanic people for approximately 7000 years (Jacobsen et al., 2003). It is thus considered to be one of the oldest crops in the Andean region. Botanically, quinoa is assigned to the dicotyledonous plant family. According to several phylogenetic classifications the *Chenopodium* genus belongs to the *Caryophyllales*. Both sweet and bitter quinoa varieties exist. The classification is dependent on the content of saponins. If the saponin content is below 0.11% the variety is considered as being a sweet variety (Koziol, 1991). *C. quinoa* is an annual herbaceous plant, which typically reaches between 0.5 and 1.5 m in height, but it may reach up to 2.5 m height in the inter-Andean valleys. The seeds are cylindrical-lenticular in shape and about 1.5–2.5 mm with a thousand kernels weight of approximately 1.9–4.3 g. The embryo is comprised of two cotyledons and surrounds the basal body. Starch reserves are mainly stored in the perisperm, while lipids and proteins are stored in the cells of the endosperm and embryo tissues, which also contain globoid crystals of phytin, phosphorus, potassium, and magnesium and proplastids that contain phytoferritin (Prego et al., 1998). The episperm has four layers and the outer layer is rich in saponins (bitter tasting chemical compounds; glycosides of steroids, steroid alkaloids, or triterpenes). Quinoa is very diverse and many different varieties exist, ranging from white, yellow, red, to black genotypes (Fig. 5.1). It adapts well to different agro-ecological conditions and it can even be produced in regions where no other plant protein sources are available.

Quinoa, as well as *kañiwa* (*Chenopodium pallidicaule*, Aellen) and other edible plants, such as amaranth (*kiwicha*—*Amaranthus caudatus*, Linn) were largely consumed by the Andean inhabitants and were staple foods in



FIGURE 5.1 Quinoa varieties—top left to right: Rosada de Huancayo (white), Blanca de Hualhuas (white); bottom left to right: Ccoito (black), Ayara (black).

those times as maize was the only other cereal available. After a long period of neglect, where they were only grown in some inter-Andean valleys, these plants were “rediscovered” in the mid/late 20th century by the Western countries and since the year 2000 there has been a considerable increase in food products from and containing quinoa available on the market. The main reasons for this renewed interest can be related to two important factors: (1) quinoa has an excellent nutritional composition, with a high quantity and quality of protein and fat, high amounts of minerals and some vitamins. As the starch granules are among the smallest known and the amylose content is very low, quinoa shows unique physicochemical properties; (2) quinoa is gluten-free and can therefore be consumed by persons who suffer from gluten intolerances. The increasing demand for gluten-free products in general, and for more nutritious gluten-free products in particular, has been (and still is) one of the most important driving forces for the increased use of quinoa in Western countries. Considering the number of persons who need to adhere to a gluten-free diet, the market can be estimated to be up to 8%–10% of the total population.

The world’s rising demand for quinoa has resulted in a great increase in its production. In 2014, 192,506 tonnes of quinoa, with an average yield

of 0.8 t/ha, were produced worldwide (FAOStat, 2016). This is an almost fourfold production increase within the last 10 years. The main producing countries are Peru and Bolivia, which together account for over 90% of the world production, and Ecuador (FAOStat, 2016), although today, it is grown in the entire Andean region, from Colombia to the north of Argentina and Chile and in many more countries and regions, like the USA, Canada, Italy, France, England, Sweden, Denmark, Netherlands, India, and in some African countries. Most of the quinoa produced in Peru and Bolivia is exported, in particular to Europe and the USA, which are the main importers (Krivonos, 2013). Since 2011, Bolivia has exported approximately half of all the quinoa it produces. In Peru, where the quinoa production area, as well as yield/hectare (up to 1.6 t/ha today) has been increased extensively, its exports have grown steadily since 2007, accounting for 23.2% of production in 2012 (Krivonos, 2013).

This chapter gives detailed information on the chemical nutrient composition of quinoa (proteins and amino acids, fat and lipid components, carbohydrates, dietary fiber, as well as micronutrients), plus antinutrients and bioactive compounds. It also summarizes the present knowledge on processing and food applications, with special attention to gluten-free foods. A final section addresses the nutritional and health-promoting properties of quinoa food products.

2 CHEMICAL COMPOSITION AND NUTRITIONAL ATTRIBUTES

As stated, one of the main reasons why quinoa has attracted so much interest in recent years, besides being gluten-free, is its excellent nutritional properties. In Table 5.1 the main chemical composition of quinoa in comparison to wheat (as representative for the true cereals) is given. It can be seen that the composition of quinoa is distinct, but more important is the fact that its major components are sometimes of excellent quality.

TABLE 5.1 Chemical Composition of Amaranth, Quinoa, and Buckwheat in Comparison to Wheat [% dm] (Schoenlechner and Tömösközi, 2014, Own Measurements, Unpublished Data)

[% dm]	Starch	Fat	Protein	Ash	Total Dietary Fiber	Total Phenolic Content ^a
Quinoa	57.18	7.73	12.18	2.72	12.75	284.5
Wheat	56.19	1.68	13.04	1.76	11.99	505.1

^aMilligram Ferulic acid equiv./100 g dm.

2.1 Proteins and Amino Acids

The protein content of quinoa is similar to that of cereals, but compared to cereals its protein is of very high quality and is more comparable to legume protein (Drzewiecki et al., 2003). The average protein content ranges from 13% to 15% (Abugoch, 2009; Hager et al., 2012; Repo-Carrasco et al., 2003), and it can vary from 8% to 22% among different varieties (Bhargava et al., 2007; Prakash and Pal, 1998; Rosero et al., 2013). Quinoa contains very high amounts of essential (indispensable) amino acids like lysine, arginine, tryptophan, and sulfur-containing amino acids (Matuz et al., 2000; Gorinstein et al., 2002; Vega-Galvez et al., 2010). Results regarding limiting essential amino acids in quinoa are contradictory, which might be due to differences in investigated varieties or analytical method. According to the WHO (2002) the balanced amino-acid composition of quinoa is close to the optimum protein reference pattern in the human diet according to FAO/WHO requirements, with only isoleucine and valine being somewhat limiting, while in a study by Ruales et al. (2002), the primarily limiting amino acids were found to be tyrosine and phenylalanine, followed by lysine and threonine. Net protein utilization in quinoa was found to be 67.7–75.7 and biological value 71.1–82.6, both significantly better compared to cereals.

Also differing from cereals are the main storage proteins in quinoa, which are the globulins and albumins. Together they account for up to 80% of total protein (Kozioł, 1992). Another unique attribute of quinoa seeds (and also amaranth seeds) is the presence of a second albumin fraction, which can be separated by water after an extensive extraction of globulins and albumins (Drzewiecki et al., 2003; Gorinstein et al., 2005). Prolamins are present in very small amounts (Gorinstein et al., 2002; Drzewiecki et al., 2003; Prakash and Pal, 1998; Thanapornpoonpong et al., 2008). Additionally, in contrast to cereals quinoa prolamins are characterized by a low content of proline (Comino et al., 2013).

Immunological, Western blot, or ELISA tests have shown that quinoa proteins are not toxic to patients suffering from celiac disease (Berti et al., 2004; Bergamo et al., 2011; De Vincenzi et al., 1999; Mickowska et al., 2013; Penas et al., 2014). A clinical study, where 19 celiac disease patients consumed 50 g of quinoa daily for 6 weeks, confirmed that quinoa was well tolerated (Zevallos et al., 2014).

2.2 Fat and Lipid Components

The amount of fat in quinoa is about 4 times higher than in wheat (Table 5.1), and it can range from 4.0% to 9.7% (Miranda et al., 2012; Ruales and Nair, 1993a). The quality of fat is very high, with a polyunsaturation index (PUFA/SFA, sum of polyunsaturated fatty acids/sum of saturated fatty acids) of 3.7–4.9 (Ruales and Nair, 1993a; Vidueiros et al., 2015). The content of unsaturated fatty acids is about 82.7%–85.0% of the total amount of fatty acids. The main fatty acids in quinoa are linoleic (more than 50%), oleic (more than 20%), and palmitic

acids (8%) (Kozioł, 1992; Repo-Carrasco et al., 2003; Ruales and Nair, 1993a; Vidueiros et al., 2015). Additionally, it contains oleic and α -linolenic acids (Vidueiros et al., 2015). Polar lipids represent some 25.2% of the total lipid content, of which lysophosphatidyl ethanolamine (LPE) is the major one with 43.2% (Przybylski et al., 1994).

2.3 Carbohydrates (Starch and Sugars)

Starch is the main glycemic carbohydrate in quinoa and it is present in similar proportion to cereals. This enables quinoa to be used for starch-based products. In contrast to cereals, where starch is stored in the endosperm, in quinoa the starch is stored in the perisperm. The starch granules in quinoa are polygonal and very small with a diameter of about 1.0–2.5 μm , which is only slightly bigger than amaranth starch granules (average 1 μm). They are found either as individual granules or as large compound granules of many hundreds of individual granules, as can be seen in Fig. 5.2 (Lorenz, 1990). Furthermore, quinoa starch is characterized by a low content of amylose (usually below 10%), but can vary between 4% and 20% (Atwell et al., 1983; Lindeboom et al., 2005; Praznik et al., 1999; Tang et al., 2002). Due to this different composition, quinoa starch has a relative low, but wide gelatinization temperature range (57–71°C), depending on amylose content (the higher amylose content the lower the gelatinization temperature) (Lindeboom et al., 2005), and high pasting viscosity (Ahamed et al., 1996). Also related to the low amylose content is the excellent freeze-thaw stability of quinoa starch and its resistance towards retrogradation.

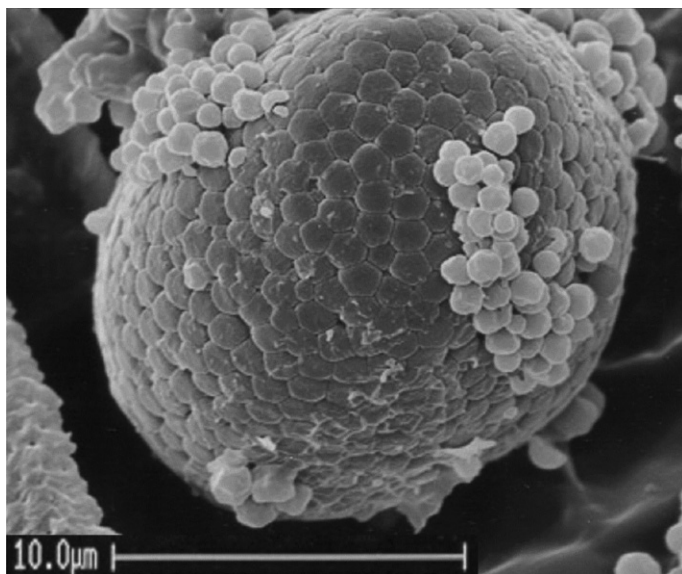


FIGURE 5.2 SEM micrograph of a quinoa compound starch granule.

The content of simple sugars is higher in quinoa than in common cereals and can vary significantly between varieties. According to [Jacobsen et al. \(2003\)](#) this may be associated with frost tolerance. Varieties from the Altiplano had higher sugar content than the quinoas from the valleys. [Repo-Carrasco \(1992\)](#) reported that the content of free sugars in quinoa was 6.20%. The following sugars and oligosaccharides were found by [Gross et al. \(1989\)](#): fructose, glucose, sucrose, raffinose, stachyose, verbascose, and α -galactosides. Sucrose was the main sugar with a content of 2.79 g/100 g dry basis. According to [Ogungbenle \(2003\)](#), quinoa flour has a high proportion of D-xylose (120.0 mg/100 g sample) and maltose (101.0 mg/100 g sample), and a low content of glucose (19.0 mg/100 g sample) and fructose (19.6 mg/100 g sample).

2.4 Dietary Fiber

The content of dietary fiber in quinoa is similar to that of cereals, but there is great variation between species and varieties, which is also common for true cereals. This may be related to environmental conditions, such as soil nutrient status and water availability or interactions between the genotype and environment ([Shewry et al., 2008](#)). Other reasons could be differences in seed handling and processing. Removal of saponins is known to decrease the fiber content. Hence, some authors report a relatively low dietary fiber content for quinoa, whereas others found higher amounts. Levels of 7.8%–14% ([Alvarez-Jubete et al., 2009](#); [Vidueiros et al., 2015](#)). [La Mothe et al. \(2015\)](#) determined a total dietary fiber content in quinoa of 10%, 78% of it was insoluble. The insoluble fiber (IDF) was mainly composed of galacturonic acid, arabinose, galactose, xylose, and glucose. The proportion of soluble fiber in quinoa (approximately 22%) is higher than in most common cereals, and was mainly composed of glucose, galacturonic acid, and arabinose.

The composition of dietary fiber in quinoa resembles more that of fruits, vegetables, and leguminous seeds rather than that of cereals and it might have a good potential for beneficial colon function. But in this respect more research is necessary.

2.5 Micronutrients—Minerals and Vitamins

Quinoa's high content of micronutrients, vitamins, and minerals is one of the features that make quinoa such an excellent nutrient source ([Table 5.2](#)) ([Nascimento et al., 2014](#); [Vega-Galvez et al., 2010](#)). The total mineral content (ash) in quinoa is about twice that in cereals and it is particularly rich in calcium, magnesium, iron, and zinc. Minerals, such as potassium and magnesium are located in the embryo, while calcium and phosphorus are associated with pectic compounds of the pericarp cell wall ([Vega-Galvez et al., 2010](#)).

Regarding vitamins, carotenes, riboflavin (vitamin B₂), tocopherols (vitamin E), and folic acid are abundant ([Ruales and Nair, 1993a](#)). Regarding the

TABLE 5.2 Content of Selected Micronutrients of Amaranth, Quinoa, and Buckwheat (mg/100 dm)

Minerals	Ca	Mg	P	Na	K
mg/100 g dm	32.7 ^a	207 ^b	384 ^d	3.7 ^c	555 ^c
	32.9 ^b	230 ^c	442 ^c	11.5 ^e	927 ^d
	49.7 ^c	250 ^d			
	148.7 ^d	270 ^e			
Trace Elements	Zn	Fe	Cu	Mn	
mg/100 g dm	1.8 ^b	4.7 ^a	0.77 ^c	1.35 ^c	
	3.3 ^c	5.4 ^c	3.7 ^e	33.0 ^b	
	4.4 ^d	5.5 ^b	5.1 ^d		
	4.8 ^e	13.2 ^d			
	5.0 ^a				
Vitamins	β-Carotene	Thiamine (B ₁)	Riboflavin (B ₂)	Niacin (B ₃)	
mg/100 g dm	0.39 ^d	0.29–0.36 ^f	0.30–0.32 ^f	1.24–1.52 ^f	
		0.38 ^d	0.39 ^d	1.60 ^d	
		0.40 ^g			
Vitamins	Pyridoxine (B ₆)	Total folates	Ascorbic acid (C)	Tocopherols (E)	
	0.487 ^f	0.13 ^h	0.18 ^f	8.7 ⁱ	
		0.18 ^f	4.0 ^d		
			16.4 ^g		

^aData from Iglesias-Puig et al., 2015.

^bData from Alvarez-Jubete et al., 2009.

^cData from Hager et al., 2012.

^dData from Koziol, 1992.

^eData from Repo-Carrasco et al., 2003.

^fData from Abugoch, 2009.

^gData from Ruales and Nair, 1993a.

^hData from Schoenlechner et al., 2010b.

ⁱData from Alvarez-Jubete et al., 2010.

tocopherols, alpha-tocopherol, gamma-tocopherol, and beta-tocotrienol, are the major ones in quinoa (Koziol, 1992; Ruales and Nair, 1993a). Most impressive is the content of folic acid in quinoa, a vitamin that is deficient in a significant portion of the world’s population (in all countries, Global North, as well as Global South). Schoenlechner et al. (2010b) determined the total folate content in the three pseudocereals amaranth, quinoa, and buckwheat in comparison to

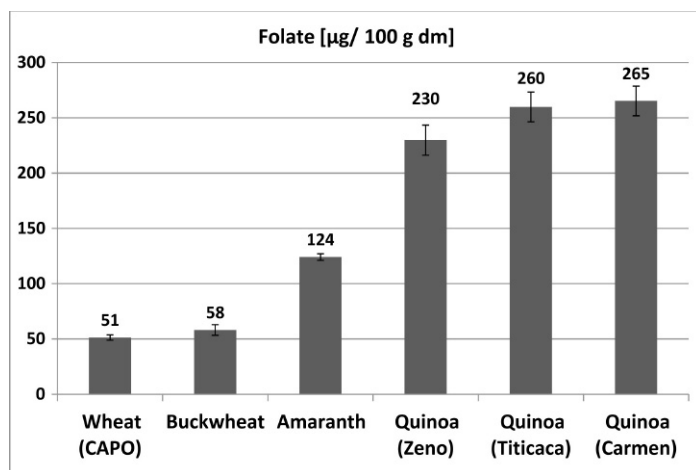


FIGURE 5.3 Folate content of quinoa varieties in comparison to common wheat, buckwheat, and amaranth. Schoenlechner, unpublished data, method: VitaFast microbiological microtiter plate test, R-Biopharm, Germany.

four cereal species and found that the folate content in amaranth was about four times higher than in cereals and in quinoa the amount was up to 10 times higher. Some quinoa species can even contain about 265 µg/100 g (Fig. 5.3, unpublished data). Only in buckwheat, was folic acid in the range of true cereals. As the daily-recommended intake for folic acid is 300 µg (DACH, 2015), quinoa definitely can be considered as a high source for folic acid.

2.6 Bioactive Compounds

Phenolic compounds, which are phytochemicals present in plants and can provide health benefits related to their antioxidant capacity, are present in quinoa, although their amount is lower than in cereals (Table 5.1). Again, great variation in levels exists between species, and the levels are also dependent on growing conditions (Repo-Carrasco and Astuahuaman, 2011). According to Miranda et al. (2010), Pasko et al. (2009), and Repo-Carrasco and Astuahuaman (2011) the total phenolic compound content ranged from 1.59 to 3.74 mg gallic acid equivalent to (GAE)/100 g in different quinoa varieties. Comparison of data for total polyphenols in quinoa is difficult due to the different analytical methods applied, and in particular differences in the polyphenol extraction process. Pasko et al. (2009) used a two-step extraction process, first with methanol and then with acetone and found a higher content of total polyphenols (3.75 mg GAE/g) compared to Repo-Carrasco and Astuahuaman (2011) who used methanol only (1.59 mg GAE/100 g). Hence, some polyphenols may not have been included in the extract analyzed by the latter authors. Yawadio Nsimba et al. (2008) analyzed the total phenolic compounds in quinoa and amaranth

(*Amaranthus hypochondriacus* and *Amaranthus cruentus*) and found levels between 94.3 and 148 mg tannin acid equiv./g. In work by the author (2016, data unpublished) total phenols (TP) were determined as mg ferulic acid (FA) equiv./100 g dm. In six white, red, and black quinoa varieties contents for TP between 93 and 279 mg FA equiv./100 g dm were determined. White varieties had a significantly lower TP content than the black varieties. The proportion of bound phenols was significantly lower than of free phenols in the white varieties, in the black varieties the ratio was opposite. During sprouting of quinoa seeds, the total phenol content can increase (Gallagher et al., 2010).

The composition of phenolic compounds in quinoa was studied by Repo-Carrasco et al. (2010). They detected caffeic acid, ferulic acid, *p*-coumaric acid, *p*-hydroxy-benzoic acid, and vanillic acid. However, compared to common cereals, quinoa contains generally less phenolic acids. The phenolic acid composition of the six aforementioned quinoa types (white, red, and black) showed great variation (own data, unpublished). Ferulic acid was the only one that could be detected in all varieties and none of them contained gallic or salicylic acid.

Flavonoids occur in abundance in quinoa, and mainly comprise glycosides of the flavonols kaempferol and quercetin (Alvarez-Jubete et al., 2010; Gallagher et al., 2010; Zhu et al., 2001). Repo-Carrasco et al. (2010) found myricetin and isorhamnetin in some quinoa varieties and Vega-Galvez et al. (2010) detected isoflavones, particularly daidzein, and genistein.

2.7 Saponins and Phytates

Besides these bioactive compounds, quinoa contains considerable amounts of bitter tasting saponins, which are commonly considered to be antinutrients. However, at low concentration they present health-promoting properties, like cholesterol-reducing ability (Zhu et al., 2002), antiinflammatory activity (Mujica, 1994), anticarcinogenic properties (Guclu-Ustundag and Mazza, 2007), or immune stimulatory and antioxidant effects (Guzman-Maldonado and Paredes-Lopez, 1998). Quinoa (whole seeds) contains between 0.03% and 2.05% of bitter tasting saponins (Chauhan et al., 1995; Cuadrado et al., 1995; Gee et al., 1993; Ridout et al., 1991; Ruales and Nair, 1993b), but these values are still below those in soybeans. In quinoa, the saponins comprise oleanic acid and three other sapogenols, identified as hederagenin, phytolaccagenic acid, and deoxyphytolaccagenic acid (Cuadrado et al., 1995; Woldemichael and Wink, 2001). Optical and electron microscopy in combination with chemical methods identified the saponin-bodies in the quinoa pericarp cells (Prado et al., 1996). The globoid-shaped saponin-bodies are about 6.5 μm in diameter and appear as an aggregate formed by four or five small granules (2.2 μm in diameter). Some 34% of the saponins are located in the hull (Chauhan et al., 1995). Dehulling and washing decrease the content by up to 72% (Gee et al., 1993; Ruales and Nair, 1993b). Processing can also destroy saponins, but the reduction in content is not as great as after washing or dehulling (Gee et al., 1993). Another way to reduce the

saponin content in quinoa seeds is by breeding of so-called sweet quinoa varieties (with low saponin content). Mastebroek et al. (2000) investigated the saponin content of various varieties and found only 0.02%–0.04% saponins in sweet varieties compared to 0.47%–1.13% in bitter varieties. According to Koziol (1991), if the saponin content is less than 0.11% the variety can be considered as a sweet variety.

Phytic acid is universally present in whole grains of all species. Although phytates have been reported to have favorable effects, such as antioxidant properties, prevention of heart diseases and anticarcinogenic effect (Haros et al., 2009), it is also well known in reducing the bioavailability of protein, mineral, and trace elements, such as Ca, Mg, Zn, Cu, and Fe (Hurrell et al., 2003). Germination of the quinoa seeds and some processing methods can reduce the phytate content. The phytate content reported for quinoa seeds shows a wide variation between 9.3 and 20.3 μ moles of phytic acid/g, and it is mainly present in the protein bodies of embryonic cells of the grain, approximately 60% of the total phytates (Ando et al., 2002).

3 PROCESSING PROPERTIES AND FOOD APPLICATIONS

Historically, quinoa has been used in a wide range of products by the pre-Hispanic people of Latin America. Processing of quinoa was mainly done by cooking the whole seeds, which were then consumed in soups, salads, various stews, and even sweet desserts, or by milling it to flour, which was added to several traditional products (e.g., porridge or flatbread) or fermented to a type of beer, called *chicha* (Fig. 5.4). Removal of the bitter tasting saponins was either performed by washing them in water (the pre-Hispanic people used this washing water as a detergent) or by dry heat treatment and then rubbing off the seed coat by hand. Roasting the seeds in a hot pan prior to cooking was commonly performed as it adds a nice, nutty flavor to the final products. This is also recommended to be applied today to adapt or improve quinoa's inherent taste for application in Western diets.

Today the main use of quinoa is by cooking and direct consumption (instead of rice) (Fig. 5.5). Also, there is a wide range of food products like breakfast cereals, beverages, bread, and pasta and other bakery products in which quinoa is often blended with common cereal flour to increase the product's nutritional quality.

3.1 General Processing Properties

In principle, quinoa can be used for many food products, in a similar way to cereals. However, for food processing it has to be considered that quinoa has different physical and functional properties compared to cereals, which are mainly a result of the different seed morphology of the pseudocereals (ring embryo) and their distinct chemical composition. In quinoa, the very small

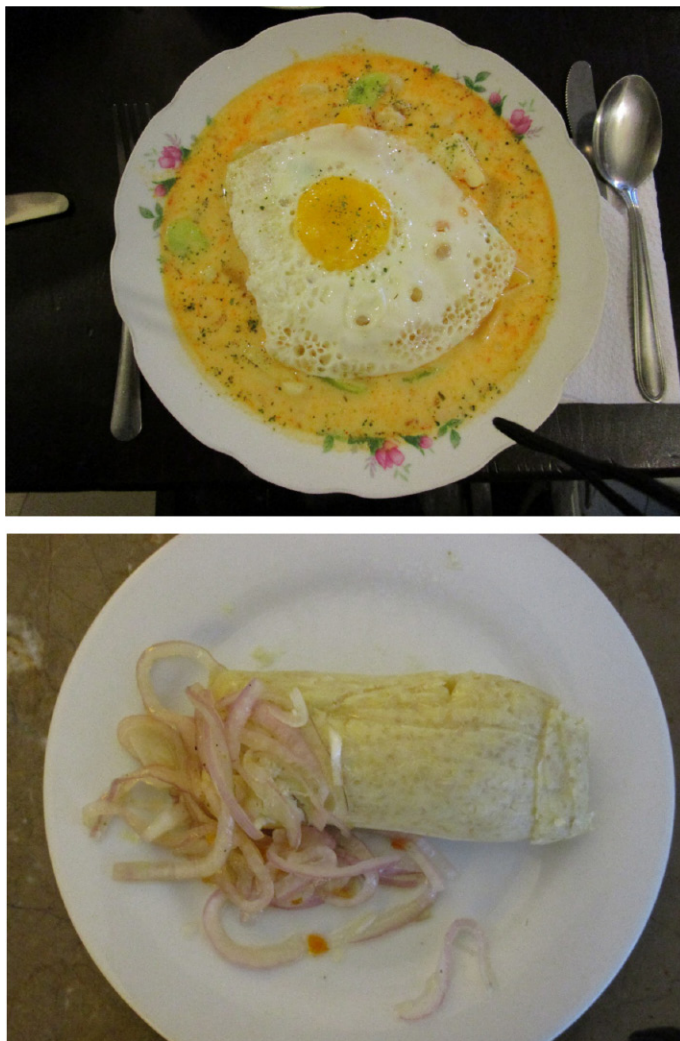


FIGURE 5.4 Traditional quinoa dishes: *chupe de quinoa* (top) and *pastel quinoa* (bottom).

starch granules and their high content of amylopectin (usually at least 90%) are responsible for the higher viscosity, good freeze-thaw stability, higher water-binding capacity, and higher swelling power compared to true cereals. In addition, their starch shows less retrogradation than cereals. Due to these properties, quinoa has excellent functionality as a thickening agent (Ahamed et al., 1996; Atwell et al., 1983; Lorenz, 1990).

Regarding protein, research has revealed that quinoa protein concentrates or isolates are highly soluble, and are thus a good ingredient for use in functional (health-promoting) foods (Bejosano and Corke, 1999; Kovacs et al., 2001;



FIGURE 5.5 Quinoa products available in the supermarket in Peru today. White quinoa, red quinoa, black quinoa, and quinoa porridge.

Segura-Nieto et al., 1999). Protein solubility is increased under alkaline conditions (Abugoch, 2009). The emulsification capacity and stability of quinoa protein is higher compared to pearl millet or wheat, whereas foaming capacity seems to be lower (Oshodi et al., 1999). Protein isolates of quinoa have a water-holding capacity of 2.8–4.5 mL water/g, depending on extraction conditions, which is similar to soy isolates (Abugoch, 2009).

The biggest restriction, though for food processing is that quinoa does not contain wheat-like gluten, and therefore dough-forming or baking properties are limited. For the production of bread and bakery products quinoa flour cannot be used without addition of further ingredients or without adaptation of processing conditions. However, up to a certain amount can be added to wheat-based products, thereby improving the product's nutritional properties.

3.2 Milling Processes

Milling and fractionation of starchy seeds is an important step that influences final product quality, because most cereal food products are not made from whole seed kernels, but flour or flour fractions. Milling can be performed either by dry or wet milling processes. The aim of dry milling is primarily to produce wholemeal flour or to separate the grain by physical fractionation techniques (e.g., grinding, sifting, sieving) into its anatomical parts, that is, separation of the starch-rich endosperm (perisperm in quinoa) from the outer layers (bran and embryo). Wet milling is applied to separate the kernel into its chemical components that is, starch, protein (concentrates, isolates), dietary fiber, and oil.

The production of wholemeal flour from quinoa is well established and does not cause specific problem, so all known processes may be applied. However, the production of flour fractions with different chemical composition and physical properties by dry fractionation techniques is extremely challenging, mainly due to its small seed size and different seed morphology (ring embryo). Various milling and fractionation techniques (at pilot scale) to produce starch-rich and protein-rich flour fractions from quinoa have been investigated

by several researchers, for example, roller milling and plansifting by [Schoenlechner et al. \(2008\)](#). Abrasive milling seems to have potential to produce flour fractions from such small seeds. It is also often applied to reduce the saponin content, as a higher portion is located in the outer layers. Alternatively, saponin can be removed by washing. Whole quinoa flour may include pericarp, if the saponins were washed out before milling, or it may include some or no pericarp if the saponins were removed by abrasion ([Taylor and Parker, 2002](#)).

Wet milling is mainly applied to isolate starch, protein, or dietary fiber for subsequent food application. A typical wet milling process includes the following steps: (1) cleaning of the grain, (2) soaking in an aqueous solution (often including alkali), (3) several milling steps, (4) filtration/sieving (mainly to remove germ and fiber), and (5) separation of starch and protein by centrifugation (mainly in laboratory scale work) or by settling tables (sedimentation of diluted starch milk by flowing over long inclined tables) or hydrocyclone method (at industrial scale). The protein fraction (lighter fraction) is then concentrated and dehydrated. The starch suspension is washed and concentrated. The two separation techniques mentioned are based on density differences between starch and protein.

Wet milling of quinoa has been investigated by several researchers. Soaking solution (alkaline, acidic, or water) was shown to have great influences on the process ([Atwell et al., 1983](#); [Lorenz, 1990](#); [Qian and Kuhn, 1999](#)). Enzyme treatment (xylanase, cellulase, and hemicellulase) can be applied to enhance separation ([Wilhelm et al., 1998](#)). [Gonzalez-Roberto et al. \(2016\)](#) optimized the steeping conditions of quinoa kernels in sulfite solution with lactic acid. [Pouvreau et al. \(2014\)](#) developed a method for processing quinoa that included alkaline agents, and/or coating the seeds with lipases, proteases, and/or esterase enzyme preparations to reduce the saponin content.

To fully develop dry and wet milling processes to obtain defined milling fractions, or isolated (or concentrated) components from quinoa, research still has to be intensified, in particular for subsequent scaling up to industrial level.

3.3 Food Uses

Breakfast cereals, cereal beverages (similar to soy beverage), ([Fig. 5.6](#)) and extruded snack foods are examples of products from quinoa, which can be found on the market. They do not demand great adaptation of processing conditions compared to common cereals. Processing of quinoa by extrusion cooking; however, requires very high shear to disrupt the quinoa starch granules, due to its high lipid and low amylose contents ([Dogan and Karwe, 2003](#)).

Bakery products like cookies (biscuits) can be made from 100% quinoa flour without great difficulties, despite the lack of gluten, as was shown by trials by [Schoenlechner et al. \(2006\)](#). [Wang et al. \(2015\)](#) produced cookies from blends of wheat and quinoa in different proportions. Cookie antioxidant activity was increased by the inclusion of quinoa flour and the peroxide value was lower



FIGURE 5.6 Beverage produced from 100% quinoa.

after storage at room temperature compared to the wheat only cookie (Watanabe et al., 2014).

Similar beverages to soy milk can be produced from quinoa flour by a hot mashing process, or by drum drying. Pineli et al. (2015) reported that quinoa beverages provide a novel alternative to current milk-substitute products as they cause no known adverse effects in humans and have increased protein content and low glycemic index (GI). Quinoa beverages are suggested to be a healthy option for preschool children or even infants, as they are a source of valuable nutrients, such as protein, vitamin E, thiamin (vitamin B₁), iron, zinc, and magnesium (Ruales et al., 2002). Repo-Carrasco et al. (2003) reported that quinoa and kañiwa (*C. pallidicaule*) can be used in weaning food mixtures. They formulated two dietary mixtures, quinoa–kañiwa-beans and quinoa–kiwicha-beans, both with high nutritional value; the mixtures had protein efficiency ratio (PER) values close to that of casein (2.5); 2.36 and 2.59, respectively.

When it comes to breadmaking, the absence of gluten in quinoa is a great challenge. Addition of quinoa, especially in high amounts, to wheat dough results in a change of dough properties and quality of the end product. These changes include increased dough yield, moist dough, decreased fermentation tolerance, lower volume, tense and nonelastic crumb, and various flavor changes (Stikic et al., 2012; Iglesias-Puig et al., 2015). Traditional breadmaking therefore has to be adapted, when high amounts of quinoa (more than 20%) are included. The main aim of adding quinoa to wheat bread is the increase in nutrient quality of the resulting product. However, it was also found that after quinoa flour addition the phytate content of the bread was significantly increased (Bilgiçli and İbanoğlu, 2015; Iglesias-Puig et al., 2015), which consequently decreases the bioavailability of nutrients like minerals. According to Iglesias-Puig et al. (2015), this effect can be easily avoided by the application of exogenous phytases from bifidobacteria. The use of flours from germinated seeds could also minimize the phytate content in bakery products. If the purpose of quinoa inclusion in breadmaking is to increase protein content and quality, protein isolates could be preferred in order to avoid quality

deterioration of the end product (Tömösközi et al., 2011). Another possibility to improve the quality of bread from/or including quinoa is the application of sour-dough fermentation. Quinoa, as well as amaranth flour, was found to be suitable for fermentation by various species of *Lactobacillus* (Coda et al., 2010; Dallagnol et al., 2015; Houben et al., 2010; Jekle et al., 2010).

3.4 Gluten-Free Foods

The aim in gluten-free processing is to replace the functionality of gluten (formation of a three dimensional network in bread, agglutination, and elasticity in pasta, etc.) by other means such as using specific ingredients or adapting processing conditions. But it is important in a gluten-free diet not only to exclude all gluten-containing components (i.e., wheat, rye, barley, and subspecies, and possibly oats) and avoidance of gluten-contamination of foods, but also to replenish deficient nutrients, especially when gut absorption is still impaired. Thus, it is critical to ensure nutritional adequacy, as well as excluding gluten, as people suffering from any gluten intolerance have to adhere to such a diet life-long. Until recent times, gluten-free processing was based on a narrow range of raw materials, mainly rice and maize. The consequence was a low nutritional quality (high energy density, but low nutrient density including a low content of vitamins, minerals, trace elements, dietary fiber, and phytochemicals) and low sensory quality, in particular for bread. The challenges in production of gluten-free foods are thus to improve the nutritional quality, as well as the sensory properties. Considering this, quinoa has a very high potential for the development of high-quality gluten-free foods.

Alvarez-Jubete et al. (2010) compared the baking properties of amaranth, quinoa, and buckwheat, each blended with rice flour (50:50), with a standard gluten-free bread (rice flour and potato starch 50:50). They showed that pseudocereal flour might be introduced into a gluten-free bread formulation to enhance crumb softness and cohesiveness without adversely affecting other sensory properties of the bread. The use of amaranth, quinoa, and buckwheat in the production of gluten-free pasta was studied by Schoenlechner et al. (2010a). These authors found that pasta produced from amaranth had decreased texture firmness and reduced cooking time, while pasta from quinoa mainly showed increased cooking loss. The least negative effects were observed in buckwheat pasta. By combination of all three pseudocereals into one-flour blend in the ratio of 60% buckwheat, 20% amaranth, and 20% quinoa, the dough matrix was improved. Dough moisture had to be reduced (30% vs. 34.5% in wheat pasta). The addition of isolated protein (the most suitable was egg albumen) had the greatest effect in improving pasta firmness. For the production of gluten-free pasta, the role of starch and its properties are important (Marti et al., 2011). Phenomena related to starch retrogradation were found to play a central role in the final texture of the products (Mariotti et al., 2011). Thus, more attention is being paid to the technology of pasta making, utilizing pregelatinized flours or dough, or applying different temperature regimes (Marti and Pagani, 2013; Mastromatteo et al. 2011). Both approaches seem to be promising for improving gluten-free pasta quality.

4 NUTRITIONAL AND HEALTH PROMOTING PROPERTIES OF QUINOA FOOD PRODUCTS

For any food, it is not only the chemical composition of its raw materials or the presence of nutrients in certain levels that are important, but also their physiological properties (e.g., bioavailability, digestibility, or retention of nutrients after processing) within final food product. As outlined in the previous sections, quinoa has an excellent nutritional composition, but also its physiological properties are interesting.

With respect to protein, together with its high content of essential amino acids and high biological value, quinoa was also found to have a high digestibility. In vitro digestibility of raw quinoa ranged between 76.3% and 80.5% (Repo-Carrasco and Serna, 2011; Ruales and Nair, 1994). This can be increased by dehulling or washing (removal of saponins) to 83%–84% (Ruales and Nair, 1994) or by cooking, up to 95% (Ruales et al., 2002). In vivo trials accomplished by feeding experiments showed a digestibility of 92% (Ruales and Nair, 1994). Digestibility of proteins can be reduced by trypsin inhibitors. However, in fact, trypsin inhibitory activity in quinoa is low (1.36–5.04 trypsin inhibitor units (TIU)/mL sample) (Chauhan et al., 1992). Inhibitory activity can be further reduced by heat treatment, washing, or dehulling (Chauhan et al., 1992; Ruales and Nair, 1992).

With regard to starch digestibility and the GI of quinoa, unfortunately available research data are contradictory. As quinoa was shown to have a high content of D-xylose and maltose, and a low content of glucose and fructose (Ogungbenle, 2003) and it has been described as having a low GI, which might make it suitable for diabetics (Oshodi et al., 1999). Also, according to Berti et al. (2005), who performed in vitro and in vivo studies to determine starch digestibility and glycemic response, quinoa seemed to have potential to lower GI, but the authors considered that further and larger studies are required to demonstrate its hypoglycemic effects. On the other hand, Wolter et al. (2014) found significant differences in the starch digestibility of pseudocereals and predicted a high GI for amaranth and quinoa. In a study on amaranth, Capriles et al. (2008) explained that particular characteristics of pseudocereals (size of starch granules in addition to type of carbohydrates and their molecular arrangement) could influence GI values. In this sense, amaranth seed was indicated as a high glycemic food, most likely because of its small starch granule size, low resistant starch content, and tendency to completely lose its crystalline and granular starch structure during processing (heat treatments). Due to the similar starch properties of amaranth and quinoa these assumptions might also be true for quinoa. Wolter et al. (2013) found the highest predicted GI in gluten-free quinoa bread compared to other gluten-free breads and concluded that the smaller starch granule diameters in quinoa (1.3 μm) resulted in a higher GI.

Resistant starch (RS), which has several recognized health benefits (e.g., prevention of colon cancer, reduction of serum cholesterol, and triglycerides)

and additionally influences the GI of the resulting product, can be increased in quinoa by some processing methods. In a study by [Linsberger-Martin et al. \(2012\)](#), hydrostatic pressure treatment of quinoa starch enhanced the RS content by a factor of about 18-fold. Such treated flours could serve as a functional ingredient for gluten-free products, such as bread.

Dietary fiber content and composition can be greatly affected by processing. After extrusion cooking, the total dietary fiber content, in particular the insoluble fraction, decreased in quinoa, while the soluble dietary fiber fraction increased ([Repo-Carrasco and Astuahuaman, 2011](#)). Such changes have also been found with common cereals by other researchers ([Björck et al., 1984](#); [Gualberto et al., 1997](#)), and are probably a result of the exposure to shear stress and high temperature, which, depending on extrusion cooking parameters can cause breakage of chemical bonds, creating smaller particles that are soluble. In an earlier study by [Ruales and Nair \(1994\)](#), total dietary fiber content of quinoa was found to be reduced by cooking and some soluble fiber was lost during cooking and autoclaving, probably due to depolymerization of fiber components. The physiological effects of quinoa flour were studied by [Konishi et al. \(2000\)](#). A diet supplemented with 3% quinoa pericarp significantly reduced serum and liver cholesterol levels in mice. This hypocholesterolemic effect of the quinoa pericarp was most likely attributable to the water-soluble dietary fiber content, similar to other fibers like oats.

Concerning micronutrients, it has been shown that quinoa has very high levels of folic acid. Vitamins are a group of the nutrients that are very sensitive to processing effects (impact of temperature and/or water) and are thus easily reduced in quantity or even lost. Folate is one of the unstable vitamins and average loss after storage or processing can lie between 35% and 70% ([Gujska and Majewska, 2005](#)). In a study on folate in pseudocereals, [Schoenlechner et al. \(2010b\)](#) produced several staple foods (bread, pasta, and cookies) from pseudocereals (amaranth, quinoa, and buckwheat) and determined the total folate content and its losses in these products and in flours stored for 3 months. Average loss of total folate in flour after storage was 34%, 51% in bread, 24% in noodles, and 16% in cookies. Despite these losses, total folate content was 17–98 µg/100 g dm in noodles, 18–62 µg/100 g dm in cookies, and 26–41 µg/100 g dm in breads. Quinoa products were characterized by highest total folate content. The data underpinned that food products made from pseudocereals (in particular amaranth and quinoa) can provide substantial levels of folate.

As indicated, the minerals in quinoa are mainly located in the outer layers of the seed. Through removal of saponins (mechanically and/or through washing) the mineral content in quinoa can be greatly reduced (e.g., 46% of the potassium can be lost) ([Konishi et al., 2004](#); [Ruales and Nair, 1993a](#)). Additionally, the phytate has adverse effects on mineral bioavailability, due to the formation of insoluble complexes, which are nonabsorbable in the human gastrointestinal tract ([Lopez et al., 2001](#); [Sandberg et al., 1996](#)). According to

Omary et al. (2012), germinating pseudocereals may improve the contents of nutrients, vitamins, minerals, total polyphenols, and antioxidant activity, while decreasing antinutrients. Thus, germinated gluten-free cereals and pseudocereals have potential to be used as natural means of fortification and enrichment in gluten-free foods. However, their inclusion may affect product texture and taste (Mäkinen et al., 2013), which needs further investigation.

In addition to these physiological properties, several studies have demonstrated specific health effects of quinoa products. Cholesterol lowering activity of quinoa was shown in studies by Paško et al. (2010) and De Carvalho et al. (2014). Prospective and double blind intervention studies for 4 weeks conducted on overweight women demonstrated that consumption of 25 g of quinoa flakes significantly reduced serum triglycerides, total cholesterol, and low density lipoprotein (LDL)-cholesterol (De Carvalho et al., 2014). In mice feeding trials, Foucault et al. (2014) found that when feeding quinoa, energy expenditure increased, and the oxidative metabolism of glucose was favored, thus inhibiting lipogenesis and leading to reduce fat accumulation in adipose tissue.

The antioxidant capacity of quinoa was evidenced in vivo experiments using quinoa extracts (made with 80% methanol) fermented with *Rhizopus oligosporus* (Matsuo, 2005). A positive influence on increasing the activity of important antioxidant enzymes, as well as reducing lipid peroxidation parameters in plasma samples, red blood cells, and several different organs (heart, kidney, liver, and brain) was found. Also, in other studies quinoa demonstrated antioxidant activities in animals fed a high-fructose diet to induce oxidative metabolic stress (Paško et al., 2010).

Giménez-Bastida et al. (2016) concluded that generally diets that contain pseudocereals have been associated with hypocholesterolemic effects, antioxidant, and antitumor activities, reducing blood glucose levels and improving conditions of hypertension and anemia. According to their review, dietary fiber alone does not completely explain the frequent association between greater intake of whole grains and the reduced risk of disease in observational studies. They proposed that future research should be directed to epidemiologic studies and toward understanding the mechanisms of action, especially in the human body.

5 CONCLUSIONS

With its excellent nutrient composition, processing properties and demonstrated health benefits, quinoa is indeed a highly nutritional ingredient. After it had been long neglected, quinoa was “rediscovered” in the mid/late 20th century, but still it took a few decades until quinoa has received close attention. Since the year 2000 an increase in food products from quinoa in the market can be observed world wide. The main reason for this is its gluten-free status, but also among the general population of countries, such as Canada, the USA, Japan and Australia, and in Europe, Andean grains generally have gained increasing

acceptance by consumers. Quinoa production and trade systems are undergoing profound changes in the Andean region, reflecting a shift from a traditional crop, primarily produced for own consumption, to a globally traded commodity. The growing global demand and booming exports from Bolivia and Peru have benefited the smallholder producers, but also pose new challenges as market dynamics change. Of great concern is the great increase in price of quinoa (in particular after the year 2008), which dramatically affects the local market and consumption patterns. Poor households replace quinoa with less expensive but nutritionally inferior food products like rice, bread, or pasta (Krivonos, 2013).

As research in the first period of quinoa's "rediscovery" focused on agricultural aspects and some preliminary chemical characterization, there is still a lack of knowledge in many areas. However, as the interest in quinoa has increased, research efforts on quinoa have now intensified. Today, research spans all areas from cultivation and breeding issues through fundamental chemical and physical properties to in vivo and clinical studies, in order to obtain detailed data concerning its health-promoting properties. Only with such a comprehensive approach will it be possible to fully exploit the high potential of quinoa and to offer its benefits to all people, in all countries of the world.

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Chapter 6

Amaranth: Its Unique Nutritional and Health-Promoting Attributes

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1 INTRODUCTION

Amaranth is an annual plant, which can grow up to a height of 0.5–3 m, depending on the species. The plants are bushy with thick stalks. It is quite similar to pigweed in many respects. Flowers are predominantly purple, red, pink, orange, or green. The leaves are relatively broad and the blossom strands can reach a length of up to 90 cm. They can grow upright or prostrate.

The genus *Amaranthus* contains about 70 species. The next, higher level of taxonomy is the foxtail family, the Amaranthaceae (Berghofer and Schoenlechner 2002). *Amaranthus* belongs to the Caryophyllales order, which includes also quinoa, spinach and beetroot. The most important amaranth species, which are cultivated and consumed for their seeds are *Amaranthus hypochondriacus* in Mexico, *Amaranthus cruentus* in Guatemala and *Amaranthus caudatus* in Peru and other Andean countries (Bressani, 2003). The main leafy cultivars belong to the species *Amaranthus blitum*, *spinosus*, and *tricolor*. Chromosome number varies with species in amaranth. The species have usually a haploid chromosome number of $n = 16$ (*A. hypochondriacus* L., *A. cruentus* L., *A. caudatus* L., *Amaranthus quitensis* L., *Amaranthus edulis* L., *Amaranthus powellii* L., and *Amaranthus retroflexus* L.) or $n = 17$ (*Amaranthus tricolor* L. and *Amaranthus spinosus* L.). The tetraploid species as *Amaranthus dubius* L. have $4n = 64$ chromosomes. Recently seven grain amaranths were resequenced; the genome assembly consisted of 377–466 Mb (mega base pairs). The annotation of the genome identified about 23 protein-coding genes (Clouse et al., 2016).

There is no worldwide data on amaranth cultivation. The main amaranth-producing countries are the tropical regions of South America, but also of Africa (especially for leaves of the amaranth plant), Central, and Southeast Asia (especially India), and to a minor extent also the warmer regions of North America. The production area in Europe is quite low, only about 1000 ha. The larger

production areas of amaranth are in Slovakia, Hungary, and Italy. In the Mediterranean region amaranth is grown as a leafy vegetable. There is much greater cultivation in Russia, amounting to about 100,000 ha (Moudry et al., 1999). Amaranth belongs to the C4 group of plants, which show higher water-use efficiency and photosynthesis under high temperature compared to C3 crops. Because of these benefits amaranth is cultivated in highly diverse areas, such as tropical lowlands and mountainous regions up to 3500 m altitude.

For amaranth seeds a wide range of harvest yields has been reported. A review by Alemayehu et al. (2015) revealed yields from 50 to 7200 kg/ha. Highest yields of 4600–7200 kg/ha are in South and Middle America, whereas in Africa crop yields are quite low, 50–2500 kg/ha. In Europe, yields are moderate, 1200–6700 kg/ha, especially in Mediterranean climates. The yield depends on many factors, for example, low seed yields of 450–700 kg/ha on dry land were significantly increased to 900–2000 kg/ha by irrigation. However, generally the water requirements for growing amaranth are much lower compared to wheat (less than 50%), and maize (less than 40%–50%), (Alemayehu et al., 2015). Amaranth is also well adapted to cultivation in marginal land and has significant potential for further breeding improvement due to its high genetic diversity and range of phenotypic plasticity. Its inherent tolerance to high temperatures, drought, poor soil conditions, and lack of major diseases makes amaranth very interesting as a crop for challenging growing conditions, especially in respect of the consequences of climate change (Alemayehu et al., 2015).

Amaranth seed structure is completely different to true cereals. Amaranth seeds are creamy to golden colored, lenticular shaped, and have a diameter of about 1 mm, ranging from 0.9 to 1.7 mm. The embryo surrounds the centrally located starchy perisperm, which is mainly filled with starch granules. The radicle, the hypocotyl, the shoot radicle and the two cotyledons are clearly visible under the microscope in the longitudinal section as shown in Fig. 6.1. The embryo is covered

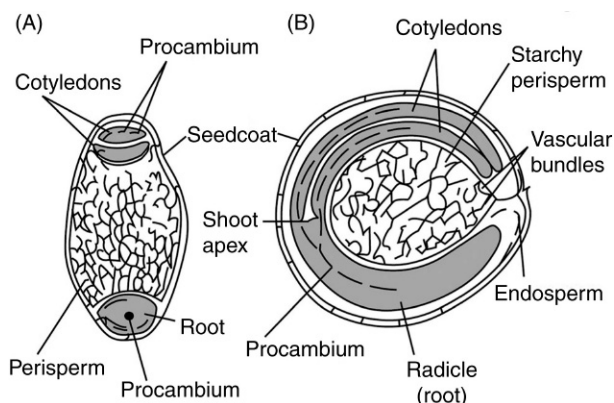


FIGURE 6.1 Amaranth seed in cross-(A) and longitudinal (B) sections. (Adapted from Irving, D.W., Betschart, A.A., Saunders, R.M., 1981. *Morphological studies on Amaranthus cruentus*. *J. Food Sci.* 46, 1170–1174.)

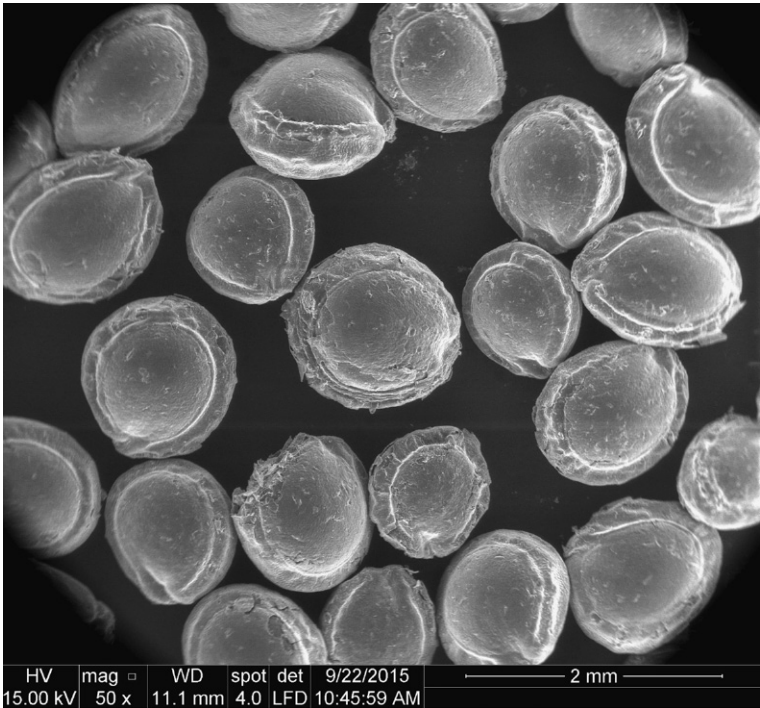


FIGURE 6.2 SEM view of partially dehulled amaranth kernels (Stefano D’Amico and Ruben Pahl).

by the seedcoat, endosperm, and pericarp, which are similar to the bran fraction in cereals. The relatively very large size of the embryo is shown in Fig. 6.2 (partially dehulled amaranth seed). The outer layers are rich in fat and protein. Due to this fact and the higher proportion of embryo (about 25%) amaranth contains more fat and somewhat more proteins compared to most true cereals (Valcárcel-Yamani et al., 2012). A general overview about macronutrients is given in Table 6.1.

TABLE 6.1 Chemical Compositions of Amaranth Seeds		
	Amaranth ^a	Wheat ^b
Starch (g/100 g)	61.4	71.2
Protein (g/100 g)	16.5	12.6
Dietary fiber (g/100 g)	20.6	12.2
Fat (g/100 g)	5.7	1.5
Ash (g/100 g)	2.8	1.6

^aData from Alvarez-Jubete et al. (2009); nitrogen-to-protein conversion factor 5.85.
^bWheat, hard red winter, USDA National Nutrient Database for Standard Reference, Full Report 20072 from 12th January 2016; starch content was calculated by difference.

2 CHEMICAL COMPOSITION AND NUTRITIONAL ATTRIBUTES

2.1 Proteins and Amino Acids

The nutritional value of pseudocereals is strongly related to their protein content and quality, which is higher compared to cereal grains. This is especially the case with amaranth, which has the highest protein content, 13.1%–21.0%, among pseudocereals (Alvarez-Jubete et al., 2010a; Bhat et al., 2015; Venskutonis and Kraujalis, 2013). Generally, the protein content depends on variety and environmental conditions. Analysis of 48 *A. hypochondriacus* and 11 *A. caudatus* lines revealed that *A. caudatus* lines had a higher protein content than *A. hypochondriacus* lines (Kaur et al., 2010). In a study by Tömösközi et al. (2009) eight samples of *A. hypochondriacus* and *A. caudatus* lines, grown in Hungary and Austria, showed a range of protein content of between 14.23% and 17.40%.

Amaranth proteins consist of about 40% albumins, 20% globulins, 25%–30% glutelins, and only 2%–3% prolamins (Venskutonis and Kraujalis, 2013). A lower proportion of 0.48%–0.79% prolamins was found by Muchova et al. (2000). Globulins and albumins constitute the main protein fraction in amaranth (Shevkani and Singh, 2015), as in the seeds of all dicotyledonous plants. According to their sedimentation behavior, two main classes of globulins can be differentiated, 7S and 11S globulins (Quiroga et al., 2015). The 11S globulin (amaranthin) is the most abundant grain storage protein in amaranth and the 7S globulin (conamaranthin) is present in much lower amounts (Condés et al., 2009). The molecular mass of 11S globulin is about 56 kDa. The 7S globulin is composed of 4 subunits of 66, 52, 38, and 16 kDa, in total about 200 kDa (Quiroga et al., 2015). Montoya Rodriguez et al. (2015) characterized the protein composition and their bioactive peptide sequences in detail. In total, 15 main proteins were identified in amaranth seeds, 11S globulin, 7S globulin, α -amylase inhibitor, trypsin inhibitor, antimicrobial proteins, nonspecific lipid-transfer-protein-1, superoxide dismutase, ring-zinc finger protein, prosystemin, amaranth albumin 1, glucose-1-phosphate adenylyltransferase, glucosyltransferase, polyamine oxidase, granule-bound starch synthase 1, and acetolactate synthase.

2.1.1 Nutritional Quality of Amaranth Protein

Of great importance for human nutrition is the ratio of essential (indispensable) amino acids. Venskutonis and Kraujalis (2013) presented a comprehensive overview of the amino acids in amaranth summarized from eight studies. For some amino acids the overview showed considerable variations, especially for lysine (3.3–9.2 mg/g protein) and leucine (3.6–7.9 mg/g protein). The ranges for cystine, methionine, and tryptophan were lower, 2.9–4.2 mg/g protein, 1.7–2.3 mg/g protein, and 0.8–1.8 mg/g protein, respectively. Due to the high proportion of globulins and albumins, pseudocereals contain less glutamine and proline than cereals, and more essential amino acids, such as lysine, methionine + cystine, and histidine. The result is that amaranth protein

has a well-balanced amino acid composition. [Aguilar et al. \(2015\)](#) showed that amino acid scores were between 33%–48% for valine and 65%–100% for lysine compared to the indispensable amino acid requirements proposed by the WHO/FAO/UNU for preschoolers of 1–3 years old ([WHO, 2007](#)). Digestibility influences the nutritional value of proteins, which is used to calculate the Protein Digestibility Corrected Amino Acid Score (PDCAAS) based on concentrations of essential amino acids. PDCAAS indicates the quality for a human diet according to different stages of life ([WHO, 2007](#)). For amaranth, a quite high protein digestibility of about 89% was been mentioned ([Ferreira and Areas, 2004](#); [Kumar et al., 2016](#)). Other studies reported lower values of 80% and 86% ([Escudero et al., 2004](#); [Gamel et al., 2004](#)). However, [Aguilar et al. \(2015\)](#) found true digestibility values of only 68.8%–75.4% and [Awasthi et al. \(2011\)](#) measured only 66.1%–76.7% in vitro protein digestibility. Antinutritional compounds like trypsin inhibitors and polyphenols can affect digestibility negatively. A high correlation was found between the protein digestibility and the concentration of polyphenols, whereas only a weak correlation was found with presence and activity of trypsin inhibitors ([D'Amico et al., 2017](#)).

Processing by popping had no effect on in vivo protein digestibility, although the in vitro digestibility was slightly higher compared to raw seeds, but nutritional quality was reduced by heat treatments, due to a loss of essential amino acids ([Gamel et al., 2004](#)). Also, extrusion cooking can improve the in vitro digestibility of amaranth protein, as reported for two amaranth varieties of *A. caudatus* ([Repo-Carrasco-Valencia et al., 2009](#)). In recent work involving four amaranth cultivars, values for biological value of 44.53%–64.28% and PDCAAS of 0.23–0.36 were obtained ([Aguilar et al., 2015](#)). The PDCAAS of these amaranth cultivars was low due to low valine content and also the fact that lysine was below the requirements. The authors suggested that these new amaranth cultivars could be adequate for human consumption and as a complementary protein source. [Mota et al. \(2016\)](#) found higher PDCAAS values of close to 1, with only small deficits in isoleucine, leucine, valine, and lysine. However, these limiting levels of essential amino acids in amaranth are not a serious problem because they have a far more balanced amino acid profile compared to cereals and hence are easily complemented by other foods ([Montoya Rodriguez et al., 2015](#); [Mota et al., 2016](#)).

2.1.2 Health-Related Aspects of Amaranth Protein

Beside their nutritional value, the allergenic potential of proteins is of great interest. Immunological evaluation of the prolamin fraction from amaranth and quinoa was performed by [Bergamo et al. \(2011\)](#). The intestinal T-cells from celiac disease (CD) patients and transgenic mice did not show any immune reactivity unlike for wheat gliadins. [Ballabio et al. \(2011\)](#) showed after analysis of 40 amaranth varieties using electrophoresis, immunoblotting methods, and ELISA tests that the content of gluten-like proteins was below 20 ppm.

Recent research has focused on the bioactive properties of amaranth peptides and protein isolates. A water-soluble extract of amaranth seeds which contained four novel peptides, possessed antifungal properties (Rizzello et al., 2009). The inhibition of fungal growth was confirmed during storage of gluten-free and wheat flour breads. The peptide profile of hydrolyzates from unprocessed and extruded amaranth showed some biological activity (Montoya-Rodríguez et al., 2015). These results indicated the potential of amaranth peptides for prevention of important chronic diseases. A novel study by Manólio Soares et al. (2015) examined the ability of in vitro digested amaranth peptides to inhibit enzymes of cholesterol biosynthesis. Three major peptides with a mass less than 3 kDa accounted for more than 90% of hydrolyzed peptides and these significantly reduced the activity of a particular reductase involved in cholesterol production, indicating a positive hypocholesterolemic effect. Also, gastrointestinal digested peptides with strong antioxidant properties were identified and characterized by Delgado et al. (2016). Additionally, they found four peptides that had even antithrombotic potential due to their inhibition of fibrin coagulation. Native proteins did not show this ability. Amaranth protein isolates and their alkaline hydrolyzates were also able to replace salt in restructured gelified fish products (García Fillería and Tironi, 2015). Furthermore, they acted as antioxidants and partially inhibited lipid oxidation processes in these products.

2.2 Fat and Lipid Components

Amaranth has a much higher fat content compared to most cereals and even slightly higher than quinoa (Alvarez-Jubete et al., 2010a). A wide range of fat content from 3.24% to 8.60% has been found, (Awasthi et al., 2011; Gimplinger et al., 2007; Kaur et al., 2010). However, Tang et al. (2016) found a more similar fat content of 6.98%–7.22% among seven accessions from three different species. A frequency distribution of 48 lines of *A. hypochondriacus* and 11 lines of *A. caudatus* revealed that the fat content lies mainly between 7% and 8% for *A. caudatus* and 4.8% and 5.4% for *A. hypochondriacus*, which indicates that *A. hypochondriacus* usually contains less fat than *A. caudatus* (Kaur et al., 2010). Some earlier studies mentioned very high fat contents of 17.0% and 19.3% for *A. spinosus* and *tenuifolius*, respectively (Opute, 1979; Singhal and Kulkarni, 1988). This is in accordance with data from supercritical carbon dioxide extraction under optimal conditions where total oil yields of 10.6%–16.7% were achieved (Kraujalis and Venskutonis, 2013).

An overview of the fatty acid composition of amaranth oil, adapted and up-dated from Venskutonis and Kraujalis (2013), is shown in Table 6.1. The most abundant fatty acid is linoleic acid (33.0%–55.9%), followed by oleic acid (18.7%–38.9%), palmitic acid (14.04%–26.0%), and stearic acid (3.11%–4.47%). Also, linolenic acid is present in low concentrations (0.20%–1.97%). The proportion of saturated fatty acids ranges between 20.1% and 30.9% and the amaranth fat contains mainly polyunsaturated fatty acids (33%–50%), which indicates a high nutritional value (Table 6.2).

TABLE 6.2 Overview of Fatty Acid Composition of Amaranth Oil

Fatty Acid (%)	Amaranth ^a	A. <i>cruentus</i> ^b	A. <i>cruentus</i> ^c	Amaranth ^d	A. <i>cruentus</i> ^e	Mean 21 acc ^f	A. <i>hypochondriacus</i> ^g	A. <i>cruentus</i> ^g	A. <i>cruentus</i> ^h	12 A. spp. acc ⁱ	4 Species ^j	A. <i>cruentus</i> ^k	A. <i>cruentus</i> ^l	Range 7 acc ^m
<i>Lauric, C12:0</i>		0.75										0.7		
<i>Myristic, C14:0</i>		0.36		0.12			0.21–0.29	0.27		0.13–0.28	Tr to 0.3	0.2		
<i>Palmitic, C16:0</i>	20.9 ± 0.3	26.10	17.1–21.3	20.89	19.00	18.50	21.4–23.8	22.20	20.75	14.04–25.91	19.1–23.4	20.40	23.45 ± 1.26	18.84–20.21
<i>Palmitoleic, C16:1</i>		0.14		0.29			0.10–0.19	0.11	16.57	0.33–0.60		0.40		
<i>Heptadecanoic, C17:0</i>				0.08						0.07–0.15		0.10		
<i>cis-10-Heptadecanoic, C17:1</i>										0.59–1.25		0.70		
<i>Stearic, C18:0</i>	4.1 ± 0.1	3.24	3.1–3.8	4.47	3.40	3.20	3.11–3.98	3.57	3.79	3.17–4.62	Tr to 1.1	3.90	3.16 ± 0.37	3.70–4.21
<i>Oleic, C18:1</i>	23.7 ± 0.1	29.24	20.3–32.0	21.74	34.00	22.00	22.8–31.5	30.10	23.57	20.18–36.22	18.7–38.9	32.10	24.66 ± 1.76	22.72–31.76
<i>C18:1 w7</i>												1.20		1.39–1.99
<i>Linoleic, C18:2c</i>	47.8 ± 0.2	37.97	33.5–43.9	43.13	33.00	44.8	39.4–49.1	42.2	35.31	37.08–46.95	36.7–55.9	38.2	47.05 ± 1.30	37.11–45.92
<i>Linolelaidic, C18:2t</i>										0.17–0.34				
<i>Linolenic, C18:3</i>	0.9 ± 0.0	1.97		0.76		0.20	0.65–0.93	0.69		0.51–1.21		0.70	0.69 ± 0.14	0.64–1.40
<i>Arachidic, C20:0</i>	0.8 ± 0.0	Tr		0.76			0.56–0.89	0.68		0.53–0.92		0.80		
<i>cis-11-Eicosenoic, C20:1</i>		Tr		0.18			0–0.24			0.15–0.65		0.30		0.19–0.30

(Continued)

TABLE 6.2 Overview of Fatty Acid Composition of Amaranth Oil (*cont.*)

Fatty Acid (%)	Amaranth ^a	A. <i>cruentus</i> ^b	A. <i>cruentus</i> ^c	Ama- ranth ^d	A. <i>cruentus</i> ^e	Mean 21 acc ^f	A. <i>hypochondriacus</i> ^g	A. <i>cruentus</i> ^g	A. <i>cruentus</i> ^h	12 A. spp. acc ⁱ	4 Species ^j	A. <i>cruentus</i> ^k	A. <i>cruentus</i> ^l	Range 7 acc ^m
<i>cis</i> -11,14-Eicosadienoic, C20:2	0.3 ± 0.0	0.15												
<i>Arachidonic</i> , C20:4	± 0.09	Tr								0.09–0.29				
<i>Behenic</i> , C22:0	0.4 ± 0.0	Tr					0.14–0.32	0.24		0.11–0.35		0.30		
<i>Lignoceric</i> , C24:0	0.4 ± 0.0	nd		0.26						0.11–0.24				
<i>Saturated</i>	26.9 ± 0.2	30.45	20.1– 25.1	26.30	22.40	21.70	26.8–28.6	26.96	24.54	20.1–30.9		26.10	26.61 ± 1.63	22.54–24.42
<i>Monounsaturated</i>	23.9 ± 0.1	29.24	20.3– 32.0	22.20	21.70	22.00	23.1–23.9	30.21	40.14	20.8–38.1		34.70	24.66 ± 1.76	24.30–34.05
<i>Polyunsaturated</i>	49.1 ± 0.2	40.09	33.5– 43.9	43.90	33.00	45.00	47.0–50.0	42.89	35.31	40.2–49.2		38.90	47.74 ± 1.44	37.75–47.32

^aAlvarez-Jubete et al. (2010a).

^bSujak and Dziwulska-Hunek (2010).

^cBerganza et al. (2003).

^dBartkowiak et al. (2007).

^eYanez et al. (1994).

^fBudin et al. (1996).

^gJahaniaval et al. (2000).

^hEscudero et al. (2004).

ⁱKraujalis and Venskutonis (2013).

^jHe et al. (2002).

^kLeon-Camacho et al. (2001).

^lOgrodowska et al. (2014).

^mTang et al. (2016).

Fat-soluble Vitamin E is a collective term for tocotrienols and tocopherols (α -, β -, γ -, and δ -), of which α -tocopherol has the highest antioxidant and biological value (Leth and Sondergaard, 1977). The amount and composition of tocopherols can vary among amaranth seeds from different species and origin. Tang et al. (2016) reported values of 7.28–27.90 μg total tocopherols/g seeds, which is equal to 0.73–2.79 mg/100 g seeds. The δ -homologous compound was dominant in amaranth at a concentration of 8.95–10.96 $\mu\text{g/g}$ seeds. It was higher in *A. hypochondriacus* at 8.76–13.87 $\mu\text{g/g}$ seed than in *A. cruentus*, which showed lower and more variable values of 1.24–7.74 $\mu\text{g/g}$ seed. The amount of β -tocopherols showed high variation of 0.53–9.74 $\mu\text{g/g}$ seed and γ -tocopherol was only detected in trace amounts. Palombini et al. (2013) found 1.15 ± 0.01 mg/100 g α -tocopherol and 1.35 ± 0.01 mg/100 g of other tocopherols (sum of β - and γ -tocopherol) in *A. cruentus*, which was within the range of values aforementioned. Another study also characterized oil from *A. caudatus* extracted by different techniques (cold pressing, supercritical fluid, and solvent extraction) (Czaplicki et al., 2012). The most abundant homologous compounds were β -tocopherols at a concentration of 34.0 mg/100 g oil and δ -tocopherol, 31.8 mg/100 g oil. The total tocopherol content of cold pressed oil was 101.0 mg/100 g oil. Solvent extraction and supercritical fluid extraction significantly increased the yield of tocopherols to 127.9 and 131.7 mg/100 g oil, respectively. β -Tocopherols were especially enriched, whereas the amount of α -tocopherols remained more or less unchanged. Similarly, Bruni et al. (2002) found that oil from *A. caudatus* seeds extracted with supercritical CO_2 contained higher levels for α -tocopherol with 26.37–34.81 mg/kg seed, β -tocopherol 33.18–43.86 mg/kg, γ -tocopherol 1.42–1.81 mg/kg, and δ -tocopherol 39.36–48.79 mg/kg. Both studies showed a similar distribution of tocopherols and higher yields after supercritical CO_2 extraction. However, findings indicated that total amount of tocopherols and ratio of homologs was strongly affected by species. In contrast, for carotenoids lutein concentrations were quite similar, 3.55–4.44 $\mu\text{g/g}$ seed, among seven amaranth accessions from three different species (Tang et al., 2016). β -Carotene was not detected and zeaxanthin was present only in very low concentrations.

Squalene is an intermediate triterpene of cholesterol biosynthesis with important biological activity, for example, reducing serum cholesterol (Ogrodowska et al., 2014). Furthermore, squalene has a high antioxidant capacity and contributes, together with tocopherols, to the good radical scavenging properties of amaranth oil. Squalene concentrations in amaranth seeds were found to vary between 2.26% and 5.94% as a percentage of lipids (Berganza et al., 2003; Ott et al., 2015). Ogrodowska et al. (2014) detected 469.96 ± 104.23 mg squalene/100 g seeds, which is about 5.66% of total fat content.

Sterols are commonly present in plant oils and fats and total sterols in amaranth lipids can represent approximately 20% of the unsaponifiable part (Ogrodowska et al., 2014). According to a review by Alvarez-Jubete et al. (2010a) the predominant sterol is chondrillasterol. Another study reported also quite high

sterol levels, but identified Δ^7 -ergosterol (315 mg/100 g of oil), Δ^7 -stigmastenol (279.6 mg/100 g of oil) and Δ^7 -avenasterol (140.3 mg/100 g of oil) as the most abundant (Czaplicki et al., 2012). Total sterol content was 1931 mg/100 g oil and was further increased to 2490 mg/100 g oil by supercritical fluid extraction. The remarkable content of these sterols was also confirmed by Ogrodowska et al. (2014); however, they found highest amounts for α -spinasterol plus sitosterol at 100.3 mg/100 g seed. Another study found γ -sitosterol and ergost-5-en-3-ol in ethanolic extracts (Psodorov et al., 2015). In summary, the abundance of sterols in amaranth has been confirmed by several studies, but with respect to identified compounds contradictory findings have been obtained.

Generally, amaranth oil is quite stable against oxidation due to its low concentrations of linolenic acid (Szterk et al., 2010). Also the protective effect of tocopherols and squalene contributed to the high stability. A study by Czaplicki et al. (2012) revealed that processing (expansion and flaking of seeds) did not affect composition of fatty acids. However, the total fat content and concentrations of tocopherols were reduced, whereas sterols were even slightly enriched.

2.3 Carbohydrates

Although amaranth seeds contain less starch than cereal grains, it is still the most abundant component, 48%–69% by weight (Bhat et al., 2015). Amaranth is one of the few sources for small-granule starch. The granules are typically 1–3 μm in diameter and are uniform in granule size. Amaranth starch contains mainly short-chain branched amylopectin glucans with average molar masses of 12×10^6 – 17×10^6 g/mol (Venskutonis and Kraujalis, 2013). The proportion of amylose is very low compared to cereals. Robin et al. (2015) measured an amylose content of only 3.8% based on total starch. In contrast, quinoa starch was found to comprise a significant higher proportion of amylose, 8.8%. Kong et al. (2009) also reported low, but variable amylose contents, ranging from 4.7% to 12.5%. The different proportions of amylose influenced starch-pasting properties. Kaur et al. (2010) studied the flour characteristics of 48 *A. hypochondriacus* and 11 *A. caudatus* lines. They found that *A. hypochondriacus* had higher pasting temperature and lower peak viscosity, breakdown and setback compared to *A. caudatus*. Rapidly digestible starch was found to be about 30% dw, which resulted in a lower predicted glycaemic index (87.2) compared to wheat starch. Starch digestibility was found to be increased by processing through cooking, extrusion, and popping (Repo-Carrasco-Valencia et al., 2009) and was similar to that of white bread, whereas flaked and roasted seeds were found to show only slightly increased glycaemic response (Capriles et al., 2008). The small starch granule size, low resistant starch content, and tendency to lose its crystalline structure by heating are most likely responsible for the high-glycaemic properties of amaranth.

Little data is available concerning sugars in amaranth. According to Awasthi et al. (2011) the total sugar content varied between 3.08% and 3.29% among

13 genotypes of amaranth. Lower values of $1.95\% \pm 0.21\%$ for free sugars were reported by Kumar et al. (2016). Gamel et al. (2006a) also found lower total sugar concentrations, 1.84%–2.17%. The concentrations of sugars were: sucrose (0.58–0.75 g/100 g), glucose (0.34–0.42 g/100 g), fructose (0.12–0.17 g/100 g), and maltose (0.24–0.28 g/100 g) in *A. cruentus* and *A. caudatus* seeds. Additionally, the trisaccharide raffinose (0.39–0.48 g/100 g) and the tetrasaccharide stachyose (0.15–0.13 g/100g) were detected in appreciable amounts, whereas inositol was only present in traces. The presence of tetroses was confirmed by Psodorov et al. (2015). In the same study ribose and a glucofuranoside were also identified.

2.4 Dietary Fiber

The amount of dietary fiber in amaranth is between 8.0% and 20.6% (Alvarez-Jubete et al., 2010a; Berghofer and Schoenlechner, 2002). In recent studies, lower and more similar values have been reported, ranging from 8% to 11% (Chauhan et al., 2015; La Mothe et al., 2015; Robin et al., 2015; Wefers et al., 2015a). The major part of dietary fiber is insoluble, whereas soluble fiber accounts for about 17%–34% (Chauhan et al., 2015; Kumar et al., 2016; La Mothe et al., 2015). In commercial flour from *A. caudatus* 7.91 ± 0.85 insoluble and 5.66 ± 0.95 g/100 g soluble dietary fiber were found, which corresponded to a proportion of about 42% soluble fiber based on total dietary fiber (Collar and Angioloni, 2014). The total quantity of dietary fiber and ratio of insoluble and soluble dietary fiber is strongly dependent on the milling fraction. A study of Kumar et al. (2016) showed total dietary varied from 9.1% for the flour fraction to 25.8% for the seed coat fraction. Recently some studies analyzed and characterized amaranth fiber in detail. As a dicotyledonous plant, the cell walls of amaranth seeds contain no arabinoxylans, which are typical for cereals. Amaranth fiber is mainly composed of pectic polysaccharides and xyloglucans in varying amounts, depending on the fiber fraction. In the insoluble fraction pectic polysaccharides and arabinans predominate, which resulted in a measured composition of 30.3% arabinose and 22.2% galacturonic acid (Wefers et al., 2015b). Lower proportions of glucose (20.1%) and xylose (10.4%) were found in the same fraction. In contrast, the soluble fraction contained more xylose, 15.5% of monosaccharide composition, which revealed that xyloglucans were the major soluble dietary fiber component. These findings were confirmed by a study of La Mothe et al. (2015), who detected 22.0% xylose and 31.2% glucose in soluble amaranth fiber. The high Xyl/Glc ratio of 0.69 for insoluble and 0.71 for soluble fiber indicated highly branched xyloglucans in which glucose linkage was mainly (1→4) and xylose linkage (1→2). Pectins in amaranth have high proportions of homogalacturonans and lower proportions of rhamogalactans because of high abundance of (1→4)-linked-galacturonic acid (La Mothe et al., 2015). Arabinose residues were found to be terminal arabinofuranose and (1→3)-, (1→5)-, and (1→3,5)-linked. Galactose was found as terminal

galactopyranose (1→4)-linked. These types of linkages showed that the rhamnogalactan sections of the pectic hemicellulose have arabinan and galactan side chains. Around 7% of glucose in the insoluble fiber was attributed to cellulose (La Mothe et al., 2015). The occurrence of cellulose was also confirmed by Wefers et al. (2015b), who found significant higher amounts of glucose after hydrolysis with sulfuric acid. Mannose has been detected only in low proportions of 2.4% for insoluble and 5.4% for soluble fiber, based on total monosaccharide composition (La Mothe et al., 2015). The cell walls of amaranth also contain appreciable amounts of polymer-bound phenolic acids. Ferulic acid and also lower levels of coumaric and caffeic have been found (Wefers et al., 2015a). Furthermore, diferulic acid was detected, which indicated crosslinks between hemicellulose chains.

The resistant starch content in 25 amaranth cultivars was determined by Mikulikova and Kraic (2006). They found an average resistant starch content of 1.24 ± 0.22 g/100 g (dw). Another study, however, reported lower values of 0.65% (González et al., 2007). Notwithstanding, these levels of resistant starch are remarkably lower than in other pseudocereals and true cereals (Venskutonis and Kraujalis, 2013).

2.5 Vitamins

Murakami et al. (2014) comprehensively analyzed the B-vitamins in raw and popped amaranth seeds. Riboflavin (B_2), niacin (B_3), folate, pyridoxine (B_6), and phanthothenic acid were detected in concentrations of 147 ± 9 , 3230, $340,152 \pm 16,454$, $47,24.8 \pm 3.7$, and 1150 ± 60 µg/100 g, respectively. Another study found similar levels of riboflavin, 0.19–0.23 mg/100 g, but much less niacin, only 1.17–1.45 mg/100 g. Thiamin (B_1) and ascorbic acid levels were reported to be 0.07–0.10 mg/100 g and 4.50 mg/100 g, respectively (Valcárcel-Yamani et al., 2012). The niacin contents found in both these studies were confirmed by Gamel et al. (2006a), with 1.25–2.13 mg/100 g niacin and 1.59–2.80 mg/100 g niacinamide being measured, giving a total vitamin B_3 level of 3.05–3.72 mg/100 g. The same study reported 2.30–2.98 mg/100 g ascorbic acid, 0.24–0.41 mg/100 g riboflavin, and 0.45–0.61 mg/100 g pyridoxine in *A. caudatus* and *A. cruentus* seeds. Above all, the high vitamin C content has to be pointed out, because wheat has very low amounts of ascorbic acid, less than 0.5 mg/100 g in whole kernels (Litschinger et al., 1997).

The folate content of several amaranth species and their milling fractions has been intensively studied by Schoenlechner et al. (2010a). Whole meal flours contained 52.8–73.0 µg total folate/100 g seeds, flour 45.5–53.6, and the bran fraction 60.5–82.2, which was much higher compared to wheat and rye, but lower compared to quinoa. The sample preparation method applied in this study with only two enzymes for release of bound folate could be responsible for the lower contents compared to other studies. However, the aforementioned data from various studies also showed some variation, mainly as a result of different analytical methods.

Taken overall, a comparison with human vitamin requirements according to the Standard Table of Food Composition in Japan 2010 revealed amaranth to be a potent resource of vitamins due to its balanced vitamin composition (Murakami et al., 2014).

2.6 Minerals

Pseudocereals are commonly rich in minerals and contain much higher contents compared to cereals like wheat. An overview for important minerals is shown in Table 6.3, which reveals exceptionally high levels of macro- and microelements in amaranth seeds. The high Ca content should be signaled out as it is more than 5 times higher compared to wheat and even significantly higher than quinoa (Alvarez-Jubete et al., 2010a). Other minerals like P, K, and Na are present in reasonable amounts, whereas for Zn, Cu, and Mn only moderate levels have been found (Alvarez-Jubete et al., 2010b; Bolaños et al., 2016; Murakami et al., 2014; Palombini et al., 2013; Sujak and Dziwulska-Hunek, 2010). Fe occurs in high concentrations of 4.6–10.7 mg/100 g, about 2–3 times higher compared to wheat. Palombini et al. (2013) even found values for Fe of up to 29.4 mg/100 g. Other essential trace elements, such as Mo (59.6 µg/100 g) and Cr (6.8–14.4 µg/100 g) have been detected in appreciable concentrations relatively to human nutritional needs (Bolaños et al., 2016; Murakami et al., 2014).

The presented data show some high variation between the results of different studies. Nevertheless, according to Murakami et al. (2014) they reveal that amaranth contains suitable concentrations of all macro- and most microelements required for human nutrition. Only small deficits were found for Zn, Mn, and Cr, when compared to the Standard Table of Food Composition of Japan, 2010. In the same study, popped seeds were also analyzed, which showed that mineral content was even enriched with processing due to the evaporation of water. One exception was Se, the level of which was marginally reduced by popping. This was in agreement with the lower values in commercial products (Rybicka et al., 2015).

Summing up, amaranth has a high and balanced mineral content. Thus, amaranth may be used to combat nutritional deficiencies. In this respect the very high concentrations of Fe and Ca, which are very important for pregnant women and children, should be pointed out. This was concluded and confirmed by the study of Sanz-Penella et al. (2013), who showed a strong increase in the mineral content of wheat bread with addition of amaranth flour. However, it should be mentioned that the high levels of phytates in amaranth (see Section 2.8) could adversely affect the mineral bioavailability of zinc, calcium, and iron.

2.7 Bioactive Compounds

Phenolic compounds are commonly defined to be any compound containing a benzene ring with one or more hydroxyl groups, for example, phenolic acids,

TABLE 6.3 Overview of Important Minerals in Amaranth Seeds

Minerals	Units	Alvarez-Jubete et al. (2010a)	Awasthi et al. (2011)	Bolaños et al. (2016)	Murakami et al. (2014)	Palombini et al. (2013)	Sujak and Dziwuls-ka-Hunek (2010)	Winter Wheat ^a
Calcium (Ca)	mg/100 g	180.1 ± 6.1	147–201	158.85 ± 1.46	234 ± 6	283.14 ± 5.74	230 ± 10	29.00
Iron (Fe)	mg/100 g	9.2 ± 0.2	4.60–6.55	n.d.	10.70 ± 0.04	29.35 ± 0.60	8.54 ± 0.1	3.19
Magnesium (Mg)	mg/100 g	279.2 ± 1.1	n.a.	318.84 ± 3.47	308 ± 4	425.21 ± 8.62	427 ± 10	126.00
Phosphorus (P)	mg/100 g	n.a.	449–526	588.72 ± 7.39	779 ± 36	55.59 ± 1.13	119 ± 10	288.00
Potassium (K)	mg/100 g	n.a.	n.a.	529.11 ± 6.21	632 ± 10	770.15 ± 15.61	892 ± 25	363.00
Sodium (Na)	mg/100 g	n.a.	n.a.	n.d.	1.9 ± 0.4	4.14 ± 0.08	3.97 ± 0.02	2.00
Zinc (Zn)	mg/100 g	1.6 ± 0.0	3.08–4.72	2.58 ± 0.04	3.11 ± 0.04	n.a.	9.38 ± 0.03	2.65
Copper (Cu)	mg/100 g	n.a.	n.a.	n.d.	0.75 ± 0.28	1.25 ± 0.03	1.09 ± 0.0	0.43
Manganase (Mn)	mg/100 g	n.a.	n.a.	3.71 ± 0.06	3.51 ± 0.04	4.07 ± 0.08	5.45 ± 0.01	3.99
Selenium (Se)	µg/100 g	n.a.	n.a.	50 ± 2	40.4 ± 3.0	n.a.	n.a.	70.70

n.d., Not detected; n.a., not analyzed.

^aWheat, hard red winter, USDA National Nutrient Database for Standard Reference, Full Report 20072 from 12th January 2016.

flavonoids, tannins, coumarins, or alkyl-resorcinols (Dykes and Rooney, 2007). They can be found in all foods and they affect the appearance, taste, odor, and oxidative stability. Several studies have focused on polyphenols in amaranth species, and have resulted in the identification of many phenolic acids, flavonoids, and their glycosides.

The content of phenolics is commonly determined by the Folin–Ciocalteu reaction. However, the comparison of data regarding total phenolic content in literature is difficult because different extraction solvents and substances for calibration are used and data are variously expressed in quercetin (Q), catechin (C), gallic (GA), or ferulic acid (FA) equivalents (E). These issues can be responsible for high variations in measured phenolic contents, but also genetic and environmental factors have to be considered. In the study of López-Mejía et al. (2014) amaranth seeds from *A. hypochondriacus* were extracted with methanol, ethanol, and hexane by means of soxhlet and magnetic stirring. Total phenolic content (TPC) varied between 16 and 25 mg GAE/100 g (dw) by soxhlet extraction. Lowest values were obtained with methanol, whereas ethanol and hexane resulted in significant higher values. In respect of the antioxidant capacity, opposite results were found. Methanol extraction resulted in 25–30 mg Trolox E/100 g compared to ethanol and hexane extraction with only about 5 mg Trolox E/100 g. These findings indicated different antioxidant capacity of the various compounds with differing polarity and solubility. A review by Okarter (2012) revealed that quercetin, kampferol, and epigallocatechin gallates have the strongest cellular antioxidant activity, whereas other phenolic acids, especially those bound to hemicelluloses, contributed only marginally to antioxidant capacity in vivo. On the other hand, in vitro antioxidant capacity correlated well with the amount of phenolics among cereals and pseudocereals (Dykes and Rooney, 2007).

Several research groups have identified different unbound phenolic acids in amaranth. Protocatechuic acid ($13.6 \pm 9.4 \mu\text{mol}/100 \text{ g}$) was found to be the most abundant by Alvarez-Jubete et al. (2010c). A comprehensive characterization of phenolics in amaranth was performed with HPLC-DAD by Pasko et al. (2008). Gallic acid was found to be predominant (400–440 mg/kg), followed by *p*-hydroxybenzoic acid (8.5–20.7 mg/kg) in two varieties of *A. cruentus* seeds. Vanillic acid (15.5 mg/kg) was detected in one variety, whereas *p*-coumaric and syringic acids were found only after germination. Ferulic and caffeic acids were not detected in seeds or sprouts. Up to seven phenolic acids were quantified in expanded seeds and flakes from seven *A. cruentus* accessions; vanillic, *p*-hydroxybenzoic, and ferulic acids were the major ones with more than 80 mg/kg for each acid, while caffeic, sinapic, and cinnamic acids were found in lower concentrations (Ogrodowska et al., 2012). In a study by Steffensen et al. (2011), 18 different amaranth genotypes were characterized for their profile of phenolic acids. Protocatechuic, vanillic, 4-hydroxybenzoic, *p*-coumaric, syringic, caffeic, ferulic, and salicylic acid were identified, the concentrations of which varied with genotype, species, and location.

Another study analyzed five cultivars from each of the three species of pseudocereals in respect to polyphenols and their antioxidant activity (Vollmanova et al., 2013). It was found that amaranth had a polyphenol content of 138–287 mg GAE/100 g, and that rutin was the main compound with a concentration of 3.0–50.8 mg/100 g. Although the concentration of compounds with principal antioxidant potential was higher compared to quinoa, lower antioxidant activity, average 3.26 mmol Trolox-Equivalents (TE)/kg, was measured. Thus, no significant correlation between phenolics and antioxidant potential was observed. Similar findings were reported by Chlopicka et al. (2012). Amaranth contained similar levels of polyphenols (2.7 ± 0.1 mg/g) and flavonoids (65.0 ± 8.0 mg/g), but antioxidant properties of amaranth (Ferric reducing ability of plasma—FRAP 38.6 ± 1.2 mg/100g and radical scavenging activity 3.60 ± 0.34 mmol TE/kg) were significantly lower compared to quinoa. Rutin at an average concentration of 65.0 ± 5.7 mg/kg was found by Kalinova and Dadakova (2009) in different *A. hypochondriacus* seeds harvested in 2006. Further analyses of rutin from different amaranth varieties were performed for seeds harvested in 2006 and 2007. The average values were 70 ± 7 mg/kg for *A. hypochondriacus*, 55 ± 3 mg/kg for *A. caudatus*, 99 ± 4 mg/kg for *A. hybridus*, 11 ± 1 mg/kg for *A. retroflexus* mg/kg, and 7 ± 1 mg/kg for *A. tricolor*. These results suggested that varieties commonly cultivated for their seeds were richer in rutin than other varieties where the leaves are mainly used.

Besides rutin, kaempferol glucosides like nicotiflorin (kaempferol-3-O-rutinoside) have also been identified in amaranth. Steffensen et al. (2011) found levels of up to 6.1 μ g/g among 18 different genotypes. These findings were confirmed by Barba de la Rosa et al. (2009) who detected 4.8–7.2 μ g/g nicotiflorin in flour of four varieties of *A. hypochondriacus*. The flavanones, vitexin, and isovitexin occurred in minor amounts, 266–410 mg/kg (Pasko et al., 2008). The abundance of flavonoids in amaranth has been confirmed by several studies, for example, Jo et al. (2015) found 1.53 ± 0.17 mg catechin equivalents (CE)/g compared to a total content of 1.69 ± 0.12 mg GAE/g phenolics in methanolic extracts. Furthermore, tannins were detected with concentrations of 0.316 ± 0.05 mg tannic acid equivalents (TAE)/g. Extraction with hot water obtained much higher yields of total phenolic compounds [4.23 ± 1.00 mg gallic acid equivalents (GAE)/g] and tannins (0.511 ± 0.01 TAE/g), but the concentration of flavonoids decreased remarkably to 0.08 ± 0.00 mg CE/g. This study again revealed that analysis of phenolics is very complex due to the diversity of compounds and is highly affected by methodology, especially extraction solvent.

Betalains are plant pigments that are found in plants of the order Caryophyllales. According to Khan (2016), who proposed a daily intake of 100 mg betanin, betalains show in vitro and in vivo biological activities, mainly due to their radical-scavenging activities. Based on their structure, betalains can be divided into red to violet betacyanins or yellow betaxanthins. Amaranthine, isoamaranthine, and betanin at 1.0 ± 0.2 , 0.8 ± 0.2 , and 0.1 ± 0.2 mg/100 g, respectively, were

detected in pink amaranth grains, whereas white seeds contained no betalains (Venskutonis and Kraujalis, 2013). No other studies have mentioned betalains in amaranth seeds, but several studies have reported high concentrations in amaranth leaves (Venskutonis and Kraujalis, 2013). Some studies reported moderate levels of anthocyanins, 90.83 ± 9.2 – 103.6 ± 10.4 mg (Pasko et al., 2009) and 35.33 ± 1.70 mg/100 g (López et al., 2011). Since the UV absorption maxima of anthocyanins is similar to betalains, it is possible that the reported presence of betalains was an artefact. However, as amaranth belongs to the Caryophyllales order, betalains should be the main pigment compounds in amaranth seeds. However, this issue has not been clarified and further studies are required.

Lignans or resinols are phenolic substances derived by dimerization of cinnamic alcohols and are often present in edible plants. Resinols are metabolized by the gut microflora to phytoestrogens and exert several potentially beneficial activities, such as antioxidant, antiviral, antitumor, antibacterial, fungistatic, insecticidal, estrogenic and antiestrogenic, and protective effects against coronary heart disease (Spilioti et al., 2014). The contents of several individual compounds in amaranth seed bran were measured by Smeds et al. (2007). Highest concentrations were observed for 7-hydroxymatairesinol (519 μ g/100 g), 7-oxomatairesinol (207 μ g/100 g), medioresinol (114 μ g/100 g), and secoisolariciresinol (98 μ g/100 g). The total level of lignans of about 1000 μ g/100 g bran in amaranth bran was much lower compared to cereal brans from rye or wheat, but in similar range to maize, millet (species not stated) and quinoa.

In general, processing of foods affects antioxidant compounds and properties to a great extent. Kunyanga et al. (2012) found a TPC level of 1.07 g CE/100 g in amaranth seeds, which was reduced by more than 50% with cooking or roasting. Radical scavenging activity was $84.7 \pm 1.2\%$ and ferric reducing activity (FRAP) was 44.9 ± 3.0 mmol Fe[II]/g extract. Cooking and roasting showed totally the opposite effect on the antioxidant properties compared to TPC, radical scavenging activity remained nearly constant (81.0% and 87.3% DPPH) and FRAP was increased substantially (233–418 mmol Fe[II]/g extract). Germination of amaranth seeds promoted antioxidant activity (Alvarez-Jubete et al., 2010c; Pasko et al., 2009). Generally, the level of phenolic acids was reduced, whereas flavonoids were generally enriched during sprouting (Pasko et al., 2008).

These summarized data and brief discussion show that amaranth is rich in polyphenols, which consist mainly of flavonoids, especially rutin. However, buckwheat contains much higher levels and quinoa shows higher antioxidant potential, although less phenolic compounds have been detected. Evidently the predominance of rutin and very low levels of nonglycosylated flavonoids among the phenolic compounds is responsible for the low antioxidant potential of amaranth seeds. Other phenolic compounds like resorcinols and betalains occur only in low concentrations and should not significantly affect the health-promoting properties of amaranth.

2.8 Antinutrients

Amylase and protease (e.g., trypsin) inhibitors (ATIs) are present in all plants for protection against natural enemies like insects. They also have health-promoting properties, for example, anticarcinogenic, antioxidant, blood glucose regulatory, as well as antiinflammatory effects (Champ, 2002). Amaranth contains only low quantities of protease inhibitors compared to cereals (D'Amico et al., 2017). Tamir et al. (1996) identified and characterized a trypsin–chymotrypsin inhibitor in amaranth seeds as a single-chain protein of 8 kDa. Gamel et al. (2006b) found trypsin inhibitor activity in the range of 3.05–4.34 TIU (trypsin inhibitor units)/mg, chymotrypsin inhibitor activity (CIU), from 0.21 to 0.26 CIU/mg, and amylase inhibitor activity from 0.23 to 0.27 AIU/mg. The inhibitor protein seemed to be thermolabile, Kunyanga et al. (2012) found that α -amylase inhibition activity in amaranth was strongly reduced by roasting. Wet cooking had a less strong effect.

Phytic acid or myo-inositol hexaphosphate (InsP6) is a negatively charged compound, which has the ability to complex positively charged cations, such as calcium, magnesium, and iron and, as mentioned, it could have adverse effects on mineral bioavailability in amaranth. Sanz-Penella et al. (2013) analyzed myo-inositol phosphates in amaranth in detail. Whole amaranth flour contained 21.1 ± 2.1 mmol/g InsP6, 2.3 ± 0.5 InsP5, and 0.86 ± 0.08 InsP4. Homologs with lower numbers of phosphate groups were not found. The high-phytate levels of amaranth were confirmed by García-Mantrana et al. (2014) who analyzed phytates in wheat bread with different levels of amaranth inclusion. Compared to whole-wheat flour bread, a 50% amaranth composite increased the total of InsP6 and InsP5 from 2.9 ± 0.7 to 7.8 ± 0.5 μ mol/g bread. In contrast, other phytates with lower numbers of bound phosphorus (InsP4 and InsP3) were present in lower quantity compared to the wheat bread. The also study showed that addition of phytases from different sources (bacteria and fungi) were able to reduce the phytate concentrations significantly.

With regard to effects of processing, Ferreira and Gómez-Áreas (2010) found the same levels of phytic acid (82.0 mg/g) in extruded amaranth flour compared to raw flour. Total phytate contents of 4.0–4.1 g/kg in *A. caudatus* and *A. cruentus* seeds were found by Gamel et al. (2006b). Processing by cooking, popping, and germination reduced phytate contents to 3.1–3.5 g/kg.

Another charged antinutrient is oxalate. Levels in the range of 85–129 mg/100 g were found among different amaranth genotypes and species (Awasthi et al., 2011).

Saponins are bitter-tasting alkaloids, which have surface-active properties as they consist of a steroid or triterpenoid aglycone, which is associated with one or more monosaccharides. There are very high levels of saponins in quinoa, whereas amaranth contains only trace amounts (Alvarez-Jubete et al., 2010a). Oleszek et al. (1999) found four saponins in *A. cruentus* seeds with a total concentration of 0.09%–0.1%. The study concluded that low toxicity and amount of saponins in amaranth pose no significant health risks to consumers.

3 PROCESSING AND FOOD APPLICATIONS

3.1 Milling Processes

Milling whole-meal amaranth flour is well established and does not cause specific problems. Only the moisture content of the seeds is of importance, so pre-conditioning (addition of water and heat treatment) of the seeds is often required to achieve optimal moisture content (Tosi et al., 2001). Production of different flour fractions from amaranth is a challenge due to the small size and unusual seed structure compared to cereal grains. Becker et al. (1986) performed comparative tests with various types of mills. They tested several parameters and techniques, including disc mills and hammer mills, varying speeds and moisture levels. However, the results were not very successful. In a study by Berghofer and Schoenlechner (2002) a pilot scale roller mill was used in combination with a plansifter, resulting in five milling fractions, which could be classified in starch- and protein-enriched fractions. Another study also applied roller milling and obtained four different fractions with different nutritional composition (Kumar et al., 2016).

Wet milling of amaranth has been evaluated on laboratory-scale using several methods, which were similar to maize wet milling technology (Calzetta Resio et al., 2009). Roa et al. (2014) obtained starch- and lipid-protein- enriched amaranth fractions by abrasive milling and amaranth starch was isolated by a wet-milling procedure, and flours were obtained from ball milling. The technologies applied resulted in alterations in the starch, protein, and lipid fractions obtained (Roa et al., 2014).

3.2 Food Uses

Traditionally, amaranth seeds were cooked, roasted, popped, or flaked for human consumption. The aerial parts of the plant were consumed cooked as a vegetable like spinach. Due to the anatomical structure of amaranth seeds, the popping process is of great interest. Also, today popped and extruded amaranth grains are often used as the main ingredient of snacks, breakfast cereals, and crunchy bars (Ramos-Diaz et al., 2013). Fig. 6.3 shows a snack based on popped amaranth and Fig. 6.4A porridge like product from precooked amaranth seeds. The effect of popping on nutrients was studied in depth by Murakami et al. (2014). A continuous fluidized bed processing system with hot air heating was applied to pop amaranth seeds in bulk (260°C for 15 s). The results showed that the treatment did not negatively affect the content of B-vitamins and also the retention of minerals was high.

Extrusion cooking is a promising technology for amaranth processing. The water solubility index of amaranth has been found to be strongly increased by extrusion cooking, from 11% to 61% (Robin et al., 2015). Using a 20% amaranth addition to maize gave the highest expansion index compared to quinoa, kaniwa, and 100% maize (Ramos-Diaz et al., 2013). Ferreira and Areas (2004) evaluated products obtained under different extrusion conditions. The highest moisture content,



FIGURE 6.3 Popped amaranth snacks from a local market in Peru (Regine Schoenlechner).

24%, during amaranth extrusion resulted in higher protein quality compared to the lower moisture conditions. The extrusion process has also been found to affect the peptide profile after protease digestion, resulting in more peptides of smaller size and higher biological activity (Montoya-Rodríguez et al., 2015).

In bread making, the absence of gluten in amaranth is the main reason why generally amaranth alone is not suitable for bread production. On the other hand, addition of amaranth to bread formulations offers several advantages. In a study by Sanz-Penella et al. (2013) the effect of whole amaranth flour on bread properties was evaluated, with up to 40% whole amaranth flour incorporated in wheat bread. Already, an addition of 20% amaranth improved the bread nutritional quality considerably. The concentration of important minerals (Ca, Mg, Fe, and Mg) was at least doubled. Protein, lipid, and dietary fiber contents were also significantly enriched.



FIGURE 6.4 Kiwicha (*A. caudatus*) porridge in Peru (Regine Schoenlechner).

3.3 Gluten-Free Foods

The consumption and demand for gluten-free products has increased all over the world due to an increased prevalence of gluten-related disorders like CD, or the intolerance to gluten and wheat, called “non-celiac wheat or gluten sensitivity” (NCWS or NCGS) (Shewry and Hey, 2016). A study by Junker et al. (2012) identified amylase–trypsin inhibitors (ATIs) as potential triggers of innate immunity in wheat, which should be responsible for NCWS or NCGS.

In addition to persons suffering from the aforementioned disorders, gluten-free products are increasingly being purchased by people because of their health-promoting image, especially if they contain pseudocereals. During the last ten years many gluten-free products have been developed and marketed, leading to a great increase in consumption (Shewry and Hey, 2016). As result

of the efforts of the research community, products with higher functional and nutritional quality have been developed. Generally pseudocereals are very low in prolamins because they are dicotyledonous plants and hence do not contain protein fractions that are toxic to CD patients. Although it is only recently that some specific studies have been undertaken to actually prove this. In summary, the consumption of amaranth and other pseudocereals is safe for celiacs and thus their products can be included in a gluten-free diet (D'Amico et al., 2017).

The most important gluten-free products are cookies (biscuits), bread, and pasta. For cookie making, a strong protein network is not required, which makes pseudocereals very suitable. Several studies have reported that amaranth-based cookies have good sensory and texture attributes (Inglett et al., 2015). Germinated amaranth flour cookies even showed superior properties compared to cookies from wheat (Chauhan et al., 2015). Another optimized cookie recipe included 20% popped amaranth flour and 13% whole-grain popped amaranth (Caldaron de la Barca et al., 2010).

However, as a main ingredient amaranth is less suitable than most other minor- or pseudocereals for leavened products like bread. Alvarez-Jubete et al. (2010c) revealed that breads based on 50% amaranth had lower volume compared to buckwheat or quinoa. Schoenlechner et al. (2010b) investigated the production of gluten-free bread containing amaranth flour using a factorial experimental design. The content of water had the greatest effect on bread properties, whereas variation in fat content did not have any significant influence. However, the combined addition of fat and egg albumin resulted in the best overall sensory acceptance. Another study demonstrated that amaranth flour improved the freeze stability of gluten-free dough, but reduced the shelf life (Leray et al., 2010). Caldaron de la Barca et al. (2010) found that the most preferred recipe for gluten-free bread with minimal gluten content (less than 20 ppm) was based on 60%–70% popped and 30%–40% raw amaranth flours, which produced bread with a uniform crumb and higher specific volume compared to other gluten-free breads. A promising strategy to improve the quality of gluten-free bread is through application of sourdough fermentation. Jekle et al. (2010) demonstrated that amaranth sourdough properties were affected by different lactic acid bacteria.

Amaranth shows only limited capacity for pasta making. When amaranth is used as the only flour ingredient, the resulting pasta is characterized by high-cooking loss and very soft texture. If amaranth composite with other flours and pseudocereals these negative effects can be minimized. In a study by Schoenlechner et al. (2010c) a recipe with 60% buckwheat, 20% amaranth and 20% quinoa had good functional properties, which was further improved by high temperature drying of the pasta (D'Amico et al., 2015). The addition of 25% extruded amaranth flour to dried potato pulp was found to produce a well structured fresh pasta (Bastos et al., 2016). These formulations produced spaghetti with good sensory acceptance and visual quality compared to fresh wheat flour

spaghetti. A novel extrusion cooking process prior to pasta making for superior textural characteristics was developed by [Cabrera-Chávez et al. \(2012\)](#). The process reduced protein solubility and the content of free thiol groups in amaranth-enriched pasta, indicating disulfide bond formation in the amaranth proteins. The results also suggested that starch interacts well with amaranth proteins during starch gelatinization and protein denaturation. In addition to increasing protein digestibility, enrichment with amaranth was shown to improve the mineral and fiber contents of rice-based pasta ([Cabrera-Chávez et al., 2012](#)).

4 CONCLUSIONS

Amaranth grain is an ingredient of great interest due to its good nutritional composition, especially in respect of its very high content of vitamins and minerals. The unique combination of Mg, Ca, Fe, and folate in high levels can be used to supplement food products for celiacs, children, or pregnant women, in order to compensate nutritional deficiencies resulting from special diets or high requirements. Also, the balanced composition of essential amino acids contributes to its good nutritional quality. Recent studies have revealed high biological activities of digested amaranth peptides. Amaranth is a suitable raw material for non-leavened foods like snacks. Popped and extruded amaranth products showed no significant losses of sensitive nutrients like vitamins or minerals. For leavened products or pasta, amaranth is less suitable but it can considerably improve the nutritional quality of bread and noodles. Further research and product developments are necessary to increase the market share of amaranth as an ingredient for foods in general, and gluten-free foods, in particular.

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Chapter 7

Buckwheat: Its Unique Nutritional and Health-Promoting Attributes

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1 INTRODUCTION

Buckwheat is an ancient dicotyledonous plant cultivated in many parts of the world for its seeds, and nowadays for the green plant (leaves) as well. Buckwheat belongs to the genus *Fagopyrum* of the family Polygonaceae (Biacs et al., 2002). Thus, it is not related to cereals, but due to its similar chemical composition and utilization it is called as a pseudocereal along with amaranth and quinoa (Krkošková and Mrázová, 2005).

The genus *Fagopyrum* consists of about 19 species, in addition to numerous wild species (Zhang et al., 2012). Two buckwheat species have been commonly cultivated around the world for centuries: common buckwheat (*Fagopyrum esculentum* Moench) and tartary buckwheat [*Fagopyrum tataricum* (L.) Gaertn.] (Alvarez-Jubete et al., 2010; Cai et al., 2016). Common buckwheat was first cultivated in Asia, possibly around 6000 BP (Ohnishi, 1998). Domestication took place in Yunnan province of China on the edge of the Tibetan Plateau and on the Himalayan hills. From there it spread to Central Asia and Tibet, and then to the Middle East and Europe (Bonafaccia et al., 2003; Eggum et al., 1980).

Buckwheat is a short-season, undemanding crop that has broad ecological adaptability to different agronomical conditions, such as low-fertility or acidic soils, low precipitation, and marginal lands with harsh environments. The plant is frost resistant so it is common in high-altitude areas at 2000 m, and in Tibet it is found at elevations of up to 4500 m. It is also suitable for environmentally sustainable cultivation, without the use of fertilizers or pesticides (Zhang et al., 2012). Buckwheat is an annual melliferous crop, its flower nectar is used for making a dark-colored honey. The small, wind-pollinated buckwheat flowers are born in clusters or in heads (Fig. 7.1A). Usually, the flower is hermaphrodite and has a variable number of parts. Sometimes, the plant is used as a green

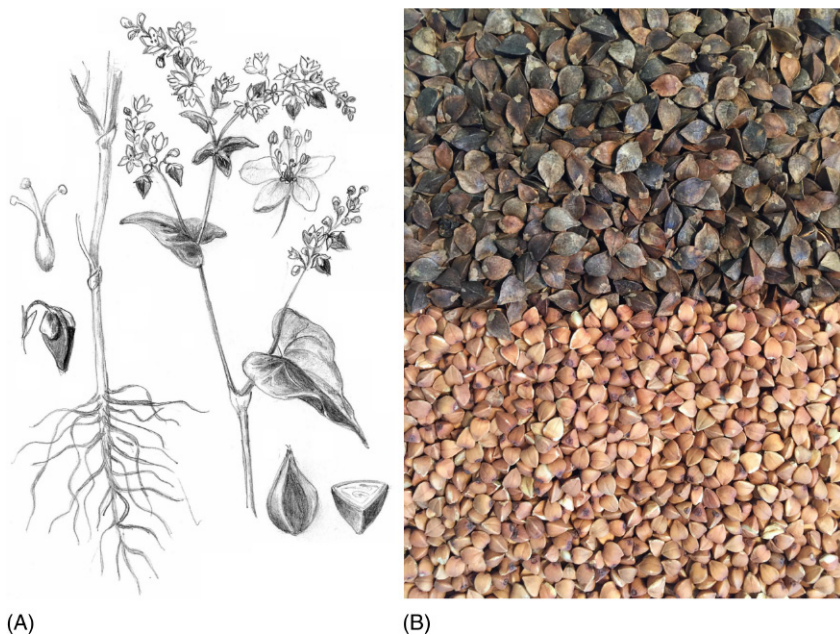


FIGURE 7.1 Buckwheat plant (A) and achene (B).

manure, as forage, as wildlife cover, and it also controls soil erosion ([Aubrecht and Biacs, 2001](#)).

In the past few decades, the cultivation of buckwheat has decreased. However, recently it has been observed to increase, with world seed production exceeding 2 million tonnes per annum with a cultivation area of 2.5 million ha. The biggest producer and consumer is Europe (53.1%), with Asia at the second position (38.6%). America's and Africa's share is not significant, having 7.1 and 1.1%, respectively. Currently, the top buckwheat producers are Russia, China, Ukraine, France, and Poland ([FAOSTAT, 2014](#)).

In this chapter we have tried to give a wide overview about the varieties, composition, and utilization of buckwheat. For better understanding data have been compared with the average wheat parameters.

2 BUCKWHEAT SEED MORPHOLOGY

The buckwheat plant bears a mostly triangular-shaped fruit, called achene ([Fig. 7.1](#)). The achenes are 4–9 mm long and the weight of thousand kernels ranges from 15 to 35 g. In general, tartary buckwheat seeds are smaller than common buckwheat seeds ([Cai et al., 2016](#)). The achene consists of two parts: the hull and the groat. The hull (pericarp, fruit coat) is the outer layer of the achene; usually its color varies from glossy or dull dark gray to brown or black. The inner part of the achene is the groat ([Fig. 7.1B](#)). The groat (dehulled achene)

is made up of three parts: the seed coat (perisperm), the endosperm, and the embryo. The seed coat is 1–3 cells thick. The endosperm cells are filled with starch granules. The embryo is positioned at the top of the achene, and the two cotyledons extend through the endosperm (Steadman et al., 2000; Stevens, 1912).

3 CHEMICAL COMPOSITION OF THE BUCKWHEAT SEED

Buckwheat seed is a rich source of nutrients (Table 7.1). It contains many valuable compounds, such as starch, proteins, dietary fiber, antioxidant substances, and trace elements (Krkošková and Mrázová, 2005). However, genotype and growing conditions (e.g., soil, environment, and fertilization) are likely to affect its nutritional composition (Wang et al., 2012).

3.1 Carbohydrates

Digestible carbohydrates are the major components (58%–73%) of buckwheat seeds as in true cereal grains, and they are present mainly in the form of starch. In the whole groats of buckwheat, starch, content varies from 59% to 70% (dry basis), demonstrating fluctuations under variable climatic and cultivation conditions. The other major pseudocereals, amaranth and quinoa, have lower starch content (Steadman et al., 2000). Qian and Kuhn (1999) analyzed buckwheat starch from different countries by enzymatic analysis and the amylose content of these starches ranged from 21.3% to 26.4%. However, some studies reported higher (~50%) amylose content (Berghofer and Schoenlechner, 2007; Christa and Soral-Šmietana, 2008). The degree of polymerization in buckwheat starch varies from 12 to 45 glucose units (Christa and Soral-Šmietana, 2008). Generally, buckwheat starch granules are round, oval, or polygonal in shape. The size of buckwheat starch granules varies from 2 to 15 μm, which is still below the size of most of the true cereal species (Berghofer and Schoenlechner, 2007). Around 35% of the buckwheat starch is resistant to digestion (Cai et al., 2016).

Buckwheat whole groat also contains 1%–6% soluble carbohydrates, which are mostly located in the embryo and aleurone layer. These levels are higher as

TABLE 7.1 General Composition of Buckwheat Whole Groat in Comparison With Wheat (g/100 g, Dry Basis) (USDA, 2016)		
	Whole Buckwheat Groats	Whole Wheat Grain (Hard Red Winter)
Carbohydrates	70.6	71.2
Dietary fiber	10.0	12.2
Fat	3.1	1.5
Ash	1.8	1.6
Protein	12.6	12.6

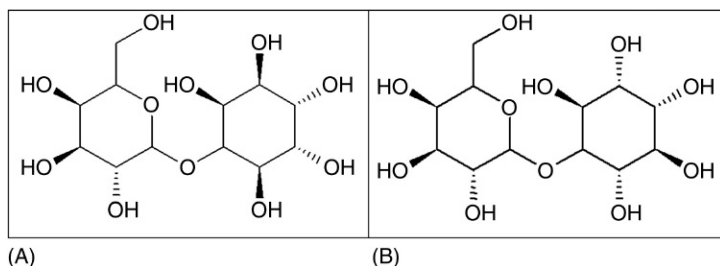


FIGURE 7.2 Chemical structure of fagopyritol A1 (A) and fagopyritol B1 (B).

compared to cereal grains and even other pseudocereals. Buckwheat soluble carbohydrates are mostly present as reducing sugars and fagopyritols. Fagopyritol A1 (O- α -D-galactopyranosyl-(1 \rightarrow 3)-D-chiro-inositol) and fagopyritol B1 (O- α -D-galactopyranosyl-(1 \rightarrow 2)-D-chiro-inositol) are the most remarkable of all the fagopyritols in buckwheat seeds (Fig. 7.2, Christa and Soral-Šmietana, 2008).

Buckwheat seeds contain 7.0%–10.9% dietary fiber, which is lower as compared to whole-wheat grains but similar to other cereal grains and higher than that of amaranth and quinoa (Christa and Soral-Šmietana, 2008). Common buckwheat has higher levels of dietary fiber than tartary buckwheat (Steadman et al., 2000). Usually, buckwheat fiber is free of the antinutrient phytic acid. Around 20%–30% of buckwheat fiber is soluble, which is higher than that in true cereals (Wang et al., 2012).

3.2 Protein

The protein content of buckwheat groats is around 12%, similar to wheat, but lower than the other pseudocereals (Steadman et al., 2000). Table 7.2 shows the amino acid composition of buckwheat whole groat. When compared to wheat, buckwheat proteins show a similar or even higher content of nearly all amino acids; lysine, threonine, and valine are the most important ones as they are essential for the human body (Pomeranz and Robbins, 1972). The glutamine and proline amino acid contents of buckwheat are considerably lower than true cereals (Aubrecht and Biacs, 2001).

Characterization of buckwheat seed proteins on the basis of their solubility has been performed in several studies. Osborne solubility fractions were found in the following ratio: albumin was the predominant protein fraction (30%–40%), followed by glutelin (11%–29%), and minor fractions were prolamin (2%–10%) and globulin (3.0%–7.82%) (Pomeranz, 1983; Wei et al., 2003). Different extraction methods and various species may lead to extremely different results. The four fractions had adequate amounts of the essential (indispensable) amino acids, histidine, threonine, valine, isoleucine, and leucine (Guo and Yao, 2006). Among nonessential amino acids, the levels of glutamic acid and aspartic acid were adequate in all fractions.

TABLE 7.2 Amino Acid Composition of Buckwheat Whole Groat (Christa and Soral-Šmietana, 2008) Compared to Wheat (FAO) and the WHO Recommendation of Essential Amino Acid Daily Intake for Adults (*Essential Amino Acids) (WHO, 2007)

Amino Acids	Content in Buckwheat Whole Groats (g/100 g Protein)	Content in Wheat Whole Grain (g/100 g Protein)	Recommended Daily Intake (mg/kg of Body Weight/Day)
Asp	5.2–9.5	3.08	
Thr*	1.9–4.04	1.83	15
Ser	2.4–4.9	2.87	
Glu	9.7–19.38	18.6	
Pro	2.6–7.93	6.21	
Gly	4.2–6.23	2.45	
Ala	3.0–4.82	2.26	
Cys	2.06–3.27	1.59	
Val*	3.4–4.97	2.76	26
Met*	0.99–2.3	0.94	10.4
Ileu*	2.6–3.41	2.04	20
Leu*	2.8–6.12	4.17	39
Tyr*	1.5–3.03	1.87	25
Phe*	2.0–4.42	2.82	25
Lys*	4.9–6.7	1.79	30
His	1.4–2.52	1.43	
Arg	5.4–11.6	2.88	

3.3 Lipids

There is 2%–4 % lipid in the whole seed, which is concentrated in the embryo. The content of bound lipids is two times higher than that of free lipids (Cai et al., 2016). Buckwheat lipids are composed of nine fatty acids; major ones are palmitic (16:0), oleic (18:1), and linoleic (18:2) acids. Some of the total fatty acids, 75%–80% are unsaturated, of which more than 40% is polyunsaturated, a higher portion as compared to other grains (Steadman et al., 2000).

3.4 Minerals

Buckwheat seems to have a high amount of minerals, higher than quinoa and similar to amaranth. The macroelements K, Mg, Ca, Na and microelements Cu,

Zn, Fe, Mn are present in notably high levels (Krkošková and Mrázová, 2005). Trace elements, such as Cr and Se are present only at very low levels. Minerals accumulate in the embryo (mainly as phytate deposited in protein bodies) and in the outer layers of the seed and hull (Christa and Soral-Šmietana, 2008).

3.5 Vitamins

Buckwheat has been recognized as a good source of B vitamins, with the highest levels of vitamin B being present in the bran part of the seed. Kim et al. (2002) analyzed the vitamin B composition of the achene and found the following levels: vitamin B1 (thiamin, 3.3 mg/kg), B2 (riboflavin, 10.6 mg/kg), B3 (niacin, 18.0 mg/kg), B5 (pantothenic acid, 11.0 mg/kg), and B6 (pyridoxine, 1.5 mg/kg). Total vitamin B content is comparatively higher in tartary buckwheat (Bonafaccia and Kreft, 1994). Conversely, common buckwheat contains more of the lipid-soluble vitamin E (tocopherol), 0.05–0.14 mg/kg, respectively (Cai et al., 2016; Kim et al., 2002).

3.6 Phytochemicals

In addition to these major components there are also minor constituents, which are important in respect of their health promoting properties. Their contents and compositions differ depending on the buckwheat species and growing conditions (Christa and Soral-Šmietana, 2008).

3.6.1 Flavonoids

Flavonoids represent a major group of natural antioxidants. There are differences in flavonoid content and composition between various buckwheat species. It has been found that the flavonoid content of tartary buckwheat is four times higher than common buckwheat. The bitter taste of tartary buckwheat groats has been ascribed to these components (Cai et al., 2016). Kreft et al. (2005) isolated six flavonoids from buckwheat: rutin, quercetin, orientin, vitexin, isovitexin, and isoorientin. Rutin is the predominant one and buckwheat is the only pseudocereal that contains rutin, hence it is a significant source of this flavonoid.

Rutin (quercetin-3-rutinosid, Fig. 7.3) is a flavonol glycoside plant metabolite. It plays the role of a protectant against ultraviolet radiation. Rutin is mainly found in the flowers and in the green parts of buckwheat plants. Typically, buckwheat leaves contain 10 times more rutin than the seeds (Christa and Soral-Šmietana, 2008; Kitabayashi et al., 1995; Kreft and Germ, 2008). In the seeds there is less rutin and usually there is more in whole seed buckwheat flour than in the refined flour. Kitabayashi et al. (1995) reported that its content in buckwheat whole groats ranges from 12 to 36 mg/100 g. Kreft et al. (2005) reported an average of 21.8 mg/100 g in whole groat buckwheat flour, which would give buckwheat a significant dietary content.

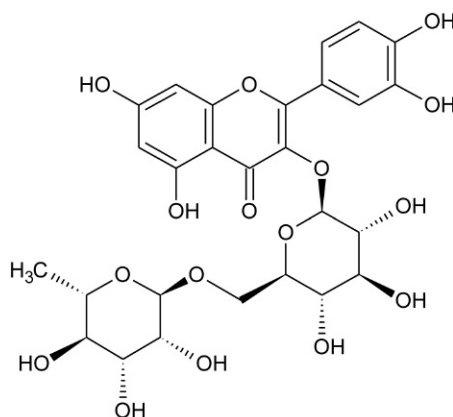


FIGURE 7.3 Chemical structure of rutin.

3.6.2 Sterols

Buckwheat seeds contain low levels of phytosterols. Beta-sitosterol is especially important, which cannot be synthesized in the human body (Krkošková and Mrázová, 2005). The content of sterols in dehulled groats after lipid extraction is around 700 mg/kg for β -sitosterol, 95 mg/kg for campesterol, and a low amount of stigmasterol has been measured (Horbowicz and Obendorf, 1992).

4 ANTINUTRITIONAL FACTORS

Buckwheat also contains some antinutritional components, such as trypsin inhibitors (I, II, and III), which have been isolated from buckwheat seeds. Besides trypsin these inhibitors can also inhibit chymotrypsin (Krkošková and Mrázová, 2005). Phytate is also present in protein bodies of the embryo and aleurone cells. Steadman et al. (2001) found 35–38 g/kg phytic acid in buckwheat seeds. Buckwheat bran is also a rich source of tannins, Zhang et al. (2012) measured a high tannin content of 1.6%. The high level of fiber in buckwheat may also be considered as an antinutritional factor, however, during dehulling process these compounds, which are located in the hull, are mostly removed (Cai et al., 2016).

4.1 Allergic Reactions

Allergic reactions may be caused by ingesting buckwheat and its products or by exposure to buckwheat dust. Buckwheat flour contains proteins that cause a hypersensitive reaction (allergy). This immunoglobulin (IgE)-mediated hypersensitive response can cause serious symptoms with anaphylactic shock (Wang et al., 2004). Buckwheat allergies are not common. However, it is considered to be a very potent allergen, particularly in children (Park et al., 2000). Allergy to buckwheat was first reported in early 1900s. Since then, an increasing number

of cases have been observed in people especially in Europe, North America, and Japan as well as some Asian countries who consume buckwheat-containing food products often and in high quantities (Morita et al., 2006). Sensitization to specific buckwheat allergens can be related to specific symptoms, such as predominant gastrointestinal or cutaneous symptoms, and at worst anaphylaxis (Heffler et al., 2011). It has been revealed that low molecular weight proteins, particularly those with molecular weights of 9, 16, 19, and 24 kDa proteins are strong candidates to be major allergens (Park et al., 2000). Also, some studies have found IgE-binding effects with proteins in the lower molecular weight range (<9 kDa) (Christa and Soral-Šmietana, 2008). Clinically relevant cross-reactivities have been described between buckwheat proteins and other allergens, such as rice, poppy seeds, and hazelnuts (Oppel et al., 2006). There have been various attempts to eliminate allergic proteins of buckwheat grains, such as enzymatic modifications or specific fermentations performed by yeast (Christa and Soral-Šmietana, 2008). During buckwheat grain milling and food processing, some workers suffer from allergic reactions, such as itching nose, sneezing, and even more serious symptoms like asthma (Krkošková and Mrázová, 2005; Wieslander and Norbäck, 2001). Clearly, it is necessary to know more about the behavior and processing properties of the specific buckwheat allergenic proteins.

Ingestion of the entire buckwheat plant can cause a serious light sensitivity, called fagopyrism. Fagopyrin is a naftodianthrone, which is related to hypericin, but has less toxicity. Phototoxicity of fagopyrin is connected with sensitivity to ultraviolet rays (Stojilkovski et al., 2013). This condition primarily occurs in animals, which are eating the plant's leaves, but it has been also reported in people who eat large amounts of buckwheat sprouts (Li and Zhang, 2001). Studies showed that the flowers of common buckwheat contained 0.64 mg/g fagopyrin and the leaves contained 0.4–0.6 mg/g, but no fagopyrin was found in buckwheat groats. However, there is no information on the phototoxic dose in humans (Stojilkovski et al., 2013). On a positive note, this light-dependent activity of the fagopyrins may also be used as sensitizers in photodynamic therapy (Benkovič et al., 2014).

5 HEALTH-PROMOTING ASPECTS OF BUCKWHEAT CONSUMPTION

Buckwheat has been utilized as an effective medicinal herb in Chinese traditional therapy, in the treatment of many diseases for more than 1000 years (Cai et al., 2016). Nowadays, it has come to the fore as a functional food raw material and additive because of its beneficial nutritional properties.

Buckwheat carbohydrates have favorable traits. Investigations into the nutritional quality of buckwheat starch showed that it is of potential use in the formation of foods with lower glycemic index, due to its high amylose content and high amount of resistant starch (Cai et al., 2016). Cereal fibers have been

shown to have many health-promoting effects. Notably, they help in decreasing gastric emptying and increasing transit time in the lower gastrointestinal tract. These fiber components in buckwheat can be fermented by microflora in the digestive tract, producing short chain fatty acids, and gases (Steadman et al., 2000). The higher level of soluble fiber seems to be effective in lowering the risk of nutrition-related diseases, such as obesity or cardiovascular diseases. A unique active component of buckwheat-soluble carbohydrates are the fagopyritols. They are of considerable interest for noninsulin dependent diabetes and polycystic ovarian syndrome treatment (Christa and Soral-Šmietana, 2008).

As shown, the amino acid composition of buckwheat proteins is nutritionally well balanced. Buckwheat is well known as a dietary source of protein with favorable amino acid composition, particularly rich in lysine. This is an advantage compared to other plant proteins, as lysine is the first limiting indispensable amino acid in plant-based diets. In buckwheat, threonine and methionine are the first and the second limiting amino acids (Krkošková and Mrázová, 2005; Pomeranz and Robbins, 1972). Additionally, pseudocereal proteins, especially buckwheat proteins have considerably higher biological value (above 90%), compared to true cereals (Berghofer and Schoenlechner, 2007; Eggum et al., 1980). This can be explained by a high and balanced concentration of the indispensable (essential) amino acids. Due to the presence of exogenous antinutrients in the whole groats (including dietary fiber, protease inhibitors, and tannin-type compounds) and the low susceptibility of the protein to proteolytic action, the true protein digestibility is slightly below 80% (Bonafaccia and Krefte, 1994; Pomeranz and Robbins, 1972).

Many beneficial effects of the unsaturated fatty acids have been shown. The high ratio of unsaturated fatty acids (which are mostly polyunsaturated) in buckwheat seed is very favorable, and buckwheat is nutritionally superior in fatty acid composition to true cereal grains (Krkošková and Mrázová, 2005).

Further, in comparison to most frequently used cereals, buckwheat has been reported to possess higher antioxidant activity, mainly due to its high rutin content (Sedej et al., 2011). Rutin in the human diet seems to have other health benefits as well, including antimicrobial and antiinflammatory activities (Cai et al., 2016).

6 UTILIZATION IN FOOD MANUFACTURE

6.1 Milling and Fractionation

Whole grain flour is prepared by milling the whole buckwheat seed in a similar way to wheat, but the buckwheat achenes must first be dehulled by impact milling or abrasion with emery stones or grinding plates. This procedure removes 25%–30% of the achene. The groats are roller-milled into various grades of white flour for food processing. The extraction yield is around 55%, mainly depending on variety (Zheng et al., 1998). Bonafaccia et al. (2003) obtained 55.4% for common and 55.6% for tartary buckwheat with this milling

TABLE 7.3 Composition of Buckwheat Seed Milling Fractions (g/100 g Dry Basis) (Steadman et al., 2000)

		Total Protein	Ash	Total Lipid	Starch	Total Dietary Fiber
Milled from achenes	Hull	6.2	4.9	10.1	17.8	16.0
	Bran	20.1	4.6	5.6	16.4	37.8
	Grits	4.7	0.7	1	72.1	1.7
	Fancy flour	6.2	1.3	1.5	64.8	3.7
Milled from groats	Bran	35.5	7.0	10.9	17.8	15.1
	Supreme flour	11.5	2.2	3.3	52.0	8.5
	Fancy flour	5.4	0.8	1.0	75.0	2.3

technique, while Wronkowska and Haros (2014) obtained a yield of 58.8% using a wet milling system. The composition of the milling fractions is very different depending on the tissues (endosperm, embryo, and maternal tissues) that comprise the fraction (Table 7.3).

Steadman et al. (2000) investigated about milling the whole achene and also the hulled achene (groat). In both cases, the milled tissues were separated into fancy, light-colored flour, and bran fractions. The bran fraction contained pericarp, aleurone layers, and also the cotyledons and a large fragment of the embryo. When intact achenes were milled, hull fragments got separated with the bran, after then the hull was removed by sifting. The grits mostly consisted of large chunks of endosperm. The milling and separating process resulted in fancy flour. This was compared to whole groat milling fractions: bran, supreme flour, and fancy flour. Supreme flour was derived from the dehulling process, and was essentially whole groat flour with hull. In both cases the bran fractions had the highest content of protein and dietary fiber, and also the lipid content was dominant in the bran and hull parts. The starch content of the fancy flours was over 70%. Grits was similar to fancy flour and fancy flour had poorer nutritional quality compared to the supreme flour. Bonafaccia and Kreft, (1994) and Sedej et al. (2011) also obtained the same results for white-type, light-colored fancy flours with both common and tartary buckwheat.

6.2 Flour Technological Properties

Obviously, the behavior of buckwheat flour is different from wheat flour, and it is difficult to make wheat flour-like foods because there are no gluten-forming proteins in buckwheat. Our research group evaluated two commercial white

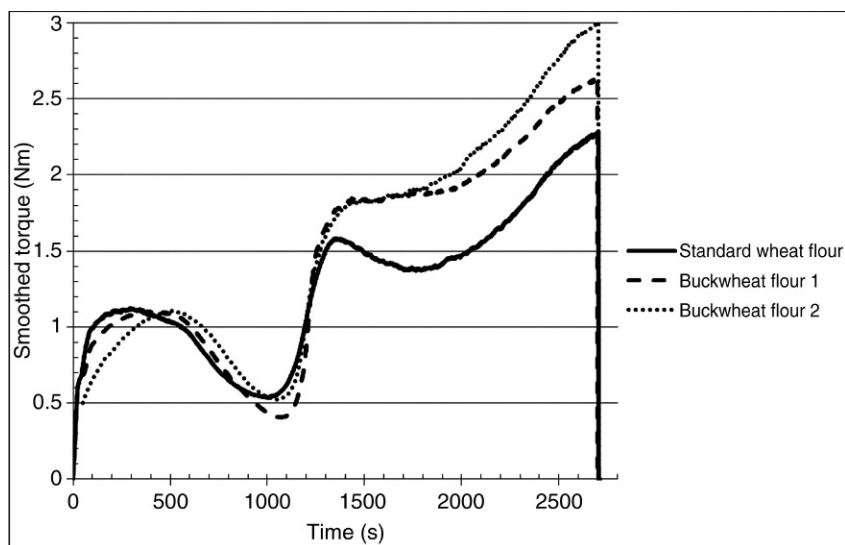


FIGURE 7.4 Comparison of complex mixing and viscous profiles of two different buckwheat cultivars and a standard wheat flour as determined using the Mixolab (Chopin) (own, non-published results).

buckwheat flours using the Mixolab dough rheological instrument. The curves are presented in Fig. 7.4.

There are remarkable differences in the characteristic points of the curve: increasing dough developing times have been observed compared to the standard wheat flour. The water absorption of buckwheat flours was higher (66.0%–69.3%) than control wheat (62.0%). These differences can be attributed to the higher lipid and fiber content of the buckwheat flours compared to the standard wheat flour. Due to the weaker structure forming ability of buckwheat proteins, the doughs of both buckwheat flours had reduced stability. During heating in the second part of the profile, the buckwheat curves showed neither pasting peak nor setback, rather there was a continuous increase in viscosity on holding at 95°C. This is in agreement with [Zheng et al. \(1998\)](#), where they investigated buckwheat starch properties. The stable viscosity of buckwheat flour on heating was probably because of the rigidity of its granules. [Qian and Kuhn \(1999\)](#) also observed that buckwheat starch had much higher viscosity than those of true cereal starches. [Cai et al. \(2016\)](#) reported higher peak viscosity, higher gelatinization temperature, greater swelling power, and generally slower retrogradation when compared with cereal starches (maize and wheat).

Buckwheat flour is sometimes mixed with wheat flour and other flours before use. Blends of 30% buckwheat and 70% wheat flour are commonly used in households for bread preparation in many parts of Europe, for example, in Slovenia ([Cai et al., 2016](#); [Kreft and Germ, 2008](#); [Steadman et al., 2000](#)). [Sedej et al. \(2011\)](#) investigated different wheat doughs enriched with buckwheat flour in a ratio of

10%–50% using the same analysis as in our work. Compositing with buckwheat flour had the same effects as 100% buckwheat flour, and reduced dough stability. However, the water absorption was lower in their work. Addition of buckwheat flours in dough formulations resulted in a decrease in starch retrogradation. This could have a positive effect on final bread product quality. They concluded that enrichment of wheat dough with buckwheat flour resulted in altered rheological parameters of the enriched dough in comparison to the control wheat dough. However, no significant effect of substitution level was observed.

In addition to functionality, it is necessary to also investigate the sensory characteristics of buckwheat products. Fessas et al. (2008) found no differences in appearance, color, and overall sensory attributes for buckwheat–wheat composite breads. These breads were rated higher in terms of flavor and mouth feel compared to wheat bread. Such buckwheat–wheat composite breads also have a higher rutin content, good antioxidant activity, and radical scavenging ability (Lin et al., 2009). Additionally, buckwheat flour positively affected major parameters of bread quality (volume and loaf size) (Lin et al., 2009). Further, such composite breads were also found to be proportionally enriched with proteins and microelements, especially Cu and Mn (Krupa-Kozak et al., 2011).

6.3 Traditional Food Products

A large variety of traditional buckwheat foods have been produced for centuries. Buckwheat can be utilized in many ways and dishes made from buckwheat seeds can be classified into two groups: groats dishes and flour dishes (Fig. 7.5).

The most popular buckwheat groat dish is a porridge-like dish, called *kasha*, made of roasted groats boiled in water or milk, which is common in Russia and Poland. The dish was introduced to America by immigrants but in the USA *kasha* is usually mixed with pasta or used as a stuffing. Buckwheat groats can also be sprouted and then eaten raw or cooked.

Light-colored flour is used for pancakes, breads, and noodles. The most common food is buckwheat noodles, which are very popular in Japan, China, and Italy and they are made from buckwheat flour–water dough. The noodle products have different names according to the area in which they are produced. In Japan it is called *soba*, in Italy it is referred to as *pizzoccheri*, and in Korea as *guksu*. In Japan, there are many noodle-making factories producing buckwheat noodles. These products are sold in precooked, boiled, dried, or instant forms, as well as being produced for direct sale. In some parts of India, on fasting days people of the Hindu community replace cereals with noncereal ingredients, such as buckwheat. One of the most famous dish is *ki puri* (pancakes). Buckwheat pancakes leavened with yeast, are eaten in several countries, such as in France, Belgium, and Russia (Cai et al., 2016; Heffler et al., 2011).

Other products made from buckwheat are available across the world. Buckwheat flowers give a high yield honey with a characteristic taste (Biacs et al., 2002). Buckwheat tea called *sobacha* is a relatively common tea in Japan. There are many steps involved in creating the tea. Raw whole seeds are first

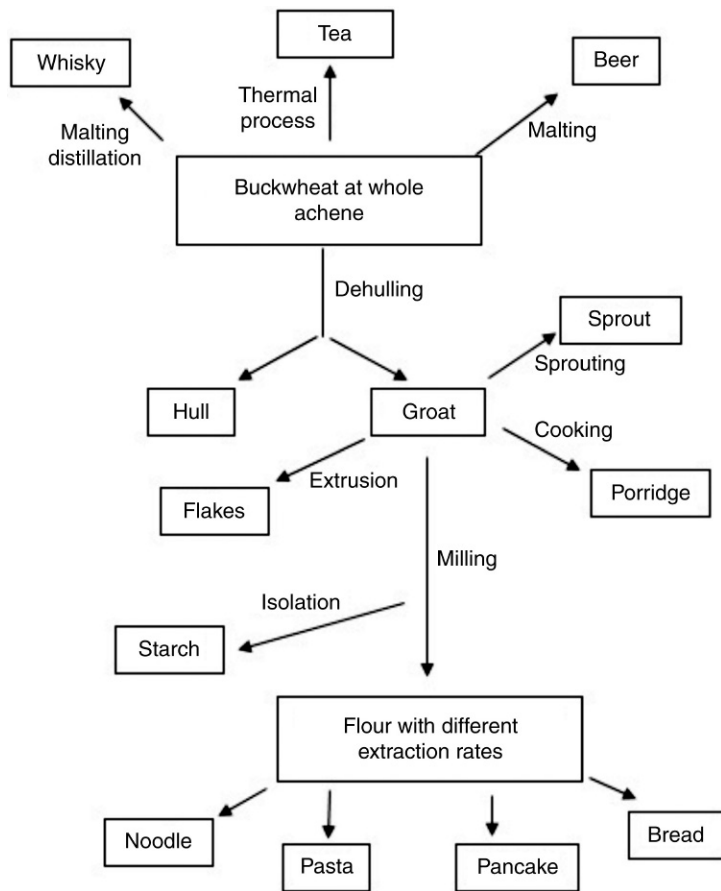


FIGURE 7.5 Diagram of different buckwheat-based products.

soaked in water, then steamed, and dried before they are removed from their hulls. The dehulled groats are then roasted so that the tea can be made (Zhang et al., 2012). Buckwheat whisky is distilled by a French company and beer products can also be made from buckwheat (Cai et al., 2016; Giménez-Bastida et al., 2015). The fresh green parts of plant can be used as a vegetable and dried leaves are a suitable material for enriching functional foods due to their high rutin content. Consequently, the leaves have potential for preventive nutrition (Cai et al., 2016; Kreft et al., 2005).

6.4 Potential Role in the Gluten-Free and Nongluten-Free Diets: New Developments

Beside traditional foods, buckwheat (together with other pseudocereals and less-utilized cereals) is suitable for gluten-free food manufacturing (Giménez-



FIGURE 7.6 Modern commercial buckwheat gluten-free products. (A) Pancakes and (B) pasta

Bastida et al., 2015). Fig. 7.6 shows modern, commercial, gluten-free pancake, and pasta products where buckwheat flour is the major component, 49% in the pancakes and 80% in the pasta. Additionally, the products contain rice flour, and in the case of the pancakes various starches plus the hydrocolloid methyl cellulose.

Buckwheat seeds are very low in the prolamin and glutelin protein fractions and this is an important difference regarding the proteins of buckwheat flour and wheat flour (Aubrecht and Biacs, 2001). Immunological assays have revealed that buckwheat contains no toxic prolamins and thus its flour is suitable for use in diets or food products for patients with celiac disease (autoimmune enteropathy), one of the most common lifelong dietary disorders (Wieslander and

Norbäck, 2001). Nowadays, gluten-free products represent one of the most profitable food product markets and buckwheat has a well-deserved place in such products (Giménez-Bastida et al., 2015). This is not just because of the fact that it does not contain gluten but also because of its high nutritional quality. This is important because studies have revealed that 20%–38% of celiac patients have protein, dietary fiber, or mineral and vitamin deficiencies (Biacs et al., 2002).

Due to its positive attributes, buckwheat alone is suitable for gluten-free diets. There are also some examples of the nutritional supplementation of cereals with buckwheat flour, particularly products made from wheat flour (Cai et al., 2016; Li and Zhang, 2001). Wronkowska and Haros (2014) described some special health programs with buckwheat. In these programs, buckwheat is included in the normal diet for children and adults. Some programs promote its healthy properties, such as the North American Buckwheat Promotion Committee in Canada or a project called “Buckwheat Conservation and Utilization” in Bhutan.

New trends in usage of buckwheat in food products are being predicted, including improvement of traditional foods, development of new functional (health-promoting) foods, and formation of additives (nutraceuticals) from buckwheat with special physiological effects (Krkošková and Mrázová, 2005). There are also some novel ways to use buckwheat. For example, the hull is used in the production of therapeutic mattresses and cushions, which have a positive impact on the posture of the body; they rapidly absorb body moisture, do not heat up, and are always cool. Due to the presence of tannins, they also inhibit the growth of harmful microorganisms (Heffler et al., 2011). The by-products from the processing of buckwheat are used as a raw material for the production of granular biofuels (Wronkowska and Haros, 2014).

7 OUTLOOK AND PERSPECTIVES

The buckwheat species and varieties can be valuable actors in agriculture, world-wide. However, if we would like to better utilize its excellent nutritional quality in human nutrition, we have to find the place for buckwheat-based food products in both traditional and modern food markets. Today, the tradition and its gluten-free status are not enough to increase the utilization of this pseudocereal. We have to obtain more knowledge about its chemical composition, particularly about the health-promoting compounds, such as phytochemicals and their genetic and environmental (G×E) variability. We have limited knowledge about the technological behavior of different buckwheat varieties and also about the relationships between chemical composition, such as protein subunit composition, starch and nonstarch polysaccharide profiles, and their technological characteristics. A widely accepted quality system for buckwheat is also missing. With the continuous expansion of knowledge we have a better chance to develop more sophisticated milling and processing technologies, which optimize the valuable and health-promoting nutritive qualities and phytochemical and produce more widely accepted and palatable buckwheat food products for the 21st century consumer.

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Chapter 8

Lupins: Their Unique Nutritional and Health-Promoting Attributes

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1 INTRODUCTION

Lupin L. (US spelling lupine, species of the genus *Lupinus*, family Fabaceae) is an ancient pulse crop (Hondelmann, 1984). It is, however, a new genus to modern agriculture, with seeds having great potential for high-protein food, animal feed, fodder, and improved soil fertility and the plant as a cover crop, for crop residues as stubble feed, and for soil remediation (Gladstones, 1998; Lambers et al., 2013). Recently, there is considerable interest in lupin seeds as a human health food as the seeds are very high in dietary fiber, are gluten-free, have virtually no starch, and thus have very low glycemic impact (Sipsas, 2008). An additional valuable attribute of lupins is that there are no genetically modified (GM) lupin varieties under commercial cultivation (Department of Agriculture and Food, 2016; ISAAA, 2016).

Lupin is well known for its ability to fix nitrogen and to grow on infertile soils, and its value in agricultural growing season rotations with cereal grains, hay, oilseeds, a disease break crop for other legumes pulses and pastures (Gladstones, 1970, 1998; Seymour et al., 2012). Lupin seeds, as an energy and protein source for animal feed, compete well with cereals and oilseed meals, complement other feed components, and are cost-effective (Edwards and Van Barneveld, 1998; Glencross et al., 2015).

Lupinus is a large genus comprising approximately 267 species (Drummond et al., 2012) that grow in a very wide range of environments and regions, including the Mediterranean, Northern and Eastern Africa, North and Central America, Andean South America, and Atlantic South America (Gladstones, 1970; Hughes and Eastwood, 2006; Maciel and Schifino-Wittmann, 2002; Wolko

et al., 2011). They range from herbaceous annuals and herbaceous to shrubby perennial plant types and grow from sea level to alpine tundra with a wide range of climates (Gladstones, 1998). Generally, lupins are plants of open and well-lit habitats and do not tolerate shading, preferring well-drained soils with acid to neutral pH (Gladstones, 1998; Pascual et al., 2006).

Wild and landrace lupins contain bitter alkaloids. Some bitter lupin production occurs, particularly of *Lupinus albus*, where it is processed in salt water to reduce alkaloids, thereby producing an edible snack food product (Erbaş, 2010). However, modern varieties have been bred such that single recessive genes confer large reductions of total alkaloids in seeds (Gladstones 1970). All modern varieties of the species *L. angustifolius* are classified as sweet by food safety organizations (such as Food Standards Australia New Zealand, 2016b) when total alkaloid levels in seed are a maximum of 200 mg/kg (0.02%) or less, which is approximately 100 fold lower than wild type seed alkaloid levels. This level is generally achievable through the incorporation of the low alkaloid gene in *L. angustifolius*. In lupin species such as *L. albus* and *L. luteus*, various single genes also provide “sweet” levels of alkaloids in seed (Gladstones, 1970). In the Andean lupin species (*L. mutabilis*), low alkaloid genotypes have been developed through mutation breeding (Pakendorf, 1974; Williams et al., 1984) and by selection of spontaneous mutants from germplasm after successive steps of breeding (von Baer and von Baer, 1988).

Compared with nearly all other food crops, lupins have only recently been the focus of modern crop breeding. Fully domesticated lupin varieties were developed in Europe and Australia only in the 20th century (Gladstones, 1970). The species that have achieved modern grain crop status are *L. angustifolius* *L.* (commonly known as narrow-leaved lupin and blue lupin), *L. albus* (albus lupin, white lupin), *L. luteus* (yellow lupin) from the Old World and the New World species, and *L. mutabilis* (Andean lupin, tarwi, chochos). Figs. 8.1 and 8.2 present flower raceme and mature seed images of a typical example of each of these species. The main differences between wild or landrace and the domesticated lupin genotypes are that domesticated types, known as “sweet lupin,” have seeds containing approximately 100-fold less total alkaloids at levels of ~0.02 g/100 g or less, more permeable seed coats, and nonshattering pods and are relatively early flowering (Clements et al. 2005a; Gladstones, 1970; Lee et al., 2007). Unless otherwise stated as “bitter” (high alkaloid), all information in this chapter will refer to “sweet” lupin varieties with low seed alkaloid levels.

This chapter describes the current status of lupin as a crop, the chemical composition of its seeds, uses of lupin seeds and their fractions as foods and food ingredients, lupin allergy, and the evidence for positive health benefits of lupin seeds and their fractions from human clinical studies.



(A)



(B)



(C)



(D)

FIGURE 8.1 Typical examples of flower racemes of the commonly cultivated grain lupin species. (A) *Lupinus angustifolius*, (B) *L. luteus*, (C) *L. albus*, (D), *L. mutabilis*.

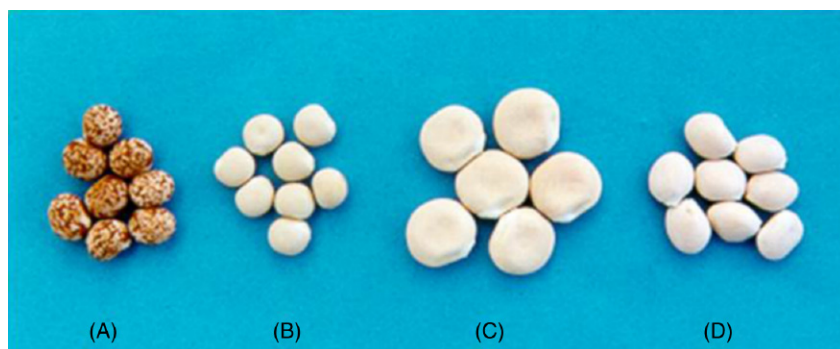


FIGURE 8.2 Typical examples of mature seeds of the commonly cultivated grain lupin species. (A) *Lupinus angustifolius*, (B), *L. luteus*, (C) *L. albus*, (D) *L. mutabilis*.

2 GLOBAL PRODUCTION OF LUPIN SEEDS

Global production of lupin seeds has increased rapidly since the 1970s, dominated by Australian production and rising to a peak in 1999 and returning currently to the levels as in the mid-1980s (Table 8.1) (FAOSTAT, 2016). In Australia, lupin production has declined since 1999 (Fig. 8.3), mostly due to the lower profitability relative to wheat and canola and the increasing cost of weed control (Sweetingham and Kingwell, 2008). An increasing interest in growing lupins in the United Kingdom and Europe commenced in the 1990s in response to demand for locally grown, nonGM vegetable protein animal feed and lower reliance on soybean imports (de Visser et al., 2014). It is estimated that 500,000 tonnes of food products are manufactured each year that contain European white lupins and/or Australian sweet lupins as an ingredient (Lupin Foods, 2013). Inclusion as an ingredient is often a small percentage, implying that tonnages of lupin destined to food products is currently only a fraction of global production, with feed being the primary end-use.

Table 8.2 presents a summary of the current yield and composition traits of the crop lupin species. *L. angustifolius* (narrow-leaved lupin) is the dominant species cultivated in Australia (typically 90% of production). It is primarily grown in Western Australia on account of its adaptation to the widely occurring acid and sandy well-drained soils (Gladstones, 1998). Furthermore, lupins have been shown to provide the highest benefit as a rotational break crop to wheat (Seymour et al., 2012) and are commonly used in a 1-in-4-year rotation with cereals and canola. The average yield of lupin in Australia over the past 10 -year period is 1.15 tonnes/ha (FAOSTAT, 2016; Pulse Australia, 2016).

The major regions for yellow lupin (*L. luteus*) cultivation have been the North European Plain, the forest-steppe zone in Ukraine, and the Bryansk

TABLE 8.1 Lupin Production (Tonnes) of Major Producing Countries over the Past 40 Years, Including the Peak Production Year (1999) (FAOSTAT, 2016)

Country	1975	1980	1985	1990	1995	1999	2005	2010	2014
Australia	103,925	96,007	524,278	757,670	1,559,000	1,968,000	1,285,000	629,000	565,100
Poland	61,219	41,435	119,094	125,000	45,000	23,061	40,913	126,200	139,802
Russian Federation ^a	240,000	138,000	368,000	150,000	12,470	15,300	31,850	9,738	75,690
Germany	9,892	9,500	14,196	10,000	—	—	50,000	30,600	40,800
Belarus					—	—	78,603	39,370	34,137
Ukraine					—	—	9,000	60,400	28,930
South Africa	4,000	7,000	7,000	7,918	6,000	13,000	14,100	16,100	18,770
Chile	10	10,000	16,352	21,182	50,000	22,416	63,246	73,325	16,781
France				6,842	9,189	16,590	17,597	15,568	15,020
Peru	1,449	4,714	3,700	3,300	5,371	7,790	9,480	10,521	12,156
Italy	7,700	6,800	4,600	4,200	5,144	4,577	3,500	5,400	5,710
Spain	1,800	1,300	1,642	1,700	8,800	8,900	5,627	3,689	3,100
Lithuania					1,000	800	4,900	6,800	3,100
Egypt	5,200	7,545	12,000	6,110	7,154	4,673	2,786	3,077	2,400
World total	444,011	332,995	1,080,000	1,102,537	1,715,723	2,104,316	1,626,245	1,032,755	981,481

—, Data not available.

^aRussian Federation, previously USSR, affects figures given for Belarus, Lithuania, and Ukraine.

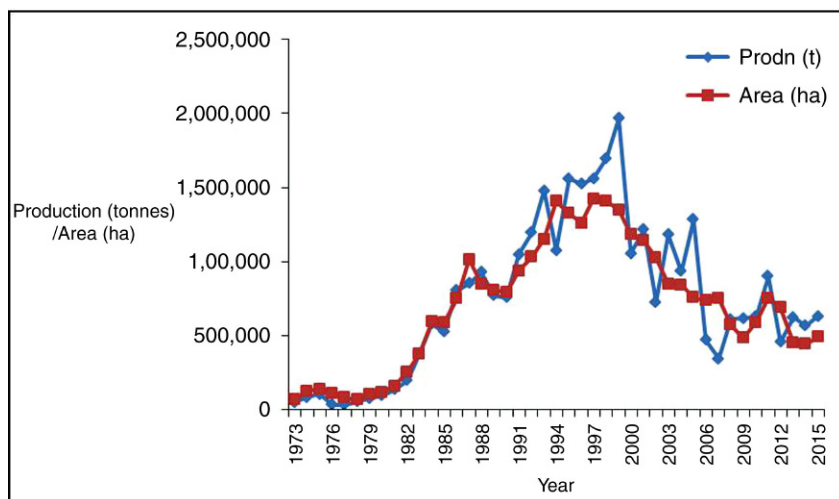


FIGURE 8.3 Australian lupin production (tonnes) and area sown (ha) since the release of the first fully domesticated *L. angustifolius* variety in 1973.

Province of European Russia (Kurlovich, 2002). However, there has been a steady decline in both *L. luteus* and *L. albus* (white or albus lupin) production in favor of *L. angustifolius* in Europe since the 1980s due to the greater resistance of the latter to anthracnose disease (Sweetingham and Kingwell, 2008). In countries such as Poland, Germany, Chile, and South Africa, there has been a recent rise in production. Poland is currently the second largest producer of lupins worldwide (Table 8.1) due to the widespread occurrence of acid, sandy soils, and breeding research focusing on their role as a summer crop (Swiecicki and Swiecicki, 1995; Swiecicki et al., 2000). In Chile, lupin production increased greatly during 1990–2010 (Table 8.1) to meet animal feed and aquaculture feed markets' needs (Bórquez et al., 2011; Glencross et al., 2007; Tacon, 2005; Saez et al., 2015), providing good yield of protein and oil (von Baer, 2008). It is frequently difficult to determine proportions of the different crop species of lupins grown; however, comments from colleagues at international meetings indicate that *L. angustifolius* has become dominant in most countries, with exceptions such as Chile, Italy, and Egypt where *L. albus* is dominant.

In the Andean highland regions of Ecuador, Peru, and Bolivia small areas of bitter *L. mutabilis* are still cultivated using traditional methods by farmers (Jacobsen and Mujica, 2004). Lupin cultivation, particularly *L. albus* and *L. angustifolius*, occurs in small areas in Argentina, USA, and Canada (FAOSTAT, 2016), whereas in South Africa, in climates similar to Western Australia, lupins with a focus on *L. angustifolius* have been consistently grown. In many of these countries, an interest in lupin for human food is emerging.

TABLE 8.2 General Characteristics of the Crop Lupin Species

	<i>L. albus</i>	<i>L. luteus</i>	<i>L. angustifolius</i>	<i>L. mutabilis</i>
(A) Yield traits				
Growing season climate	Cool to moderately warm, some frost tolerance	Mild temperatures, frost susceptible	Cool to mild temperatures, moderately tolerant to frost	Narrow temperature range, very frost susceptible
Soil adaptation	Mildly acid to mildly calcareous loamy sands and loams, very intolerant to waterlogging, cluster roots give efficient P uptake, low cadmium accumulation, manganese accumulator	Strongly to mildly acid sands and sandy loams, some waterlogging tolerance, aluminum tolerant, sensitive to alkaline soils, cadmium accumulator, more effective uptake of P and Zn than <i>L. angustifolius</i> (tertiary/secondary clumped lateral roots), high-N-fixing efficiency	Moderately acid to neutral sands and sandy loams, intolerant to waterlogging, low cadmium accumulation	Mildly acid to neutral loamy sands and loams, tolerant to waterlogging, low cadmium accumulation, low P requirement, high internal P-use efficiency
General soil fertility requirement	Moderate	Low	Low to moderate	Moderate
Water requirement	Moderate	Low to moderate	Low	Moderate
Fungal diseases	Very susceptible to anthracnose but some resistance anr-2, susceptible to fusarium, rust and botrytis. Resistance to phomopsis generally, although susceptibility reported in S. Africa	Susceptible to anthracnose, single gene resistances available for fusarium. Resistant to <i>Pleiochaeta</i> root rot and good sources of resistance to brown spot (polygenic). Moderate resistance to phomopsis, Eradu patch resistance	Susceptible to anthracnose, moderate resistance available (AnR-1 and other genes). Susceptible to fusarium. Susceptible to <i>Pleiochaeta</i> root rot and brown spot but polygenic resistance available. Susceptible to phomopsis but resistance available (Phr1, Phr2)	Susceptible to anthracnose but less than <i>L. albus</i> . Resistance available to fusarium. Very susceptible to <i>Pleiochaeta</i> root rot and brown spot but some genetic variation. Relatively resistant to phomopsis.

(Continued)

TABLE 8.2 General Characteristics of the Crop Lupin Species (*cont.*)

	<i>L. albus</i>	<i>L. luteus</i>	<i>L. angustifolius</i>	<i>L. mutabilis</i>
Virus diseases	CMV: tolerant. BYMV: moderate problem and seed borne in east and central Europe, and USA; not seed-borne in Australia. A nonnecrotic strain causing concern in Australia.	CMV: susceptible. Serious problem in east and central Europe—carried over through lupin seed. Resistance to seed transmission occurs—single gene resistance Ncm-1. BYMV: serious problem in east and central Europe, and in USA - carried over through lupin seed. Resistance to seed transmission occurs. Partial resistance to BYMV infection used in breeding in Europe. Very low alkaloid lines susceptible to aphids	CMV: highly susceptible. Serious problem, seed-borne, partial resistance to seed transmission used in breeding in W. Australia. BYMV: serious problem, high susceptibility, not seed-borne, partial resistance to infection by aphids occurs. Two strains, necrotic and nonnecrotic. Aphid resistance	CMV: susceptible. Moderate problem, seed transmission not recorded, resistance found in one line. BYMV: highly susceptible.
Herbicide tolerances	Moderate tolerance to simazine and diflufenican, susceptible to metribuzin, tolerant to grass selective herbicides	Moderate tolerance to simazine and diflufenican, susceptible to metribuzin, tolerant to grass selective herbicides	Tolerant to simazine and diflufenican, some varieties tolerant to metribuzin, tolerant to grass selective herbicides	Moderate tolerance to simazine, susceptible to metribuzin, tolerant to grass selective herbicides
(B) Composition				
Protein (% in seed)	36.1	38.3, higher S-amino acids	32.2	42.0
Oil (% in seed)	9.1	5.6	5.8	18.0
Lysine	1.58	2.07	1.46	2.56

Cysteine + cystine ^a	2.3	3.2	2.0	^b
Methionine	0.24	0.27	0.20	0.31
Seed coat (% of seed)	18	25	24	13
Other traits	Specific antioxidants (lutein and others), higher isoflavone levels (genistein)			Very thin seed coat, low NSPs
Main alkaloids	Lupanine, 13-hydroxylupanine, albine ^c , angustifoline, multiflorine, isolupanine	Lupinine, sparteine, gramine ^c	Lupanine, 13-hydroxylupanine, angustifoline, isolupanine	Lupanine, 13-hydroxylupanine, sparteine

BYMV, Bean yellow mosaic virus; CMV, cucumber mosaic virus.

^aFrom *Sipsas et al. (2004)* using method of *Barkhold and Jensen (1989)*.

^bNot available.

^cVariously present in some lines.

Sources: Gladstones, J.S., 1970. Lupins as crop plants. Field Crop Abstracts 23, 123–48; Hove, E.L, King, S., Hill, G.D.Composition, protein quality, and toxins of seeds of the grain legumes *Glycine max*, *Lupinus* spp., *Phaseolus* spp., *Pisum sativum*, and *Vicia faba*. New Zeal. J. Agric. Res. 21, 457–62; Culvenor, C.C.J., Petterson, D.S., 1986. Lupin toxins – alkaloids and phomopsins. In: Proceedings of the 4th International Lupin Conference, Department of Agriculture Western Australia, Perth, Australia, pp. 188–198; Römer, P., Jahn-Deesbach, W., 1988. Developments in *Lupinus mutabilis* breeding. In: Proceedings of the 5th International Lupin Conference. International Lupin Association, Poznan, Poland, pp. 40–50; Barkhold, V., Jensen, A.L., 1989. Amino acid analysis: determination of cysteine plus half-cystine in proteins after hydrochloric acid hydrolysis with a disulfide compound as additive. Anal. Biochem. 177, 318–322; Jones, R.A.C., McLean, G.D., 1989. Virus diseases of lupins. Ann. Appl. Biol. 114,609–637; Wink, M., Meibner, C.,Witte, L., 1995. Patterns of quinolizidine alkaloids in 56 species of the genus *Lupinus*. Phytochemistry 38, 139–153; Petterson, D.S., Sipsas, S., Mackintosh, J.B., 1997. The Chemical Composition and Nutritive Value of Australian Grain Legumes.Grains Research and Development Corporation, Canberra, Australia; Caligari, P.D.S., Romer, P., Rahim, M.A., Huyghe, C., Neves-Martins, J., Sawicka-Sienkiewicz, E.J., 2000. The potential of *Lupinus mutabilis* as a crop. In: Knight, R. (Ed.), Linking Research and Marketing Opportunities for Pulses in the 21st Century. Proc. 3rd Int. Food Legumes Res. Conf. Kluwer Academic Publishers, Dordrecht, 569–573; Cheng, Y., Jones, R.A.C., 2000. Biological properties of necrotic and non-necrotic strains of bean yellow mosaic virus in cool season grain legumes. Ann. Appl. Biol. 136, 215–227; Jones, R.A.C., 2001. Developing integrated disease management strategies against non-persistently aphid-borne viruses: A model program. Integrated Pest Management Reviews 6, 1–46; Cheng, Y., Jones, R.A.C., Thackray, D.J., 2002. Deploying strain specific hypersensitive resistance to diminish temporal virus spread. Ann. Appl. Biol. 140, 69–79; Clements, J.C., Dracup, M., Galwey, N.W., 2002. Effect of genotype and environment on proportion of seed hull and pod wall in lupin. Aust. J. Agric. Res. 53, 1147–1154; Jones, R.A.C., Coutts, B.A., Cheng, Y., 2003. Yield limiting potential of necrotic and non-necrotic strains of bean yellow mosaic virus in narrow-leaved lupin (*Lupinus angustifolius*). Aust. J. Agric.I Res. 54, 849–859; Clements, J.C., Zvyagin, A., Silva, D., Wanner, T., Sampson, D., Cowling, W.A., 2004. Investigation of optical coherence tomography to measure the hull thickness of lupin seeds. Plant Breed. 123, 266–270; Sipsas, S., Snowden, J., St John, C., 2004. Sulphur amino acid content in lupins. In: Proceedings of the 5th European Conference on Grain Legumes. Dijon, France. European Association for Grain Legume Research.

3 AGRONOMIC ADVANTAGES

Lupins are recognized to produce substantial benefits to cereal crops in farming crop rotations, and the crop residues after harvest have a high grazing value for stock. In comparison to other legumes, lupin species are considered to be highly efficient at fixing atmospheric nitrogen (GRDC, 2014; Unkovich et al., 2010) at levels similar to faba bean, but higher than other legumes (Herridge et al., 2008), to give biomass production of a similar order to that of pea and faba bean (Unkovich et al., 2010). Lupin crops contribute to good soil N, biology and structure, better water infiltration and storage for the subsequent cereal crops, better weed competition and provision of a ‘disease break’, leading to increased yield of the next crop in the rotation (Asseng et al., 1998; Haynes and Beare, 1997; Seymour et al., 2012).

Lupins have high potential to mobilize soil nutrients, in particular phosphorus (P) and micronutrients, for themselves as well as for interplanted or subsequent rotation crops (Gilbert, 2009). The deep root penetration of *L. angustifolius* (Hamblin and Hamblin, 1985) allows it to effectively extract and recycle soil potassium (Rowland et al., 1986). They can also play a role in phytoremediation of soils through accumulation or promotion of microorganisms capable of detoxifying soil contaminants, such as heavy metals and hydrocarbons (Lambers et al., 2013). Particularly in Europe, lupins have contributed to environmental activities, such as stabilization of disturbed soils after road works or vegetation clearing, as a green manure and game fodder crop, in fire-protection belts in forests, in enhancement of soil fertility in pine forests, and in sand-dune stabilization or provision of shelter for young trees (Lambers et al., 2013; Rehfuess et al., 1991; Sprent and Silveste, 1973; Vyšniauskienė et al., 2011).

4 LUPIN BREEDING: FOCUS ON AUSTRALIA

The history of lupin breeding has been reviewed by several authors (Cowling et al., 1998; Clements et al., 2005a). The identification of simply inherited and natural but rare spontaneous mutant genes by von Sengbusch (1942) in Germany in the early 20th century for reduction of alkaloids was the major domestication step that rendered lupins palatable for animals and for human food.

Further breeding combined early flowering with naturally occurring mutant genes for nonshattering pods, white flowers and seeds, and permeable seed coats (Cowling et al., 1998; Gladstones, 1970). In Australia, Unicrop (1973) was the first cultivar globally that combined all domestication traits (including fully nonshattering pods through the incorporation of two additive genes) and marked the beginning of the highly successful history of *L. angustifolius* lupin in that country (Cowling et al., 1998). Further improvements in yield and incorporation of disease-resistant genes from wild germplasm have also occurred in Australia (Berger et al., 2012; Cowling and Gladstones, 2000; Gladstones, 1970). Since the mid-1990s, anthracnose disease has become a

worldwide issue and intensive efforts have been made in Australia to select lines with resistance (Gladstones, 1970; Yang et al., 2008).

Considerable efforts have been made in the development of genomic resources for marker-assisted selection for the key diseases of anthracnose and phomopsis and domestication genes (Yang et al., 2004; Yang et al., 2015a,b). Notable activities have been the publication of a lupin genome sequence (Yang et al., 2013) and transcriptome resources (Kamphuis et al., 2015). Continuing efforts are now being made to enhance disease tolerance to anthracnose, *Fusarium* wilt, bean yellow mosaic virus, and cucumber mosaic virus (Fischer et al., 2015; Kehoe et al., 2014; Yang et al., 2008). Future development of genomic selection and genetic modification/transformation methods, such as CRISPR/Cas9 gene editing (Bortesi and Fischer, 2015), should facilitate breeding for yield and agronomic traits and seed quality characteristics.

5 NUTRIENT AND ANTINUTRIENT COMPOSITION

Legumes include lupins that are an important food source providing nutrients to millions of people living in developing countries. However, they are sometimes referred to as “poor man’s meat” (Khan and Basha, 2015), a term that does not give credit to their nutritional potential for food security.

Lupin seeds are harvested when mature and dry and as such are commonly referred to as a “pulse” or “grain legume”. The edible portions are the whole seeds that will be referred to as “seeds” throughout this chapter, the seed coat that will be referred to as “hull”, and the dehulled seeds that will be referred to as “kernel” (botanically being the cotyledons).

Lupin seeds are high in protein (Table 8.2) relative to other cool-season grain legumes, such as lentil, pea, chickpea, and faba bean (Clements et al., 2005b; Petterson et al., 1997), with a level similar to soybean (United States Department of Agriculture, undated). Their kernels are also notably high in total dietary fiber at ~40 g/100 g dry basis (db) (Table 8.3), making the lupin unique among the ancient grains and legumes.

5.1 Protein

The protein content of the seed varies between species of lupin (Table 8.2B), with *L. mutabilis* generally having the highest. As recently reviewed by Carvajal-Larenas et al. (2016), the average seed protein content (g/100 g db) reported in the literature was *L. albus*, 38.2; *L. angustifolius*, 33.9; *L. luteus*, 42.2; and *L. mutabilis*, 43.3. Within *L. angustifolius*, the protein content of the seed varies with variety, growing location/season, and management practices (Villarino, 2014). At ~40 g/100 g db, lupin kernels have the highest protein level of any commonly consumed pulse (Mülayim et al., 2002). Table 8.3 shows the protein content of the kernels of some commercial *L. angustifolius* varieties

TABLE 8.3 Proximate Composition (g/100 g Dry Basis) of *L. angustifolius* Kernel Grown in the Same Location and Season in Western Australia^a Compared with United States Department of Agriculture National Nutrient Database Values for Lupin and Some Other Legumes^b

Variety	Protein	Total Dietary Fiber	Fat	Ash	Total Available Carbohydrates by Difference
<i>Lupinus angustifolius</i> kernel ^{c,d}					
Belara	39.6 ^A ± 0.4	38.9 ^A ± 1.9	8.8 ^C ± 0.4	3.3 ^A ± 0.1	9.4 ^A ± 3.0
Coromup	42.4 ^E ± 0.3	39.3 ^A ± 0.9	7.8 ^B ± 0.8	2.9 ^A ± 0.9	7.4 ^A ± 0.7
Gungurru	41.4 ^C ± 0.4	40.0 ^A ± 1.3	8.5 ^C ± 0.0	2.8 ^A ± 0.2	7.4 ^A ± 0.9
Jenabillup	41.9 ^D ± 0.4	39.2 ^A ± 1.9	7.8 ^B ± 0.5	3.8 ^A ± 0.1	7.4 ^A ± 1.6
Mandelup	40.8 ^B ± 0.5	37.5 ^A ± 0.4	7.1 ^A ± 0.3	3.4 ^A ± 0.0	11.1 ^A ± 1.1
Tanjil	40.5 ^B ± 0.4	40.2 ^A ± 0.4	8.8 ^C ± 0.2	3.2 ^A ± 0.1	7.3 ^A ± 1.3
United States Department of Agriculture National Nutrient Database values (edible portion) ^e					
Lupins, mature seeds, raw	40.4	21.1	10.9	NR	45.1
Beans, pinto, mature seeds raw	24.2	17.5	1.4	NR	70.5
Soybeans, mature seeds, raw	39.9	10.2	21.8	NR	33.0

NR, Not reported.

^aSource: Villarino (2014).

^bSource: United States Department of Agriculture (undated).

^cMeans (n = 2) ± standard deviation.

^dValues within columns for *L. angustifolius* kernel with different superscript capital letter denote significant difference (P < 0.05) using Duncan's test.

^eConverted to dry basis using database moisture values.

grown in the same season and location in Western Australia (Villarino, 2014). These vary between 39.6 and 42.2 g/100 g db, with var. Coromup having the highest level.

The major fraction of proteins within the lupin kernel is the globulins with albumins making up the remainder (Duranti et al., 2008; Petterson, 1998). The major globulin fractions are α -conglutin (35–37 g/100 g total protein), $\beta\beta$ -conglutin (44–45 g/100 g total protein), γ -conglutin (4–5 g/100 g total protein), and δ -conglutin (10–12 g/100 g total protein) (Blagrove and Gillespie, 1975; Duranti et al., 2008; Foley et al., 2011, 2015; Petterson, 1998).

The nutritionally limiting amino acids in lupin protein are the sulfur-containing amino acids methionine and cysteine (Gulewicz et al., 2008). Compared to soybean, which is complete with respect to its indispensable amino acid profile (World Health Organization, 2007), lupin protein has been reported as slightly lacking in the required levels of sulfur amino acids for adult human requirements (Chew et al., 2003). However, it has also been reported that lupin protein has sulfur amino acid levels similar to those of soybean (Sipsas et al., 2004). This apparent contradiction is possibly due to variation in the levels in lupin protein due to variety and production environment.

Carvajal-Larenas et al. (2016) reviewed in detail the amino acid composition of whole lupin seeds and concluded that there was little difference between species. In terms of in vitro digestibility, uncooked lupin protein has been reported as high at ~98% (Chew et al., 2003) of a similar level to that of soy (World Health Organization, 2007). Given the complementary nature of wheat proteins in terms of their amino acid composition, lupin–wheat composite foods (e.g., bread) have been demonstrated to provide higher protein quality than either alone (Villarino et al., 2015a).

5.2 Dietary Fiber

Dietary fiber is the component of foods that is not digested by human gut enzymes and thus reaches the colon where it may be fermented or provide bulk that can assist with prevention of chronic diseases (Dhingra et al., 2012). It includes a wide range of nonstarch polysaccharides and the associated lignin and indigestible oligosaccharides (Dhingra et al., 2012). Lupin is unique among legumes for its high dietary fiber level, being higher than that of other pulses and soybean (KohaJdoVá et al., 2011; United States Department of Agriculture, undated). However, care needs to be exercised when comparing literature values for “fiber” in lupin, since different analytical methods for its determination can give very different results. Formerly, the “crude fiber” method was used to measure the “fiber” content in foods; however, this method does not detect all “dietary fiber” components as some are degraded (Dhingra et al., 2012). Hence, when crude fiber determination methods are used to describe lupin seed or kernel composition (Carvajal-Larenas et al., 2016), total dietary fiber content is severely underestimated. Furthermore, some conventional methods for assessing total dietary fiber content of foods do

not capture the significant oligosaccharide fraction in lupin seed. Therefore in most published data (Table 8.3), the total dietary fiber content may be further underestimated. More recent methods of dietary fiber determination can quantify all the nondigestible carbohydrate components, including oligosaccharides (Food Standards Australia New Zealand, 2016d).

5.2.1 Hull Dietary Fiber

The hull fraction of *L. angustifolius* seeds is very high in total dietary fiber (~90 g/100 g db), primarily insoluble fiber (KohaJdoVá et al., 2011). Small amounts of protein, lipid, and ash (minerals) (Bailey et al., 1974; Evans et al., 1993) are also present, and the major proportion of phytochemicals of the seed is located in the hull fraction (Duenas et al., 2006; Khan et al., 2015; Luo et al., 2016). In addition, the majority of the calcium of the seed and significant levels of other minerals, such as Al, K, Na, Mg, Zn, Fe, and Mn, are located in the hull fraction (Hung et al., 1988). The hull dietary fiber comprises cellulose (~50%), arabinoxylans (~13%), and pectins (30%) (Brillouet and Riochet, 1983; Evans et al., 1993; White et al., 2007). Thus, the high dietary fiber content of lupin hull and the presence of significant levels of minerals and phytochemicals indicate the potential of lupin hull as a high fiber food ingredient, though little is known of its physiological effect in humans and its mineral and phytochemical bioavailability.

5.2.2 Kernel Cell Wall Dietary Fiber

A major proportion of the total dietary fiber of the lupin seed is found as thickened cell walls within the kernel and is predominantly comprised of nonlignified, noncellulosic, and nonstarch polysaccharides containing a rhamnogalacturonan backbone, with side chains of galactose and arabinose (Evans et al., 1993). In the study by Villarino (2014) (Table 8.3), the total dietary fiber content of the *L. angustifolius* kernels ranged from 37.5 to 40.2 g/100 g db, with no significant differences between varieties grown in the same season and location in Western Australia. Hall et al. (2005b) reported that the total dietary fiber fraction of *L. angustifolius* kernel flour consisted of 74% insoluble dietary fiber and 26% soluble dietary fiber. Lupin kernels have been used for the isolation of purified dietary fiber ingredients (Clark and Johnson, 2002). Compared to the levels in the kernel flour, these purified dietary fiber fractions have higher levels of soluble dietary fiber (e.g., ~50% of the total dietary fiber fraction) (Hall et al., 2005a), perhaps due to the effect of processing, reducing the integrity of the cell wall material. Lupin kernel fiber, when added to foods, has demonstrated a range of health-protective effects in human clinical studies (Hall et al., 2005a).

5.2.3 Oligosaccharides

The raffinose family oligosaccharides (RFOs) (raffinose, stachyose, verbascose) are another important dietary fiber fractions that are high in lupin seeds

compared to other pulses. RFOs are known for their flatulence-inducing effects, though there is no direct evidence for this for lupin oligosaccharides in the literature for humans. In lupin seeds grown in Western Australia, [Karnpanit et al. \(2016\)](#) reported that total RFO contents varied significantly depending on the cultivar, with highest levels in var. Mandelup (16.8 g/100 g db) and the lowest in PBA Barlock (7.6 g/100 g db). However, no significant differences were reported by [Villarino \(2014\)](#) in total oligosaccharides between commercial varieties of *L. angustifolius* kernels (with total levels around 5 g/100 g db) grown in the same season and location in Western Australia.

5.3 Lipids

Lupin species vary widely in their lipid content ([Table 8.2](#)), with *L. mutabilis* having lipid levels higher than other commonly consumed pulses but lower than those of soybean (as reviewed by [Kouris-Blazos and Belski, 2016](#)). The average lipid contents of the seeds (g/100 g db) reported in the literature ([Carvajal-Larenas et al., 2016](#)) are: *L. albus*, 11.2; *L. angustifolius*, 6.3; *L. luteus*, 5.5; and *L. mutabilis*, 13.0, with high proportions of oleic (C18:1) and linoleic (C 18:2) across all species. The lipid content of *L. angustifolius* kernels grown in the same location and season has been reported to range from 7.8 to 8.8 g/100 g db ([Villarino, 2014, Table 8.3](#)), with var. Mandelup having the lowest level. [Kouris-Blazos and Belski \(2016\)](#) reported that the lipid profile of lupin flour (presumably kernel flour of *L. angustifolius*) was: saturated, 19%; monounsaturated, 33%; polyunsaturated, 48% of which omega-3 linolenic contributed 6% of the total lipids.

5.4 Available Carbohydrates

Available (glycemic) carbohydrate levels in foods are commonly determined by difference (100 – %moisture, – %fat, – %protein, – %ash, – % total dietary fiber) ([Food Standards Australia New Zealand, 2016a](#)). Literature values for the “carbohydrate” fraction in lupin seeds can vary widely ([Table 8.3](#)). In part, this may be linked to the different analytical approaches used to assess the total dietary fiber fraction ([Section 5.2](#)), which can underestimate total dietary fiber and thus overestimate the available carbohydrate fraction. Given that RFOs have been reported at 5.0–16.8 g/100 g db ([Karnpanit et al., 2016; Villarino et al., 2015a](#)), they appear to make up the majority of the level of “available” carbohydrate reported in [Table 8.3](#).

5.5 Micronutrients

There is little information concerning the levels of essential dietary minerals in lupin seed. According to the USDA National Nutrient Database ([United States Department of Agriculture, undated](#)), mature raw lupin seeds have

similar levels of most essential dietary minerals as raw mature pinto bean seeds; however, the level of zinc is higher in lupin. [Carvajal-Larenas et al. \(2016\)](#) reviewed the mineral levels reported in lupin seed and concluded that comparisons were difficult to make due to the potential influence of production environment and analytical method on the literature values. The mineral contents (g/100 g as is) of Australian produced lupin flour (presumably *L. angustifolius* kernel flour) have been reported as: Fe, 4.9; Ca, 84; Zn, 3.6; Mg, 189; and K, 810 ([Food Standards Australia New Zealand 2010](#), cited in [Kouris-Blazos and Belski, 2016](#)), values which are in the range of other pulse and cereal grains.

There is little data available on the vitamin levels in lupin seeds. According to the USDA National Nutrient Database ([United States Department of Agriculture, undated](#)) mature raw lupin seeds have similar levels of vitamins as raw mature pinto bean seeds. The levels of carotenoids of some commercial varieties of *L. angustifolius* grown in the same season and location in Western Australia have been reported by [Villarino \(2014\)](#), with var. Mandelup having the highest total carotenoid level of 20.1 $\mu\text{g/g}$ db (consisting of lutein 7.6; β -carotene 5.5; zeaxanthin 4.4, and α -carotene 2.6 $\mu\text{g/g}$ db). The vitamin E content in lupin oil has been reported as similar to soybean but is lower than that of sunflower and rapeseed oil ([Lampart-Szczapa et al., 2003](#)).

5.6 Phytochemicals and Antioxidant Capacity

A major class of phytochemicals of importance to human health are the phenolics, compounds, which have antioxidant activity and that may provide protection for diseases related to oxidative stress, including type 2 diabetes and cardiovascular disease ([Pérez-Matute et al., 2009](#)). [Magalhães et al. \(2017\)](#) analyzed 29 European-produced samples of seeds of lupins, chickpeas, field peas, faba beans, and common vetch seeds and found that lupins, *L. luteus*, and *L. angustifolius* had the highest total phenolic content. In lupin, flavonoids were predominant over phenolic acids, whereas the reverse was the case for other species.

Due to the diverse methods used to measure polyphenols and antioxidant capacity, values are expressed in many different noninterchangeable units; therefore, care is required when comparing literature data. Commercial varieties of *L. angustifolius* grown in the same location and season in Western Australia have been found to have kernel total polyphenol content between 1.6 and 1.9 mg gallic acid equivalents (GAE)/g db and total antioxidant capacities between 2.6 and 5.4 μmol Trolox equivalents (TE)/g db ([Villarino, 2014](#)). In comparison, [Rumiyati et al. \(2013\)](#) reported total polyphenol values of 0.95 mg GAE/g db in *L. angustifolius* kernels, which rose to 7.88 mg GAE/g db in the dehulled sprout after 9 days of germination. Similarly, the antioxidant capacity of the sprouted sample was far higher than that of the kernel. This suggests that germinated lupin has potential as a high antioxidant-rich fresh food or ingredient for incorporation into other foods.

The oil fraction of *L. angustifolius* kernel has also been reported to have antioxidant activity by [Rumiyati et al. \(2013\)](#) who hypothesized that it may have been, in part, a result of the phytosterols they identified in the oil.

Compared to the other seed fractions, the hulls of *L. angustifolius*, *L. luteus*, and *L. albus* are reported to be highest in free phenolic acids ([Lampart-Szczapa et al., 2003](#)). Total antioxidant capacity of lupin hull has been reported at 0.14 mg TE/g dry sample ([Ranilla et al., 2009](#)). In contrast, those of the hulls of 26 varieties of kidney bean were much higher and ranged from 7.1 to 102.4 mg TE/g dry sample ([Kan et al., 2016](#)).

5.7 Antinutrients and Toxins

5.7.1 Antinutritional Factors

In general, lupin is considered low in antinutritional factors as compared to some other legumes, including soy. Lupins do not contain lectins ([Pettersen et al., 1997](#)), while *Phaseolus* spp. contain 1–10 mg/g ([Nasi et al., 2009](#)). Saponins in *L. angustifolius* are reported to be present at low levels, approximately 570 mg/kg seed (0.057%) ([Gurfinkel and Rao 2002](#)), compared with defatted soy flour having 0.58% and navy bean seed with 0.32%, as reported by the same authors. Quinoa has saponin levels of approximately 0.65%, which necessitates their removal through processing prior to consumption ([Ward, 2001](#)). Little data are available on the tannin content and types of tannins in lupin seeds. Tannins can act as metal ion chelators, considerably inhibiting nonheme iron absorption, and can have the adverse effect of reducing protein digestibility, although they may also have beneficial antioxidant effects in humans ([Santos-Buelga and Scalbert, 2000](#)). The level of condensed tannins in the hull of varieties of *L. albus*, *L. angustifolius*, and *L. luteus* was reported as 0.013–0.077 mg catechin equiv./g db and that of the hulls at 0.001–0.009 mg/g ([Lampart-Szczapa et al., 2003](#)). This is in stark contrast to the levels in hull of common bean varieties, which were reported in the range of 50–350 mg catechin equiv./g db ([Mojica et al., 2015](#)).

Protease inhibitors are present at very low levels and are of minor importance in crop lupin species ([Wink, 2006](#)). Trypsin inhibitor activity has been described as “negligible” in *Lupinus* spp. as compared to “very intense” in soybean [43–84 trypsin inhibitor units (TIU)/mg] and high in common bean (17–51 TIU/mg) ([Guillamón et al., 2008b](#)). Phytates are present in all grains, including pulses, and in pulses they are concentrated in the hull ([Ghavidel and Prakash, 2007](#)). Phytates chelate essential minerals, such as iron, calcium, and zinc, reducing their bioavailability ([Sanchez-Chino et al., 2015](#)). The phytic acid content of *L. albus* lupin seeds has been reported at 1487 mg/100 g db ([Nilgün and Nermin, 2014](#)), while that of *P. vulgaris* had a range of 200–1900 mg/100 g db ([Champ, 2002](#)).

5.7.2 Phytoestrogens

Phytoestrogens are phytochemicals that may assist in combating menopausal symptoms. However, as reviewed by [Sirtori et al. \(2005\)](#), their purported role

in cardiovascular disease prevention is equivocal and they may be toxic. Sirtori et al. (2004) reported lower levels of these compounds (56 mg/100 g as is) in *L. albus* seeds compared to the range reported for US soybean (116–274 mg/100 g as is) (Wang et al., 2000). However, Ranilla et al. (2009) only found these compounds in *L. mutabilis* seeds and not in *L. albus* and *L. angustifolius* seeds.

5.7.3 Alkaloids

Bitter-tasting varieties of lupin seeds contain quinolizidine alkaloids (e.g., lupanine, 1, 3-hydroxylupanine and angustifoline, Table 8.2B) that are potentially toxic to humans (Kamel et al., 2015; Petterson, 1998). These toxic effects have been recently reviewed by Carvajal-Larenas et al. (2016). As such, their maximum legal level is legislated at 0.02 g/100 g in lupin flour and products by several authorities, including those of Australia, New Zealand, United Kingdom, and France (Food Standards Australia New Zealand, 2016b; Ministry of Agriculture Fisheries and Food and Department of Health, 1996; Resta et al., 2008). No difference in kernel total alkaloids was found among commercial *L. angustifolius* varieties grown in the same location and season in Western Australia (Villarino, 2014), with all samples being below the maximum permitted level for human food use.

5.7.4 Phomopsins

Phomopsins are a fungal toxin produced by *Diaporthe* spp. toxic (European Food Safety Authority, 2012; Food Standards Australia New Zealand, 2016b), which can infect seeds when they have been exposed to high humidity. In Australia, New Zealand, and the United Kingdom the maximum permitted level in lupin for food use is 5 µg/kg (Petterson, 1998). The highest concentration of phomopsins is found in the hull (EFSA, 2012). Therefore, dehulling can lower the level of contamination. Phomopsins are stable to soaking, steaming, and fermentation (Battilani et al., 2011), though high temperature high pressure extrusion cooking has potential to reduce the levels, given its known effect on other mycotoxins (Bullerman and Bianchini, 2007).

6 LUPIN MILL PRODUCTS AND ISOLATED FRACTIONS AS FOOD INGREDIENTS

6.1 Kernels, Flakes, Grits, Meals, and Flour

Lupin seeds are sorted, graded, and cleaned of any extraneous materials with the use of a vibrating screen and metal detector and then passed through a dehuller to split the kernel and separate it from the hull (Villarino et al., 2015b). Lupins have a relatively thick hull compared to other legumes and, in general, this necessitates dehulling before the lupin kernel is further processed (Clements et al., 2005b). The kernels are milled and sieved to particle sizes ranging from

<150 to >600 μm (Irwin Valley, 2011). Lupin flakes, grits, crumb, and meal have larger particle sizes compared to lupin flour, with no existing standards to differentiate their size. However, the US standards for soy (Kanzamar et al., 1993) require that flour should pass through the #100 mesh (0.149 mm), whereas grits of different sorts pass through #10 mesh (2.0 mm) to #80 mesh (0.177 mm). Lupin flakes are manufactured by a propriety mechanical process that differs from conventional milling to give particles with flake-like geometry (Lupin Food Australia, personal communication) and a reported flake particle diameter of 1.5–3.0 mm (Terrena Lup'ingredients, undated). The particle size of milled lupin is an important quality parameter in food applications. For example, Villarino et al. (2015b) reported that an increase in the particle size of lupin flour added to wheat bread could significantly increase the amount of lupin flour incorporation before adversely affecting bread quality.

Lupin flour or its extracted components, such as protein or fiber, can be added to foods so as to enhance their nutritional quality (reviewed by Villarino et al., 2016). Such additions increase protein levels by 46%–352% and dietary fiber content by 106%–346%, with 30%–40% substitution of wheat flour by lupin flour in different food products. Studies have investigated the use of lupin kernels in fermented foods, such as tofu (Jayasena et al., 2010b) and tempeh, as a replacement for soybeans (Coorey, 1995; Fudiyansyah et al., 1995). Lupin flour incorporation into staple wheat-based foods, such as breads (Ballester et al., 1988; Bartkiene et al., 2011; Doxastakis et al., 2002; Guemes-Vera et al., 2008; Mubarak, 2001; Paraskevopoulou et al., 2010; Villarino et al., 2015a), biscuits (Jayasena and Nasar-Abbas, 2011), instant noodles (Jayasena et al., 2010a), and pasta (Clark and Johnson, 2002; Martinez-Villaluenga et al., 2010) has been investigated to increase the protein and dietary fiber content of the products while minimizing any reduction in consumer acceptability. Up to ~10% lupin flour addition to wheat flour in breadmaking has been reported to increase dough and loaf quality and inhibit staling. In instant noodles, substitution by up to ~20% lupin flour increased nutritional quality without any significant effect on cooking and sensory quality (Jayasena et al., 2010a). In addition, the yellow color of lupin flour (from the pigments lutein, zeaxanthin, and β -carotene, Wang et al., 2008) can be imparted into foods (e.g., cakes and biscuits) and the need for egg yolk and butter as colorants can thus be reduced (KohaJdoVá et al., 2011; Krawczyk et al., 2015).

The main barriers to the use of lupin in leavened wheat-based products, such as pan breads, are the low elasticity of lupin proteins and high water binding capacity of lupin dietary fiber (Turnbull et al., 2005). This causes a less interconnected gluten matrix (Güemes-Vera et al., 2004), low loaf volume, and hard and chewy texture (reviewed by Villarino et al., 2016). To address this issue, Villarino et al. (2015b) used a statistical modeling approach to maximize the incorporation rate of lupin in wheat-based leavened bread rolls by which a 28% replacement of wheat flour by milled lupin kernels was achieved while maintaining consumer acceptability of the bread.

Another challenge in the incorporation of lupin into products is the potential for undesirable aftertastes, which have been described as grassy, beany, metallic, fatty, hay-like, meat-like, and cheese-like (Bader et al., 2009). Consumers have detected aftertastes or unusual tastes in baked products (Hall and Johnson, 2004). This resulted in reduced flavor acceptance of muffins with >30% lupin incorporation and biscuits with >20% incorporation, with a “beany” flavor (well known in soybean products, Shin et al., 2012) being reported (Jayasena and Nasar-Abbas, 2011; Nasar-Abbas and Jayasena, 2012).

Roasting or heating lupin seeds can reduce their “beany” flavor (Yañez et al., 1986) and extend the shelf life of the flour (Auger and Corre, 1993) by reducing rancidity development. Deoiling of lupin flakes has also shown promise to reduce the “legume-like” flavor and improve consumer acceptance of lupin protein (Bader et al., 2011). Also, sourdough fermentation has been investigated in lupin breadmaking to mask undesirable lupin flavors by desirable flavors from the fermentation (Bartkiene et al., 2011; Schindler et al., 2011).

Lupin kernels, flakes, grits, and flour may be further processed into various fractions, for example, protein isolates, purified kernel dietary fiber, and water-soluble by-products (i.e., “whey” proteins and oligosaccharides) that will be described in the following section.

6.2 Protein Isolates and Concentrates

Legume protein isolates, including those from lupin, can be extracted and isolated by a range of ways, including either isoelectric precipitation (Lusas and Riaz, 1995) or ultrafiltration (Chew et al., 2003). Lupin protein isolates are extracted by solubilization of protein from wet-milled kernels or lupin flour (defatted or nondefatted) at high alkaline pH (e.g., 9), removal of the insoluble portion (dietary fiber) through centrifugation, followed by acid precipitation of the major globulin proteins (i.e., α - and β -conglutins) at pH 4.5 (Coorey et al., 2013; Sipsas, 2008) (Fig. 8.4). The insoluble fiber residue, acid-precipitated protein, and acid-soluble “whey fraction” can then be dried for use as shelf-stable food ingredients.

The major α -, β -conglutin fraction produced by isoelectric precipitation has excellent emulsifying properties (Sironi et al., 2005) but little viscosity and gel-forming properties that may be required when used as a food ingredient. The acid-soluble whey fraction, once considered as waste, also contains valuable protein components, such as the bioactive peptide γ -conglutin (Sironi et al., 2005), and stable foam-forming properties (Coorey et al., 2013; Wong et al., 2013). Due to their functional properties important in food manufacture, lupin protein fractions have been categorized as E (emulsifying) fraction (α -, β -conglutin) and F (foaming) fraction (γ -conglutin-rich) (Sironi et al., 2005; Wäsche et al., 2001).

Lupin protein isolates have been shown to have useful technological functionalities, for example, in frankfurters (Alamanou et al., 1996), and have been proposed as

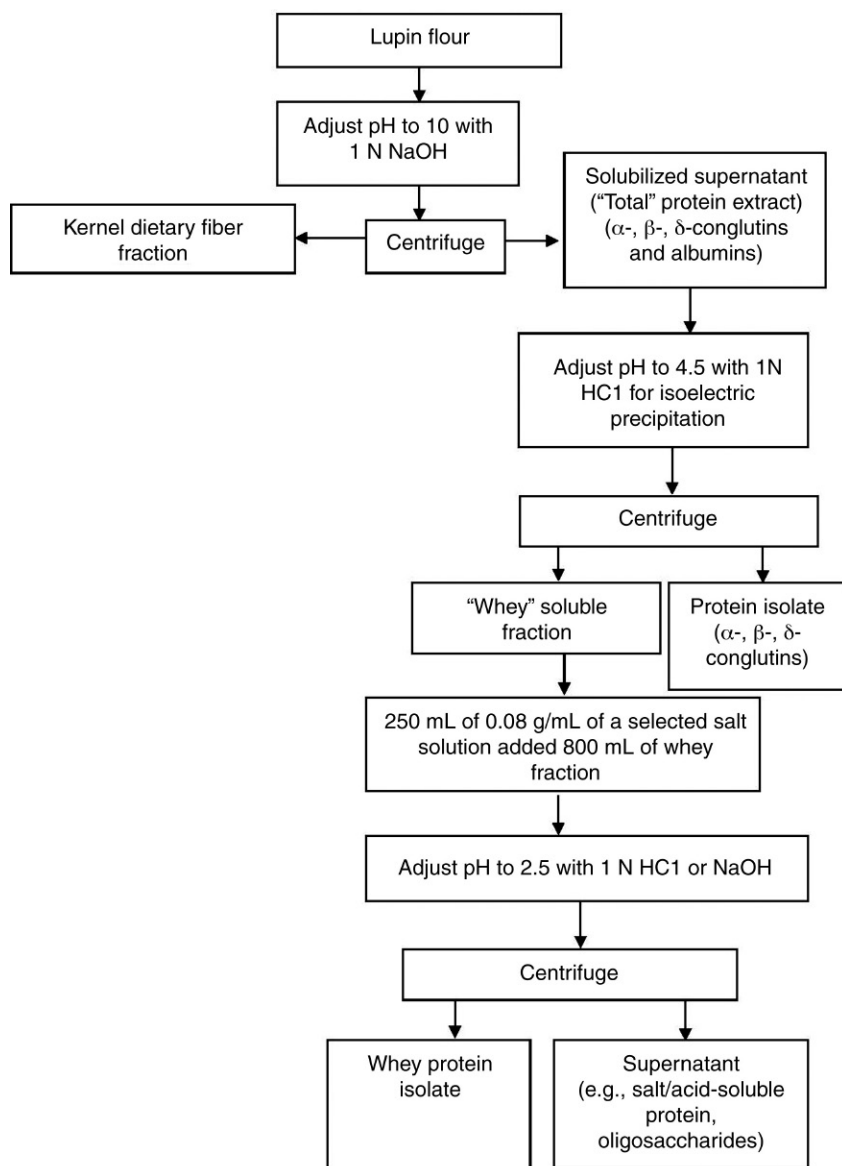


FIGURE 8.4 Fractionation procedure of defatted lupin flour to obtain lupin protein fractions and dietary fiber. (Adapted from Coorey, R., Chao, K.I., Kumar, V., Jayasena, V., 2013. The effect of lupin (*Lupinus angustifolius*) protein isolation on its dietary fibre and whey protein. *Qual. Assur. Safe. Crops Foods* 5, 287–294.)

a potential vegan egg white replacer (Wong et al., 2013). Much of the detail of their performance in foods remains proprietary information. However, to ensure competitiveness in the global vegetable protein market, further investigations are required to develop enhanced functionalities (e.g., viscosity and gelling) in lupin protein fractions.

6.3 Dietary Fiber Fractions

Only limited studies have been reported on the use of lupin dietary fiber fractions as food ingredients for the development of high-fiber foods. However, lupin kernel fiber has been reported as an effective fat replacer in sausage patties by Archer et al. (2004). The substitution of wheat flour with lupin fiber by up to ~10% in pasta significantly increased the dietary fiber level with no significant reduction in its overall acceptability (Clark and Johnson, 2002). The acid-soluble whey from lupin fractionation contains oligosaccharides, which may have prebiotic activity (which stimulates the growth of beneficial gut bacteria; (Roberfroid, 2007). However, there is currently no clinical evidence of this potentially beneficial property. Examples of commercial lupin fiber ingredients will be described in Section 7.

6.4 Lupin Oil

Oil can also be extracted from lupin seeds by aqueous extraction with extrusion pretreatments or protease addition (Jung, 2009) or solvent extraction (Ortiz and Mukherjee, 1982). Given the low level of oil in many varieties of lupin compared to that in the oilseed legumes, lupin oil may remain a high-cost niche product.

7 COMMERCIAL LUPIN FOOD INGREDIENTS

Some commercially available lupin seed derived ingredients from various countries are presented in Table 8.4. Lupin flour is produced in Australia, Austria, and Germany. In the Netherlands, flour mixes, such as enzyme active flour and flour with fiber, are being sold. Lupin grits and flakes are recommended for use in special breads, cereals, and snack products to improve shelf life, taste, and texture. Lupin hull fiber is commercially available in Chile and Germany (Table 8.4). Fiber from *L. albus* hull is recommended for use in baked products, cereals bars, and pasta and marketed as a fat replacer and source of dietary fiber in meat products. Milled hulls are marketed as lupin “bran” and aside from increasing the dietary fiber content, these are also promoted to increase the shelf life of bread. Commercial lupin protein extracts may be classified into protein isolates (>90 g protein/100 g db), concentrates (60–90 g protein/100 g), and protein-enriched meal (<60 g protein/100 g). According to a commercial manufacturer, lupin protein isolates have emulsion, solubility and foam and gel formation capacities, which can beneficially influence the structure, texture, and sensory properties of food and can be used as milk, egg, and meat substitutes.

TABLE 8.4 Commercially Available Food Ingredients Derived from Lupin Seeds

Product Categories	Countries
<i>A. Flour and mixes</i>	
Flour	Australia, Austria, Germany
Flour mixes	Netherlands
<i>B. Flakes, grits and meals</i>	
Flakes	Australia, France
Grits	Australia, Austria, Chile, France, Netherlands
Meal	Australia
<i>C. Dietary fiber</i>	
Hull fiber	Australia, Chile, Germany, Netherlands
<i>D. Proteins</i>	
Protein concentrate	France, Germany, Netherlands
Protein isolate	Germany
<i>E. Oil</i>	
Oil	Germany
<i>F. Miscellaneous</i>	
Split kernels	Australia
Food supplement	Australia

Commercial protein concentrates are reported to improve emulsifying properties, crispness, and stickiness of cake and batters. A German company sells lupin oil, which is described as a yellowish to brownish liquid, extracted by CO₂ extraction from seeds of *L. angustifolius* for recommended use in bakery goods, meat products, and pasta manufacture.

8 COMMERCIAL LUPIN-CONTAINING FOOD PRODUCTS

Examples of food product types containing lupin seed and lupin fractions are shown in [Table 8.5](#). Lupin ingredients have been commonly found in the European diet since the early 2000s ([Fletcher 2006](#)), with about 15,000 tonnes consumed annually in the European Union, mainly as the minor inclusion of lupin flour in wheat-based baked goods. Lupin is slowly gaining increased popularity for inclusion in a range of palatable and nutritionally enhanced breads, baked goods, pasta, meat products, and beverages ([Belski et al., 2011](#)). In 2015, of all bakery product launches incorporating lupin flour, 22% were in Germany, followed by France (21%) and Italy (11%).

TABLE 8.5 Applications of Lupin Seeds and Fractions in Commercial Food Products	
Product Type and Lupin Fraction Used	Countries
<i>A. Breads</i>	
Whole seed flour	Australia, Germany, United Kingdom
Hull	Australia
Protein	Italy, Germany, Spain, United Kingdom, USA
<i>B. Cookies</i>	
Flour	Australia
<i>C. Muffins and waffles</i>	
Flour	UK
Hull	Australia
<i>D. Crispbreads and crackers and cones</i>	
Flour	UK
Protein	Australia, Germany, Italy, Spain, United Kingdom, USA
<i>E. Breakfast cereal</i>	
Flour	Australia
<i>F. Egg substitute /replacer</i>	
Flour	Germany
<i>G. Meat analogs</i>	
Kernels	Germany
Flour	Netherlands
Protein	Austria, Germany
Fiber	Germany
<i>H. Pasta</i>	
No information	Italy
Flour	UK
Flour and protein	Australia
<i>I. Snacks</i>	
Seeds	Australia, Germany, Italy, Portugal, South Africa, Spain, USA
<i>J. Dips and mayonnaise</i>	
Not indicated	Germany, Italy
<i>K. Desserts and confectionary</i>	
Not indicated	Germany, United Kingdom
Flour	Germany, Netherlands, United Kingdom
Protein isolate	United Kingdom
<i>L. Ready meals</i>	
Seeds	Ecuador

9 LUPIN ALLERGENICITY

Lupin does carry a risk of allergic reaction and is one of the 14 allergens that have to be declared as an ingredient on products under the EU Food Information Regulation that came into effect in 2014 (Food Standards Agency, 2016). Currently a proposal for compulsory labeling of lupin as an allergen on foods is in the public consultancy stage in Australia and New Zealand (Food Standards Australia New Zealand, 2016c). There is a relatively small percentage of people that are allergic to ingesting or inhaling lupin protein, with less than 2% of 1522 patients showing positive allergy tests for lupin, compared to peanut (8%) and soy (11%) (Hieta et al., 2009). Exposure to trace quantities of lupin can, however, result in a severe anaphylaxis (Moneret-Vautrin et al., 1999; Smith et al., 2004). Of those allergic to peanuts, ~5% also showed symptoms when exposed to lupin (Hieta et al., 2009; Reis et al., 2007; Sanz et al., 2010; Smith et al., 2008). There may be several locations(s) of allergenic epitopes in lupin protein since β -, γ -, and δ -conglutins have all been reported as allergenic (Jappe and Vieths, 2010; Sanz et al., 2010). Furthermore, α -conglutin has been reported as the allergen in a cross-reactivity study using blood samples from 34 peanut allergenic participants and 5 nonpeanut allergenic participants (Sirtori et al., 2011). For individuals specifically allergic to *L. angustifolius*, the β -conglutin family of proteins were potential allergens (Foley et al., 2011), whereas for *L. albus*, both conglutin β and conglutin α fractions were reported as allergens (Guillamón et al., 2010b). Rapid methods have been developed for the detection of traces of lupin protein in foods, including a sandwich enzyme-linked immunosorbent assay (Ecker and Cichna-Markl, 2012) and a liquid chromatographic-electrospray ionizing-tandem mass spectrophotometric, proteomic method (Mattarozzi et al., 2012).

Various processing methods have been applied to lupin foods with the aim of reducing their allergenicity. For example, Alvarez-Alvarez et al. (2005) investigated extrusion, boiling, and microwave heating but with no effect. However, the allergenicity of lupin was destroyed by autoclaving at 138°C for 30 min with a controlled pressure drop for 3 min at 6 bar (Guillamón et al., 2008a, 2010a).

Given the reported occurrence of lupin allergenicity, it is likely that as lupin becomes more popular as a food worldwide, authorities will propose mandatory labeling of it as an allergen. In a recent review of the subject, Ramanujam et al. (2016) concluded that “*Appropriate product labelling by manufacturers and awareness among physicians and general public are required for overcoming the challenges associated with lupin allergy.*”

10 CURRENT EVIDENCE FROM CLINICAL STUDIES OF POSITIVE HEALTH EFFECTS OF LUPIN CONSUMPTION IN HUMANS

There is developing evidence from human clinical studies that foods containing lupin seed fractions can provide beneficial effects with respect to risk factors of cardiovascular disease (overweight and obesity, elevated blood glucose level,

elevated insulin level, elevated cholesterol levels, and high blood pressure) that together make up the metabolic syndrome (Hodgson et al., 2015; Kouris-Blazos and Belski, 2016; Villarino et al., 2016). The high fiber, high protein, and low available carbohydrate composition of all species of lupin may be responsible for these protective effects (Hodgson et al., 2015; Kouris-Blazos and Belski, 2016; Villarino et al., 2016). Table 8.6 summarizes the clinical studies that have investigated the effect of consumption of foods containing lupin-derived ingredients on biomarkers of chronic disease risk. These studies will now be described in more detail.

10.1 Antiobesity Effects

There is clinical evidence that foods containing lupin or its fractions can strongly reduce appetite after eating (highly satiating), an effect that may assist in long-term reduction in food intake and therefore help with maintaining healthy body weight. For example, an equal energy breakfast of wheat bread containing 40% lupin flour gave higher levels of self-reported satiety and lower energy intake at lunch, compared to a wheat flour-only bread in a study of 16 healthy adults (Lee et al., 2006). A similar study in 20 healthy adults also found a higher perception of self-reported satiety after the lupin-wheat bread than the wheat-only bread (Keogh et al., 2011). However, no differences in self-reported satiety or energy intake at lunch were reported between wheat-only and lupin-wheat bread (Hall et al., 2005b), possibly due to the lower level of lupin flour incorporation (10%). Postmeal satiety effects of lupin kernel fiber have also been reported in a study in 38 men consuming either a full fat sausage patty breakfast or a lower energy breakfast with a reduced fat-patty where some of the fat was replaced by lupin fiber (Archer et al., 2004). In this study, the satiety effect was hypothesized to due to a combination of lupin fiber's high water binding properties in the upper gastrointestinal tract (Turnbull et al., 2005) and its fermentation to short-chain fatty acids in the colon (Johnson et al., 2006).

Longer-term clinical trials over weeks or months duration have provided less convincing evidence of an “antiobesity” effect of lupin foods. For example, no differences in body weight and composition were seen in 88 overweight adults who consumed either wheat-only or 40% lupin flour bread daily for 16 weeks (Hodgson et al., 2010). Similarly, inconclusive findings were reported another study where lupin flour baked goods or breakfast cereal were consumed for 3 months as part of an energy-restricted diet (Belski et al., 2011). Based on the available evidence the promising postmeal satiety effect of lupin foods have not translated into actual effects on weight loss in clinical studies.

10.2 Type 2 Diabetes Protective Effects

Glycemic index (GI) is a concept that is often misunderstood. It refers to the ability of a portion of food containing a set amount of available (digestible)

TABLE 8.6 A Summary of the Findings of Clinical Studies Investigating Effects of Lupin Intake on Markers of Chronic Diseases

References	Lupin Fraction	Effect on Biomarker					
		Satiety/ Weight Loss	Blood Glucose	Blood Cholesterol	Blood Pressure	Bowel Function	Prebiotic
Short-term (postmeal) studies							
Archer et al. (2004)	Kernel dietary fiber	+	–	–	–	–	–
Hall et al. (2005b)	Kernel flour	o	+	–	–	–	–
Lee et al. (2006)	Kernel flour	+	+	–	–	–	–
Keogh et al. (2011)	Kernel flour	+	–	–	–	–	–
Dove et al. (2011)	Kernel flour	–	+	–	–	–	–
Bertoglio et al. (2011)	γ-conglutin rich	–	+	–	–	–	–
Long-term (dietary intervention) studies							
Hall et al. (2005a)	Kernel dietary fiber	–	o	+	–	–	–
Johnson et al. (2006)	Kernel dietary fiber	–	–	–	–	+	–
Smith et al. (2006)	Kernel dietary fiber	–	–	–	–	–	+
Lee et al. (2009)	Kernel flour	–	–	–	+	–	–
Hodgson et al. (2010)	Kernel flour	o	o	o	–	–	–
Belski et al. (2011)	Kernel flour	o	o	–	+	–	–
Sirtori et al. (2012)	Protein isolate	–	–	+	–	–	–
Bahr et al. (2013)	Protein isolate	–	–	+	–	–	–
Fechner et al. (2013)	Kernel dietary fiber	–	–	o	–	+	–
Fechner et al. (2014)	Kernel dietary fiber	–	–	+	–	+	–

+, The lupin treatment gave significantly improved levels of the biomarker compared to the control (nonlupin) treatment; o, no difference in the levels of the biomarker between the lupin and the control treatment; –, biomarker not assessed, or experimental design not valid for comparison.

carbohydrate, in comparison to a standard, such as white bread or glucose, containing the same amount of available carbohydrate, to increase the duration and amplitude of raised blood glucose levels after its consumption (Wolever et al., 1991). GI is therefore a measure of how well the absorption and metabolism of glucose from the available carbohydrate in high available carbohydrate foods can be controlled (i.e., by insulin). In light of this, lupin cannot have a measurable GI as it has virtually no available carbohydrate. Lupin, however, being very low in available carbohydrate, will intrinsically lower the glycemic load (GL) of any meal. GL is the GI of a food multiplied by its available carbohydrate (g) content per serving expressed as divided by 100 and is thus a measure of both the quantity and quality of available carbohydrates in a meal (Glycemic Index Foundation, 2016). Low GL foods in principle may improve the quality of that meal as part of a type 2-diabetes-protective diet (Buyken et al., 2010).

Furthermore, the addition of lupin flour to a starchy food, such as white bread has the potential to lower the GI of the product through its kernel fiber (Turnbull et al., 2005), which has high water binding capacity. This is as a result of the lupin reducing the rate of wheat starch digestion and glucose absorption. In addition, the high level of protein in lupin may stimulate insulin activity and thus further reduce the glycemic response. Australian sweet lupin flour added to white bread has been reported to reduce the GI of a breakfast in which it formed the major component and the bread was palatable to the healthy human volunteers (Hall et al., 2005b; Lee et al., 2006).

Ideally, clinical studies should be performed in an “at-risk” population but are difficult due to ethical considerations and the confounding factor of changes in prescribed therapy during the course of a study. Notwithstanding this complication, the effect on postmeal blood glucose and insulin levels of a glucose drink with and without lupin flour addition in type-2 diabetics has been evaluated (Dove et al., 2011). The inclusion of lupin lowered the glucose response but raised that of insulin. Blood glucose lowering activity was attributed to the γ -conglutin protein fraction of lupin seed. Evidence of just one clinical trial had demonstrated that oral intake of a lupin extract enriched with γ -conglutin can lower blood glucose (Bertoglio et al., 2011) at a dose lower than a conventional drug therapy, metformin. However, the γ -conglutin-enriched preparation was not pure (Bertoglio et al., 2011) making the findings of the study equivocal.

Two measures of good long-term blood glucose control and effectiveness of the insulin response (insulin sensitivity), and thus reduced risk of type 2 diabetes, are low fasting glucose and insulin levels. The long-term effect of incorporating lupin flour-containing foods into the diet on fasting blood glucose and insulin levels has been investigated. In one study a diet including wholemeal wheat bread and biscuits enriched with lupin flour compared to the wholemeal wheat-only control gave lower fasting insulin level but similar levels for glucose (Belski et al., 2011). In another similar study, however, no differences were found between the two diets in terms of these biomarkers (Hodgson et al., 2010).

10.3 Cardiovascular Disease Protective Effects

Reducing levels of blood total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C) and triglycerides, and increasing levels of high-density lipoprotein cholesterol (HDL-C) can reduce the risk of cardiovascular diseases (World Heart Federation, 2016). There is no conclusive evidence from long-term clinical trials that addition of lupin flour to the diet has any beneficial effects on blood cholesterol levels (Hodgson et al., 2010). In contrast, the addition of lupin kernel fiber to the diet incorporated into a range of daily food items for 28 days was found to result in a clinically significant reduction in LDL-cholesterol and TC in healthy men (Hall et al., 2005a). Beneficial effects on cholesterol levels of lupin kernel fiber consumption in a dietary intervention trial of moderately hypercholesteremic adults have also been reported (Fechner et al., 2014). The authors hypothesized that the cholesterol-lowering effect could be attributed to concurrent increase in short-chain fatty acids butyrate and acetate that were measured in the feces. In contrast, in another study on participants with normocholesterolemic, it was found that addition of lupin kernel fiber to the diet did not modify levels of blood lipids (Fechner et al., 2013).

Lupin protein isolate consumption of 25 g/day for 4 weeks has also been reported to beneficially lower LDL-C in adults with high original cholesterol levels compared to milk protein isolate (Bahr et al., 2013). Similarly, a 4-week dietary intervention involving 25 participants with moderately elevated cholesterol, where a lupin protein isolate was included in the diet, showed a significant reduction in TC compared to an equivalent case in supplemented diet which did not (Sirtori et al., 2012). It appears that the effect of lupin protein on cholesterol may only be apparent in subjects with elevated cholesterol, which is the same in the case of soy protein (Sirtori et al., 2012).

High blood pressure is an important risk factor for a cardiovascular disease (World Heart Federation, 2016). There is evidence from studies involving overweight adults that lupin flour incorporation in foods, such as bread, biscuits, and pasta, as a long-term dietary regime can result in beneficial lowering of blood pressure compared to a dietary regime with the equivalent grain foods without lupin flour (Belski et al., 2011; Lee et al., 2009).

10.4 Bowel Health Improvement Effects

Recently there has been a surge in understanding the importance of gastrointestinal microflora balance and the role of probiotic (good) bacteria in good health (Sarao and Arora, 2017). In tandem, there has been appearance of many prebiotic food ingredients, which can stimulate the growth of probiotic bacteria. There is limited but important evidence that lupin kernel fiber can act as a prebiotic ingredient and support healthy bowel function. Smith et al. (2006) reported a dietary study in which lupin kernel fiber was added into a range of daily foods (chocolate milk drink, pasta, bread, muffin, chocolate brownie, etc.)

in 18 healthy men for 4 weeks. The lupin kernel fiber containing diet, compared to the control, resulted in reduced levels of the *Clostridia* group bacteria in the feces, while concurrently increasing the levels of *Bifidobacterium* spp. that are potentially beneficial. Based on this finding, lupin kernel fiber was classified as “prebiotic” by the authors. Following the same study protocol with 38 healthy men, it was also found that the lupin kernel fiber enriched diet provided improved bowel function (e.g., reduced transit time), beneficially reduced the pH of the feces, and gave higher fecal butyrate levels (butyrate being a substrate for healthy colonic cell development), while not changing self-reported perceptions of bowel health (Johnson et al., 2006). Similarly, Fechner et al. (2013, 2014) reported beneficial effects to bowel function and fecal chemistry after addition of lupin kernel fiber to the diet.

11 CONCLUSIONS

Lupins have great potential to develop as a viable ‘alternative crop’ as part of sustainable agricultural systems for well-drained, acid, sandy soil types in low-to-medium rainfall regions with Mediterranean-type climates. Lupin seeds have a unique combination of high protein and dietary fiber when compared to other pulses and as such should increasingly contribute to the human food market as a plant protein and dietary fiber source. However, lupin seeds have a relatively thick hull compared to other legumes necessitating its removal before human consumption (Clements et al., 2005b) resulting in a high level of waste. Thus, innovation in the processing of lupin hull to convert it to a bioactive fiber from which the constituent minerals and phytochemicals are more bioavailable may provide a useful new value-added fiber ingredient. This could contribute to help fill the gap in dietary fiber intake that is prevalent throughout the developed world (Australian Bureau of Statistics, 2015). The development of high protein varieties of lupin with increased levels of sulfur-amino acids (methionine and cysteine) through conventional breeding or GM approaches holds promise to increase demand for lupin both as a higher-value food and animal feed (Glencross et al., 2007; Sipsas et al., 2004). However, the use of GM technologies risking the current GM advantage of lupin remains controversial within lupin breeding programs. NonGM molecular breeding techniques, such as CRISPR/Cas9 may thus provide better solutions to solve specific lupin seed quality objectives.

In addition to being a valuable source of protein and dietary fiber for human nutrition, it is apparent that lupin has potential as a health-promoting functional food ingredient for societies with increasing risk of obesity, diabetes, high blood pressure, cardiovascular disease, and bowel cancer. However, compared to soy there are very few clinical trials evaluating the effect of lupin on chronic disease risk biomarkers. Also, there are no major clinical studies that have compared the effects of lupin with other legumes to identify any unique benefits of lupin as a functional food. There also remains the need to substantiate the chronic

disease risk reduction properties of lupin in “at-risk” participant groups, such as those with type-2 diabetes. Lupin kernel fiber has demonstrated promising postmeal effects on satiety (e.g., Archer et al., 2004). However, its efficacy as a weight loss agent has yet to be evaluated in a long-term clinical study. The apparent potent glucose lowering effect of the γ -conglutin-rich lupin protein fraction reported by Bertoglio et al. (2011) holds great promise for the development of natural antidiabetic food ingredients. However, food grade large-scale purification processes for effective manufacture of pure γ -conglutin and/or breeding of high γ -conglutin varieties are still required as are further clinical trials to substantiate the glucose modulating activity of this lupin protein. Given the promising findings of limited clinical studies on the protective role of lupin kernel fiber in bowel health risk markers (Johnson et al., 2006), further studies to substantiate any prebiotic effects of lupin should be a priority.

The allergenicity of lupin represents a barrier to both industry and consumer uptake of lupin, especially with the recent development of an allergen-free soybean through conventional breeding (Schmidt et al., 2015); therefore, reduction of allergenicity in lupin is an important long-term breeding objective. Maintaining low and stable alkaloids levels in lupin seed will also provide a more reliable seed quality for inclusion in food products (Beyer et al., 2015).

Consumer “pull” as well as industry “push” is required to expand the uptake of lupin as human food. This consumer pull will necessitate investment through promotional campaigns to best leverage the unique properties of lupin seed as a sustainable, nutritious, and healthy human food ingredient.

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Chapter 9

African Legumes: Nutritional and Health-Promoting Attributes

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1 INTRODUCTION

Cowpea (*Vigna unguiculata* L. Walp), Bambara groundnut (*Vigna subterranean* L. Verdc), and marama bean [*Tylosema esculentum* (Burchell) A. Schreiber] (Fig. 9.1A–C) are among some of the most significant African legumes. Cowpeas and Bambara groundnuts are grain legumes or pulses similar to the common bean, while marama bean is considered as an oilseed legume similar to soybean or peanuts. Two other African legumes of interest are the West African locust bean [*Parkia biglobosa* (Jacq.) R. Br. ex G. Don] which is an oilseed legume and the African yam bean [*Sphenostylis stenocarpa* (Hochst. ex. A. Rich.) Harms] which is a pulse (Fig. 9.1D–F). All these legumes are indigenous to Africa and are consumed in various forms in African communities.

The production and utilization of these legumes is by no means restricted to Africa. For instance, cowpeas are very well-known in the USA (commonly called black-eyed peas), which is also a significant producer and exporter. Cowpeas are also a significant crop in Latin America with countries such as Brazil and Ecuador being important producers and consumers. There is considerable and increasing interest in Bambara groundnuts in South-east Asia and it is grown in countries such as India, Malaysia, Philippines, and Thailand. Therefore, these legumes may be regarded as important food crops not just in Africa but also worldwide.

Despite their importance as food sources, these legumes are relatively underutilized and underresearched as compared to other well-known legumes, such as the common bean. The marama bean for instance, is currently not formally cultivated but grows wild in arid regions of Southern Africa. Due to the fact that these legumes are underutilized and underresearched, they are considered as neglected food crops and have actually been described as “lost crops of Africa” (National Research Council, 2006). These legumes are important plant



FIGURE 9.1 African legumes. (A) Cowpeas, (B) Bambara groundnuts, (C) marama beans (D) unfermented African locust bean, (E) fermented African locust bean, and (F) African yam bean (*Images courtesy: Parts A–C, K.G. Duodu; Parts D–E, Y.A. Duodu; Part F, Adewale and Dumet, 2010.*)

protein sources and play a significant role as suppliers of protein and essential (indispensable) amino acids among rural African communities, who often have limited access to animal sources of protein due to its high cost. They also provide micronutrients, such as vitamins and minerals. As an oilseed legume, the marama bean is also a potentially significant source of oil.

Apart from their nutrients, African legumes are also sources of nonnutritive phytochemical constituents for which there is significant evidence about their health benefits. In most of sub-Saharan Africa, rapid urbanization accompanied by poor dietary choices are contributing factors for the growing incidence of diet-related noncommunicable diseases, such as cancer, cardiovascular diseases, and diabetes. Research also shows that these African legumes are important sources of bioactive components, such as phenolic compounds, which may contribute in health-promoting properties ([Hachibamba et al., 2013](#); [Nderitu et al., 2013](#)).

There is growing awareness about climate change and global warming that bring with them extreme weather events and variable climates that negatively affect food and water supplies. Climate change is projected to have a negative effect on agricultural productivity and food security [Food and Agricultural Organization ([FAO](#)), 2016a] and the sub-Saharan African region is expected to be one of the hardest hit ([Zewdie, 2014](#)). However, an important feature of these African legumes is the fact that they are drought tolerant. Therefore, they could be regarded as strategic, climate-friendly food sources worldwide.

This chapter reviews the nutritional and health-promoting properties of African legumes, specifically cowpea, Bambara groundnuts, marama bean, African locust bean and yam bean. Given the fact that they are underutilized and underresearched, the overall aim is to highlight their significance as climate-friendly African legumes with an important role to play as food sources not only in sub-Saharan Africa but also in other parts of the world.

2 PRODUCTION AND UTILIZATION OF AFRICAN LEGUMES

2.1 Production

According to statistics from the FAO, over the period from 1993 to 2014, world production of cowpeas and Bambara groundnuts was predominantly from Africa ([FAOSTAT, 2016](#)). Four of the top five cowpea-producing countries in the world were from Africa (Nigeria, Niger, Burkina Faso, and Tanzania) and these accounted for 95.3% of the world cowpea production. With an average production of 2.5 million metric tons, Nigeria was the top world producer of cowpeas. Over the period, world production of Bambara groundnuts was exclusively from Africa with the major producers listed as Burkina Faso, Mali, Cameroon, Niger, and the Democratic Republic of Congo. In contrast to cowpeas, production of Bambara groundnuts is on a smaller scale. Burkina Faso, the top Bambara groundnut producing country registered an average production of 41,900 metric tons from 1993 to 2014. As stated, unlike cowpeas and Bambara groundnuts,

the marama bean is a nondomesticated, wild growing oilseed legume that has not been subjected to cultivation and commercial production. As a result, there are no production statistics available for marama beans. Various aspects of the marama beans including agronomic characteristics, nutritional properties, processing, and utilization have been reviewed extensively by [Jackson et al. \(2010\)](#).

The African locust bean is a leguminous tree species that grows extensively in the Savanna regions of West Africa. Most of the existing trees are wild growing without any form of deliberate cultivation and production efforts. However, in recent years, there have been research efforts aimed at conserving and improving its germplasm by application of agronomic measures ([National Research Council, 2006](#)). The African yam bean is a tuberous legume and described as a climbing herbaceous vine. Although, there is some cultivation of this legume, it appears this is not on a very large scale and restricted to only subsistence levels. According to the [FAO \(2016b\)](#), both wild and cultivated varieties of the African yam bean occur across a broad region of sub-Saharan Africa. The African yam bean occurs in East Africa from Eritrea to Zimbabwe in South Africa, and also throughout the West Africa from Guinea to Southern Nigeria to Togo and the Ivory Coast.

An important aspect of these legumes is the contribution that they make toward sustainable agriculture, mainly by their use in intercropping and crop rotation systems. Cowpea, Bambara groundnut, and African yam bean for instance, are noted to have significant ability to fix nitrogen in the soil and therefore are valued as “green manure” due to their contribution to soil fertility. Cowpeas are regularly intercropped with cereals such as sorghum and maize, while the African yam bean is usually grown together with maize and cassava.

2.2 Utilization

The food uses of cowpea and Bambara groundnut are largely very similar. The dried grains can be boiled, seasoned, and cooked into savory stews which may be eaten with various dishes made from boiled or fried roots and tubers. Cowpea grains in particular may be cooked in combination with cereals, such as rice or parboiled maize in the preparation of composite foods ([Madodé et al., 2011](#)). In West African countries, such as Nigeria and Ghana, seasoned cowpea pastes are deep fried to produce “*akara*” (in Nigeria) or “*koose*” (in Ghana) or steamed to obtain “*moin-moin*” (in Nigeria) ([Phillips and McWatters, 1991](#); [Taiwo, 1998](#)). These pastes are traditionally prepared first by dehulling the grains after soaking in water so as to loosen the seed coat, followed by grinding the dehulled grains into a paste using either a stone, mortar, electric blender, or a commercial mill ([Dovlo et al., 1976](#)). In contrast, utilization of marama beans for food is not on a comparable level with cowpea and Bambara groundnut. This is essentially due to the fact that marama beans grow wild. The seed coats are discarded and the cotyledons are roasted and consumed as a snack mainly by the San community of the Kalahari in Southern Africa ([Jackson et al., 2010](#)). The dual use of these

legumes in the sense that apart from the seeds, the leaves of cowpea and Bambara groundnut may also be consumed as green leafy vegetables is worthy of note.

Another important form in which the seeds of these African legumes are utilized is as flours which can be used in various food applications. Dehulled cowpea or Bambara groundnut grains can be milled into flour and blended with wheat flour to produce various baked goods, such as bread, cookies, and muffins (Sharma et al., 1999). Such flours can also be used as ingredients in weaning foods. In a recent EU research project, the production of defatted flours from marama bean (Maruatona, 2008) for use in various food applications has been studied (Jackson et al., 2010).

Seeds of the African locust bean are processed into a food condiment commonly called “*dawadawa*” (Fig. 9.1E) by the Hausa community of Nigeria and used as a food seasoning and as an ingredient in the preparation of stews. The condiment is produced after a period of fermentation of the cooked and dehulled locust bean seeds (FAO, 2016c). The African yam bean is grown primarily for its dry seeds although its roots and leaves are also used as food sources. However, it is not to be confused with the yam bean “*jicama*” [*Pachyrhizus erosus* (L.) Urb.] which has its origins in Latin America (FAO, 2016b) and whose round tubers are sold in many US supermarkets and are used in salads (National Research Council, 2006). Food uses of African yam bean seeds are very similar to those for cowpea and Bambara groundnut. The dried seeds are grounded into flour, processed into paste with water and condiments, wrapped in plantain leaves, and boiled and eaten as a snack. The cooked seeds can also be made into sauces and eaten with starchy staples. There are also references to the consumption of the starch-rich and tuberous roots also in salads or in flour form and consumption of the leaves of the yam bean plant as a type of spinach (FAO, 2016b).

3 NUTRITIONAL QUALITY OF AFRICAN LEGUMES

3.1 Macronutrients

3.1.1 Proximate composition of African legumes

Table 9.1 shows the proximate composition of African legumes in comparison with the more commonly consumed common (*Phaseolus* type) bean and soybean. Their high protein content (at least 19%) is typical of legumes. Cowpea, Bambara groundnut, and African yam bean (regarded as pulses) are generally similar in proximate composition to the common bean (Table 9.1) and have higher carbohydrate content (mostly starch) compared to marama bean and African locust bean. In contrast, marama bean and African locust bean contain high oil content than cowpea and Bambara groundnut. The high oil content of marama bean is comparable to that of oilseeds used for the production of commercial vegetable oils, such as soybean (as shown in Table 9.1) sunflower, rapeseed, and peanuts (Jackson et al., 2010).

TABLE 9.1 Proximate Composition (g/100 g) of African Legumes in Comparison With Common Bean and Soybean

	Cowpea ^a	Bambara Groundnut ^b	Marama Bean ^c	African locust Bean ^b	African yam Bean ^b	Common White Bean (<i>Phaseolus vulgaris</i>) ^a	Soybean ^a
Moisture	11.95	8.4	3.5	7.0	13.3	11.32	8.54
Lipid	1.26	5.9	36.8	19.5	1.5	0.85	19.94
Protein	23.52	20.1	31.7	32.3	18.9	23.36	36.49
Carbohydrate	60.03 (difference)	58.9 (available)	2.5 (difference)	33.0 (available)	47.1 (available)	60.27 (difference)	30.16 (difference)
Dietary fiber	10.6	3.7	22.6	4.1	16.7	15.2	9.3
Ash	Np	3.1	2.9	4.1	2.6	Np	Np

Np, Not provided.

^aUSDA NDL (2016).^bFAO (2012).^cHolse et al. (2010) (recalculated from values reported on dry basis).

3.1.2 Starch

The starch in cowpea, Bambara groundnut, and African yam bean is stored in starch granules that are generally described as oval or elliptical in shape of variable sizes (reviewed by Emmambux and Taylor, 2013). Cowpea starch granules have been described as ellipsoidal (Jane et al., 1994), oval and kidney shaped (Agunbiade and Longe, 1999). Bambara groundnut starch granules have been described variously as being elliptical, spherical (Enwere and Huang, 1996), oval and round (Adebowale and Lawal, 2002; Sirivongpaisal, 2008) in shape. African yam bean starch granules have been described as oval and kidney shaped (Agunbiade and Longe, 1999), or oval and round (Adebowale et al., 2009), while African locust bean starches have been described as large, rhombic with some of small size (Ihegwuagu et al., 2009), or oval (Sankhon et al., 2012). A very wide range of granule sizes for cowpea, Bambara groundnut, and African yam bean starch has been reported from as low as 1 μm to as high as 92 μm (reviewed by Emmambux and Taylor, 2013). Cowpea, Bambara groundnut, and African locust bean starches seem to have similar starch amylose contents of 27%–29% (Ashogbon and Akintayo, 2013), 22% (Sirivongpaisal, 2008), and 23.8% (Ihegwuagu et al., 2009), respectively. African yam bean starch appears to have relatively higher starch amylose content with values of 35.2% (Adebowale et al., 2009) and 34.4% (Agunbiade, 1998) reported.

In contrast to the other African legumes considered here, marama bean seeds do not contain starch. The starch content of marama bean is negligible (0.2% dry matter) (Mosele et al., 2011). A spectroscopic study of marama bean using techniques including proton NMR and Fourier Transform Raman spectroscopy reported detection of no starch (Holse et al., 2011).

3.1.3 Protein and amino acid composition

Using the well-known Osborne-type protein fractionation procedure, seed proteins can be fractionated into albumins (water soluble), globulins (salt soluble), prolamins (aqueous alcohol soluble), and glutelins (acid/alkali soluble). In cowpea, globulins occur in greatest proportion (48%–90%) compared to albumins (3%–14%), prolamins (5%–13%), and glutelins (7%–23%) (Chavan et al., 1989). In contrast, it appears that albumins (73%) represent the major protein fraction in Bambara groundnut, followed by glutelins (8.6%), globulins (8.2%), and prolamins (0.8%) (Yagoub and Abdalla, 2007). Globulins (53%) are the most abundant protein constituents in marama beans, followed by albumins (23.3%), prolamins (15.5%), alkali-soluble glutelins (7.7%), and acid-soluble glutelins (0.5%) (Bower et al., 1988).

The legume globulins can be separated usually by ultracentrifugation or chromatography into two major components, namely vicilin (7S) and legumin (11S). The vicilin component is reported to be the major protein in cowpea and more closely related to soybean globulin (Sefa-Dedeh and Stanley, 1979). According to Amonsou et al. (2012), the vicilin and acidic 11S globulin components seemed to be absent in marama bean. These authors reported the presence

of a major basic legumin (11S) and some medium (63 kDa) and high (148 kDa) molecular weight proteins in marama bean.

Table 9.2 shows the amino acid composition of African legumes in comparison with common beans and soybean. The amino acid composition of cowpea, Bambara groundnut, and African locust bean is generally similar to common bean and dominated by asparagine, glutamine, leucine, phenylalanine + tyrosine, lysine, and arginine. The African yam bean similarly contains significant levels of lysine, asparagine, glutamine, and glycine. Marama bean is rich in asparagine, glutamine, leucine, and arginine but particularly richer in phenylalanine + tyrosine as compared to the other African legumes, common bean and soybean. As would be expected, all the African legumes are rich in lysine (unlike in cereals) but have very low levels of sulfur-containing amino acids, in which regard they compare fairly well with common bean and soybean. This underscores the utility of these legumes as components of composite foods together with cereals (often referred to as “blends” as in corn-soy blend) for improved protein quality. Overall, these African legumes have good nutritional value with regard to indispensable amino acids and are able to meet the recommended daily requirements for adults on a 100 g protein basis.

It has been hypothesized that the strong presence of aromatic (histidine, phenylalanine, and tyrosine) and aliphatic (alanine, isoleucine, leucine, proline, and valine) amino acids in marama bean could make marama bean protein more hydrophobic and stable than other legume proteins, such as soybean (Amonsou et al., 2012). An examination of the amino acid composition of African legumes, particularly cowpea and Bambara groundnut, suggests that this hypothesis could also apply to their proteins. Amonsou et al. (2012) further hypothesized that the high tyrosine content of marama bean could also contribute to the stability of its protein due to the possibility of forming dityrosine crosslinks.

3.1.4 Lipid and Fatty Acid Composition

As mentioned, the lipid contents of cowpea, Bambara groundnut, and African yam bean (shown in Table 9.1) are typical of pulses and those of marama bean and African locust bean are typical of oilseeds. Pulses store their energy mainly in the form of starch, hence the high starch contents of cowpea and Bambara groundnut. Oilseeds, such as marama bean store their energy mainly in the form of triglycerides, hence their high-oil content. The marama bean is therefore a leguminous crop that could potentially be processed for its oil just like other oilseeds, such as sunflower and soybean. A recent European Union project conducted extensive research into the properties of marama bean oil as an edible vegetable oil and concluded that marama bean oil had great potential in terms of consumer acceptability as a cooking oil although its potential acceptability as a salad oil is unexplored (Jackson et al., 2010).

Table 9.3 shows the fatty acid composition of oil from African legumes in comparison with common bean and soybean. All the African legumes are rich in unsaturated fatty acids with high proportions of linoleic acid (C18:2).

TABLE 9.2 Amino Acid Composition (g/100 g Protein) of Cowpea, Bambara Groundnut, and Marama Bean

	Cowpea ^a	Bambara Groundnut ^b	Marama Bean ^c	African Locust Bean ^d	African Yam Bean ^e	Common White Bean (<i>P. vulgaris</i>) ^a	Soybean ^a	WHO Requirements for Adults ^f
Essential (indispensable) amino acids								
Leucine	7.7	7.8	7.9	7.4	4.3	8.0	9.1	5.9
Isoleucine	4.1	4.3	4.3	2.4	2.3	4.4	5.4	3.0
Valine	4.8	5.3	4.8	4.1	4.0	5.2	5.6	3.9
Threonine	3.8	3.3	3.2	2.8	4.3	4.2	4.8	2.3
Phenylalanine + tyrosine	9.1	9.3	15.1	8.2	5.6	8.2	10.0	3.8
Lysine	6.8	6.6	5.7	6.6	7.1	6.9	7.4	4.5
Histidine	3.1	3.2	2.7	2.7	3.6	2.8	3.0	1.5
Methionine + cystine	2.5	2.9	1.1	2.9	2.8	2.6	3.3	2.2
Arginine	6.9	6.4	8.0	6.8	3.5	6.2	8.6	
Nonessential amino acids								
Asparagine	12.1	10.6	9.4	6.9	7.9	12.1	14.0	
Glutamine	18.9	17.0	15.2	14.1	10.6	15.2	21.6	
Serine	5.0	5.1	5.5	4.8	3.5	5.4	6.5	
Glycine	4.1	3.6	5.9	4.7	6.3	3.9	5.2	
Alanine	4.6	4.3	3.5	3.7	5.4	4.2	5.2	
Proline	4.5	4.9	7.2	2.6	2.4	4.2	6.5	

^aUSDA NDL (2016).^bApata and Ologhobo (1994).^cAmonsou et al. (2012).^dHassan and Umar (2005).^eEkop (2006).^fWHO (2007).

TABLE 9.3 Fatty Acid Composition (% Total Fatty Acids)^a of African Legumes, Common Bean, and Soybean

Fatty Acid	Cowpea ^b	Bambara Groundnut ^c	Marama Bean ^d	African Locust Bean ^e	African Yam Bean ^f	Common White Bean (<i>P. vulgaris</i>) ^b	Soybean ^b
Lauric acid (C12:0)	0.10	—	—	—	1.45	—	—
Myristic acid (C14:0)	0.31	—	—	—	2.53	0.15	0.30
Palmitic acid (C16:0)	26.51	20.89	13.80	—	19.31	31.20	11.41
Palmitoleic acid (C16:1)	0.42	0.30	0.56	12.38	—	—	0.30
Margaric acid (C17:0)	—	0.71	—	—	—	—	—
Stearic acid (C18:0)	5.53	7.23	8.05	11.43	4.54	1.98	3.84
Oleic acid (C18:1)	9.19	22.96	42.16	16.19	40.72	11.26	23.45
Linoleic acid (C18:2)	35.80	36.48	31.11	55.24	22.49	30.14	53.53
Linolenic acid (C18:3)	20.77	1.32	—	—	2.39	25.27	7.17
Arachidic acid (C20:0)	—	2.03	2.50	4.76	1.06	—	—
Gadoleic acid (C20:1)	0.10	0.56	—	—	0.44	—	—
<i>cis</i> -11,14-Eicosadienoic acid	—	0.07	—	—	—	—	—

(C20:2, <i>n</i> – 6)	—	—	—	—	—	—	—
Arachidonic acid (C20:4, <i>n</i> – 6)	—	0.05	0.40	—	—	—	—
Behenic acid (C22:0)	—	5.49	1.44	—	2.39	—	—
Erucic acid (C22:1)	1.25	—	—	—	—	—	—
Lignoceric acid (C24:0)	—	1.89	—	—	—	—	—

^aAll % total fatty acids values have been recalculated based on provided values of % oil content and % fatty acid content of the seed.

^bUSDA NDL (2016).

^cYao et al. (2015).

^dJackson et al. (2010).

^eElemo et al. (2011).

^fNwokolo (1987).

Marama bean and African yam bean contain up to about twice the proportions of the monounsaturated oleic acid (C18:1) compared to the other legumes. Interestingly, cowpea and the common bean contain a higher proportion of the polyunsaturated linolenic acid (C18:3) than soybean. With the exception of African locust bean, all the African legumes also contain significant proportions of the saturated palmitic acid (C16:0).

3.1.5 *NonStarch polysaccharides*

Some data on dietary fiber in the African legumes are also shown in [Table 9.1](#). It must, however, be borne in mind that dietary fiber values for these legumes are variable, in part as a result of the use of different methods of fiber analysis. [Tshovhote et al. \(2003\)](#), reported dietary fiber levels ranging from 5.2%–5.8% in three South African cowpea varieties. [Khan et al. \(2007\)](#) reported total dietary fiber content of 18.2% in cowpeas of which 14.8% was insoluble dietary fiber and 3.3% was soluble dietary fiber.

[Jideani and Maphosa \(2016\)](#) reported yield of soluble dietary fiber in Bambara groundnut in the range of 15.4%–17.1%. Yield of insoluble dietary fiber was in the range of 12%–15.6%. They reported the presence of various sugars, such as arabinose, galactose, fucose, mannose, rhamnose, and xylose as well as uronic acids in the Bambara groundnut dietary fiber material. The presence of these sugars in the Bambara groundnut dietary fiber material is indicative of the presence of nonstarch polysaccharides, such as galactomannans, arabinoxylans, arabinogalactans, rhamnogalacturonans, and pectic substances.

Total dietary fiber in marama bean has been reported to be between 18.7% and 26.8% ([Holse et al., 2010](#)). It consists predominantly of insoluble dietary fiber with only about 4% occurring as soluble dietary fiber. Marama bean appears to have a higher dietary fiber content compared with other leguminous oilseeds, such as peanuts (9%) and soybeans (10%) ([Holse, 2012](#)). Carbon-13 NMR studies of marama bean soluble and insoluble polysaccharides showed a major contribution from ester and acid groups which pointed to the significant presence of pectins or galacturonic acids. Complementary Raman spectroscopic studies indicated that a large portion of the insoluble polysaccharides in marama bean is homogalacturonans. [Mosele et al. \(2011\)](#) also used histochemical methods and electron microscopy to show that most of the carbohydrates in marama bean are insoluble polysaccharides present in cell walls.

3.2 **Micronutrients**

3.2.1 *Vitamins and minerals*

The levels of some vitamins and minerals in African legumes in comparison to soybean are shown in [Table 9.4](#). The marama bean stands out as having higher levels of the fat-soluble vitamins (A, D, and E) than the other African legumes and soybean. [Holse et al. \(2010\)](#) conducted a study of various marama bean

TABLE 9.4 Vitamin and Mineral Content^a of African Legumes in Comparison With Soybean

	Cowpea ^b	Bambara Groundnut ^b	Marama Bean ^c	African Locust Bean ^b	African Yam Bean ^b	Soybean ^d
<i>Vitamins</i>						
Vitamin A-RAE (μg)	3	2	270			1
Retinol (μg)	0	0				
β-Carotene eq. (μg)	32	10–30				13
Vitamin D (IU)	0	0	132.9 IU			
Vitamin E (mg)	0.42		6.27			0.85
Thiamin (mg)	0.71	0.30–0.47	0.38	0.3	0.69	0.87
Riboflavin (mg)	0.15	0.10–0.14	0.06	0.2		0.87
Niacin (mg)	3.1	1.8–2.0	9.21	3.0		1.62
Vitamin B6 (mg)	0.20–0.51		1.71			0.38
Folate (μg)	395–439		140			375
Vitamin B12 (μg)	0	0	0.4			
Vitamin C (mg)	0.8	Tr		6		6
<i>Minerals</i>						
Calcium (mg)	82	65	119–133	291	40	277
Iron (mg)	7.3	3.3	1.3–3.7	33.2	4.1	15.7
Magnesium (mg)	187	199	248–374			280

(Continued)

TABLE 9.4 Vitamin and Mineral Contenta of African Legumes in Comparison With Soybean (*cont.*)

	Cowpea ^b	Bambara Groundnut ^b	Marama Bean ^c	African Locust Bean ^b	African Yam Bean ^b	Soybean ^d
Phosphorus (mg)	387	275	334–554	384	253	704
Potassium (mg)	1210	1190	757–1316		1290	1797
Sodium (mg)	19	29	0.2–2.9		2	2
Zinc (mg)	4.61	3.38	3.3–3.8		2	4.89
Copper (mg)	0.68	0.89	0.6–1.6			1.66

IU, International unit; RAE, retinol activity equivalents; Tr, trace.

^aValues for cowpea and Bambara groundnut given per 100 g edible portion; values for the other legumes given per 100 g as is basis.

^bFAO (2012).

^cVitamin data from *Müseler and Schönfeldt (2006)*; minerals data from *Holse et al. (2010)*.

^dUSDA NDL (2016).

samples sourced from Botswana, Namibia, and South Africa and reported that the vitamin E consisted predominantly of γ -tocopherol with much lower proportions of α - and β -tocopherol. They reported only traces of δ -tocopherol and some β - and γ -tocotrienol were found in some samples. No α - and δ -tocotrienol was found in marama bean.

For the water-soluble vitamins, [Table 9.4](#) also shows that the African legumes (with the exception of African yam bean) contain higher levels of niacin compared to soybean, while cowpea and marama bean contain appreciable levels of folate. Generally, levels of other water-soluble vitamins, such as thiamin and riboflavin in the African legumes are similar to soybean.

With regard to their mineral contents, using soybean as a reference, the African legumes generally contain appreciable levels of the macroelements, such as calcium, magnesium, phosphorus, potassium, and trace minerals, such as iron and zinc ([Table 9.4](#)). The prevalence of vitamin and mineral deficiencies is a problem not only in sub-Saharan Africa but also in various other communities around the world. African legumes could therefore play an important role in alleviating the effects of micronutrient deficiencies within vulnerable communities throughout the world. However, mineral bioavailability may be an issue ([Section 3.3](#)).

3.3 Non-nutritive Phytochemical Constituents

Phytochemicals are nonnutritive chemical plant constituents that are capable of health-promoting effects ([Khan et al., 2015](#)). They are produced in plants to function as chemical defense compounds, especially in plants that produce energy-rich stores either as carbohydrates, lipids, or proteins in their seeds ([Enneking and Wink, 2000](#)). This is particularly the case with legume seeds. These chemical defense compounds are developed and accumulated in the seeds against herbivorous animals, microorganisms, and viruses and have often been referred to as antinutritional or toxic factors. Although the terms “antinutritional” and “toxic” do not sound positive, this needs to be seen in the correct perspective. The fact of the matter is that these compounds can be significantly and effectively reduced or removed from legumes using most normal food processing techniques (as shown in [Table 9.7](#)) and therefore do not present any problems with regard to exerting any antinutritional or toxic effects in processed legume foods.

It is critical to be aware that the occurrence of these so-called antinutritional factors is by no means restricted to African legumes as they are also present in the more mainstream legumes such as the common bean, as shown in [Tables 9.5 and 9.6](#). Some of these compounds reported in African legumes will now be briefly discussed including food-processing techniques for their reduction or removal. There is also increasing focus on the more positive aspects of these compounds, such as their potential health-promoting properties which will also be discussed.

TABLE 9.5 Levels of Enzyme Inhibitors, Polyphenols, and Phytate Reported in African Legumes in Comparison With Common Bean

Samples	Enzyme Inhibitors	Polyphenols/Tannin	Phytate	References
Cowpea				
	12.5 trypsin inhibitor units/mg	2.85 g/100 g	1.65 g/100 g	Fasoyiro et al. (2006)
	2.97 Trypsin inhibitor units/mg		11.66 mg/g	Batista et al. (2010b)
	20.39 α -Amylase inhibitor units/100 mg			Batista et al. (2010b)
	15.1 Trypsin inhibitor units/mL		335.0 mg/100 g	Akinyele (1989)
	13.02 mg Trypsin inhibitor units/g	2.23 mg/g	0.46 g/100 g	Egounlety and Aworh (2003)
	9.8–20.5 mg Trypsin inhibitor units/g	1.24–1.42 mg/g	7.29–9.92 mg/g	Ene-Obong (1995)
	2400.91 Trypsin inhibitor units/g	22.63 mg/g	0.801 g/100 g	Khattab and Arntfield (2009)
	1589.91 Trypsin inhibitor units/g	26.14 mg/g	0.979% g/100 g	Khattab and Arntfield (2009)
	19.6–28.2 Trypsin inhibitor units/mg protein		280–331 mg/100 g	Ologhobo and Fetuga (1983)
	6891 Trypsin inhibitor units/g	12.1 mg/g	14.0 mg/g	Sreerama et al. (2012b)
	8.33–17.34 Trypsin inhibitor units/mg protein		2.55–5.26 mg/g	Umoren et al. (1997)
	1.0 mg Trypsin inhibitor/kg	6.04 mg/kg	18.22 mg/kg	Abiodun and Adeleke (2011)
	29.65 Trypsin inhibitor units/mg	210.17 mg/g	4.54 g/100 g	Ibrahim et al. (2002)
	6700 Trypsin inhibitor units/g			Dos Anjos et al. (2016)
	2200 Trypsin inhibitor units/g			Dos Anjos et al. (2016)
	29292 Trypsin inhibitor units/g	0.25 g/100 g		Vilakati et al. (2015)
	25.60 Trypsin inhibitor units/mg	3.42%		Onwuka (2006)
	2489.0 μ g/g Trypsin inhibitor activity			Prinyawiwatkul et al. (1996)

Bambara groundnut	5.65–6.03 Trypsin inhibitor units /mg protein		308.83–380.34 mg/100 g	Devi et al. (2015)
	2.3–3.8 Trypsin inhibitor units/mg protein			Carvalho et al. (2012)
	2.2–4.2 Chymotrypsin inhibitor units/mg protein			Carvalho et al. (2012)
	37–91 Trypsin inhibitor units/mg protein	3.90–11.96 g/kg	6.20–15.25 g/kg	Marconi et al. (1997)
	9.01–25.9 Trypsin inhibitor units/mg			Marconi et al. (1993)
	6.74–23.8 Chymotrypsin inhibitor units/mg			Marconi et al. (1993)
	19.08 Trypsin inhibitor units/mg	6.47 g/100 g	4.17 g/100 g	Fasoyiro et al. (2006)
	6.7 mg Trypsin inhibited/100 g	0.39 mg/100 g 4.60 mg/100 g	46.37 mg/100 g 1478.15 mg/100 g	Oluwole and Taiwo (2009) Mazahib et al. (2013)
		0.96 mg/100 g	15.30 mg/100 g	Adegunwa et al. (2014)
Marama bean			1.1 g/100 g	Yao et al. (2015)
	17.94 mg Trypsin inhibitor units/g	0.62 mg/100 g	255 mg/100 g	Okafor et al. (2014)
	43.9–68.4 Trypsin inhibitor units/mg protein	0.01%–0.493%		Tibe et al. (2007)
	18.70 mg/g	0.11 mg/100 g	13.2 mg/100 g	Omoikhoje et al. (2006)
	6.0–6.6 mg Trypsin inhibitor activity/g	450–470 mg/kg		Barimalaa and Anoghalu (1997)
Marama bean	255.6 Trypsin inhibitor units/mg			Richards et al. (2014)
	250.8 Trypsin inhibitor units/mg			Maruatona (2008)

(Continued)

TABLE 9.5 Levels of Enzyme Inhibitors, Polyphenols, and Phytate Reported in African Legumes in Comparison With Common be (*cont.*)

Samples	Enzyme Inhibitors	Polyphenols/Tannin	Phytate	References
African locust bean		0.15 g/kg	0.84 g/kg	Enujiugha and Ayodele-Oni (2003)
	19.4 mg/100 g Trypsin inhibitor		163.0 mg/g	Elemo et al. (2011)
	2.9 mg/g Trypsin inhibitor activity	40 mg/g	2.4 mg/g	Esenwah and Ikenebomeh (2008)
African yam bean				
	0.8 mg/kg Trypsin inhibitor	10.59 mg/kg	30.71 mg/kg	Abiodun and Adeleke (2011)
	1.47 mg/100 g Protease inhibitor	5.13 mg/100 g	18.23 mg/100 g 2.4%	Oke et al. (2013) Oboh (2006)
	24.37; 26.98 Trypsin inhibitor units/mg	7.45; 8.99 g/100 g 0.95–6.25 mg/100 g	4.18; 5.05 g/100 g	Fasoyiro et al. (2006) Aminigo and Metzger (2005)
	17.11–33.56 Trypsin inhibitor units/mg	3.95–7.83 g/100 g	3.30–4.20 g/100 g	Ajibade et al. (2005)
	25.4; 30.8 mg Trypsin inhibited/g	5.32; 7.80% 0.14 mg/100 g	0.148 mg/100 g	Onyeike and Omubo-Dede (2002) Oboh et al. (1998)

Common bean (<i>Phaseolus</i> spp.)				
	2.5–14.9 α -amylase inhibitor units/mg protein			Mojica and Gonzalea de Mejia, 2015
	28.46; 28.54 Trypsin inhibitor units/mg		19.18; 20.19 mg/g	Pedrosa et al. (2015)
	27.7; 38.3 Trypsin inhibitor units/mg			Olmedilla-Alonso et al. (2013)
	15.12–20.12 μ g/mg Trypsin inhibitor	0.18–10.38 mg/g		Campion et al., 2013
	20.34 Trypsin inhibitor units/mg		1152.16 mg/100 g	Ertas and Turker (2012)
	33.9; 42.3 Trypsin inhibitor units/mg			Piergiiovanni et al. (2012)
	4.61; 4.64 Trypsin inhibitor units/mg		8.18; 11.26 mg/g	Batista et al. (2010a)
	16.08; 18.16 α -amylase inhibitor units/100 mg			Batista et al. (2010a)
	5.92–10.9 mg/g Trypsin inhibitor activity	0.03–19.9 g/kg	9.9–13.8 g/kg	Wang et al. (2010)
	37.7–818.3 Trypsin units inhibited/g			Deepika and Nath (2010)
	55.7–892.7 Trypsin units inhibited/g			Deepika and Nath (2010)
	3122.78; 3583.22 Trypsin inhibitor units/g	26.66; 67.09 mg/g	1.158; 1.188 g/100 g	Khattab and Arntfield (2009)

TABLE 9.6 Levels of Indigestible Oligosaccharides Reported in African Legumes in Comparison With Common Bean

Legume Types	Stachyose	Raffinose	Verbascose	References
Cowpea				
	2.38–3.87 g/100 g	0.71–6.86 g/100 g		Nwinuka et al. (1997)
	2.9 g/100 g	2.4 g/100 g		Akinyele (1989)
	3.53 g/100 g	0.78 g/100 g		Egounlety and Aworh (2003)
	1.99 g/100 g	0.84 g/100 g	1.36 g/100 g	Khattab and Arntfield (2009)
	1.92 g/100 g 1.78 g/100 g	1.67 g/100 g 1.03 g/100 g	1.79 g/100 g 0.36 g/100 g	Khattab and Arntfield (2009) Sreerama et al. (2012b)
	2.04 g/100 g	0.52 g/100 g		Ibrahim et al. (2002)
	4.44 g/100 g	0.41 g/100 g	0.48 g/100 g	Sosulski et al. (1982)
Bambara groundnut				
	1.89 g/100 g 1.00; 0.75 g/100 g	2.85 g/100 g 0.27; 0.22 g/100 g		Omoikhoje et al. (2006) Apata (2008)
African yam bean				
	1.81–2.46 g/100 g	0.29–0.82 g/100 g	0.11–0.15 g/100 g	Azeke et al. (2007)
	2.863 g/100 g	0.664 g/100 g	0.317 g/100 g	Oboh et al. (2000)
	4.14 g/100 g	1.08 g/100 g		Nwinuka et al. (1997)
Common bean (<i>Phaseolus</i> spp.)				
	2.724; 2.792 g/100 g	1.245; 1.280 g/100 g		Pedrosa et al., 2015
	2.29; 2.75 g/100 g	0.33; 0.40 g/100 g		Olmedilla-Alonso et al. (2013)
	3.04–3.59 g/100 g 2.27; 2.31 g/100 g	0.13–0.68 g/100 g 1.78; 1.79 g/100 g	0.023–0.151 g/100 g 1.96; 2.08 g/100 g	Wang et al. (2010) Khattab and Arntfield (2009)

3.3.1 *Enzyme inhibitors*

As the name suggests, these are chemical components which inhibit digestive enzymes which is how they exert antinutritional effects. The most predominant enzyme inhibitor in African legumes is the trypsin inhibitor (Table 9.5), although others such as α -amylase inhibitors have also been reported. These inhibitors are themselves proteins. According to Rao and Suresh (2007), most protease inhibitors in legume seeds have low molecular weight (4–20 kDa) and have nonglycosylated polypeptide chains. As can be seen, a wide range of trypsin inhibitor activities have been reported in African legumes.

3.3.2 *Polyphenolic compounds*

Phenolic compounds are ubiquitous in the plant kingdom. The major phenolic compounds in legume seeds are phenolic acids, flavonoids (Hachibamba et al., 2013), anthocyanins (Ojwang et al., 2012), and proanthocyanidins (Ojwang et al., 2013). The phenolic compounds are concentrated in the seed coat of legumes (Dueñas et al., 2006). Generally, pigmented legumes have higher phenolic content than nonpigmented or less-pigmented cultivars of the same legume type (Kayitesi, 2013; Nderitu et al., 2013). With regard to antinutritional effects, the proanthocyanidins (also called condensed tannins) seem to be the most important of the phenolic compounds. These condensed tannins are essentially oligomers and polymers of flavonoids, such as flavan-3-ols. Proanthocyanidins reported in cowpea include procyanidin dimers, trimers (Nderitu et al., 2013), prodelphinidin oligomers (Kayitesi, 2013), and other oligomers and polymers with degree of polymerization exceeding 10 (Ojwang et al., 2013). Catechin dimers have been reported in Bambara groundnut (Nyau, 2013). Proanthocyanidins comprising mainly prodelphinidins with epigallocatechin gallate and epicatechin gallate as terminal units, and epicatechin, epigallocatechin, epicatechin gallate, and epigallocatechin gallate as extension units, have been reported in aqueous extracts of maramba bean seed coat (Shelembe et al., 2012). The antinutritional significance of condensed tannins lies in their ability to form complexes with digestive enzymes and also dietary proteins, minerals, and vitamins, thus reducing their bioavailability.

3.3.3 *Phytates*

Phytates, which are inositols with four to six phosphate groups attached, are important antinutritional components of African legumes (Table 9.5). Phytates are believed to serve primarily as a storage compound for phosphorus, inositol, and inorganic phosphate ions, which are used in the energy metabolism of the plant during processes, such as germination (Enneking and Wink, 2000). As would be expected therefore, germination significantly reduces the amount of phytates in legumes due to activity of phytase enzymes (Devi et al., 2015; Ibrahim et al., 2002). The presence of the phosphate groups makes the phytate a highly charged molecule and therefore an excellent chelator. Thus, it is able to

form insoluble complexes with mineral cations, such as iron, zinc, and magnesium and further this decreases their bioavailability when consumed as foods. Phytates can also form indigestible complexes with dietary proteins and inhibit digestive enzymes.

3.3.4 *Cyanogenic glycosides*

Cyanogenic glycosides are glycosides of 2-hydroxynitriles and are widely distributed in legumes including cowpea (Onwuka, 2006) and Bambara groundnut (Nkafamiya et al., 2015). They, however, appear to be absent from marama bean (Dubois et al., 1995; Holse et al., 2010; Jackson et al., 2010). In line with plant cellular compartmentation, cyanogenic glycosides occur in the vacuoles, while their hydrolytic enzymes, the β -glucosidases, occur in the cytosol (Enneking and Wink, 2000). When a plant is injured by herbivores, insects or other sources, its cellular structure is disrupted and cyanogenic glycosides come into contact with activated β -glucosidase, which catalyzes the hydrolysis of the β -glucosidic bond to release 2-hydroxynitrile. Hydroxynitrile lyase then cleaves the 2-hydroxynitrile to release the corresponding aldehyde or ketone and hydrogen cyanide (HCN), which is toxic. However, the toxicity of cyanogenic glycosides is not of concern in processed legume foods due to the fact that most normal food processing procedures significantly reduce their levels.

3.3.5 *Saponins*

Saponins are a complex and chemically diverse group of naturally occurring plant compounds consisting of a triterpenoid or sterol aglycone (sapogenin) which is covalently attached to one or more carbohydrate (mono- or oligosaccharide) moieties (Augustin et al., 2011). They are widely distributed in legumes and derive their name from their ability to form stable, soap-like foams in aqueous solutions. They are amphiphilic in nature as they contain a lipophilic aglycone and a hydrophilic glycoside (Shi et al., 2004). Saponins at various concentrations have been reported in cowpeas (Abiodun and Adeleke, 2011; Ayogu et al., 2016), Bambara groundnuts (Marcel et al., 2014), and African yam bean (Abiodun and Adeleke, 2011; Onyeike and Omubo-Dede, 2002) seeds. The presence of saponins has been reported in the stem bark of the African locust bean tree (Builders et al., 2012).

3.3.6 *Lectins*

Lectins, also known as phytohemagglutinins, have been reported in cowpea (Batista et al., 2010b; Carvalho et al., 2012; Marconi et al., 1993, 1997), and African yam bean (Machuka et al., 1999; Machuka and Okeola, 2000; Oboh et al., 1998). Lectins are glycoproteins that are able to bind with carbohydrate membrane receptors due to their affinity for specific sugar molecules (Akande et al., 2010). They can bind to intestinal mucosa and enterocytes and thus interfere with absorption and transportation of nutrients during digestion

(Akande et al., 2010; Kumar, 1991) and also agglutinate red blood cells (Kumar, 1991). Generally, lectins are heat labile and are reported to be particularly susceptible to more complete destruction by wet-heat treatment (Ayyagari et al., 1989; Almeida et al., 1991).

3.3.7 Indigestible Oligosaccharides

Indigestible oligosaccharides are also called α -galactosides since they are made up of a sucrose unit bearing one or more α -D-galactose moieties. The common ones reported in legumes include raffinose, stachyose, and verbascose (Guillon and Champ, 2002). Raffinose has one α -D-galactose moiety attached to the sucrose unit, while stachyose and verbascose have two and three α -D-galactose moieties, respectively, attached to the sucrose unit through α -(1,6)-glycosidic bonds (Fig. 9.2). Stachyose is reportedly the most abundant α -galactoside in cowpea and most other legumes (Sosulski et al., 1982). These compounds can cause flatulence and other abdominal discomforts in consumers, thereby reducing consumption and utilization of legumes (Enneking and Wink, 2000). This is because the human intestinal mucosa lacks the enzyme α -1,6-galactosidase

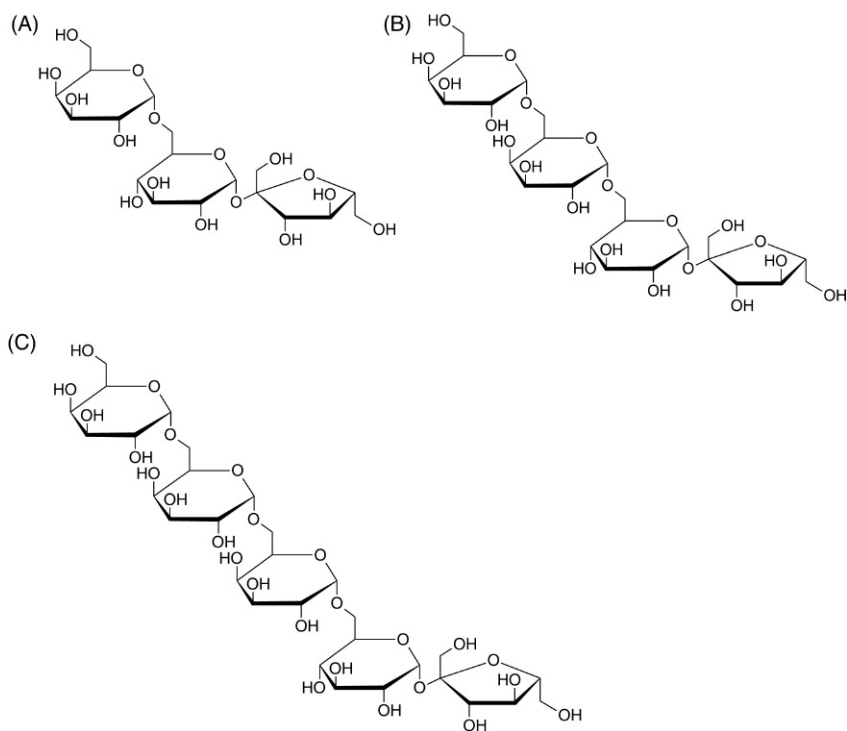


FIGURE 9.2 Chemical structures of indigestible oligosaccharides (α -galactosides) in African legumes. (A) Raffinose (molar mass 504.42), (B) stachyose (molar mass 666.58), and (C) verbascose (molar mass 828).

enzyme required for hydrolysis of the α -(1,6)-galactosidic bonds to release α -D-galactose units for absorption (Suarez et al., 1999). The oligosaccharides therefore pass into the large intestine undigested and are subsequently fermented by the anaerobic colonic microbiota to produce gases (Sreerama et al., 2012b).

The levels of indigestible oligosaccharides reported in African legumes are summarized in Table 9.6. It is noteworthy that indigestible oligosaccharides have not yet been quantified in marama bean. However, Holse et al. (2011) tentatively suggested a water-soluble carbohydrate present in marama bean to be raffinose. A positive aspect of these indigestible oligosaccharides is in regard to their potential contribution to gut health. There is increasing focus on their ability to function as prebiotics (Wang et al., 2016).

3.4 Food Processing Technologies to Reduce or Remove Antinutritional Factors

Processing methods, such as irradiation, dehulling, soaking, germination, fermentation, boiling, and roasting can reduce the antinutritional factors in legumes (Gonçalves et al., 2016). Table 9.7 gives a brief summary of processing methods that have been used to reduce various antinutritional factors in African legumes.

3.4.1 Washing, Soaking, and Germination

Simple processing techniques, such as washing and soaking of legume seeds in water reduces the concentration of water-soluble antinutrients, such as indigestible oligosaccharides, cyanogenic glycosides, trypsin inhibitors, and phytic acid. As would be expected, longer soaking times appear to be more effective than relatively shorter periods (Ibrahim et al., 2002; Onwuka, 2006). Germination (sprouting) of legumes, such as cowpeas, Bambara groundnuts (Ibrahim et al., 2002), and African yam bean (Obboh et al., 2000) promotes the degradation of indigestible oligosaccharides. Soaking and germination both reduced the concentration of extractable phenolics in cowpea (Towo et al., 2003). Soaking in acid (0.02% lactic acid solution, pH 3.5) and alkali (0.5% sodium bicarbonate solution, pH 8.3) were more effective than soaking in water. Similarly, Ibrahim et al. (2002) demonstrated that soaking cowpea seeds for 16 h in 0.03% sodium bicarbonate solution was more effective than soaking in water for the same duration, in reducing the levels of phytic acid, trypsin inhibitor, and raffinose. Dehulling (removal of the seed coat) is another important and effective method for removing phenolic compounds and indigestible oligosaccharides (Towo et al., 2003).

3.4.2 Fermentation

Legumes, such as cowpea, Bambara groundnut, and African locust bean may be fermented to produce condiments and tempeh-type snacks and this fermentation process is reportedly useful for degrading a number of the antinutritional

TABLE 9.7 Effect of Processing on Antinutritional Factors in African Legumes

Legume Types	Processing Method	Effect of Processing	References
Cowpea	Soaking for 6, 12, and 18 h	Decreased trypsin inhibitors (by up to 11%), hemagglutinin (by up to 14%), hydrogen cyanide (by up to 58%), and tannin (by up to 13%)	Onwuka (2006)
	Boiling for 40, 60, and 80 min	Decreased trypsin inhibitors (by up to 40%), hemagglutinin (by up to 37%), hydrogen cyanide (by up to 76%), and tannin (by up to 44%)	Onwuka (2006)
	Soaking for 12 h followed by boiling for 40, 60, and 80 min	Decreased trypsin inhibitor (by up to 88%), hemagglutinin (by up to 81%), hydrogen cyanide (by up to 94%), and tannin (by up to 63%)	Onwuka (2006)
	Dehulling	Decreased raffinose content by 49% and stachyose content by 18%	Nwinuka et al. (1997)
	Soaking for 6 and 12 h	Decreased raffinose content (by up to 80%), and stachyose content (by up to 52%)	Nwinuka et al. (1997)
	Soaking for 6 and 12 h followed by boiling	Decreased raffinose content (by up to 96%) and stachyose content (by up to 85%). Boiling after soaking further decreased raffinose content by 22% and stachyose content by 61% compared to 6 h soaking alone. Boiling after soaking also further decreased raffinose content by 80% and stachyose content by 68% compared to 12 h soaking alone	Nwinuka et al. (1997)
	Fermentation with <i>Rhizopus oligosporus</i>	Decreased stachyose by 91.5%, phytic acid by 32.6% and completely eliminated trypsin inhibitors	Egounlety and Aworh (2003)
	Fermentation (spontaneous)	Decreased phytic acid by 39%	Oluwole and Taiwo (2009)
	Germination for 24 and 48 h	Decreased tannins (by up to 26%), phytic acid (by up to 23%), trypsin inhibitors (by up to 54%) and completely eliminated raffinose and stachyose	Ibrahim et al. (2002)
	Autoclaving	Totally eliminated trypsin inhibitor and hemagglutinin activities and significantly reduced phytic acid content by up to 71%	Umoren et al. (1997)
	Extrusion cooking	Decreased trypsin inhibitor activity by 38.2% and phytic acid by 33.2%	Batista et al. (2010b)

(Continued)

TABLE 9.7 Effect of Processing on Antinutritional Factors in African Legumes (*cont.*)

Legume Types	Processing Method	Effect of Processing	References
Bambara groundnut	Soaking (in cold or hot water)	Decreased trypsin inhibitors by an average of 12%–31%	Barimalaa and Anoghalu (1997)
	Soaking	Decreased trypsin inhibitors by 53%, hemagglutinin by 52%, tannin by 55%, phytate by 24%, raffinose by 36%, and stachyose by 51%	Omoikhoje et al. (2006)
	Dehulling	Decreased trypsin inhibitors by 64%, hemagglutinin by 65%, tannin by 64%, phytate by 32%, raffinose by 46%, and stachyose by 57%	Omoikhoje et al. (2006)
	Germination	Decreased trypsin inhibitors by an average of 17%	Barimalaa and Anoghalu (1997)
	Germination	Decreased trypsin inhibitors by 70%, hemagglutinin by 78%, tannin by 73%, phytate by 61%, raffinose by 74%, and stachyose by 83%	Omoikhoje et al. (2006)
	Germination	Decreased trypsin inhibitors by 17%, tannins by 21%, phytate by 25%, and hemagglutinin by 20%	Okafor et al. (2014)
	Fermentation (spontaneous)	Decreased trypsin inhibitors by an average of 40%	Barimalaa and Anoghalu (1997)
	Boiling	Decreased tannin by 43% and phytate by 26%	Adegunwa et al. (2014)
	Autoclaving	Decreased tannin by 69% and phytate by 39%	Adegunwa et al. (2014)
	Roasting	Decreased tannin by 26% and phytate by 4%	Adegunwa et al. (2014)
	Roasting	Decreased trypsin inhibitors by 37%, tannins by 43%, phytate by 30%, and hemagglutinin by 41%	Okafor et al. (2014)

Marama bean	Dry heating	Heating at 100°C for 20 min decreased trypsin inhibitor activity by 13%. Heating at 120°C for 20 min decreased trypsin inhibitor activity by 26%. Heating at 150°C for 20 min decreased trypsin inhibitor activity by 99%	Maruatona (2008)
African yam bean	Dehulling and soaking (in water for 30 min)	Decreased phytate by 60%, saponin by 17%, trypsin inhibitors by 37.5%, and tannin by 65%	Abiodun and Adeleke (2011)
	Dehulling, soaking (in water for up to 12 h), and cooking (in water for 30 min)	Dehulling reduced raffinose by 23% and stachyose by 7%. Soaking reduced raffinose by 87% and stachyose by 49%. Soaking for 12 h and cooking for 30 min reduced raffinose by 63% and stachyose by 90%	Nwinuka et al. (1997)
	Cooking (in water at 100°C for 3 h or in alkaline solution, pH 11 for 2.5 h); soaking (in water at room temperature) with cooking (in water at 100°C for 2.5 h)	Cooking in water reduced total galactosides by 33.5%. Cooking in alkali reduced total galactosides by 73%. Soaking with cooking reduced total galactosides by 83%	Oboh et al. (2000)
	Germination for up to 96 h	Decreased total galactosides by up to 72%	Oboh et al. (2000)
	Autoclaving at 121°C, 15 psi for 20 min	Decreased cyanogenic glycosides by up to 46%, tannin by up to 29%, saponin by up to 25%, and trypsin inhibitors by up to 67%	Onyeike and Omu-bo-Dede (2002)
	Cooking in water at 98°C for 3.5 h	Decreased cyanogenic glycosides by up to 67%, tannin by up to 72%, saponin by up to 49%, and trypsin inhibitors by up to 87%	Onyeike and Omu-bo-Dede (2002)
African locust bean	Depulping, dehulling, and boiling in water for 30 min	Decreased trypsin inhibitors by 62%, tannin by 37%, and phytic acid by 37%	Esenwah and Ikenebomeh (2008)
	Fermentation (spontaneous) for up to 72 h	Decreased trypsin inhibitors by 71%, tannin by 36%, and phytic acid by 40%	Esenwah and Ikenebomeh (2008)

factors present in them. [Egounlety and Aworh \(2003\)](#) reported a reduction in the contents of oligosaccharides, trypsin inhibitor, phytic acid, and tannins when cowpea was processed into tempeh, an Indonesian *Rhizopus*-fermented snack. It is essential to note that the process of tempeh preparation involves various unit operations, such as washing, soaking, dehulling, boiling, and fermentation of the legume seeds ([Egounlety and Aworh, 2003](#)). The observed effect of fermentation is therefore a cumulative effect of all the unit operations involved. Spontaneous lactic acid fermentation followed by *Rhizopus oligosporus*-inoculated fermentation was effective in reducing the tannin content of Bambara groundnut ([Obizoba and Egbuna, 1992](#)).

3.4.3 Irradiation

[Tresina and Mohan \(2011\)](#) demonstrated gamma-irradiation (2–25 kGy) to reduce the levels of cyanogenic glycosides, phytic acid, trypsin inhibitor activity, indigestible oligosaccharides, and hemagglutinin activity of an Indian cowpea variety in a dose-dependent manner. However, [Tresina and Mohan \(2011\)](#) observed a dose-dependent increase in total free phenolics and tannins in cowpea upon gamma-irradiation. They attributed the observed increase in total free phenolics to enhanced activity (induced by gamma-irradiation) of the enzyme phenylalanine ammonia lyase which is responsible for synthesis of phenolic compounds, while the increased tannin content was attributed to enhanced extractability due to gamma-irradiation. [Villavicencio et al. \(2000\)](#) on the other hand, observed gamma-irradiation (up to 10 kGy) to reduce the total phenolics and tannin content in raw and cooked samples of a Brazilian cowpea variety. This may indicate that different cowpea varieties may respond differently to gamma-irradiation treatment.

3.4.4 Thermal Processing

Legume seeds are most generally processed thermally by boiling in water or roasting, in order to make them palatable and improve the availability of their nutrients. Thermal processing, such as soaking seeds in hot water, boiling in water, pressure cooking, and autoclaving can cause some thermal degradation and leaching of some antinutritional factors into the cooking water. Roasting may also thermally degrade some antinutrients ([Barimalaa and Anoghalu, 1997](#); [Gonçalves et al., 2016](#); [Khokhar and Owusu Apenten, 2003](#)). In most legume food processing, several processing methods (such as soaking and dehulling) are combined with thermal processing. These processes alter the antinutrients by varying degrees and a single processing method may therefore not be effective in removing all the antinutrients present ([Gonçalves et al., 2016](#)).

In comparing the effects of soaking, boiling, and combination of the two treatments on antinutritional factors, [Onwuka \(2006\)](#) observed that soaking in water, boiling in water, and soaking followed by boiling all reduced the contents of trypsin inhibitor, cyanogenic glycosides, lectins, and tannins in cowpeas ([Table 9.7](#)). Increasing the duration of soaking or boiling correspondingly

resulted in greater losses of the antinutrients. Combination treatments were more effective than the individual treatments. Soaking for 12 h followed by boiling for 80 min was the most effective method for detoxifying cowpea of the antinutrients. [Nwinuka et al. \(1997\)](#) reported similar effects of soaking, boiling, and the combination treatment on the levels of raffinose and stachyose in nine cowpea varieties.

4 HEALTH-PROMOTING PROPERTIES OF AFRICAN LEGUMES

Several bioactive and health-promoting properties have been attributed to phytochemicals present in African legumes. Of these, the dietary phenolic compounds have been most studied and their health-promoting properties are the most reported. The potential health-promoting properties resulting from the phytochemicals which are present in African legumes can be classified into inhibition or prevention of oxidative stress and inflammatory disorders, and prevention of chronic diseases, such as cardiovascular and coronary heart diseases, diabetes, and cancer.

4.1 Inhibition or Prevention of Oxidative Stress

Free radicals, such as reactive oxygen species and reactive nitrogen species (ROS/RNS) may be produced constitutively in the body through various metabolic processes. At low levels, these free radicals play a major role in cell signaling and regulation of metabolic processes ([Pham-Huy et al., 2008](#)). The free radicals may also be produced in large amounts in response to invading pathogens and if not controlled or regulated, they may damage host cellular components, such as the cell membrane, cellular proteins and lipids, and DNA. The body produces endogenous antioxidants, such as glutathione, glutathione peroxidase, catalase, and superoxide dismutase that react with and quench these free radicals. Under pathological conditions where immunity falls, the concentration of free radicals produced in the body, may exceed that of the protective antioxidants. This leads to oxidative stress which is believed to play a central role in the onset of many chronic diseases ([Fearon and Faux, 2009](#); [Pham-Huy et al., 2008](#)). It is hypothesized that exogenous sources of antioxidants, such as dietary sources, can complement the protective role of the endogenous antioxidants ([Pham-Huy et al., 2008](#)).

The phenolic compounds in African legumes are believed to play a protective role in the body against oxidative stress and its effects due to their antioxidant properties. These antioxidant properties have been determined mostly on the basis of their *in vitro* free radical-scavenging and metal-chelating properties. More biological-type assays, such as inhibition of lipid peroxidation, human low-density lipoprotein oxidation, and oxidative hemolysis of human erythrocytes ([Kayitesi, 2013](#); [Shelembe et al., 2012](#)) have also been applied. [Table 9.8](#) shows a summary of some antioxidant properties of African legumes.

TABLE 9.8 In Vitro Antioxidant Capacities of African Legumes

Samples	In Vitro Antioxidant Activity	References
Cowpea		
<i>ABTS^a radical scavenging capacity</i>		
Raw reddish-brown cowpea (Glenda variety), acidified methanol extract	157.7 ± 8.1 μmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Raw reddish-brown cowpea (Glenda variety), aqueous acetone extract	109.0 ± 17 μmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
Raw red cowpea (Dr Saunders variety), acidified methanol extract	161.1 ± 1.6 μmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Raw brownish-cream (Bechuana white variety), acidified methanol extract	148.0 ± 6.6 μmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Raw brownish-cream (Bechuana white variety), acidified methanol extract	146.7 ± 12.9 μmol Trolox Equivalents/g dry weight basis	Apea-Bah et al. (2014)
Raw golden-yellow cowpea (Agrigold variety), aqueous acetone extract	38 ± 3 μmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
Raw cream cowpea (Blackeye variety variety), acidified methanol extract	43.2 ± 1.2 μmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Boiled reddish-brown cowpea (Glenda variety), acidified methanol extract	97.7 ± 0.4 μmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Boiled reddish-brown cowpea (Glenda variety), aqueous acetone extract	74.0 ± 5.0 μmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
Boiled red cowpea (Dr Saunders variety), acidified methanol extract	97.7 ± 0.2 μmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Boiled brownish-cream cowpea (Bechuana white variety), acidified methanol extract	96.6 ± 0.4 μmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Boiled golden-yellow cowpea (Agrigold variety), aqueous acetone extract	26.0 ± 3.0 μmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
Boiled cream cowpea (Blackeye variety), acidified methanol extract	37.0 ± 1.1 μmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Simulated in vitro gastrointestinal digest of reddish-brown cowpea (Glenda variety) aqueous acetone extract	145 ± 5 μmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)

TABLE 9.8 In Vitro Antioxidant Capacities of African Legumes (*cont.*)

Samples	In Vitro Antioxidant Activity	References
Simulated in vitro gastrointestinal digest of golden-yellow cowpea (Agrigold variety), aqueous acetone extract	59 ± 10 µmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
<i>Oxygen radical absorbance capacity</i>		
Raw reddish-brown cowpea (Glenda variety), acidified methanol extract	235.5 ± 1.1 µmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Raw reddish-brown cowpea (Glenda variety) aqueous acetone extract	139.0 ± 25 µmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
Raw red cowpea (Dr Saunders variety), acidified methanol extract	221.8 ± 8.8 µmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Raw brownish-cream (Bechuana white variety), acidified methanol extract	233.1 ± 4.5 µmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Raw golden-yellow cowpea (Agrigold variety), aqueous acetone extract	83 ± 3 µmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
Raw cream cowpea (Blackeye variety), acidified methanol extract	123.7 ± 6.0 µmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Cowpea (4 Pakistani varieties), aqueous methanol extract	83.8–96.2 µmol Trolox Equivalents/g	Zia-Ul-Haq et al. (2013)
Boiled reddish-brown cowpea (Glenda variety), acidified methanol extract	134.9 ± 4.8 µmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Boiled reddish-brown cowpea (Glenda variety), aqueous acetone extract	118.0 ± 5.0 µmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
Boiled red cowpea (Dr Saunders variety), acidified methanol extract	128.6 ± 2.3 µmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Boiled brownish-cream cowpea (Bechuana white variety), acidified methanol extract	144.5 ± 5.7 µmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Boiled golden-yellow cowpea (Agrigold variety), aqueous acetone extract	76.0 ± 8.5 µmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
Boiled cream cowpea (Blackeye variety), acidified methanol extract	98.2 ± 3.1 µmol Trolox Equivalents/g dry weight basis	Kayitesi (2013)
Simulated in vitro gastrointestinal digest of reddish-brown cowpea (Glenda variety) aqueous acetone extract	186 ± 6 µmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)

(Continued)

TABLE 9.8 In Vitro Antioxidant Capacities of African Legumes (cont.)

Samples	In Vitro Antioxidant Activity	References
Simulated in vitro gastrointestinal digest of golden-yellow cowpea (Agrigold variety), aqueous acetone extract	166 ± 28 µmol Trolox Equivalents/g dry weight basis	Hachibamba et al. (2013)
<i>DPPH^b radical scavenging capacity</i>		
Raw brownish-cream cowpea (Bechuana white variety), acidified methanol extract	11.6 ± 0.7 µmol Trolox Equivalents/g dry weight basis	Apea-Bah et al. (2014)
Cowpea (Carilla variety), acidified methanol extract (unfermented, fermented and autoclaved)	5.06–9.47 IC ₅₀ /mg	Dueñas et al. (2005)
Cowpea (4 Pakistani varieties), aqueous methanol extract	25.1–32.5 µmol Trolox Equivalents/g dry weight basis	Zia-Ul-Haq et al. (2013)
<i>NO^c radical scavenging capacity</i>		
Raw brownish-cream cowpea (Bechuana white variety), acidified methanol extract	5.1 ± 0.2 µmol Trolox Equivalents/g dry weight basis	Apea-Bah et al. (2014)
Cowpea (4 Pakistani varieties), aqueous methanol extract	108–138 µg/mL (IC ₅₀)	Zia-Ul-Haq et al. (2013)
<i>Hydroxyl radical scavenging capacity</i>		
Cowpea (4 Pakistani varieties), aqueous methanol extract	80.6–92.4 µg/ml (IC ₅₀)	Zia-Ul-Haq et al. (2013)
<i>Superoxide anion radical scavenging capacity</i>		
Cowpea (4 Pakistani varieties), aqueous methanol extract	91.2–112.0 µg/ml (IC ₅₀)	Zia-Ul-Haq et al. (2013)
<i>Ferric reducing antioxidant power</i>		
Cowpea (4 Pakistani varieties), aqueous methanol extract	13.2–19.4 mmol Fe ²⁺ /g	Zia-Ul-Haq et al. (2013)
<i>Total radical-trapping antioxidant potential</i>		
Cowpea (4 Pakistani varieties), aqueous methanol extract	65.6–87.3 µmol Trolox Equivalents/g	Zia-Ul-Haq et al. (2013)
<i>Inhibition of linoleic acid peroxidation</i>		
Cowpea (4 Pakistani varieties), aqueous methanol extract	88.1–96.6%	Zia-Ul-Haq et al. (2013)
Bambara groundnut		
<i>DPPH radical scavenging capacity</i>		
Raw Bambara groundnut, aqueous acetone extract	84.6 ± 1.6% DPPH scavenged	Oboh et al. (2009)

TABLE 9.8 In Vitro Antioxidant Capacities of African Legumes (*cont.*)

Samples	In Vitro Antioxidant Activity	References
Raw Bambara groundnut, saponified residue	64.5 ± 2.1% DPPH scavenged	Oboh et al. (2009)
Raw brown Bambara groundnut, aqueous methanol extract	477.5 ± 3.5 µg dried extract/mL (EC ₅₀) ^d	Nyau et al. (2015)
Raw brown Bambara groundnut, aqueous extract	347.0 ± 4.2 µg dried extract/mL (EC ₅₀)	Nyau et al. (2015)
Raw red Bambara groundnut, aqueous methanol extract	525.5 ± 7.8 µg dried extract/mL, (EC ₅₀)	Nyau et al. (2015)
Raw red Bambara groundnut, aqueous extract	495.5 ± 12.0 µg dried extract/mL, (EC ₅₀)	Nyau et al. (2015)
Boiled, dehulled, and fermented Bambara groundnut, aqueous acetone extract	86.1 ± 1.5% DPPH scavenged	Oboh et al. (2009)
Boiled, dehulled, and fermented Bambara groundnut, saponified residue	56.7 ± 1.4% DPPH scavenged	Oboh et al. (2009)
<i>Ferric-reducing antioxidant power</i>		
Raw brown Bambara groundnut, aqueous methanol extract	9.70 ± 0.07 mmol Fe ²⁺ /100 g dry basis	Nyau et al. (2015)
Raw brown Bambara groundnut, aqueous extract	5.65 ± 0.21 mmol Fe ²⁺ /100 g dry basis	Nyau et al. (2015)
Raw red Bambara groundnut, aqueous methanol extract	8.01 ± 0.13 mmol Fe ²⁺ /100 g dry basis	Nyau et al. (2015)
Raw red Bambara groundnut, aqueous extract	5.00 ± 0.13 mmol Fe ²⁺ /100 g dry basis	Nyau et al. (2015)
Raw Bambara groundnut, aqueous acetone extract	0.74 ± 0.04 AU ^e	Oboh et al. (2009)
Raw Bambara groundnut, saponified residue	0.55 ± 0.06 AU	Oboh et al. (2009)
Boiled, dehulled, and fermented Bambara groundnut, aqueous acetone extract	0.76 ± 0.03 AU	Oboh et al. (2009)
Boiled, dehulled, and fermented Bambara groundnut, saponified residue	0.65 ± 0.04 AU	Oboh et al. (2009)
Marama bean		
<i>ABTS radical scavenging capacity</i>		
Full fat, defatted, heated, and unheated marama bean flour, and acidified methanol extract	14.1–15.8 µmol Trolox Equivalents/100 mg dry basis	Kayitesi et al. (2012)

(Continued)

TABLE 9.8 In Vitro Antioxidant Capacities of African Legumes (*cont.*)

Samples	In Vitro Antioxidant Activity	References
<i>DPPH radical scavenging capacity</i>		
Marama bean seed coat, aqueous extract	707.0 ± 10.6 µmol Trolox Equivalents/g dry basis	Shelembe et al. (2012)
African yam bean		
<i>DPPH radical scavenging capacity</i>		
Raw African yam bean, aqueous acetone extract	84.1 ± 2.1% DPPH scavenged	Oboh et al. (2009)
Raw African yam bean, saponified residue	66.2 ± 1.3% DPPH scavenged	Oboh et al. (2009)
Boiled, dehulled, and fermented African yam bean, aqueous acetone extract		
Boiled, dehulled, and fermented African yam bean, saponified residue	90.0 ± 1.8% DPPH scavenged	Oboh et al. (2009)
Raw, brown-colored African yam bean	70.3 ± 2.5% DPPH scavenged	Aminigo and Metzger (2005)
Raw African yam bean, marble variety	166 Trolox equivalents/g	Aminigo and Metzger (2005)
Raw, cream-colored African yam bean	144 Trolox equivalents/g	Aminigo and Metzger (2005)
<i>Ferric reducing antioxidant power</i>		
Raw African yam bean, aqueous acetone extract	32.6 Trolox equivalents/g	Oboh et al. (2009)
Raw African yam bean, saponified residue	0.23 ± 0.02 AU	Oboh et al. (2009)
Boiled, dehulled, and fermented African yam bean, aqueous acetone extract	0.10 ± 0.04 AU	Oboh et al. (2009)
Boiled, dehulled, and fermented African yam bean, saponified residue	0.65 ± 0.05 AU 0.55 ± 0.03 AU	Oboh et al. (2009)

EC50, Effective concentration of extract for inhibiting DPPH by 50%; IC50, inhibitory concentration of extract for quenching 50% of the radical.

^a2,2'-Azinobis (3-ethyl-benzothiazoline-6-sulphonic acid).

^b2,2'-Diphenyl-1-picrylhydrazyl.

^cNitric oxide.

^dEC50 of Trolox is 21.0±1.4.

^eAbsorbance units measured at 700 nm.

Crude phenolic extracts from raw, micronized, and boiled cowpea, as well as their simulated *in vitro* gastrointestinal digests, have been shown to possess antioxidant properties through their ability to scavenge free radicals (Apea-Bah et al., 2014; Hachibamba et al., 2013; Kayitesi, 2013; Zia-UI-Haq et al., 2013). They have also been demonstrated to protect erythrocytes from oxidative hemolysis (Kayitesi, 2013). This suggests that cowpea could potentially protect itself against radical-induced cell necrosis. Similar studies have also been reported for Bambara groundnut (Nyau et al., 2015; Oboh et al., 2009) and marama bean (Kayitesi et al., 2012; Shelembe et al., 2012). In a study investigating the effect of spontaneous natural fermentation on phenolic composition and antioxidant properties of cooked Bambara groundnut and African yam bean, Oboh et al. (2009) noted that natural fermentation increased the antioxidant properties of the cooked legumes. Also, the free soluble phenols had higher antioxidant and reducing properties than the bound phenols in both unfermented and fermented Bambara groundnut and African yam bean.

As indicated in Table 9.8, cowpea is the most studied indigenous African legume in terms of antioxidant properties. In general, pigmented legumes have higher antioxidant properties than the nonpigmented or less pigmented ones. For example, Hachibamba et al. (2013) reported higher oxygen radical absorbance (ORAC) values for a reddish-brown compared to a golden-yellow cowpea type. Brown colored and marble African yam bean varieties have higher 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging capacity than a cream-colored type (Aminigo and Metzger, 2005). It is also well-known that the phenolic compounds are largely responsible for the antioxidant properties that accumulate in the seed coat (Dueñas et al., 2006). Therefore, efforts are being targeted at demonstrating the suitability of indigenous African legume seed coats for developing functional food ingredients and nutraceuticals (Shelembe et al., 2012).

In an *in vivo* study, the effect of fermented legume (Bambara groundnut and African locust bean) condiments diet on oxidative stress in streptozotocin-induced diabetic rats was studied (Ademiluyi and Oboh, 2012). This study was based on a hypothesis that oxidative stress is involved in the development and progression of diabetic tissue damage (Dias et al., 2005) and that a diet based on these African legumes that was rich in phenolic antioxidants could attenuate these effects. Diabetic rats who were not fed with the legume condiments diet showed high levels of liver damage marker enzymes (alanine aminotransferase, aspartate aminotransferase, and alkaline phosphatase) and malondialdehyde (a marker compound for oxidative damage) and reduced activities of the detoxifying enzyme glutathione-S-transferase and the antioxidant enzyme catalase (Ademiluyi and Oboh, 2012). Treatment of the diabetic rats with the fermented Bambara groundnut and African locust bean condiments reversed the above observations toward normal conditions. This is an indication of the ability of the fermented legume condiments to reduce oxidative stress due to their high phenolic content and antioxidant capacity (Ademiluyi and Oboh, 2012).

4.2 Antiinflammatory Properties

Inflammation occurs when the body tissues are injured by physical trauma, intense heat, irradiation, irritating chemicals, or pathogenic infection. The main purpose of inflammation is to resolve infection and repair the damaged tissue (García-Lafuente et al., 2009; Nathan, 2002) and it is manifested by symptoms, such as redness, heat, swelling, pain (Vane and Botting, 1987; Nathan, 2002), and disturbed physiological function (Chandra et al., 2012). However, if the inflammation is not controlled as in the case of chronic inflammation, it could lead to tissue damage and subsequent chronic diseases (Serhan and Savill, 2005).

Phenolic compounds possess antiinflammatory properties (Burdette et al., 2010). However, there is limited information on the antiinflammatory properties of African legumes. Hachibamba (2014) and Ojwang et al. (2015) demonstrated that cowpea extracts possess antiinflammatory properties related to cardiovascular disease, through their ability to suppress expression of the pro-inflammatory genes that encode tumor necrosis factor- α (TNF- α), interleukin-6 (IL-6), intercellular adhesion molecule 1 (ICAM-1), and vascular cell adhesion molecule 1 (VCAM-1). This property varies among cowpea cultivars and was considered to be related to the phenolic composition of the cowpea. Overall, it may be inferred that consumption of cowpea could potentially contribute to protection of consumers against oxidative stress and inflammatory disorders.

4.3 Inhibition or Prevention of Cardiovascular Disease and Antihypertensive Properties

Cardiovascular disease involves formation of an atherosclerotic plaque which can block small blood vessels (Madamanchi et al., 2005). Atherosclerotic plaques are formed from arterial foam cells resulting from cholesterol-loaded macrophages (Aviram and Fuhrman, 2002). The cholesterol accumulating in foam cells is from plasma low density lipoprotein (LDL), which is taken up by the macrophages and smooth muscles when they are oxidized. Oxidation of LDL is therefore central to the development of cardiovascular disease (Regnström et al., 1993). Consequently, prevention of LDL oxidation may be a potential way to alleviate cardiovascular disease.

There is little published research on the ability of African legumes to prevent LDL oxidation. Most of the related studies are based on inhibition of LDL oxidation, measured using the thiobarbituric acid reactive substances (TBARS) assay. Extracts from boiled cowpea and their simulated in vitro gastrointestinal digests, have been demonstrated to protect human LDL from copper-catalyzed peroxidation (Hachibamba et al., 2013; Kayitesi, 2013), which is implicated in atherogenesis and consequent cardiovascular disease. Salawu et al. (2014) reported that cell wall preparations and whole seeds of cowpea inhibited copper-catalyzed oxidation of human LDL. The protective effect of Bambara groundnut against lipid peroxidation has been reported both for unfermented and fermented (spontaneous or natural fermentation) cooked Bambara groundnut

(Obboh et al., 2009). Fermentation increased the lipid peroxidation inhibitory capacity of the cooked Bambara groundnut. Also, the free soluble phenols showed better lipid peroxidation inhibitory capacity than the bound phenols for both unfermented and fermented Bambara groundnut. The protective effect of marama bean phenolic extracts against copper-catalyzed human LDL oxidation has also been reported (Shelembe et al., 2012). This observed ability of the legumes to protect against LDL oxidation has been attributed to their constituent phenolic compounds (Obboh et al., 2009; Shelembe et al., 2012). Phenolic compounds have the ability to scavenge free radicals through hydrogen atom transfer (Huang et al., 2005). They also chelate transition metal ions that serve as metal activators in peroxidation reactions (Huang et al., 2005) such as the copper ions that catalyze the LDL oxidation process.

In an in vivo study, diabetic rats treated with an aqueous extracts of fermented African locust bean exhibited elevated high-density cholesterol (HDL) serum levels and low levels of LDL leading to a high HDL:LDL ratio (Odetola et al., 2006), which is indicative of lowered risk of coronary heart disease.

The inhibition of angiotensin I-converting enzyme (ACE-I) is used as an indicator of antihypertensive properties. ACE-I converts inactive angiotensin I to angiotensin II which is a vasoconstrictor, and at the same time, degrades the peptide bradykinin which is a vasodilator (De Leo et al., 2009). The action of ACE-I therefore leads to increased blood pressure and hypertension. Sreerama et al. (2012a) reported that phenolic extracts from cowpea showed dose-dependent inhibitory effects against ACE-I. The cowpea ACE-I inhibitory ability was similar to that of horse gram (*Macrotyloma uniflorum* L.) and chickpea (*Cicer arietinum* L.) at the highest inhibitor concentration of 120 µg/mL. The ability to inhibit ACE-I by African legumes is not restricted to phenolic compounds. Protein hydrolyzates and peptide fractions from cowpea have also been reported to possess ACE-I inhibitory properties (Segura-Campos et al., 2010, 2011). Drago et al. (2016) also reported that cowpea protein hydrolysates exhibited ACE-I inhibitory properties after incorporation into wheat pasta and cooking.

4.4 Anticancer Properties

There is limited information on the anticancer properties of African legumes. Anticancer property in cowpea has been indicated using the ability of boiled cowpea and their simulated in vitro gastrointestinal digests to inhibit oxidative DNA damage (Nderitu et al., 2013). A dark red cowpea cultivar was 3 times more effective than a cream cowpea cultivar in protecting plasmid DNA from oxidative damage. This was attributed to the higher phenolic content of the red cowpea cultivar. Another study on the effect of micronization (infrared cooking) on phenolic compounds and antioxidant properties of cowpeas also reported that micronized and nonmicronized cowpea samples were able to protect DNA from oxidative damage (Kayitesi, 2013). Salawu et al. (2014) also reported that both cell wall preparations and whole seeds of cowpea possess the ability to inhibit

oxidative DNA damage. This demonstrates the ability of cowpeas to potentially protect against radical-induced point mutation and consequent carcinogenesis. Further studies in this area and on other indigenous African legumes are needed.

Potential anticancer properties have also been demonstrated by ability of extracts to inhibit proliferation of cancer cells *in vitro*. [Gutierrez-Urbe et al. \(2011\)](#) reported that phenolic extracts from seed coats, cotyledons, and whole cowpea seeds inhibited proliferation of hormone-dependent mammary (MCF-7) mammary cancer cells. A 36 kDa protein isolated from cowpea seeds (which exhibited homology to polygalacturonase-inhibiting proteins) inhibited proliferation of MBL2 lymphoma and L1210 leukemia cells ([Tian et al., 2013](#)). Other legume proteins, such as protease inhibitors have also been reported to inhibit proliferation of cancer cells. [Joanitti et al. \(2010\)](#) reported that a trypsin/chymotrypsin inhibitor isolated and purified from cowpea seeds reduced cell viability and proliferation of MCF-7 mammary cancer cells.

4.5 Antidiabetic Properties

In diabetes therapy, the control of blood glucose level is of importance and therefore inhibition of the starch-hydrolyzing enzymes α -amylase and α -glucosidase is used to provide an indication of antidiabetic properties ([McDougall and Stewart, 2005](#)). [Sreerama et al. \(2012a\)](#) demonstrated potential antidiabetic effects of cowpea by reporting dose-dependent inhibition of α -amylase and α -glucosidase by phenolic extracts from cowpea. The inhibitory effect of the cowpea extracts against α -glucosidase in particular was superior to that of extracts from horse gram and chickpea.

[Odetola et al. \(2006\)](#) studied the hypoglycemic effect of fermented African locust bean condiment in alloxan-induced diabetic rats in comparison with glibenclamide, a diabetic drug. The administration of alloxan to the rats led to significant increase in fasting plasma glucose. However, when the rats were fed diets supplemented with fermented African locust bean, there were significant reductions in fasting plasma glucose to a similar extent as obtained with glibenclamide. The authors suggested that the observed hypoglycemic effects of the fermented African locust bean condiment could be by protection of pancreatic β -cells resulting in insulin-stimulatory effects possibly due to the presence of phytochemical compounds such as flavonoids in the locust bean.

5 CONCLUSIONS

African legumes can contribute significantly to the dietary supply of nutrients especially protein, essential amino acids, dietary fiber, vitamins, and minerals in the diet. However, compared to the well-known pulses, such as the common bean and oilseed legumes, such as soybean, the African legumes are greatly underutilized and underresearched. Marama bean is currently obtained from the wild and not produced by any form of organized cultivation. There is a lack of information

on the bioavailability of health-promoting phytochemical constituents in indigenous African legumes, as well as their mechanisms of action in chronic disease prevention and their in vivo target sites. There is also a lack of epidemiological information regarding consumption of African legumes and health status among consumers. Research studies in these areas should contribute to an increase in the utilization of African legumes. Given the fact that the African legumes are drought-tolerant crops, they are excellent candidates for utilization as climate-friendly food crops. Global warming and climate change with the resultant effects of low agricultural productivity and food insecurity are important global issues. African legumes therefore have great global potential as sustainable food sources.

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Chapter 10

Wild Rice: Nutritional and Health-Promoting Attributes

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1 INTRODUCTION

Wild rice (*Zizania* spp.), also known as Canadian rice, Indian rice, water oats, marsh oats, and blackbird oats, is native to North America and grows predominantly in shallow lakes in the Great Lakes region (Anderson, 1976). It reportedly originated from North America and dispersed to eastern Asia through the Bering land bridge (Xu et al., 2010). The plant is a large-seeded, aquatic grass with a hollow cylindrical stem and long, narrow, blade-like leaves resembling those of wheat, oats, barley, and giant cut grass *Zizaniopsis miliacea*. The kernel has a long and narrow cylindrical shape (Fig. 10.1), with a length from 7.5 to 18 mm and a width from 1.5 to 4.0 mm (Fig. 10.2). It is represented by *Zizania* species, such as *Z. palustris* L., *Z. aquatica* L., *Z. texana* H., *Z. latifolia* G., *Z. caudiflora* Turcz., *Z. clavulosa* Michx., *Z. dahurica* Turcz. ex Steud., and *Z. interior* (Fassett) Rydb.; however, only four of these species, namely, *Z. palustris*, *Z. aquatica*, *Z. texana*, and *Z. latifolia*, have been harvested by the native North Americans for food (Surendiran et al., 2014). *Z. palustris* is an annual species that grows predominantly in shallow lakes and rivers present in the Great Lakes region of the United States and Canada. *Z. aquatica*, like *Z. palustris*, is also an annual species and is grown along the St. Lawrence River in the eastern and southeastern regions of the United States and in Louisiana. *Z. texana* and *Z. latifolia* are both perennial species, with *Z. latifolia* widely grown in southeastern Asia, and the relatively rarer *Z. texana* species native to the Saint Marcos River in Texas (Surendiran et al., 2014).

Wild rice is gaining popularity among health-conscious consumers due to its reportedly better nutritional quality compared to white or brown rice (*Oryza* spp.). For instance, wild rice is a good source of dietary fiber (~6.2%) and has a protein content nearly double the amount found in white rice (Timm and Slavin, 2014). The antioxidative phytochemicals in wild rice are more



FIGURE 10.1 Wild rice kernels, cultivated in USA, sold in Eastern Europe.



FIGURE 10.2 Wild rice single kernels, real size from 9 to 15 mm.

diverse and the contents are several times higher than those occurring in white rice, resulting in several folds increase in antioxidant activity over the white rice species. Wild rice has significantly lower lipid content compared to brown rice species with markedly higher contributions from the essential fatty acids (56.5%–66.5% vs. 36.9%–39.1%). The total amount of omega-3 fatty acids in wild rice is approximately 4–8 times higher than in brown rice, although the level is generally lower than what is required for significant therapeutic relevance. The relatively high ash content of wild rice indicates a rich source of minerals, such as potassium and phosphorus. Indeed, the Minnesota Agricultural Experimental Station's comparative study of 1924 concluded that wild rice had significantly greater food value than the cultivated polished rice ([Kennedy, 1924](#)).

The antioxidant activity, cholesterol-lowering effects, and cardiovascular benefits of wild rice consumption have been clearly demonstrated in experimental animals. For instance, a recent study by [Surendiran et al. \(2013\)](#) showed that consumption of wild rice significantly reduced the size and severity of atherosclerotic lesions in the aortic roots of male and female mice by 71 and 61%,

respectively, compared to the control group of the same gender fed with white rice or a commercial carbohydrate source. The authors suggested cholesterol-lowering effects of wild rice was probably the main factor for the prevention of atherogenesis in the LDLr-KO mice (Surendiran et al., 2013). According to Han et al. (2013), replacing white rice and processed wheat starch with wild rice as the chief source of dietary carbohydrate in rats fed with a high-fat/cholesterol diet ameliorated abnormal glucose metabolism, suppressing high-fat/cholesterol diet-induced insulin resistance. The current review summarizes available literature on the phytochemical constituents and nutritional and health-promoting attributes of wild rice (*Zizania* spp.).

2 PROCESSING AND USES OF WILD RICE

The nutritional importance of wild rice has been appreciated by the native people of North America for centuries, as in the past it was consumed as a staple food. In the late 20th century, wild rice was commercially cultivated to meet the increased demand. In the mid-1960s, farmers in northern Minnesota began growing wild rice under controlled conditions in paddies, much like those used for regular rice production. Most of the wild rice is now produced for commercial use in Minnesota and California. However, more countries, such as Finland, are taking an interest in producing wild rice (Makela et al., 1998).

Wild rice is harvested at relatively high moisture (c. 45%) to prevent excessive grain loss due to shattering during the postharvesting processing (Oelke and Boedicker, 2000; Oelke et al., 1997). Traditional processing of wild rice typically involves: grain drying, dehulling of dried grain, and hull separation. The cleaned wild rice is graded based on its kernel size or length. The commercialization of wild rice production brought many changes and innovations in the processing; however, the principles of the traditional methods remain unchanged. These changes were necessary to increase the yield of production and to enhance the quality of wild rice. Modern wild rice processing involves some additional steps, such as curing, scarification, and modification in the drying process. The curing process leads to changes in the color of immature grains and also affects the flavor (Strait, 1982), whereas parching results in a characteristic rich, dark shade, and nutty flavor and starch gelatinization (Strait, 1982; White and Jayas 1996). Depending on the requirements of the final product, scarification step may be applied, and therefore the wild rice obtained requires more consistent and shorter cooking time (Oelke and Boedicker, 2000).

According to the Canadian Wild Rice Council, standard wild rice is the product obtained from *Z. aquatic* or *Z. palustris* after the processing steps of curing, parching, and hulling and should have a moisture content not more than 11% by weight (Oelke and Boedicker, 2000). Unlike many conventional whole grains, wild rice is typically never refined (Surendiran et al., 2014). Processed wild rice seeds are stable and can be stored for long time if kept at low temperature and at less than 70% relative humidity. However, the grains and flour of wild rice

are susceptible to growth of microorganisms, mainly *Aspergillus* spp., *Rhizopus* spp., *Cladosporium* spp., and *Penicillium* spp. (White and Jayas, 1996).

Nowadays, the utilization of wild rice is gaining popularity, as it is commonly available in stores and restaurants. It is generally used as a substitute for potatoes or white rice. Due to its unique flavor, wild rice is used as an ingredient in a variety of foods, such as casseroles, soups, salads, and desserts. Wild rice is sold in raw form mostly as a blend with long-grain rice, but its processed form is also available in the market. However, wild rice from natural stands is still more expensive than cultivated wild rice.

3 NUTRITIONAL CONSTITUENTS

3.1 Lipids

Przybylski et al. (2009) analyzed seven North American wild rice species and reported lipid contents ranging between 0.7% and 1.1%. Similar studies by Zhai et al. (2001) and Aizawa et al. (2007) revealed lipid contents of 1.1 and 1.4% for the Chinese and Japanese wild rice, respectively. Corresponding data on conventional white or brown rice showed lipid contents between 2.6% and 2.8%, representing up to a four fold higher amount of lipids in the regular *Oryza* spp. compared to wild rice (*Zizania* spp.). Although lipids generally account for relatively smaller amounts of macronutrients in rice, the significantly lower content in wild rice is of advantage to a population craving for a low-fat diet. Beyond contents, the lipid profile of wild rice is superior to those of regular white or brown rice (Table 10.1); wild rice contains 55.6%–66.5% essential fatty acids compared to 36.9%–39.1% present in brown rice (Przybylski et al., 2009). The level of omega-3 fatty acids in wild rice (20%–31%) is up to 18 times higher than the amounts found in brown rice (Przybylski et al., 2009). The ratios of omega-6 to omega-3 reported for wild rice samples range from 1.1 to 1.8, whereas those in regular rice were from 20.2 to 22.4 (Przybylski et al., 2009). The significantly lower ratios of $n - 6/n - 3$ in wild rice lipids have been suggested to have a beneficial effect on human blood lipids (Schaefer, 2002). According to Aizawa et al. (2007), 60% of the triacyl glycerol species of Japanese wild rice (*Z. palustris*) are palmitoyl dilinolein (PLL), palmitoyllinoleoyl linolenin (PLLn), dilinoleoyl linolenin (LLLn), trilinolein (LLL), and oleyllinoleoyl linolenin (OLLn), with PLL, LLL, and OLLn predominating.

3.2 Proteins

Unlike its lipid content, available data indicated that wild rice has a higher content of protein (12%–18%) than many cereals (Capen and LeClerc, 1948; Kennedy, 1924; Lindsay et al., 1975; Wang et al., 1978). Zhai et al. (1994) evaluated seven Chinese (*Z. latifolia*) and North American (*Z. aquatica*) wild rice samples for their protein contents and reported value ranging from 11.95 to 15.15/100 g, concluding that the wild rice samples contained up to twice

TABLE 10.1 Major Fatty Acids of Wild Rice Lipids (% Lipid Content) Compared to Selected Cereal Grains

Fatty Acids	Wild Rice	Brown Rice	White Rice	Oats	Barley	Wheat
Palmitic	14.1–18.4	15.1–20.4	28.2–33.8	15.8–22.0	23.3–27.6	17.0–24.5
Stearic	1.0–1.3	1.9–2.1	2.7–2.9	1.6–2.0	1.0–1.7	1.0–2.1
Oleic acid	12.9–16.2	39.2–41.6	23.7–41.2	26.8–41.2	10.4–17.1	8.3–21.0
Linoleic	35.0–37.7	29.2–37.5	18.0–37.6	38.0–42.5	53.7–57.4	55.1–59.8
Linolenic	20.1–31.5	1.0–1.7	1.5–1.9	1.3–2.1	4.5–6.7	3.4–4.9
Total fat ^a	0.50–1.23	2.41–3.04	2.6–2.8	3.1–11.6	3.1–3.6	1.2–2.1

^ag/100g rice, as is weight basis.
Source: Data based on Lindsay R.C., Lund, D.B., Marth, E.H., Stuber, D.A., 1975. Report of Wild Rice Research Activities. University of Wisconsin, Madison, WI; Lugay, J.C., Juliano, B.O., 1964. Fatty acid composition of rice lipids by gas-liquid chromatography. J. Am. Oil Chem. 41, 273–275; Nelson, J.H., Glass, R.L., Geddes, W.F., 1963. The triglycerides and fatty acids of wheat. Cereal Chem. 40, 343–351; Przybylski, R, Klensporf-Pawlik, D., Anwar, F., Rudzińska, M., 2009. Lipid components of North American wild rice (*Zizania palustris*). J. Am. Oil Chem. Soc. 86, 553–559.

the protein contents found in the cultivated white rice (*Oryza sativa*) control. Their finding was similar to an earlier report that wild rice had twice the protein content of cultivated brown rice (Capen and LeClerc, 1948). Studies by Lindsay et al. (1975) and Wang et al. (1978) clearly indicated that the fermentation step, which is unique in wild rice processing, did not affect its protein content. Reported protein content for wild rice, however, need to be carefully evaluated, as different nitrogen/protein conversion factors are often used and values are either based on dry or wet weight, information that is not often clearly communicated.

Besides the relatively higher level and quality of proteins, compared to major cereal grains (Table 10.2), wild rice is also gluten free. Thus, unlike wheat, barley, and rye that contain the proinflammatory gluten proteins, wild rice can be safely consumed by individuals who are gluten intolerant.

The protein efficiency ratio (PER), described as the ratio of body weight gain (in specific time) to the gram of protein consumed, has been used in the past to describe the nutritional values of proteins. Available data indicated that the PER of wild rice (1.72–1.76) is higher than most cereal grains (e.g., barley, 1.6; corn, 1.4; rye, 1.3; and wheat, 0.9), but considerably lower than that of casein (2.50), which is often used as the standard protein (Pomeranz, 1973; Wang et al., 1978). However, the PER of wild rice is comparable to oats (1.8) and regular rice (1.8) (Julino, 1972; Pomeranz, 1973). According to Wang et al. (1978), the relatively high PER of wild rice, compared to other cereals could be in part attributed to its low proportion of the alcohol-soluble prolamins, which are often low in lysine. The 18 amino acids of wild rice protein are presented in Table 10.2. Generally, the amino acid composition of wild rice protein is considered superior to those of other cereals, such as regular rice, maize, barley, or rye (Lorenz, 1981; Oelke, 1976; Terrell and Wiser, 1975; Wang et al., 1978; Watts and Dronzek, 1981; Zhai et al., 1994, 2001). In their study of wild rice from China, the United States, and Canada, Zhai et al. (1994, 2001) concluded that the amino acid composition of wild rice samples showed generally higher amounts of essential amino acids than those reported for white rice, barley, and maize grown in China. In unprocessed wild rice, threonine is the first limiting amino acid and lysine is the second limiting amino acid (Watts and Dronzek, 1981; Zhai et al., 1994, 2001); however, for high temperature processed rice (parched at 135°C for 25 min), lysine is the first limiting and threonine second limiting amino acid (Zhai et al., 1994, 2001), and lysine is the only amino acid significantly affected by the parching process. Lysine level in cereals is particularly important, as lack of lysine often lowers the nutritional quality of cereal protein (Watts and Dronzek, 1981); however, as shown in Table 10.2, the lysine level of wild rice exceeds those of white rice, oats, and wheat, and is comparable to the content usually found in whole-grain high-lysine maize (Bauman et al., 1974). The content of sulfur-containing amino acids, methionine and cysteine, in wild rice are similar to white rice and oats, but somewhat higher than the levels present in wheat (Table 10.2).

TABLE 10.2 Protein and Amino Acids of Wild Rice Compared to Selected Grains

Amino Acids (AA)	Wild Rice	White Rice	Oats	Wheat
Alanine	0.62–0.81	0.30–0.47	0.48–0.67	0.22–0.33
Arginine	0.99–1.34	0.55–0.68	0.78–1.20	0.48–0.72
Aspartic acid	1.04–1.43	0.63–0.87	0.75–1.12	0.32–0.55
Cystine	0.34–0.40	0.19–0.21	0.25–0.50	0.21–0.30
Glutamic acid	2.21–2.79	1.37–1.61	1.97–3.34	3.16–5.05
Glycine	0.53–0.69	0.30–0.46	0.51–0.76	0.40–0.51
Histidine	0.36–0.43	0.16–0.23	0.29–0.56	0.28–0.35
Isoleucine	0.44–0.58	0.25–0.31	0.38–0.57	0.48–0.57
Leucine	0.85–1.11	0.61–0.66	0.77–1.01	0.96–1.03
Lysine	0.55–0.73	0.23–0.34	0.37–0.56	0.28–0.42
Methionine	0.28–0.35	0.13–0.24	0.17–0.23	0.18–0.24
Phenylalanine	0.57–0.78	0.34–0.38	0.46–0.74	0.67–0.72
Proline	0.31–0.44	0.23–0.31	0.71–0.86	1.31–1.60
Serine	0.60–0.77	0.35–0.49	0.43–0.77	0.23–0.63
Threonine	0.40–0.51	0.23–0.28	0.36–0.52	0.36–0.44
Tryptophan	0.16–0.25	0.09–0.14	0.14–0.22	0.18–0.26
Tyrosine	0.39–0.53	0.32–0.43	0.28–0.50	0.22–0.26
Valine	0.62–0.83	0.39–0.46	0.53–0.75	0.58–0.69
Total	11.34–14.63	7.48–8.57	10.11–15.40	10.72–14.97
Essential AA	4.24–5.44	2.75–3.24	3.50–5.11	3.77–5.14
Protein ^a	11.95–15.15	7.60–8.68	11.38–17.75	11.60–17.22

^ag/100 g rice, dry weight basis.

Source: Data based on Santos, K.F.D.N., Silveira, R.D.D., Martin-Didonet, C.C.G., Brondani, C., 2013. Storage protein profile and amino acid content in wild rice *Oryza glumaepatula*. Pesq. Agropec. Bras. Brasília. 48, 66–72; Shoup, F.K, Pomeranz, Y, Deyoe C.W, 1966. Amino acid composition of wheat varieties and flours varying widely in bread-making potentialities. J. Food Sci. 31, 94–101; Vilmane, L., Zute, S., Straumite, E., Galoburda, R., 2015. Protein, amino acids and gluten content in oat (*Avena sativa* L.) grown in Latvia. Proc. Latvian Acad. Sci. B. 69, 170–177; Zhai, C.K., Lu, C.M., Zhang, X.Q., Sun, G.J., Lorenz K.J., 2001 Comparative study on nutritional value of Chinese and North American wild rice. J. Food Comp. Anal. 14, 371–382.

3.3 Carbohydrates

Carbohydrates, including starch, sugar, and other carbohydrate substances, represent about 75% of wild rice macronutrients and are the main sources of energy in wild rice. The total carbohydrate content reported for wild rice (72.3%–75.3%) is slightly less than that of brown rice (77.4%) and white regular rice (80.5%), but greater than those of oat (68.2%), wheat (71.7%), and

maize (72.2%) (Anderson, 1976). The sugar content of raw wild rice ranges between 1.8% and 2.7%, decreasing to about 1% in processed rice. Starch content of wild rice ranges from 60% to 65% depending on the variety. The type and quality of starch in wild rice differ from those in regular white rice, as wild rice contains more rapidly digestible starch and less slowly digestible and resistant starch as compared to the regular white rice (Surendiran et al., 2013).

Generally, the swelling power and the water solubility index (WSI) of wild rice starches are significantly higher than those of white rice (Wang et al., 2002) and wheat (Hoover et al., 1996; Lorenz, 1981). Wang et al. (2002) reported a range of 54.3%–60.2% for the β -amylolysis limit of six wild rice varieties, significantly lower than the 64.1% obtained for the long-grain white rice (Cypress variety) control, indicating that wild rice starch has a more branched structure, which is not readily accessible to β -amylase (Wang et al., 2002). The amylose contents of the wild rice samples (18.0%–20.0%) and white rice Cypress variety (18.6%) were rather similar, although slightly higher in wild rice (Wang et al., 2002). According to Wang et al. (2002) and Hoover et al. (1996), wild rice starch gelatinization temperature (64.0–67.4°C) could be up to 10 and 12°C lower than those of white rice (77.6°C) and brown rice (79.0°C), respectively. These data, however, are different than the ones reported by Lorenz (1981) wherein wild rice starch gelatinization temperature (73°C) was comparable to that of brown rice (75°C), but significantly higher than the value for wheat starch (61°C). Wild rice starch performed better than wheat starch in fillings stored for several days at room temperature and under refrigeration (Lorenz, 1981). In general, the degree of retrogradation of wild rice starch (32.8%–37.9%) is lower than those of regular rice (40.8%) (Hoover et al., 1996; Wang et al., 2002). Retrogradation expresses the formation of crystalline regions of the starch polysaccharides, which, upon cooling and storing of gelatinized starch, makes starch harder to digest, thus increasing the amount of resistant starch.

Glycemic index (GI) relates to the rate at which carbohydrates are digested and absorbed, determining their influence on blood glucose level. Although data is rather scanty on the GI of wild rice carbohydrates, available data indicated that the GI of Saskatchewan wild rice was 57; Canadian brown rice, 66; and Canadian white rice, 72; compared to glucose standard (Foster-Powell et al., 2002).

Dietary fiber, including nonstarch polysaccharides and resistant oligosaccharides (e.g., cellulose, polyfructose, inulin, gums, mucilages, and pectins), analogous carbohydrates (e.g., resistant maltodextrins, polydextrose, methyl cellulose, and hydroxypropylmethyl cellulose), and lignin (including waxes, phytate, cutin, and tannins), is the edible but indigestible parts of food derived from plants (AACC Reports, 2001). The health benefits of dietary fiber, especially in relation to normal functioning of the digestive system, obesity, diabetes, and cardiovascular diseases are well documented (Aljuraiban et al., 2015; Anderson, 1985; Burkitt et al., 1972; Encarnacao et al., 2015; Krumbeck et al., 2016; Liu et al., 2015; Rebello et al., 2016; Wrick et al., 1983). Wild rice is a rich source of

dietary fiber, containing 0.6%–2% of crude fiber and 5.2% of total dietary fiber, with 3.3% insoluble fiber and 0.8% soluble fiber (Capen and LeClerc, 1948; Surendiran et al., 2014; Zhai et al., 2001). The neutral monosaccharide composition of the insoluble fiber fractions were determined to be 52.7% glucose, 17.7% arabinose, 17.7% xylose, 6.5% galactose, and 5.4% mannose and that of the soluble fraction was 8.6% arabinose, 6.3% xylose, 42.9% mannose, 23.5% glucose, 18.7% galactose, and trace amounts of fucose (Bunzel, 2001; Bunzel et al., 2002). Tahara and Misaki (2001) reported the composition of wild rice noncarbohydrate constituents of the dietary fiber complex as lignin, a phenolic polymer; suberin, a polymer comprised of a polyaliphatic domain and a polyaromatic domain; cutin, a polyaliphatic polymer; and waxes. Bunzel et al. (2003) reported the presence of two 8–8 coupled sinapic acid dehydrodimers and at least three sinapate–ferulate heterodimers as saponification products from different insoluble and soluble cereal grains dietary fiber; the total amounts of 8–8 coupled sinapic acid dehydrodimers in wild rice was 10, 13, and 28 times the amounts found in regular rice, wheat, and spelt, respectively, with only negligible amounts reported for rye, barley, maize, oat, and millet (Bunzel et al., 2003).

According to the USDA data, wild rice at 6.2% raw dietary fiber contains nearly 5 times and twice the amount in white rice (1.3%) and brown rice (3.5%), respectively (USDA, 2013). Currently, a food is considered to be a “good source of fiber” if it contains 10% of the recommended amount (2.5 g/serving) and an “excellent source of fiber” if it contains 20% of the recommended amount (5 g/serving); therefore wild rice is considered a good source of fiber based on a standard serving of 45 g, whereas brown and white rice fall below the 10% threshold of fiber per serving (Timm and Slavin, 2014).

4 PHYTOCHEMICALS AND MINERALS

Phytochemicals are defined as bioactive nonnutrient compounds found in whole grains, fruits, vegetables, and other foods. Working together with a nutrient compounds found in plant food, they are linked with reduced risk of major chronic diseases (Liu, 2003). The predominant groups of phytochemicals in whole grains, including wild rice, are phytosterols, γ -oryzanol, and tocochromanols.

4.1 Sterols

4.1.1 Phytosterols

Phytosterols or plant sterols are naturally occurring components in cell membranes of different plants. Plant sterols play the same basic function in plants as cholesterol plays in animal tissues (Law, 2000). Phytosterols include a wide variety of compounds with the chemical structure similar to cholesterol, but with the expanded and modified side chains at carbon C-24 and double bond at C-22. According to Berger et al. (2004), phytosterols are divided into two

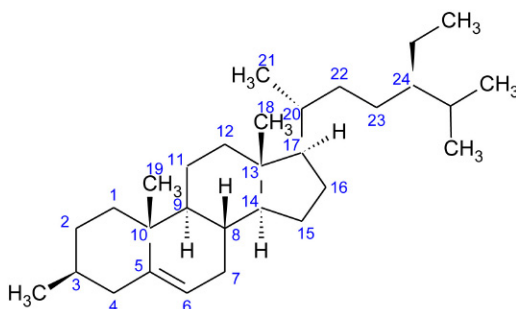


FIGURE 10.3 Chemical structure of β -sitosterol.

distinct classes, the sterols and stanols. However, the predominant form found in nature is sterols. Fig. 10.3 presents the structure of β -sitosterol.

North American wild rice can be recognized as a source of bioactive phytosterols. Przybylski et al. (2009) identified 11 different plant sterols in wild rice lipids. The predominant phytosterols were β -sitosterol, campesterol, and cycloartenol, comprising 54%–75% of total sterols, depending on the wild rice variety. In regular brown rice the amounts of 24-methylenecycloartenol and stigmasterol were higher than in wild rice. Additionally, other minor sterols were observed in wild rice samples namely clerosterol, 23-dehydrositosterol, gramisterol, citrostadienol, Δ^5 -avenasterol, and Δ^7 -avenasterol. Total sterols content varied from 70 to 145 g/kg of wild rice lipids, compared to brown rice, 27 g/kg. Total phytosterol content in wild rice lipids is much higher than in brown rice and various cereal by-products (Table 10.3) (Jiang and Wang, 2005; Przybylski et al., 2009).

However, if the data are corrected for the amount of lipids in particular grains, the phytosterol content ranges from 0.7 to 1.3 mg/g of product and 0.6 to 0.9 mg/g in wild rice varieties and regular brown rice, respectively. Comparing the amount of total sterols in wild rice with those obtained in raw cereal by-products, it could be seen that total sterols in cereal by-products are much higher, varying from 0.3 to 4.5 mg/g, mainly because of the higher lipid content in these products (Jiang and Wang, 2005).

4.1.2 γ -Oryzanol

γ -Oryzanol is a common name for the mixture of ferulic acid esters of triterpene alcohols and phytosterols. The amount of individual components of γ -oryzanol, as well as the composition, is affected by the environmental factors and genotype, especially in regular rice (Bergman and Xu, 2003; Miller and Engel, 2006). γ -Oryzanol is not only found in rice, particularly in the bran fraction (Xu and Godber, 1999), but also in milling fractions of rye and wheat (Nystrom et al., 2007).

TABLE 10.3 Major Phytosterols Composition (%) and Total Sterols Content (mg/g) of Lipids and of Product

	β -Sitosterol (%)	Campesterol (%)	Cycloartenol (%)	Total sterols (mg/g) of lipids	Total sterols (mg/g) of product
Wild rice	19.1–32.5	14.3–51.7	4.7–12.2	70–145	0.7–1.3
Brown rice	25.2–28.8	142–16.8	9.0–11.7	22–31	0.6–0.9
Rice bran	24.3	12.8	16.4	20.33	4.5
Wheat bran	25.6	20.7	2.7	17.67	1.2
Wheat germ	52.8	22.1	3.3	21.28	2.4
Durum wheat	31.3	14.4	2.1	15.07	1.8
Oat bran	45.7	6.5	7.5	3.41	1.5
Oat hull	50.0	8.3	6.5	8.18	0.7
Corn fine fiber	57.3	10.1	3.0	48.25	0.3

Source: Data based on Jiang, Y., Wang, T., 2005. Phytosterols in cereal by-products. J. Am. Oil Chem. Soc. 82, 439–444; Przybylski, R., Klensporf-Pawlik D., Anwar F., Rudzirska M., 2009. Lipid components of North American wild rice (*Zizania palustris*). J. Am. Oil Chem. Soc. 86, 553–559.

γ -Oryzanol was at first presumed to be a single component, but later it was determined to be a fraction containing ferulate esters of triterpene alcohols and plant sterols (Roger et al., 1993). Moreover, Xu and Godber (2001) revealed that the major three components of γ -oryzanol were cycloartenyl ferulate, 24-methylenecycloartanyl ferulate, and campesterol ferulate, and they accounted for 80% of γ -oryzanol. However, the majority of the studies have focused on the total amount of γ -oryzanol in rice products (Hoed et al., 2006; Lee et al., 2009a; Przybylski et al., 2009).

Total amounts of γ -oryzanol in lipids of seven commercial varieties of wild rice were reported by Przybylski et al. (2009). The authors revealed that North American wild rice contained 459–730 mg/kg of lipids, whereas regular brown rice contained 459–613 mg/kg of lipids. Compared to rice bran oil, which is regarded as a rich source of oryzanol, North American wild rice lipids contained significantly higher amounts of γ -oryzanol (Table 10.4).

Significant differences observed in total γ -oryzanol content in wild rice lipids and regular brown rice lipids (Table 10.4) in two separate research studies

TABLE 10.4 γ -Oryzanol Content mg/kg of Lipid/Oil

Products	γ -Oryzanol
Wild rice lipids ^a	459–730
Wild rice lipids ^b	850–1352
Regular brown rice lipids ^a	459–613
Regular brown rice lipids ^b	688–916
Refined rice bran oil	510–787
Brazilian rice bran oil	290
Rice bran oil	359
High-oryzanol rice bran oil	7435
Rice bran	511–802

^{a,b}The same cultivars from different harvesting years were analyzed.

Source: Data based on Abidi, S.L., Rennick, K.A., 2003. Determination of nonvolatile components in polar fractions of rice bran oils. *J. Am. Oil Chem. Soc.* 80, 1057–1062; Aguilar-Garcia, C., Gavino, G., Baragano-Mosqueda, M., Hevia P., Gavino, V.C., 2007. Correlation of tocopherol, tocotrienol, γ -oryzanol and total polyphenol content in rice bran with different antioxidant capacity assays. *Food Chem.* 102, 1228–1232; Aladedunye, F., Przybylski, R., Rudzińska, M., Klensporf-Pawlik D., 2013. γ -Oryzanols of North American wild rice (*Zizania palustris*). *J. Am. Oil Chem. Soc.* 90, 1101–1109; Iqbal, S., Bhanger, M.I., Anwar, F., 2005. Antioxidant properties and components of some commercially available varieties of rice bran in Pakistan. *Food Chem.* 93, 265–272; Przybylski, R., Klensporf-Pawlik D., Anwar F., Rudzińska M., 2009. Lipid components of North American wild rice (*Zizania palustris*). *J. Am. Oil Chem. Soc.* 86, 553–559; Ribeiro Pestana, V., Zambiasi, R.C., Mendonça, C.R.B., Bruscatto M.H., Lerma-Garcia, M.J., Ramis-Ramos, G., 2008. Quality changes and tocopherols and γ -oryzanol concentration in rice bran oil during the refining process. *J. Am. Oil Chem. Soc.* 85, 1013–1019; Roger, E.J., Rice, S.M., Nicolosi, R.J., Carpenter, D.R., McClelland, C.A., Romanczyk, L.J., 1993. Identification and quantification of γ -oryzanol components and simultaneous assessment of tocopherols in rice bran oil. *J. Am. Oil Chem. Soc.* 70, 301–307.

are explained by the different extraction and separation methods used during analyses (Aladedunye et al., 2013).

The composition of γ -oryzanol in commercial wild rice samples was reported by Aladedunye et al. (2013). The results showed 23 γ -oryzanol derivatives, and among them cycloartenol *trans*-ferulate, 24-methylenecycloartenol *trans*-ferulate, campesterol *trans*-ferulate, and sitosterol *trans*-ferulate were the major components, and comprised an average of 75% in the wild rice samples and up to 90% in brown rice. The authors also reported significant differences in the profile of γ -oryzanol between North American wild rice and the regular brown rice. Cycloartenol ferulate is not detected in any of the wild rice samples, whereas its unsaturated form cycloartenol ferulate is one of the most abundant components in the wild rice samples, representing up to 48% of the total γ -oryzanol amount (Aladedunye et al., 2013). The breakdown of γ -oryzanol results in the liberation of its component parts, phytosterol and ferulic acid.

4.2 Vitamins

4.2.1 B-Group Vitamins

Wild rice is a whole grain rich in water-soluble vitamins, such as thiamin, riboflavin, and niacin. Zhai et al. (2001) reported the amount of thiamin in Chinese wild rice present in a range of 0.52–0.63 mg/100 g, whereas in North American wild rice, the amount is 0.36–0.50 mg/100 g. On the contrary white rice contains only 0.12 mg/100 g. Authors also revealed the riboflavin content to be 0.07–0.15 and 0.20 mg/100 g in Chinese and North American wild rice, respectively. Significant lower riboflavin concentration was observed in white rice, 0.05 mg/100 g (Zhai et al., 2001). Swain et al. (1978) identified the thiamin content to be from 0.02 to 0.25 mg/100 g, whereas the riboflavin concentration was between 0.2 and 0.4 mg/100 g. Additionally, the niacin content in wild rice samples was observed to be 4.6–10.3 mg/100 g (Swain et al., 1978).

4.2.2 Tocopherols

Natural vitamin E is composed of eight chemical compounds: α -, β -, γ -, and δ -tocopherol and four corresponding tocotrienols that have a common structure with a chromanol head and phytyl tail. Tocopherols are the compounds with fully saturated phytyl tail, whereas tocotrienols, with a polyunsaturated phytyl tail.

The total vitamin E content of wild rice was reported to be 0.2 mg/100 g lipids in North American and 0.48 mg/100 g lipids in Chinese wild rice (Zhai et al., 2001). On the contrary, Chinese white rice contained 0.1 mg/100 g lipids. According to Przybylski et al. (2009), the amount of total vitamin E in different varieties of wild rice ranged from 0.79 to 13.06 g/kg lipids. Additionally, the amount of total tocopherols in different types of rice bran oils is much lower (Table 10.5).

However, Choi et al. (2007) reported that tocol levels are cultivar dependent. They revealed that the amounts of total tocols were 7.4, 26.4, and 93.7 mg/kg

TABLE 10.5 Tocochromanols Content in Wild Rice, Rice Bran Oil, and Whole Grains

	Vitamin E (mg/kg)	Total Tocopherols (mg/kg)	Total Tocotrienols (mg/kg)
Chinese wild rice	2–4.8 ^a	—	—
North American wild rice	2 ^a	—	—
North American wild rice	791–13060	251–3682	540–9378
Chinese white rice	1 ^a	—	—
Standard brown rice	585–7043	361–2565	224–4478
Refined rice bran oil	88–1609	16–452	72–1157
Deodorized rice bran oil	463	271	192
High-oryzanol rice bran oil	1095	123	962
Rice bran (Aguilar Garcia)	196–219 ^a	41–61.3 ^a	155–163 ^a
Black rice	93.7 ^a	53.5 ^a	40.2 ^a
Brown rice	26.4 ^a	5.4 ^a	21.0 ^a
White rice	7.4 ^a	0.8 ^a	6.6 ^a
Pakistan rice bran	756–990 ^a	392–512 ^a	343–478 ^a

^aResults (mg/kg) expressed on an as is basis.

Source: Data based on Abidi, S.L., Rennick, K.A., 2003. Determination of nonvolatile components in polar fractions of rice bran oils. *J. Am. Oil Chem. Soc.* 80, 1057–1062; Aguilar-Garcia, C., Gavino, G., Baragano-Mosqueda, M., Hevia P., Gavino, V.C., 2007. Correlation of tocopherol, tocotrienol, γ -oryzanol and total polyphenol content in rice bran with different antioxidant capacity assays. *Food Chem.* 102, 1228–1232; Aladedunye, F., Przybylski, R., Rudzińska, M., Klensporf-Pawlik D., 2013. γ -Oryzanols of North American wild rice (*Zizania palustris*). *J. Am. Oil Chem. Soc.* 90, 1101–1109; Iqbal, S., Bhanger, M.I., Anwar, F., 2005. Antioxidant properties and components of some commercially available varieties of rice bran in Pakistan. *Food Chem.* 93, 265–272; Przybylski, R., Klensporf-Pawlik D., Anwar, F., Rudzińska, M., 2009. Lipid components of North American wild rice (*Zizania palustris*). *J. Am. Oil Chem. Soc.* 86, 553–559; Ribeiro Pestana, V., Zambiasi, R.C., Mendonca, C.R.B., Bruscatto M.H., Lerma-Garcia, M.J., Ramis-Ramos, G., 2008. Quality changes and tocopherols and γ -oryzanol concentration in rice bran oil during the refining process. *J. Am. Oil Chem. Soc.* 85, 1013–1019; Roger, E.J., Rice, S.M., Nicolosi, R.J., Carpenter, D.R., McClelland, C.A., Romanczyk, L.J., 1993. Identification and quantification of γ -oryzanol components and simultaneous assessment of tocols in rice bran oil. *J. Am. Oil Chem. Soc.* 70, 301–307.

in white, brown, and black rice, respectively. This could be an explanation for the differences seen among wild rice varieties. Additionally, the amount of tocols differs depending on the part of the grain (Ko et al., 2003). The identified vitamin E compounds in wild rice were α -, β -, γ -, and δ -tocopherol and α -, β -, and δ -tocotrienol. γ -Tocotrienol was not detected in wild rice samples, but it was quantified in brown rice samples and comprised between 6.6% and 67.6% of the total chromanol compounds. The predominant vitamin E compounds were α -tocopherol and α -tocotrienol. α -Tocopherol is known to be the most active component of the vitamin E complex and most powerful antioxidant in the lipid phase

of the human body (Burton and Ingold, 1989). The high concentration of vitamin E, with the presence of α -tocopherol, as a predominant compound, significantly influences the nutritional quality of wild rice. Therefore, wild rice could be recognized as a valuable source of vitamin E and would be beneficial for humans.

4.3 Minerals

The mineral composition of wild rice seems to be similar to other grains. However, generally wild rice could be recognized as a valuable source of calcium, magnesium, phosphorus, and potassium (Anderson, 1976; Zhai et al., 2001). Substantial amounts of iron, sodium, and zinc were also reported. The concentrations of magnesium, potassium, phosphorus, zinc, and iron in wild rice were higher than in brown rice and polished white rice (Anderson, 1976).

The concentration of minerals in Chinese and North American wild rice were similar. The most abundant mineral was phosphorus, present at a concentration between 290 and 340 mg/100 g in Chinese and North American wild rice, respectively (Zhai et al., 2001).

4.4 Phenolic Compounds

Phenolic compounds are the most studied whole-grain phytochemicals, with one or more aromatic rings and one or more hydroxyl groups that function in a variety of roles, mainly in plant defense. As a whole grain, wild rice is also a valued source of phenolic compounds. Total phenolic content (TPC) of nine different wild rice varieties was reported to be 419–588 mg GAE/kg (Qiu et al., 2010) and 2472–4072 mg FAE/kg (Qiu et al., 2009) (Table 10.6). The differences in

TABLE 10.6 Total Phenolic, Phenolic Acids, and Flavonoids Content in Wild Rice Samples

	Wild Rice	White Rice	Processed Wild Rice
TPC (mg GAE/kg) methanol extract	419–588	46	353
TPC (mg FAE/kg) acetone extract	2472–4072	279	2076
Phenolic acids (mg/kg) total	409–535	107	392
Ferulic acid (mg/kg)	241–355	102	232
Sinapic acid (mg/kg)	55–97	trace	79
Flavonoids (μg/g)	7-162	nd	24

Source: Data based on Qiu, Y., Liu Q., Beta, T., 2009. Antioxidant activity of commercial wild rice and identification of flavonoid compounds in active fractions. *J. Agric. Food Chem.* 57, 7543–7551; Qiu, Y., Liu, Q., Beta, T., 2010. Antioxidant properties of commercial wild rice and analysis of soluble and insoluble phenolic acids. *Food Chem.* 121, 140–147.

the obtained results are probably due to the effect of extract preparation method and different solvents used in the study. [Alves et al. \(2016\)](#) reported that total phenolic content in wild rice was strongly affected by the extraction solvent applied, and the content varied from 31 to 311 mg GAE/100 g of sample, in ethanol and acetone/water extract, respectively. In addition, a study by [Ma and Cheung \(2007\)](#) showed that individual phenolic compounds respond differently to the Folin reagent, giving the divergent results. The reported results, by [Qiu et al. \(2009, 2010\)](#), of total phenolic compounds in wild rice are significantly higher than that observed in conventional white rice, 46 mg GAE/kg and 279 mg FAE/kg. Comparing the total phenolic content of black and wild rice, [Alves et al. \(2016\)](#) reported that wild rice grains exhibited 311 mg GAE/100 g, whereas black rice have 878 mg GAE/100 g. However, TPC of wild rice was almost 8 times higher than in dehusked, long-grain rice and over 11 times higher than in polished (both long- and short-grain) rice ([Alves et al., 2016](#)). Additionally, the amount of TPC (2076 mg FAE/kg) in processed quick cooking wild rice is substantially lower than that in raw wild rice ([Qiu et al., 2009](#)). The procedure involved in quick cooking wild rice production employed soaking, cooking, and drying, which could result in a loss of phytochemicals present in raw grains ([Li et al., 2007](#)).

[Qiu et al. \(2009\)](#) reported significant differences in antioxidant activity of wild rice, determined in 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity and oxygen radical absorbance capacity (ORAC) assays. The differences can be explained by the effect of several factors, including cultivar, growing environment, and harvesting conditions. Additionally, [Mitchell et al. \(2007\)](#) in a 10-year study showed that organically grown wild rice varieties were characterized by higher antioxidant activity than conventional varieties. The high antioxidant activity of wild rice is highly correlated with the total phenolic content ([Qiu et al., 2009](#)). The authors showed a strong relationship between TPC and DPPH radical scavenging activity and between TPC and ORAC.

4.4.1 Phenolic Acids

Phenolic acids and their derivatives are secondary metabolites distributed widely in fruits, vegetables, and cereal grains. The continuously growing interest in phenolic acids profile is directly related to their antioxidant activity and potential health benefits ([Qiu et al., 2010](#)). Cereal grains contain a wide range of phenolic acids with ferulic and *p*-coumaric acids as the predominant ones ([Mpofu et al., 2006](#); [Shahidi and Naczk, 2003](#)). The most abundant phenolic acids in wild rice were ferulic acid, its content varied from 241 to 355 mg/kg, followed by sinapic acid, 55–97 mg/kg ([Table 10.6](#)). Besides ferulic and sinapic acids, a significant amount of *p*-coumaric acid was also found ([Qiu et al., 2010](#)). Hydroxycinnamic acids are the predominant phenolic acids in insoluble fractions of wild rice. Compared to wild rice, white rice samples contained at least

2 times lower amounts of ferulic acid, and sinapic acid was observed only at a trace level (Qiu et al., 2010).

Additionally, as a whole grain, wild rice is a good source of dietary fiber, which is rich in several monomeric phenolic acids and dehydrodimers of ferulic and sinapic acids (Bunzel et al., 2003).

4.4.2 Flavonoids

Flavonoids, together with phenolic acids, have received much attention due to their high antioxidant activity. As secondary plant metabolites, flavonoids are conjugated with sugars and occur as flavonoid O- or C-glycosides. The antioxidant activities of flavonoids are related to their structural aspects, with the better scavenging activity associated with the presence of the catechol moiety (Van Acker et al., 1996).

Catechin and epicatechin were found in all wild rice samples; however, the presence of procyanidin oligomers varied among samples (Qiu et al., 2009). The amount of procyanidin in raw samples ranged from 7.16 to 239.22 $\mu\text{g/g}$ (Table 10.6). Wild rice was also reported to contain 27.2 $\mu\text{g/g}$ of total anthocyanin (Abdel-Aal et al., 2006). Qiu et al. (2009) also reported the presence of flavonoids in processed sample; however, the amount was relatively low, due to the presence of mono- and dimer procyanidin only. In white rice samples no procyanidin oligomers were detected.

5 POTENTIAL HEALTH BENEFITS

The health benefits of whole grain consumption are generally attributed to their content of nutritional constituents, vitamins, minerals, and a variety of other phytochemicals. Therefore they are associated with reduced risk of cardiovascular diseases, type II diabetes, obesity, and cancers. In 2006, wild rice was recognized as a whole grain by the US Food and Drug Administration, and therefore received more attention recently. The benefits of wild rice may be attributed to the synergistic effects of its natural nutrient profiles, such as high content of dietary fiber (Zhai et al., 2001), essential fatty acids (Przybylski et al., 2009), and phenolic compounds (Qiu et al., 2009, 2010). Dietary recommendations to increase whole-grain consumption and consumer interest in ancient grains encourage the use of wild rice in human diets.

The antioxidant properties of wild rice have been reported in only a few studies, which focused on the role of wild rice in lipid peroxidation (Asamarai et al., 1996; Johnson and Addis, 1996; Minerich et al., 1991; Rivera et al., 1996; Wu et al., 1994). When incorporated into different meat products, crude or cooked wild rice was able to retard lipid oxidation and hence extracts of wild rice grains could be used as effective antioxidants. However, only phytic acid was characterized as one of the wild rice potent antioxidants (Wu et al., 1994). These findings demonstrate the ability to use wild rice

to prevent rancidity and prolong shelf life of food products. Moreover, [Qiu et al. \(2009, 2010\)](#) studied the antioxidant activity of commercial wild rice and identified the specific compounds responsible for these properties. The antioxidant activity of wild rice methanol extracts was found to be up to 10 times higher than that of white rice according to their DPPH radical scavenging activity and ORAC assay. Ferulic and sinapic acid were identified as the most abundant phenolic acids in wild rice ([Qiu et al., 2010](#)). Acetone extracts revealed over 30 times higher antioxidant activity than white rice, and the antioxidants responsible for these were flavonoid glycosides and flavan-3-ols ([Qiu et al., 2009](#)).

Additionally, the stem and leaf sheet extracts of *Z. latifolia* were reported to possess effective antioxidant properties, but only stem extract has angiotensin-converting enzyme (ACE) inhibitor activity, which could be successfully used for the treatment of hypertension ([Qian et al., 2012](#)). Another in vitro study revealed that besides the antioxidant properties, the gall extract of wild rice stimulated the promoter activity of human β -defensin-2 in colon carcinoma cells, giving a positive effect in the innate immune system and therefore contributes to human health via activating gene expression ([Ortani et al., 2009](#)). [Lee et al. \(2015\)](#) studied the potential benefits of fractionated methanol extracts from aerial parts of *Z. latifolia*. Flavonolignans and flavones were recognized as the main constituents with inhibitory activities against nitric oxide production and histamine release in vitro. The strongest antiinflammatory and antiallergic activities possessed salcolin D and *Z. latifolia* was ascertained as a possible therapeutic source ([Lee et al., 2015](#)). In a previous study ([Lee et al., 2009b](#)), reported the positive effect of methanolic extracts of whole wild rice plant. The studied extracts possessed the ability to inhibit compound 48/80-induced degranulation and antigen-induced β -hexosaminidase release in a concentration-dependent manner. This property could be useful in the prevention of type-I allergic reaction ([Lee et al., 2009b](#)). Additionally, ethanolic extract of the *Z. latifolia* gall had the ability to inhibit osteoclast formation in mice and could be developed as an effective solution for osteoporosis prevention ([Kawagishi et al., 2006](#)). The authors found that the gall extract reduced osteoclast formation by up to 49% without any cytotoxicity of the cells. A preliminary study also demonstrated that wild rice effectively reduced the numbers of large aberrant crypt foci in colon cancer in rats ([Gallaher and Bunzel, 2012](#)).

The scientific literature and information about the positive potentials of wild rice consumption remain limited, and no data are available on dietary intervention trials with wild rice in humans. However, [Zhang et al. \(2009\)](#) reported the lipid-lowering and cardioprotective effects of wild rice in rats fed with a high-fat/cholesterol diet. Incorporating wild rice as the carbohydrate source suppresses the increase in serum triacyl glycerols and total cholesterol, and decreases high-density lipoprotein levels. The increase in superoxide dismutase activity and reduction in malondialdehyde concentration in the serum and liver tissue illustrate the effectiveness of wild rice-rich diet ([Zhang et al., 2009](#)).

Moreover, [Han et al. \(2012\)](#) investigated the protective potentials of wild rice against obesity and lipotoxicity induced by a high-fat/cholesterol diet in rats. It has been observed that wild rice exerts beneficial effects against obesity and liver lipotoxicity by hindering the lipid droplet accumulation in liver and minimizing the levels of serum-free fatty acids and leptin in rats. It also inhibited the decrease of lipoprotein lipase and adipose triglyceride lipase activities ([Han et al., 2012](#)). Similar effects of improvement in body weight and lipid profile were reported by [Zhang et al. \(2009\)](#). Additionally, [Han et al. \(2013\)](#) studied the effect of replacing dietary carbohydrates with wild rice on insulin resistance in rats. Results indicated that wild rice is effective in ameliorating abnormal glucose metabolism and insulin resistance in rats. Moreover, incorporating wild rice into the diet reversed the abnormal or impaired levels of liver homogenate triglycerides and free fatty acids levels, and it also improved diet-induced lipotoxicity ([Han et al., 2013](#)). In general, it was found that wild rice consumption significantly decreased liver triglyceride, free fatty acids, and serum lipocalin-2 levels followed by an increase in adiponectin concentration in the serum and liver of rats ([Han et al., 2013](#)).

Cholesterol-lowering and antiatherogenic effects of wild rice was observed in low-density lipoprotein receptor-deficient mice ([Surendiran et al., 2013](#)). The authors revealed that consumption of wild rice significantly reduced the size and severity of atherosclerotic lesions in the aortic roots of mice, which was associated with significant reduction of plasma cholesterol levels, low-density lipoprotein levels, and very low-density lipoprotein levels. However, responsiveness to the wild rice in the diet differed between male and female mice. Female mice responded better to the wild rice's cholesterol-lowering effects. Although, the content of total phenolics and dietary fiber increased compared to white rice, the plasma and erythrocyte superoxide dismutase and catalase activity did not improve. Obtained results suggested that the cholesterol-lowering effect is the main factor for the prevention of atherogenesis in low-density lipoprotein (LDL)-receptor deficient mice, and is mainly attributed to the increased rate of fecal cholesterol excretion ([Surendiran et al., 2013](#)). Additionally, [Moghadasian et al. \(2016\)](#) tested the combined effect of phytochemicals and wild rice on prevention of atherosclerosis in LDL receptor knockout male mice. Consumption of wild rice in combination with phytosterols significantly reduced the size and severity of atherosclerotic lesions in the aortic roots as compared to the control group. This effect was strongly associated with significant reductions in plasma total, LDL, and very low-density lipoprotein (VLDL) cholesterol concentration, as well as an increase in fecal cholesterol excretion. Altogether, this study provides evidence that long-term consumption of wild rice and phytosterols is safe and reduces cardiovascular risk factors in mice ([Moghadasian et al., 2016](#)). However, the mechanism of action and potential clinical outcome remains unknown.

The potential antioxidant and health-promoting properties of wild rice are summarized in [Table 10.7](#).

TABLE 10.7 Potential Antioxidant and Health-Promoting Properties of Wild Rice: Summary

Study designs	Potential effects	Conclusions	References
In vitro, cooked wild rice/ground beef mixtures	Antioxidant potential	Wild rice reduced rancidity in ground beef frozen for 48 days	Minerich et al. (1991)
In vitro, wild rice extracts/beef or lard	Antioxidant potential	Methanol and ethanol extracts showed significant antioxidant activity	Wu et al. (1994)
In vitro, ground cooked wild rice/fresh-frozen and precooked beef patties	Antioxidant potential	Ground cooked wild rice was an effective antioxidant	Johnson and Addis (1996)
In vitro, wild rice hulls extract/ground beef	Antioxidant potential	Wild rice hull extract had high antioxidant activity	Asamarai et al. (1996)
In vitro, crude wild rice extract	Antioxidant activity	The antioxidant activity of wild rice was 30 times higher than in white rice. The potential antioxidant compounds were identified as flavonoid glycosides	Qiu et al. (2009)
In vitro, the gall extract of wild rice, Caco-2 cells	Stimulating effect on the innate immune system	The gall extract of wild rice stimulated the promoter activity of hBD-2 in Caco-2 cells	Oritani et al. (2009)
In vitro, extract of wild rice	Antiallergic activity	Methanolic extract of whole wild rice plant had inhibitory activity against compound 48/80–induced degranulation and antigen-induced β -hexosaminidase release	Lee et al. (2009b)
In vitro, crude wild rice extract	Antioxidant activity	The antioxidant activity of wild rice methanol extract was over 10 times higher than in white rice. Ferulic and sinapic acid were the most abundant acids, occurred in the insoluble form	Qiu et al. (2010)
In vitro, extract of fewflower wild rice	Antioxidant and ACE-inhibitor activity	Extracts of stem and leaf sheet had effective antioxidant activity, but only stem extract exhibited ACE-inhibitory activity	Qian et al. (2012)
In vitro, extract of wild rice, cell culture	Antiinflammatory and antiallergic effect	The tricin derivatives extracted from aerial part of wild rice are responsible for antiinflammatory and antiallergic effect	Lee et al. (2015)

In vivo, the gall extract of wild rice, mice	Osteoporosis prevention	Ethanol extract of the gall of wild rice reduced the osteoclast formation up to 49%	Kawagishi et al. (2006)
In vivo, powdered wild rice, rats	Cardioprotective effect	Incorporating wild rice into the diet improved serum lipid profile and antioxidant status, prevented hyperlipidaemia in rats	Zhang et al. (2009)
In vivo, wild rice, rats	Protective potential against obesity and lipotoxicity	Incorporating wild rice into the diet decreased lipid accumulation and increased activity of catabolic enzymes and regulated key factors in lipogenesis	Han et al. (2012)
In vivo, wild rice, rats	Effect on insulin resistance	Wild rice was effective in ameliorating abnormal glucose metabolism and insulin resistance	Han et al. (2013)
In vivo, wild rice, LDL receptor knockout mice	Atherogenesis prevention	Wild rice improved plasma lipid profile in LDLr-KO mice and has a cholesterol-lowering effect	Surendiran et al. (2013)
In vivo, wild rice + phytosterols mixture, LDL receptor knockout mice	Atherosclerosis prevention	Diet containing wild rice and phytosterols reduced in plasma total, LDL, and VLDL cholesterol concentration and reduced cardiovascular risk factors	Moghadasian et al. (2016)
ACE, Angiotensin-converting enzyme; LDL, low-density lipoprotein; LDLr, low-density lipoprotein receptor; VLDL, very low-density lipoprotein.			

6 FUTURE OBJECTIVES AND POSSIBILITIES

Although, wild rice has no relation with conventional rice grain, it was identified as a whole grain. Since then, more attention has been paid to characterize the health-promoting properties, as well as nutritional composition of wild rice. The research reveals that wild rice contains high levels of protein, a positive lipid profile, complex carbohydrates, and high levels of fiber. Even though a great deal of information has been accumulated regarding the composition of wild rice, there are areas in which further work is required. The reports on composition and content of bioactive compounds are somewhat sparse and contradictory, and therefore unification of methodology is required.

Currently, there is considerable interest in foods with high antioxidant activity. As wild rice contains substantial amounts of phytochemicals, it should be recognized as a rich source of antioxidants. The complex nature of wild rice is associated with its antioxidant properties and potential health benefits, especially in the prevention of chronic diseases. Therefore, efforts to include wild rice into daily diet should be undertaken. Incorporating wild rice into foods that are susceptible to oxidation, could not only prolong their shelf life and protect from unfavorable changes, but could also increase their health benefits. However, there are no data on human dietary intervention with wild rice, and animal research is not always adequate. Therefore, there is a strong need to conduct studies in human subjects with the practical doses of wild rice in their daily diet, to determine if the positive effects observed will be similar to that observed in animals.

In a nutshell, the composition of wild rice and the content of phytochemicals present in it makes it crucial to position it as a prominent functional food for the present and future generations, as it will be beneficial in the prevention of and protection against numerous evolving chronic diseases. However, more effort is required in this direction, including: (1) developing economically feasible methods to explore and utilize the high levels of antioxidative compounds in wild rice, considering that most of these phytochemicals occur in bound form that are not easily accessible to general extraction protocols; (2) discovering and developing cultivars and varieties with improved protein, amino acid, phytochemical contents and composition, and superior resistant starch and fiber; and (3) developing methods to incorporate wild rice products (e.g., flour and extracts) into common food items without compromising sensory attributes.

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FURTHER READING

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Chapter 11

Future Research Needs for the Ancient Grains

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1 INTRODUCTION

The preceding chapters have shown that the ancient grains are at least as nutritious as the cereal grains that dominate most people's diet today, such as wheat. They also reveal that ancient grains are generally rich in phytochemicals and there is clear evidence, although very incomplete, that their regular consumption can be protective against the development of the noncommunicable diseases, the so-called Western-type lifestyle diseases. The chapters show that a very wide range of attractive food and beverage products have been traditionally produced from the ancient grains and that novel products are being researched, especially to satisfy the rapidly expanding market for gluten-free products. Most importantly in the light of the ever-increasing threat of worldwide food insecurity resulting from on-going rapid population growth and increasing food demand due to rising living standards and changing lifestyles, in conjunction with climate change impacting negatively on agriculture, the ancient grains have much to offer as staple food crops due to their adaptation to harsh climatic conditions and low agricultural input requirements.

Despite these many advantages, the current picture with regard to ancient grains is rather mixed, as explained in [Chapter 2](#). FAO data for the past 20 years ([FAOSTAT, 2015](#)) show that production of the dominant cereal grains, wheat, maize, and rice continues to increase, with maize increasing most rapidly ([Fig. 11.1](#)). In the case of the ancient grains, the production of fonio and quinoa has increased dramatically by almost threefold, albeit from very low bases. With fonio, development of technology to mechanically dehusk this tiny grain has probably been the most important factor ([West Africa Agricultural Productivity Program, 2015](#)). In the case of quinoa, this is undoubtedly a consequence of recognition of its agronomic advantages and cultural role in its centers of origin, for example, Bolivia and Peru ([Chapter 5](#)). The demand in Western countries for

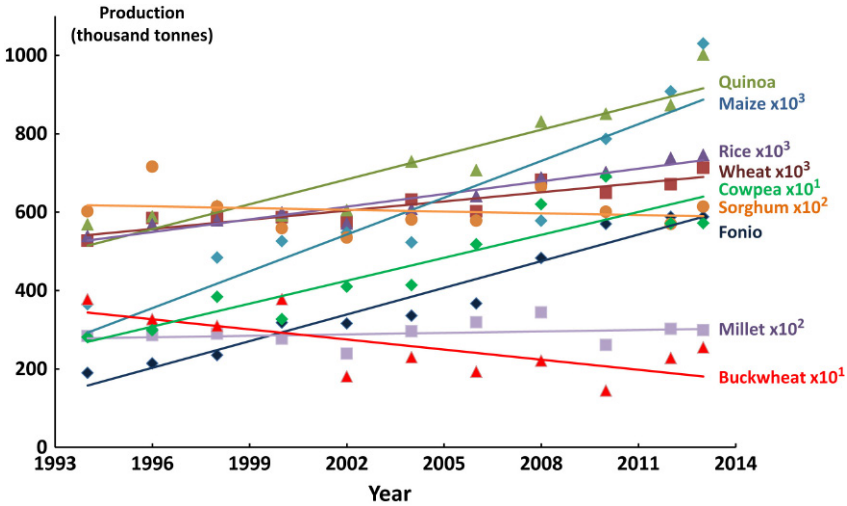


FIGURE 11.1 World production of ancient grains compared to maize, rice, and wheat, 1994–2013. (From FAOSTAT, 2015. Production: crops. Available from: <http://faostat3.fao.org/>)

this exotic gluten-free grain has also played a major role, as 2013 was promoted as the International Year of Quinoa by the FAO (FAO, 2013). With buckwheat, also a pseudocereal, the overall picture is instead that of a dramatic decline in production. However, recently there has been something of a reversal, probably due to its application in gluten-free products (Chapter 7). Most concerning is the stagnation in millet production and the slight decline in sorghum production. As both of these grain types are predominantly cultivated in African and Indian regions, with very rapid population growth, it indicates that they are being displaced as major staple foods. There is less information on the legumes, but FAOSTAT data shows that cowpea production has increased steadily, doubling over 20 years. This has largely been driven by increased productivity in Africa where 95% of the crop is produced. For example, the average yield of cowpea in Africa doubled from 0.3 tonne/ha in 1993 to 0.6 tonne/ha in 2013, essentially mirroring the increased global production (FAOSTAT, 2015). The increased production of cowpea has been a result of national agriculture research activities and their linkages with international collaborative research initiatives, such as the International Institute for Tropical Agriculture and the Bean/Cowpea & Dry Grain Pulses Collaborative Research Support Program (Michigan State University, undated).

This concluding chapter focuses on the critical issue as to what is required to reverse these adverse trends and to build on the successes. It inevitably contains a good measure of speculation and even wishful thinking. Predicting future technological developments is tricky. Just 8 years before the Wright brothers flew, the physicist Lord Kelvin stated that heavier-than-air flying machines were impossible. Predicting human behavior is even more difficult. In 1977, Mr. Ken

Olson president of the Digital Equipment Company said “There is no reason anyone would want a computer in their home.” An opinion that one of these authors certainly would have agreed with at the time.

The chapter attempts to critically examine the future research and development requirements that will enable people worldwide to benefit from the ancient grains. It follows a food chain approach starting with breeding and agriculture, through food products and processing technologies, the required quality management systems, and onto meeting consumer nutrition and health needs. Throughout, there are two important crosscutting themes: the role of collaborative research, development and implementation programs and learning from past research successes. The chapter concludes with brief recommendations pertaining to priorities.

2 BREEDING AND AGRICULTURE

2.1 Organizations Involved

Two CGIAR (Consultative Group on International Agricultural Research) institutes have mandated responsibilities for ancient grains, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) for sorghum and millets and the International Institute for Tropical Agriculture (IITA) for cowpea. In the 1990s, ICRISAT in partnership with national departments of agriculture in southern Africa achieved notable success in the breeding of several successful sorghum and pearl millet varieties (Monyo, 1998; Obilana, 1998). This work is ongoing in West and East Africa, and particularly in India (ICRISAT Exploireit, undated). ICRISAT has released a total of around 240 improved commercial sorghum varieties, both hybrids and open pollinated varieties (OPVs) in Africa and Asia. The improved sorghum varieties bring an income of nearly \$500 per hectare to farmers in Africa. Regarding IITA cowpea activities, improved varieties developed by IATA have been released in 68 countries across the world (IITAa, undated). Important traits include high yield, early- or medium-maturing, desirable end-use traits like large seeds, and desirable seed coat texture and color.

Unfortunately, the CGIAR activities with other ancient grains are limited. For example, ICRISAT and associated organizations maintain a collection of around 10,000 small millet accessions (ICRISAT Exploireit, undated) and IITA maintains a collection of some 2,000 bambara groundnut accessions (IITAa, undated). There does not seem to be any in-depth activity with regard to the pseudocereals.

Another, but smaller-scale, long-term, on-going international agricultural research activity is the United States Agency for International Development (USAID) Collaborative Research Support Programs (CRSPs) and their successors, the Feed the Future Innovation Laboratories. Two programs focus on the ancient grains: INTSORMIL and its successor SMIL (Digest Project, 2013), and the Bean/Cowpea and Dry Grain Pulses CRSP and its successor the

Legume Innovation Lab (Crawford et al., 2013). In CRSP and Feed the Future Innovation Lab projects, universities in the USA undertake collaborative research, development, and implementation work in partnership with universities and research institutes in Africa and Latin America. Probably the most important agricultural contribution of the CRSPs/Innovation Labs has been in respect of high level of training of scientists from developing countries. For example, INTSORMIL in its 30-year existence was responsible for the training of more than 200 BSc, MSc, and PhD plant breeders and some 400 scientists in other agricultural science related disciplines, such as agronomy, plant pathology, soil science, and molecular biology (INTSORMIL, 2009).

2.2 Agricultural Productivity

As indicated, the low production of the ancient grains is a severe limitation for their use (Fig. 11.1). A major reason for their low production is that their yield productivity is much lower than that of the major grains (Fig. 11.2) (FAO-STAT, 2015). Taking a worldwide average, the yield of sorghum, is by far the

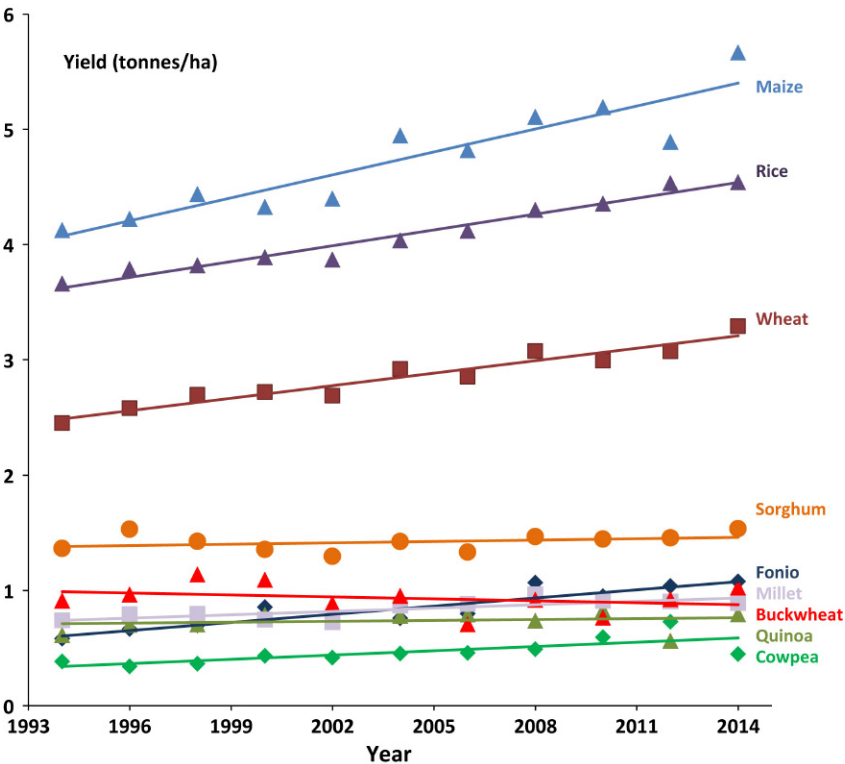


FIGURE 11.2 World average yields of ancient grains compared to maize, rice, and wheat, 1994–2014. (From FAOSTAT, 2015. Production: crops. Available from: <http://faostat3.fao.org/>)

highest of the ancient grains, at 1.5 tonnes/ha, only approx. 36% of that of maize, despite the fact that they are both very similar tropical (C4) cereals. The other ancient grains have average yields of 1 tonne/ha or less, which is only approx. one-third that of wheat, the lowest yielding of the major cereals. Such low yields do not make ancient grains attractive crops for commercial farmers, unless the price of the grain is very high or the costs of production are comparatively low.

What is perhaps even more concerning is that the yield gap between the ancient grains and the major cereals is generally widening. As it can be seen in Fig. 11.2, the yields of the major cereals have increased by 35%–37% over the past 20 years. In contrast, the yields of sorghum and quinoa have remained essentially static, while that of buckwheat has declined considerably. Yield improvements have been shown for the millets, fonio, buckwheat, and cowpea. Some reasons that can account for these trends have been proposed earlier.

A major constraint in improving the productivity of the ancient grains is that with the exception of sorghum, the major international seed-breeding companies are not significantly involved in ancient grains. This is presumably simply a matter that the market for the seeds is too small to justify the cost of development. Data concerning breeding costs versus financial benefit are difficult to obtain. However, the Australian Grains Research & Development Corporation has estimated that the benefit: cost ratio of just their national variety trials, which include wheat, as well as the so-called coarse grains, like sorghum and pulses, was marginal, only 1.0–1.2:1 (GDRC, 2011).

Hence, for the most part, ancient grain breeding and related agricultural research are carried out solely by in-country public sector organizations, namely government departments of agriculture and universities. Unfortunately, these are notoriously underfunded, especially those in developing countries, and there is good evidence that this threatens both their performance and very existence (Echeverría and Beintema, 2009).

2.3 Technological Developments

The general research and development challenges involved in improving cowpea cultivation productivity sustainably, and technological developments that can assist the process have been comprehensively reviewed by IITA (Fatokun et al., 2002). They are equally applicable to all the ancient grains and comprise:

- Genetics and breeding—including breeding for tolerance to temperature extremes and adaptation to drought and resistance to biotic stresses.
- Biotechnologies—including sequencing and mapping genes of interest, regeneration, and transformation techniques.
- Farming systems and agronomic improvement—including soil fertility management, crop rotation, and cropping systems.
- Integrated pest management—including alternative host plants for biological control and pheromone traps.

On the basis of these, here some of the current and impactful ancient grains major breeding and agriculture technological developments will be examined. Plant breeding is being revolutionized by many developments in biotechnology and informatics. The impact of these technologies on the ancient grains has the potential to be profound. They can help close the yield gap with the major grains by dramatically short cutting the breeding process. In keeping with the subject of this book, the focus will be specifically on meeting the quality needs of the end user.

2.3.1 Genomics and Biotechnology

Mapping the genomes of plant and animal species is increasing exponentially, as costs go down with the development of new technologies, currently from Second/Next Sequencers to Third-Generation Sequencers. One example of the latter, Oxford Nanopore sequencing can read single-molecule sequences of 50–100 kbp (kilobase pairs) with only a 4% error (Varshney et al., 2014).

Concerning the ancient grains, the sorghum genome was sequenced in 2009 and comprises around 730 Mbp (megabase pairs) (Paterson et al., 2009), which is much larger than rice (43 Mbp, but far smaller than maize (2300 Mbp). Since then, several other ancient grain species genomes have been sequenced, for example, foxtail millet in 2012, which has a 423-Mbp genome (Zhang et al., 2012), lupin in 2013, with a predicted 58,000 genes (Yang et al., 2013), and amaranth in 2014, which has a 426-Mbp genome (Sunil et al., 2014). As of 2016, others, such as quinoa are in progress (Yasui et al., 2016) or planned, for example, cowpea (Nealon, 2016).

One of the major benefits of understanding crop plant genomes is that it enables scientists to identify lines of a species and its near relatives with genes coding for particular desirable traits, so-called tapping the pool of genetic diversity. Using sorghum as an example, Mace et al. (2013) sequenced the genomes of 44 sorghum lines representing all the major races of cultivated sorghum (*Sorghum bicolor*), plus its progenitors and the related Asian species *Sorghum propinquum*. Among many valuable findings, they, for example, identified 324 candidate domestication and/or improvement genes in wild and weedy sorghum types versus improved inbred sorghum lines. As these genes are all within the cultivated sorghum species or genus, they can relatively easily be crossed into parent commercial lines.

Another example of the potential power of understanding the genome in breeding is using genomics in combination with mutagenesis. Recently, Jiao et al. (2016) subjected an elite sorghum line to chemical-induced mutation. They sequenced 256 mutant lines and identified >1.8 million induced mutations affecting >95% of the genes in the genome. Furthermore, they were able to identify eight genes associated with drought tolerance, of which two showed exact cosegregation with phenotype. Interestingly, chemical mutagenesis is regarded as a conventional breeding tool and thus in many countries it is not subject to the strict regulations that govern GMOs (Genetically Modified Organisms) (Forster and Shu, 2011).

An example where this approach has been applied in practice with ancient grains is in the development of herbicide-tolerant sorghum types. This trait is equivalent to that of the well-known GM Roundup Ready maize, and enables selective suppression of weeds by herbicide application without affecting the crop plant. A sorghum mutant obtained by chemical mutagenesis has been found with a specific polynucleotide encoding for mutated acetohydroxyacid synthase enzyme, which imparts increased resistance to inhibition by sulfonyl-urea- and imidazolinone-type herbicides (Uriarte et al., 2012).

Gene editing by site-directed nucleases is the general term for a group of biotechnologies that fall between GMO breeding involving insertion of new genetic material in vitro and conventional breeding. The most well known of these technologies is CRISPR (clustered regularly interspaced short palindromic repeat) where the nuclease enzyme Cas9 (CRISPR-associated 9) is directed to specific loci in the genome by synthesized guide RNAs; there it introduces tailor-made double strand breaks (Podevin et al., 2013). The potential of CRISPR/Cas9 genome editing is referred in the lupin chapter (Chapter 8). The application of CRISPR in cereal species, including sorghum, was first demonstrated in 2013 (Jiang et al., 2013). Probably the most important benefits of CRISPR/Cas9 genome editing are that precise, predictable modifications of elite (commercial variety parent) lines can be performed, and multiple traits can be modified simultaneously (Bortesi and Fischer, 2015). Hence, breeding timeframes can be dramatically reduced.

However, at present legislation is a problem hampering commercial application of gene-editing technologies, which needs to be resolved. The difference between a plant that is, or is not, a GMO is becoming ever more blurred and contentious, with the result that there is not much agreement among scientists, and current legislation does not adequately cover such issues (Araki and Ishii, 2015).

2.3.2 Phenotyping

As indicated earlier, genomics-supported plant breeding technologies can generate huge numbers of candidate plant lines that may have potentially valuable traits. It is said with some justification that the age of “big data” is only just commencing. Already a major challenge and bottleneck in plant breeding is the identification of those plants in tissue culture, greenhouse, or field that express the desired trait, i.e., phenotyping. Automated plant-phenotyping technologies are developing rapidly. This is leading to the development of a new biological discipline called phenomics (Dhondt et al., 2013). Imaging technologies, such as hyperspectral imaging and 3-D tomography are being integrated with robotic technologies, including unmanned aerial vehicles (drones) (Dhondt et al., 2013; Fahlgren et al., 2015). To date, application of such technologies to the ancient grains has been limited to sorghum and focused on plant characteristics. For example, digital imaging has been used to study sorghum plant growth response to nitrogen and water deficit (Neilson et al., 2015). A drone carrying multispectral and high-resolution cameras has been used to obtain data

of plant heights, populations, and yield in a genetically diverse sorghum population (Shi et al., 2016). With regard to phenotyping for grain quality, the technology of near infrared hyperspectral imaging shows great promise to replace the conventional, and all of the the chemical, physical, and microbiological grain analyses are normally applied by a single automated image acquisition (Sendin et al., 2016).

2.3.3 *Breeding for Nutritional Quality*

Breeding of ancient grains for improved nutritional quality in terms of macronutrients and for reduced levels of antinutrients and other undesirable components, such as bitter substances, has been going on for many years.

Concerning macronutrients, natural waxy (high-amylopectin) mutants of several ancient grain species have been identified. These include: sorghum, foxtail millet, proso millet, and amaranth (reviewed by Taylor et al., 2014). High amylopectin types are noted for their high starch digestibility and as a consequence have improved monogastric animal feed conversion rates (Rooney and Pflugfelder, 1986). With regard to proteins, there has been considerable research in developing sorghum lines of improved protein quality, both in terms of indispensable (essential amino acid) composition and protein digestibility (availability). Chemical mutagenesis and recombinant DNA technology have been used to develop high-lysine sorghum lines (reviewed by Henley et al., 2010). As a result of suppressed synthesis of particular kafirin subclasses and altered protein body morphology, such lines also have improved protein digestibility (reviewed by Henley et al., 2010 and Taylor and Taylor, 2017). Also, today sorghum lines are being developed that express both the high-amylopectin and improved protein digestibility traits (Elhassan et al., 2015; Jampala et al., 2012).

Developments in breeding out undesirable components are described in the grain-specific chapters, with the major developments being low-saponin quinoa (Chapter 5) and sweet (low alkaloid) lupin types (Chapter 8). Concerning phenolics, there is great variability in tannin and polyphenol levels between different varieties of sorghum (Chapter 3), millet species (Chapter 4), and cowpea (Chapter 9). With sorghum, the issue of polyphenols, in particular the condensed tannins, being both antinutrients and responsible for strong flavors and colors, and at the same time being health-promoting phytochemicals (reviewed by Taylor and Duodu, 2015), is resulting in the breeding of cultivars of quite differing properties with respect to polyphenols. There are now types that are rich in polyphenols, so-called black sorghum (Taleon et al., 2012) and types that are low in polyphenols, especially anthocyanin pigments, the white tan plant, so-called “food-grade,” sorghums (Reddy et al., 2004).

2.3.4 *Biofortification*

The earlier developments concerning breeding to improve macronutrient content and reduce antinutrient levels in the ancient grains can be considered as examples of biofortification. As defined by the WHO (2016), “biofortification is the

process by which the nutritional quality of food crops is improved through agro-nomic practices, conventional plant breeding, or modern biotechnology.” However, some authorities, notably [HarvestPlus \(undated a,b\)](#), which is the CGIAR organization that has pioneered biofortification, consider that biofortification primarily concerns improving the density and availability of micronutrients.

The largest and most practically successful ancient grain micronutrient biofortification activity has been the development and now implementation by ICRISAT and partners of pearl millet varieties that have elevated levels of iron and zinc. Lines having very high levels of >80 ppm Fe (compared to the normal range of 31–61 ppm) and >60 ppm Zn (normal range 32–54 ppm) have been identified ([Rai et al., 2012, 2013](#)). Furthermore, Fe and Zn contents have found to be positively and highly significantly correlated ([Rai et al., 2012](#)). ICRISAT has developed several high-iron and -zinc varieties and hybrid cultivars, notably Dhanashakti, which is an early-maturing, open-pollinated variety with a very high iron level and an elevated level of zinc, 96 and 48 ppm (own data), and is the first biofortified crop to be released in India and cultivated by farmers ([Rai et al., 2014](#)). Food intervention studies have shown that the high-iron pearl millet is efficacious. A study in Benin with young women subjects consuming pearl millet with vegetable sauce revealed that iron absorption from the food made prepared with biofortified pearl millet was double that from the control made with normal pearl millet ([Cercamondi et al., 2013](#)). The authors concluded that consumption of iron-biofortified pearl millet should be effective in combating iron deficiency in pearl millet-consuming communities.

In parallel, ICRISAT is also commencing development of high-iron and -zinc sorghum varieties ([Upadhyaya et al., 2016](#)). An alternative approach to mineral biofortification is to reduce the level of phytate in the grain and hence improve mineral bioavailability. The Africa Biofortified Sorghum (ABS) project led by the Africa Harvest Biotechnology Foundation International has developed transgenic low-phytate sorghum through modulation of the myoinositol kinase, the enzyme responsible for phytate synthesis ([Shi et al., 2008](#)), and gene-silencing technology involving the multidrug resistance-associated protein (MRP) transporter gene ([Shi et al., 2011](#)). Using the latter technology, grain phytate levels were reduced by 80%–86% ([Kruger et al., 2013](#)). These authors found that significantly improved iron availability in vitro and iron absorption in vivo (rat pup model) is between 37% and 61% and 6% and 20%, respectively. In vivo zinc absorption was also improved substantially, by 25%–39%.

The ABS project is also developing transgenic provitamin A–biofortified sorghum. Using similar technology that is used for Golden Rice, sorghum grain with greatly enhanced levels of *trans*- β -carotene of on average of 9 ppm, an 18-fold increase, has been produced ([Che et al., 2016](#)). A notable breakthrough is that the β -carotene in this provitamin A sorghum is stabilized against oxidation. This has been achieved by coexpression of geranylgeranyl transferase (GGT), an enzyme involved in tocotrienol (vitamin E) synthesis. The vitamin E extended the half-life of the β -carotene in the sorghum grain from 4 to 10 weeks.

2.4 Seed Systems

It is obviously critical to breed new varieties of ancient grains with improved agro-economic, nutritional, and end-use functionality characteristics. However, a stumbling block is getting farmers to purchase and grow them. As indicated in [Chapter 2](#), the expanding market for the so-called super foods in high-income nations is providing some market pull. Notwithstanding this, farmers in low-income countries in particular, where the ancient grains are predominantly cultivated, require a strong incentive to increase production, especially sustained local market demand. In this regard, there have been some notable successes. For example, in Uganda the development of a successful lager beer-brewing industry based on sorghum required a partnership between the brewing company, the national agricultural institute, and small-holder farmers, which enabled production of a particular sorghum variety with the required brewing quality ([Mackintosh and Higgins, 2004](#)). A sophisticated seed system had to be created from scratch, involving seed production and certification, contracting with farmers, and greatly enhanced agricultural extension.

The acute need for improved seed systems in developing countries has been widely recognized by international organizations involved in agriculture. A major collaborative project is PASS (Program for Africa's Seed Systems), which is run by the AGRA (the Alliance for a Green Revolution in Africa) and supported by organizations, such as the Bill and Melinda Gates Foundation. PASS has four subprograms focused on education and training for African crop improvement, improvement and adoption of African crops, seed production, and, perhaps most importantly, development of Agro dealers (commercial suppliers of seed, fertilizers, and cultivation know-how) in rural Africa ([AGRA, undated](#)). The huge scale of PASS's contribution can be seen by the fact that by 2012 the program was responsible for the training of 350 MSc and PhD agriculture students with 240 students graduating in that year. Regarding measurable impact on agriculture, in the 6-year period from 2007 to 2012 PASS assisted in increasing seed production in Africa from 2,000 tonnes to 57,000 tonnes ([FAO, undated](#)). Significantly, the proportion of the seed of ancient grains was relatively large (9%) and comprised sorghum, millets (presumably pearl millet and finger millet), teff, and African legumes. Another facet of seed systems in developing countries is the significant role played by nongovernmental organizations (NGOs). NGOs across Africa, the Indian subcontinent, and in Latin America are core providers of many system services, including: certified seeds, agricultural inputs, extension advice, and microfinance to small-holder farmers ([Coulibaly et al., 2014](#); [Ojiewo et al., 2015](#)). Notwithstanding the important contributions by organizations such as PASS and NGOs, the key to creation of viable seed systems for the ancient grains is not donor support, but market demand for the grains.

2.5 Sustainable and Organic Agriculture

In the light of climate change and growing concerns about protection of the rural environment, the need for sustainable and conservation agriculture is becoming

acute. With regard to the issue of market pull, consumers in high-income countries are increasingly demanding that the foods they purchase should have been produced in an ethical and environmentally friendly manner. Related to this, such consumers are often willing to pay a large premium for organically cultivated foods, up to 27% in the USA for foods that are both organic and locally produced (Ettinger, 2013).

As indicated in Chapter 1, the ancient grains are well adapted to cultivation with low inputs, and generally cultivated in developing countries using traditional, organic-type agriculture. However, this in itself does guarantee production of grains of the required quantity and quality to meet the demands of an increasingly discerning consumer market. There is an on-going need to educate and train farmers in less-developed regions about the concept of sustainable agriculture and conservation agriculture technologies. Quinoa is a particular case in point. Arising from the FAO's 2013 Year of Quinoa there has been considerable interest in the application of sustainable agricultural systems in the Altiplano (high plateau) of the Andes where it is cultivated (Garcia Cardenas and Cusicanqui, 2014). This is because the Altiplano is a highly ecologically sensitive region, as there are severe frosts, droughts, and occasional floods, which in combination with its steep mountain slopes make it very prone to soil erosion. Barrowclough et al. (2016) on the basis of a long-term study across several Andean countries found that conservation agriculture practices yield higher and cost slightly less than conventional agriculture. They further concluded that although conservation agriculture holds promise for the farmers in the Altiplano, its implementation must take careful account of the particular needs of individual farmers.

Regarding organic cultivation of ancient grains, its advantages to farmers in developed countries are clear in terms of substantially higher produce prices. For farmers in developing countries this is by no means always the case. An economic study in south-western India yielded mixed findings (Patil et al., 2014). Organic-type cultivation of finger millet in rotation with legumes, for example, which are subsistence crops, yielded higher net returns than conventional agriculture. Furthermore, in drier areas, yields were higher with organic agriculture. However, this was not always the case for commercial crops, such as coconut and cotton, where both yields and returns were lower. Rainfall also played a significant role in relative profitability, with organic agriculture being generally more profitable in the drier regions. The study also concluded that there was a general problem of a negative soil nutrient balance in the dry areas where organic-type agriculture was used. The authors proposed that this situation could be improved generally by better nutrient management through organic agricultural practices, such as manuring, use of crop residues, and vermicomposting, assuming that these inputs were available. Obviously, in the eyes of the farmer the case for organic and sustainable farming would be greatly strengthened if there were market for his/her ancient grains.

3 QUALITY SYSTEMS

A fundamental requirement for grain and grain food quality systems is the existence of safety and quality standards, and accepted methods of analysis. At the country level, this is generally the responsibility of national government departments of health, food, and agriculture, working in consultation with stakeholders. A notable example is the US Department of Agriculture (USDA), which, among many activities, is responsible for the official GIPSA US Grains Standards and the USDA Food Composition Databases. Several official international organizations and international scientific societies are also involved in the creation of grain and grain food safety, quality standards, and official methods of analysis, most notably the joint Codex Alimentarius Commission of the FAO and WHO, the International Organization for Standardization (ISO), AACC International (formerly the American Association of Cereal Chemists), and the International Association for Cereal Science and Technology (ICC). A recent trend, however, that is already impacting the supply chain for ancient grains, notably quinoa ([CBI Market Intelligence, 2015a](#)), is the imposition by major food retailing corporations of their own food safety and quality standards, such as the British Retail Consortium (BRC) Global Food Standards.

3.1 Grain and Food Composition and Quality Data

[Table 11.1](#) summarizes the situation with regard to official grain nutrient data and grading and end-use quality regulations for the gluten-free ancient grains. For some of the grains, the millets, the African legumes, and sweet lupin, official-type nutrient composition data are lacking, whereas there are data for sorghum and the pseudocereals: amaranth, buckwheat, and quinoa. Obviously, as is evident from this book's chapters on the various grains, in the research literature there are extensive nutrient data on all the grains. However, with this type of data there are always reservations as to their accuracy. An encouraging development in the official USDA National Nutrient Database for Standard Reference is the inclusion of phytochemical data on flavonoids, flavones, and proanthocyanidins from 2015 ([USDA NDL, 2016](#)). However, such data can be very misleading due to the wide compositional variations that exist within a crop species, influenced primarily not only by genetics, but also environment. For example, it is indicated that sorghum grain (item 20648) contains almost 2 g/100 g proanthocyanidins. Unfortunately, it is not pointed out that this only applies to tannin-type sorghums and that most sorghums do not contain any significant amounts of proanthocyanidins.

With regard to "reliable" food product nutrient compositional data, there are essentially only data on flour composition ([Table 11.1](#)). Even here, there are obvious weaknesses. For example, for millet products, the USDA National Nutrient Database ([USDA NDL, 2016](#)) does not give the species of millet from which the products were made. Obviously, the almost complete absence of reliable ancient grain food product compositional data means that when consumers

TABLE 11.1 Summary of Existing and Proposed Quality Data, Regulations, and Standards for the Gluten-Free Ancient Grains

Grain	Organization Responsible for the Standard	Title	Major Aspects of Standards	References
Sorghum	Codex Alimentarius Commission (Codex)	Sorghum Grains (172-1989); Sorghum Flour (173-1989), Revision 1995	Primarily grain and food safety and to a lesser extent food composition	Codex (1995)
	USDA NDL	20067 Sorghum grain; 20648 Sorghum flour, whole grain; 20650 Sorghum flour, refined, unenriched	Grain and food nutrient composition	USDA NDL (2016)
	ICC	ICC Standard 174: Determination of Germinative Energy of Sorghum Grain	End-use quality (malting)	ICC (2011)
	ICC	ICC Standard 175: Determination of Total Defects in Sorghum Grain	Grading procedure (food and feed)	ICC (2011)
	ICC	ICC Standard 176: Estimation of Sorghum Grain Endosperm Texture	End-use quality (milling)	ICC (2012)
	ICC	ICC Standard 177: Detection of Tannin Sorghum Grain by the Bleach Test	End-use quality (food and feed)	ICC (2012)
	ISO	ISO/DIS 9648 Sorghum – Determination of Tannin Content	End-use quality (food and feed)	ISO (1988)
	GIPSA	<i>Grain Inspection Handbook II, Chapter 9 Sorghum</i>	Grades and grading procedures for trade (food and feed)	GIPSA (2013)
	Grain Trade Australia	Sorghum Standards	Grades and grading procedures for trade and ensuring product safety (food and feed)	Grain Trade Australia (2015)
	DAFF	Regulations Relating the Grading, Packing and Marking of Sorghum intended for sale in the Republic of South Africa	Grades and grading procedures for trade (food and feed)	South African Department of Agriculture (2008)

(Continued)

TABLE 11.1 Summary of Existing and Proposed Quality Data, Regulations, and Standards for the Gluten-Free Ancient Grains (*cont.*)

Grain	Organization Responsible for the Standard	Title	Major Aspects of Standards	References
<i>Millets</i>	Codex	Whole and Decorticated Pearl Millet Grains (169-1989); Pearl Millet Flour (170-1989), Revision 1995	Primarily grain and food safety and to a lesser extent food composition	Codex (1995)
	USDA NDL	20031, Millet, raw; 20032, Millet, cooked; 20647, Millet, flour; 434883 Millet, puffed; 20142 Teff, uncooked; 20143Teff, cooked;	Grain and food nutrient composition	USDA NDL (2016)
	Namibian Ministry of Agriculture, Water and Forestry	Regulations relating to composition and quality of pearl millet (mahangu) products	Grades and grading procedures for trade and ensuring product safety (food)	Namibian Ministry of Agriculture Water and Forestry (2008)
<i>Quinoa</i>	Codex	Codex Alimentarius Standard for Quinoa proposed by Bolivia in 2015	Primarily grain and food safety (e.g., limits for saponins) and to a lesser extent food composition	Codex (2015)
	USDA NDL	20035, Quinoa, uncooked; 20137, Quinoa, cooked	Grain and food nutrient composition	USDA NDL (2016)
<i>Amaranth</i>	USDA NDL	20001, Amaranth grain, uncooked; 20002, Amaranth grain, cooked	Grain and food nutrient composition	USDA NDL (2016)
<i>Buckwheat</i>	USDA NDL	20008, Buckwheat; 20009, Buckwheat groats, roasted, dry; 20010, Buckwheat groats, roasted, cooked; 20011, Buckwheat flour whole-groat	Grain and food nutrient composition	USDA NDL (2016)
	Canadian Grain Commission	Official Grain Grading Guide: Buckwheat	Grades and grading procedures for trade (food)	Canadian Grain Commission (2016)

	South African Department of Agriculture	Standards and Requirements Regarding Control of the Export of Buckwheat	Grades and grading procedures for trade (food)	South African Department of Agriculture (2005)
<i>Sweet lupins</i>	FSANZ	Lupin as an allergen (proposed regulation)	Food safety	FSANZ (2016)
<i>African legumes</i>	USDA NDL	16062, Cowpeas, common (blackeyes, crowder, southern), mature seeds, raw; 16063, Cowpeas, common (blackeyes, crowder, southern), mature seeds, cooked, boiled, without salt	Grain and food nutrient composition	USDA NDL (2016)
	African Organization for Standardization	Draft African Standard CD-ARS 867 Cowpeas Specification, 2012	Grades for trade and ensuring product safety (food)	African Organization for Standardization (2012)
<i>Wild rice</i>	USDA NDL	20088 Wild rice, raw; 20089 Wild rice, cooked	Grain and food nutrient composition	USDA NDL (2016)
	Canadian Wild Rice Council	Wild Rice Products and Grades	Grading system (grain food quality)	Indian Harvest (2011)

DAFF, South African Department of Agriculture, Forestry and Fisheries; FSANZ, Food Standards Australia New Zealand; GIPSA, US Department of Agriculture Grain Inspection, Packers and Stockyards ICC, International Association for Cereal Science and Technology; ISO, International Organization for Standardization, NDL, Nutrient Data Laboratory; USDA, United States Department of Agriculture.

purchase such a product, they are essentially uniformed as to whether it will in fact meet their nutritional quality expectations.

3.2 Needs for Large-Scale Processing

Concerning regulations and standards, the situation is very mixed (Table 11.1). There are Codex Alimentarius standards for sorghum, pearl grain, and flour and similar standards are under consideration for cowpea and quinoa. The Codex-type standards are primarily concerned with food safety. As explained in the grain chapters (Chapters 3–10), there are a few potential health hazards associated with the consumption of the ancient grains, as with all cereals. Quantifying the magnitude of risk with regard to allergens in buckwheat (Heffler et al., 2011) and lupin (FSANZ, 2016) and setting standards are clearly necessary.

With regard to the grading regulations to facilitate trade, a number of countries have standards for sorghum and buckwheat, but there are very few for other grains. This is a serious impediment to the growth of the ancient grains market, and more particularly this is disadvantageous with regard to export from their traditional areas of cultivation, which are predominantly in the world's poorer regions (Taylor and Stading, 2014). In the case of amaranth, the lack of internationally accepted standards has recently been recognized by the European Union as a significant problem (CBI Market Intelligence, 2015b).

Concerning standards with respect to end use, it appears that there are essentially only national and international standards for sorghum. These standards focus on the presence of tannins in sorghum, with standards for methodology for the detection of tannin-type sorghum grain (ICC, 2012; GIPSA, 2013) and quantification of tannins in sorghum grain (ISO, 1988). Notably, there is also a standard for determination of diastatic power (total amylase activity) in sorghum malt, including malt produced from bird-proof (tannin) sorghum (SABS, 1970). As mentioned, a notable worldwide trend is that large supermarket chains are increasingly setting their own private quality standards for agricultural products (Greenberg, 2010; Tesco, undated). These “in-house standards” are beneficial in that they promote improved food product safety and quality. However, they can be very challenging for small producers to meet due to the high complexity and cost of sophisticated food quality management systems. Meeting supermarket standards can be achieved through the efforts of organizations representing individual producers of a product. In the case of wild rice, product and grade quality standards have been developed by the producer organization (Indian Harvest, 2011). This example should definitely be followed by producer organizations for other ancient grains, as it is clearly beneficial to the consumer, retailer, and grain producer.

3.3 Needs for Quality Testing and Monitoring Methods

Establishing standards to facilitate trade and efficient large-scale processing of ancient grains is going to be increasingly critical as these grains become more

important in global mainstream food processing. For this to happen, it is essential to establish a robust set of quality testing and monitoring methods that are reliable, yet simple, rapid, cost-effective, and rugged enough so that they can be readily implemented in the low-income regions where most of these grains are produced. Before testing protocols can be defined, what constitutes a critical quality factor for a grain must first be established. The critical quality factors can be either nutritional quality related, processing quality related, or both. However, given that at present the demand for ancient grains is driven, in a large part, by the assumption that they offer some superior nutritional or other benefits over the dominant commodity grains (maize, rice, and wheat), their nutritional or potential health-promoting properties will be an important part of quality criteria.

Processing quality methods can be readily developed or adapted from those routinely employed for commodity grains, as fundamental physical parameters that govern grain processability are generally similar. For example, one of the most important physical quality factors in grains is kernel hardness (Taylor and Duodu, 2009). Hardness determines key processing parameters, such as milling performance, flour particle size distribution, degree of starch damage, starch swelling properties during cooking, extrusion performance, and kernel-puffing characteristics. Established methods for measuring grain hardness such as the Single Kernel Characterization System (SKCS), density grading using solutions of known specific gravity, abrasive decortication, and milling assays, can be, and have been used to grade some of the ancient grains, such as sorghum and some millets (Chiremba et al., 2011; Hallgren and Murty, 1983; Pedersen et al., 1996). However, some of the ancient grains have particularly small seed sizes, especially teff, fonio, and amaranth, and will invariably require specialized physical quality methods. Cost and simplicity will be particularly important quality method prerequisites.

From a nutritional perspective, one of the major factors of importance with regard to the quality of ancient grains is protein in terms of content, quality, and availability. This is highly relevant, considering the persistent protein malnutrition among vulnerable groups in rural parts of developing countries where these grains are primarily produced, and also the growing positive image of plant proteins among consumers as the “good macronutrient” in high-income countries. Carbohydrate profile in relation to glycemic response and dietary fiber content are also important, considering that ancient grains are used in many modern foods as whole grains, and are an appealing way to boost dietary fiber intake. Micronutrient profile of components, particularly content of generally deficient minerals and vitamins, such as calcium, iron, zinc, as well as A and B vitamins, is also essential.

Obviously wet chemistry methods of characterizing the nutritional components are tedious and expensive. However, rapid and nondestructive predictive methods that rely on near infrared (NIR) or infrared (IR) spectroscopy technologies have become quite robust and reliable for assessing grain proximate

composition, and even more specific parameters like fatty acid composition (Sato et al., 1998), carotenoids content (Brenna and Berardo, 2004), and phenolic compounds (Dykes et al., 2014; Meng et al., 2015), among others. Furthermore, vendors of these equipments increasingly sell their instruments with extensive calibrations for different grains, negating the time-consuming need to develop them in house. In future, perhaps, NIR calibrations for various ancient grains will be made freely available online by instrument manufacturers as a way to promote their equipment. Low-cost hand-held NIR and related technology instruments that can be used by small-scale farmers in the field would add a lot of value to quality monitoring of ancient grains. Companies are already moving in this direction. For example, a 2 AA battery-operated “semiportable” (weighing 5 kg) moisture analyzer with bluetooth connectivity for use in the field is now available (Perten Instruments, undated). A game changer would involve tying this type of technology to smart phones, which are becoming ubiquitous even in rural areas of developing countries. Low-income farmers would be able to monitor key quality parameters of their crops, establish the right time to harvest, predict the price they will get for their commodities, and establish links with buyers online.

However, perhaps the most important element for ensuring uniform quality when small-holder farmers make up a majority of the producers is developing a functional value chain. This requires that seed systems are set in place where farmers access appropriate seeds, the grains are cultivated for market perhaps on a contract grower basis, and farmers receive proper training in appropriate and sustainable cultural practices to produce grain of acceptable yield and desirable quality. The incentive would of course involve guaranteed market and price for the farmers’ produce. Such systems are already in place in many developing countries through organized small-holder farmer cooperatives for the commodity staples and cash crops, such as coffee.

The requirement of grain traceability is becoming even more important, not only to ensure product quality and safety, but also to reduce instances of farmer exploitation. A growing percentage of consumers in Western countries are willing to pay a premium for products, guaranteeing that they are “ethically” or “sustainably” sourced by certification organizations, such as the Rainforest Alliance (Rainforest Alliance, undated). An important driver of these markets and certifications is a production process that goes beyond protecting the environment, but also includes improving the livelihoods and well-being of those involved in the production chain. Thus, both the food processor and consumer have a compelling interest in ensuring that the raw material meets the production criteria that they are paying the premium for. The ancient grains fit very well into the sustainable environment and livelihood criteria, given that they are generally cultivated using technologies that have low adverse impacts and that are also predominantly produced by low-income farmers. There should be a mechanism to protect such production chains, considering that as the grains become more popular, other production systems that do not necessarily fit the ethical or sustainable criteria will come into play.

4 FOODS AND FOOD TECHNOLOGIES

Development of new and improved food products and food processing technologies have always been core activities of food companies, governmental and private food research institutes, and university food science and technology departments. This continues to be so. Specifically concerning the gluten-free ancient grains, the pace is accelerating rapidly. Governmental food research institutes that have made notable contributions to the development of ancient grain foods and processing technologies include the Central Food Technological Research Institute (CFTRI) in Mysore, India (sorghum and millet foods), the Council for Scientific and Industrial Research (CSIR) in South Africa (sorghum malting and brewing), and more recently the Agriculture and Food Development Authority (Teagasc) in Ireland (ancient grain-based gluten-free foods).

Interestingly, in the 1960–70s the FAO spearheaded a Composite Flour Programme. The aim of the Programme was to improve food security in developing countries through the use of flours produced from locally grown grains, such as sorghum, millets, and pseudocereals blended with wheat flour in staple wheat-based foods like bread and pasta (De Ruiter, 1978). Significant developments, milling, and secondary food-processing technology and manufacture of composite products based on nonwheat cereal grains took place in many countries, in particular Senegal and Sudan in North Africa. The findings of research collaborations that took place during the FAO Composite Flour Programme have provided much of the foundation of modern ancient and gluten-free baked goods product development, for example, the application of hydrocolloids to create high-loaf volume nonwheat flour breads.

However, the Programme was less successful in terms of meeting its original goal. FAOSTAT data show that in 1973 the former Sudan produced 2.1 million tonnes of sorghum and imported 120,000 tonnes of wheat (FAOSTAT, 2011). By 2011 sorghum production had more than doubled to 4.6 million tonnes. However, wheat imports had increased nearly 14-fold to 1.7 million tonnes.

The activities of the USAID CRSPs and Innovation Labs in respect of ancient grain breeding have been described earlier. With regard to their food and food technology R&D work, an important characteristic that has contributed to some successes is that the projects are market led, such as small-scale pearl millet food processing in the Sahel region of West Africa (Feed the Future, 2016). This market-led approach invariably involves applying the concept of a Food Value Chain (Microlinks, undated), whereby all the scientists involved in the chain work collaboratively and in partnership with local farmers and food manufacturers. The FAO considers that “The development of sustainable food value chains can offer important pathways out of poverty for the millions of poor households in developing countries” (Neven, 2014).

A major success in the development of an industry based on ancient grains is lager and stout brewing in Africa using locally grown sorghum in place of imported barley. In the late 1980s, the government of Nigeria banned the import

of barley to support local farmers and to save foreign exchange. Within a few months, the local brewing industry was able to develop technologies to brew lager and stout beers using sorghum. The ban on barley imports has long since been rescinded, but such was the success of creating a value chain based on sorghum that today most beers produced in Nigeria are based on sorghum (Michael and Nzeka, 2012). Today, the Nigerian brewing industry has an annual turnover of \$2.7 billion and produces some 1.1 billion liters of beer (Adekoya, 2016). More recently, similar highly successful developments of sorghum lager-brewing industries have taken place in countries, such as Uganda and Zambia, as mentioned earlier. The key to their success has been the partnership between private companies and governments along the food value chain, whereby the brewing companies work with national agricultural research systems and provide technical support to local farmers, and the governments provide tax relief for brewing with sorghum instead of imported barley (Mackintosh and Higgins, 2004).

4.1 Traditional Foods and Beverages: Development Needs

The lifestyle changes resulting from rapid urbanization, particularly in developing countries, have generated an increased demand for convenience type foods and “aspirational” products, which have resulted in a general moving away from traditional foods to products such as lager beer and wheat bread (as indicated above) and carbonated soft drinks (Haggblade et al., 2016; Monteiro et al., 2013). The demand for convenience foods in developing countries has also created a growing market for modern versions of traditional ancient grain-based foods and beverages (Taylor et al., 2010), for example, snacks and long-shelf life nonalcoholic beverages (Fig. 11.3).

It is generally the small- and medium-size enterprises that are involved in producing such “niche” products that meet local consumer demands. The actual processing technologies required are well known and relatively low technology, for example, extrusion cooking to instantize the flour. However, the problems experienced by small and medium enterprises attempting to make a livelihood from manufacturing such modern-type traditional products are numerous and can be daunting. These can be categorized as both technical and business related. Technical problems include access to a regular supply of grain of consistent quality, access to processing equipment, and lack of skills in key areas, such as food safety and food labeling legislation. Regarding business skill issues, these range from basic issues, such as costing to setting up a distribution chain, marketing, and obtaining finance. It is only now that governments and NGOs are recognizing and starting to get to a grip on the problems faced by emerging small-scale food processing enterprises. Probably the most innovative approach is the business incubation center concept, where budding enterprises receive ongoing skills (and often also financial) support until they are viable enterprises (Bayhan, undated). Setting of incubation centers in university campuses appears



FIGURE 11.3 Modern locally produced commercial products based on that country's traditional ancient grain foods and beverages. (A) Amaranth snack and (B) sorghum nonalcoholic sourd beverage, southern Africa.

to be the best solution, as the enterprises can have ready access to a broad spectrum of technical and business expertise. Furthermore, such centers provide the opportunity for science and technology graduates to develop businesses based on the outcomes of their product development and research projects. This is especially relevant in many developing countries where graduate unemployment is becoming a serious social challenge and an enormous waste of valuable human capital ([Mohamedbhai, 2015](#)).

4.2 Gluten-Free Foods and Beverages: Development Needs

The gluten-free food and beverage product market continues to grow and expand in Western countries and now also in developing countries. One estimate is that over the period 2014–21 the market in the USA will increase at an annual average rate of 7.7% from 2.8 to 4.9 billion dollars ([Transparency Market Research, 2016](#)). Great success has been achieved in producing baked goods like bread and pasta products that have reasonable technological functionality

(e.g., reasonable loaf volume and crumb cohesiveness) through the use of starches and hydrocolloids (Hager and Arendt, 2013). However, with regard to type of gluten-free products demanded in the future, there is a clear developing trend toward products that are not simply gluten-free, but also have better sensory properties, provide good levels of nutrients, and are rich in health-promoting bioactives (Matos and Rosell, 2015).

The gluten-free ancient grains would seem to be ideally placed to meet these consumer demands. However, completely replacing wheat gluten functionality using ancient grain flours, especially using whole-grain flours, is technically very challenging. To date, despite of much scientific research there has been no convincing demonstration that the storage proteins of the ancient grains, neither those in cereals nor pseudocereals, can mimic the visco-elastic, gas-holding functionalities of wheat gluten when their flours are mixed with water to form a dough (Taylor et al., 2016). However, it has been shown that kafirin, the sorghum prolamins, can exhibit wheat gluten-like visco-elasticity when isolated and plasticized (Oom et al., 2008). More recently, it has been found that flour from a non-GM high protein digestibility mutant exhibited better dough and breadmaking quality than conventional sorghum (Goodall et al., 2012). Clearly, this indicates that through genomics-based plant breeding, there is potential for the ancient grains to produce better-quality gluten-free products.

With regard to gluten-free beverages, it is straightforward to simply use the ancient grains as a source of starch and hydrolyze the starch into fermentable sugars using commercial amylases (Taylor and Emmambux, 2008). However, fully replacing barley malt with malted ancient grains is also technically very challenging. Their starches generally have higher gelatinization temperatures than barley malt starch and have a different balance of hydrolytic enzyme activities (Hager et al., 2014). This can result in the wort (unfermented beer) having insufficient fermentable sugars and other yeast nutrients to be properly fermented. Again, genomics-based plant breeding may provide solutions.

4.3 Mainstream Foods and Beverages

The area that presents perhaps the greatest opportunity for ancient grains is, ironically, the mainstream products. As mentioned, demand for traditional products generally declines as economies expand and people's lifestyles demand more convenience, and their "taste buds become more global." Furthermore, even though there will always be a market for gluten-free products, it is generally expected to remain a niche category despite the apparently flattering market volume figures and popularity in the media. For example, targeted research indicates that gluten-free products commanded only 1%–3% of their wheat-substituted product market category by 2013, and based on the demand trends, the numbers are not expected to change much (Sheluga, 2014). Perhaps, this is why the per capita demand for wheat has not taken a dip in either high-income or developing regions (FAOSTAT, 2015). Thus, the best avenue to capture the potential benefits that may accrue from consuming

ancient grains is in the mainstream products that meet the needs of the majority of consumers in high-income and emerging economy countries alike.

The above facts are not lost on food manufacturers and retailers. Consumers have a growing interest in exotic trends, including ethnic flavors and ingredients to diversify their diets, as well as ways to improve health through diet. Ancient grains provide an excellent opportunity for food manufacturers to innovate with products that not only add new flavors, but also incorporate desirable components, such as proteins, dietary fiber, and micronutrients, while maintaining a clean label ([IFT Food Technology Daily News, 2016](#)). Major food companies are thus increasingly incorporating ancient grains in their products as key ingredients. For example, in Western countries it is increasingly common to see products like breakfast cereals, baked goods, and crackers, on supermarket shelves that prominently include sorghum, proso millet, quinoa, amaranth, and teff among others. Importantly, most of these products are not targeting gluten-free focused consumers. The market is in its infancy, but growth has been robust, for example, in the USA, amaranth, teff, and quinoa grew by 123, 58, and 35%, respectively in 2014 ([Whole Grains Council, 2015](#)).

In the beverage sector, ancient grains can play a truly important role in the beer category, where the interest in craft beers has seen an explosion of microbreweries in the USA and other Western English-speaking countries. For example, according to a report in the *New York Times*, in 2013 the growth in craft beer sales volume in the USA was 17.2%, compared to a decline of 1.9% in overall beer sales ([Mount, 2015](#)). Furthermore, the report also indicated that the number of microbreweries expanded from 1521 in 2008 to 3200 in 2014. As with foods, this demand for specialty beers is largely driven by consumer boredom with the monotonous and largely identical flavors of mass-produced beers. The ancient grains provide opportunities to innovate, not only with the different flavors inherent in these grains, but also natural colors some of them (like black sorghum) can add to beer. To this extent, the ancient grain that has seen some market penetration in brewing is sorghum. In the USA, for example, there are at least a few dozen sorghum beers, not only made by microbreweries, but also a few by major brewers, the long-standing one being Redbridge by Anheuser-Busch. Some of the sorghum beers are explicitly targeted at the gluten-free consumer, while many are marketed to the general craft beer consumer.

A potential benefit of the growing use of ancient grains is that it presents a good opportunity to stealthily include more whole-grain ingredients in products. One of the major reasons for the relatively low market penetration of whole grain products, despite their clear health benefits, is their poor sensory perception among consumers. We tend to stick to flavors we grow up with, thus moving from white bread, which we consumed as children, for example, to whole wheat bread as adults is not easy. The ancient grains present new flavor opportunities that consumers can more easily adapt to.

Even though products containing ancient grains command premium pricing, the cost and availability of the grains remain major bottlenecks. As the

ancient grains have generally not undergone the vast genetic improvements of the commodity grains, coupled with the fact that they are mainly produced under stressed environments, they are expectedly not as productive as their mainstream counterparts. As the demand for these grains continues to grow, the pressure to invest in advanced breeding and production technologies will become more pressing. Obviously, the question of how much genetic advancement an ancient grain should undergo before it ceases to be “ancient” will emerge.

5 BIOACTIVE COMPOUNDS AND THE FUTURE OF ANCIENT GRAINS

Perhaps, one of the strongest drivers of ancient grain demand in advanced economies is the never-ending search for the magic bullet to cure the nutrition-related problems and other chronic conditions afflicting society, especially excess weight and associated consequences, and age-related chronic conditions. The term “ancient grain” in itself sounds healthy in the mind of the consumer (in line with other vaguely defined terms like “super foods,” or “natural”). These grains are generally used in an unrefined form (whole grains), and are obviously healthier than the refined commodity grain products. However, it is not likely that most consumers would consider the ancient grains to be merely equivalent to the unrefined commodity whole grains in terms of nutritional quality or health benefits. Thus, there is an additional perceived benefit that consumers of ancient grain products expect beyond the nutrients like vitamins, minerals, and dietary fiber they can get from the cheaper-commodity grains. As the market expands and these grains become more popular, the novelty factor will eventually wear off and consumers will become more judicious in their scrutiny of the true value derived from these grains. The ancient grains will thus have to stand on their own merit sooner rather than later.

As described in [Chapter 1](#), the ancient grains are generally better adapted to climate change and sustainable production systems than the commodity grains, and this alone makes them critical global food security crops that must be nurtured and protected. However, as mentioned, the best way to sustain investment in productive technologies is to ensure robust and sustainable demand. There is no better way to ensure such consumer demand than to demonstrate specific and compelling health benefits that these grains provide over and above what can be derived from the commodity grains. The bioactive phytochemicals are a logical avenue for investigation in this regard because the pathways that govern the accumulation of specific types of the secondary metabolites in grains are species driven.

Beyond adding to dietary diversity, some of the ancient grains are also rich in some unique phytochemicals not commonly found in the commodity grains, and could thus diversify intake of the beneficial compounds. A good example is the sorghum grain, which is rich in the 3-deoxyflavonoids that have unique chemical and biochemical properties ([Chapter 3](#)). In particular, the O-methylated 3-deoxyanthocyanidins are reported to have strong phase II enzyme-inducing

properties, which their anthocyanidin analogs lack (Yang et al., 2009). Some pigmented cowpeas varieties (Chapter 9) and wild rice (Chapter 10) are also rich in anthocyanins that are typically associated with fruits and vegetables. Furthermore, cowpeas contain high levels of the rare catechin-7-O-glucoside, as well as various glycosylated proanthocyanidin dimers; the glycosylation has been reported to make catechin more bioavailable (Raab et al., 2010). Lupins (Chapter 8) and the African legumes (Chapter 9) also contain beneficial flavonoids and bioactive peptides with important biological effects (Awika and Duodu, 2016). Buckwheat (Chapter 7) is a rich source of rutin (rhamnosyl-glucoside of quercetin), with known antiinflammatory and other benefits.

Even though some of the phytochemicals in the ancient grains are commonly associated with fruits and vegetables, the vast majority of people do not consume adequate amounts of fruits and vegetables on a regular basis. Grains, on the other hand, are dietary staples that form a major part of most meals. Thus, incorporating the ancient grains in mainstream foods would be an effective way to supply beneficial phytochemicals to consumers on a consistent basis. With this said, comprehensive reliable data that document specific benefits of the ancient grain phytochemicals would go a long way in increasing their use, and claiming their status as truly healthy grains.

6 CONCLUSIONS

The increased popularity of the ancient grains will naturally draw increased scrutiny from both consumers and consumer watchdogs (legislators and the media). The premium price these grains command as raw materials and when included in products will have to be justified by tangible benefits that can be communicated to consumers. Based on the composition of these grains in terms of proteins, dietary fiber, micronutrient, and phytochemical profiles, it is likely that they do provide important health benefits when consumed regularly. However, such benefits will need to be demonstrated using rigorous clinical trials and other robust methods that will persuade consumers and, perhaps equally importantly, regulatory agencies that control health claims that can be used on foods.

Research and development priorities include:

1. Research to directly demonstrate the health benefits of the ancient grains, both independently and as components of the mainstream products, is especially critical to ensure that the demand can be sustained in the long term. This will also enable establishment of the ideal use levels of these grains in products to produce desired health benefits. Potential synergistic interactions of the bioactive compounds in the various grains would also be uncovered.
2. Greatly increased genomic, breeding, and agronomic research to enhance sustainable, economic cultivation of the ancient grains is critical. Such research should be cognizant of the economic welfare of the small-scale farmers in developing regions, who dominate the production of these grains.

3. In conjunction with (2), economic and food value chain research on how the ancient grains can be used as an effective vehicle for economic security of low income, small-scale farmers, traders, food processors, and others in the value chain in developing countries is highly important. This research must be collaborative and participatory in nature, involving all stakeholders in the countries of production. Capitalizing on the growing demand for these crops in high-income countries and opportunities associated with rapid urbanization in Africa, Asia and Latin America has the potential to majorly benefit rural societies in developing countries, which suffer from chronic poverty.
4. Processes to enhance sensory properties, as well as the potential health benefits of the ancient grains and their products are required. This is especially important in developing countries to counteract the adverse nutrition and health consequences of their nutrition transition. Technologies like limited germination, fermentation, micronization, advanced milling technologies (e.g., precision debranning and ultragrinding), among others, are known to enhance sensory profile of whole grain products, and in some cases, phytochemical profile as well.
5. Formalizing labeling requirements for ancient grains and their products will become essential, especially with respect to maintaining and promoting product identity. For example, should there be a minimum inclusion level to claim “ancient grain” on a product and should there be a requirement that the ancient grain must be included as whole grain or substantially whole grain to use such a label? The latter point is important, especially for the cereal ancient grains because when stripped of their bran, their endosperm composition is, in principle, largely identical in composition to the mainstream cereals; furthermore, the loss of the seed coat or bran removes much of their dietary fiber and most phytochemicals. Obviously, given that arriving at a universally accepted definition of ancient grains may in itself take a while, such labeling issues should be mediated in the near term by private organizations, in a similar way to the Whole Grains Council with its whole grain stamp.

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Ancient grains are today the subject of wide and growing interest but many misconceptions.

Gluten-Free Ancient Grains: Cereals, Pseudocereals, and Legumes: Sustainable, Nutritious, and Health-Promoting Foods for the 21st Century covers gluten-free grains that are not related to wheat. These grains include sorghum and the millets (including pearl, foxtail, proso, and finger millet) as well as fonio and teff, plus wild rice, the major pseudocereals (quinoa, amaranth, and buckwheat) and emerging pulse-type legumes (lupin, cowpea, bambara groundnut, West African locust bean, African yam bean, and marama bean).

Each chapter addresses a different grain or group with information about the crop and its cultivation. Detailed data are given on its nutrient and phytochemical content. Technologies for traditional ethnic-type foods made from the grain and modern food product developments, with a focus on gluten-free foods, are described. The effects of food processing on the grain's nutrient availability are explained and the literature on its health-enhancing properties is critically reviewed. Additionally, the book looks at the issues of ancient grain supply to meet the world demand and research priorities for ancient grains to become major food staples.

Of interest to many people and organizations involved in the food value chain, *Gluten-Free Ancient Grains* is important to food and agricultural scientists, food industry innovation and R&D scientists and managers, economists, nutritionists and dietitians, and public policy personnel, as well as governmental and non-governmental health department and research institute personnel.

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