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Pseudocereals
Recent Advances and New Perspectives

Edited by Viduranga Y. Waisundara

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Aims and Scope of the Series

The importance of agriculture cannot be overstated. It helps sustain life, as it gives us the food we need to survive and provides opportunities for economic well-being. Agriculture helps people prosper around the world and combines the creativity, imagination, and skill involved in planting crops and raising animals with modern production methods and new technologies. This series includes two main topics: Agronomy and Horticulture, and Animal Farming. This series will help readers better understand the intricacies of production agriculture and provide the new knowledge that is required to be successful. The success of a farmer in modern agriculture requires knowledge of events happening locally as well as globally that impact input decisions and ultimately determine net profit.

Meet the Series Editor

W. James Grichar has been employed with Texas A&M AgriLife Research for over 45 years with an emphasis on research in agronomy, plant pathology, and weed science. He obtained his BS from Texas A&M in 1972 and his Masters of Plant Protection in 1975. He has published 195 journal articles, over 330 research reports and briefs, 11 book chapters, and over 300 abstracts of profession meetings. He also directs research in many crops including corn, grain sorghum, peanuts, and sesame. He has held various positions in different professional societies including the American Peanut Research and Education Society, Southern Weed Science Society, and Texas Plant Protection Conference in addition to being Associate Editor for Peanut Science and Weed Technology. Significant accomplishments have included spearheading efforts to determine the optimum planting time for soybean production along the upper Texas Gulf Coast. These efforts have shown growers that soybean yields can be improved by 10 to 20% by following a late March to early April plant date. He also has been instrumental in developing a herbicide program for peanut production in the south Texas growing region. Through the development and use of herbicides that are effective against major weed problems in the south Texas region, peanut yields have increased by 25 to 30%.

Meet the Volume Editor

Dr. Viduranga Y. Waisundara obtained her Ph.D. in Food Science and Technology from the Department of Chemistry, National University of Singapore in 2010. She was a lecturer at Temasek Polytechnic, Singapore from 2009 to March. She relocated to her motherland of Sri Lanka and spearheaded the Functional Food Product Development Project at the National Institute of Fundamental Studies from 2013 to 2016. She was a senior lecturer temporarily at the Department of Food Technology, Faculty of Technology, Rajarata University of Sri Lanka. She is currently Deputy Principal of the Australian College of Business & Technology – Kandy Campus, Sri Lanka. She is also the present Global Harmonization Initiative (GHI) Ambassador to Sri Lanka.

Contents

Preface

Pseudocereals are mostly recognized for their outstanding protein quality and comparatively high nutritional value. Pseudocereals differ from cereals in their physical characteristics mostly because of their unique chemical makeup and peculiar seed form, which is a ring embryo. Their amino acid composition is well balanced, and they are close to the Food and Agricultural Organization's (FAO) and World Health Organization's (WHO) optimal protein reference pattern for the human diet. Notably, lysine, tryptophan, arginine, and methionine – amino acids containing sulfur – are present in larger amounts in pseudocereals than they are in grains.

Pseudocereals can withstand extreme weather conditions like heat stress, salt, and water scarcity. Both agricultural system diversification and the security of food and nutrition could benefit from these crops. The type of crop variety is thought to be the main determinant of the potential yield of any crop, which is applicable even to pseudocereals. However, one of the most important factors in closing the yield gap between potential and reality is field management techniques.

This book, *Pseudocereals – Recent Advances and New Perspectives* contains a lot of contemporary information on pseudocereals. The chapters have been written by experts in the field, who have agreed to impart their knowledge on recent developments in the field, most of which focus on nutritional perspectives of pseudocereals. The book is organized into two sections: "Recent Updates" and "Functional Properties".

I would like to take this opportunity to extend my appreciation to the authors who have contributed so many wonderful chapters to this book. This project would not have been a success had it not been for their timely contributions and dedication. My heartfelt appreciation also goes to IntechOpen with whom I have worked with for almost seven years now. I would especially like to thank Publishing Process Manager Ms. Romina Rovan Bakarcic, whom I have enjoyed working with on three book projects thus far.

I sincerely hope this book will be a hit among scientific and non-scientific communities alike. Pseudocereals is an area that requires urgent attention, given all the food, agricultural, and economic problems the world is facing right now.

May there be peace on Earth!

Dr. Viduranga Y. Waisundara
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Section 1

Recent Updates

Chapter 1

Introductory Chapter: Pseudocereals as Subexploited Food

Viduranga Y. Waisundara

1. Introduction

Pseudocereals constitute a category of food comprising of non-grass plant species, which cannot be essentially classified as cereals, but have similar properties, applications, and uses to them. According to physical and botanical characteristics, pseudocereals are dicotyledonous and therefore, different from cereals, which are monocotyledonous [1, 2]. Because of their similar physical characteristics to cereals—such as their starch content, texture, palatability, and cooking method—the name "pseudocereals" is still used to describe them. Due to their extremely dense nutritional qualities and simplicity of use in farming and agriculture, quinoa (*Chenopodium quinoa*), amaranth (Amaranthus spp.), chia (*Salvia hispanica*), and buckwheat (*Fagopyrum* spp.) are the most grown and researched pseudocereals in current contexts.

Subexploited food could be defined as those, which were part of different populations for many years in the past and were replaced in the early twentieth century by other foods, which prevailed under contemporary contexts of consumerism and agricultural conditions. Pseudocereal crops have been explored as remedies to attain food security as subexploited food products because it is estimated that the world population will reach 9700 million of people in 2050, and they could be an alternative with potential benefits not only in terms of nutritional value but also in a socioeconomic perspective where food production is anticipated to be limited [3]. The Food and Agriculture Organization (FAO) defines food security as the state in which every individual, at all times, has physical and financial access to enough, safe, and nutritious food that satisfies their dietary needs and food preferences for an active and healthy life [4]. Within this definition, pseudocereals are viewed as a category of food products, which have a significant potential in curbing food insecurity, malnutrition, and agricultural losses due to climate change.

2. Nutritive value of pseudocereals

Pseudocereals have been described as "the grains of the twenty-first century" by the Food and Agricultural Organization due to their excellent nutritional value [5]. They are high in fiber, carbohydrates, and high-quality proteins with a composition of essential amino acids that are balanced and rich in sulfur-containing amino acids [6]. They also have minerals (calcium, iron, and zinc), vitamins, and phytochemicals

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such as saponins, polyphenols, phytosterols, phytosteroids, and betalains, which have purported health benefits [6].

Buckwheat, quinoa, and amaranth are rich sources of flavonoids, phenolic acids, trace elements, fatty acids, and vitamins. These groups of compounds have demonstrated and proven effects on human health, such as prevention and reduction of many degenerative diseases. Fagopyritols, a type of soluble carbohydrates, are widely present in buckwheat seeds. A significant source of D-chiro-inositol, which improves glycemic control in people with non-insulin-dependent diabetes mellitus (NIDDM), is fagopyritol [7]. The main nutrients found in buckwheat grains are proteins, polysaccharides, dietary fiber, lipids, rutin, polyphenols, and micro- and macroelements. These compounds are known to be rich sources of total dietary fiber (TDF) and soluble dietary fiber (SDF), which are used to prevent diabetes and obesity [8]. Buckwheat grains comprise abundant nutraceutical compounds, and they are rich sources of B group vitamins.

Amaranth contains a huge amount of crude fiber, protein, tocopherols, and squalene. All of which have a cholesterol-lowering function [9]. Quite possibly, the only grain that naturally balances the essential amino acids in its protein is quinoa. The presence of essential amino acids, such as histidine, isoleucine, leucine, phenylalanine, threonine, tryptophan, valine, lysine, and methionine, indicates its high quality [10]. Both amaranth and quinoa are rich in minerals such as K, Ca, P, Mn, Zn, Cu, Fe, and Na, dietetic fibers, and vitamins C and E [11].

Quinoa seeds are another excellent source of flavonoids, which are mostly glycosides of the flavonols quercetin and kaempferol [12]. The phenolic compounds found in amaranth seeds are ferulic acid, caffeic acid, and phydroxybenzoic acid [13]. Pseudocereal lipids, which are abundant in pseudocereals, include phytosterols—an important class of physiologically active substances. Because of their structural similarity to cholesterol, they are indigestible by the human gut and prevent intestinal cholesterol absorption, decreasing plasma levels of both total and low-density lipoprotein (LDL) cholesterol [14]. Quinoa seeds contain a noteworthy content of saponins. These taste bitter and contain compounds that are surface-active and have a structure made up of one or more sugar chains and an aglycone that is either steroid or triterpenoid. Saponin levels vary within the range of 0.01–4.65% with a mean value of 0.65% between different varieties of quinoa [15].

3. Cultivation of pseudocereals

Pseudocereal cultivation has expanded because of a greater understanding of their biological activities and a growing health consciousness among consumers. Global quinoa cultivation, production, and consumption have increased three times in the last six years according to observations [16]. The production of quinoa was expected at 39,000 million tons (MT) in Bolivia, 28,649 MT in Peru, and 929 MT in Ecuador in the year of 2005 [17]. Moreover, the production of buckwheat in China, Russia, Ukraine, Poland, and France was expected to reach 800,000, 605,640, 274,700, 72,096, and 124,217, MT, respectively [17]. Pseudocereal cultivation is still very uncommon, and according to FAO production data statistics, amaranth is not even registered.

Compared to conventional cereals, fewer breeding efforts have been made to maximize the use of pseudocereals in high-input farming systems. Nonetheless, there are plenty of chances to grow these underutilized food items. These crops can be effectively grown, and their worldwide production will rise, provided that the climate, length of the growing season, and quantity of arable land are all favorable. It is anticipated that thorough analysis and characterization of the germplasm would result in the development of superior cultivars possessing desired characteristics concerning food and nutritional security. New biotechnological methods, for instance, genome editing, next-generation sequencing, and whole-genome sequencing, are anticipated to provide further opportunities to enhance pseudocereal production [18]. These methods will be able to allow breeders and researchers to alter genome sequences and introduce genetic material conferring desirable traits.

Pseudocereals are touted as a panacea for the two global issues that plague humanity today. The food crisis brought on by the lately widespread coronavirus and the pandemics of obesity, diabetes, and other noncommunicable diseases. It has been determined that pseudocereals, with their significant resistance to abiotic stress, resilience to climate change, consistent yields, high nutritional content, appealing biological activities, and good edible quality, would all be important crops in the future to feed the world's population [19]. While extensive work has been conducted on the diverse biological properties of components from pseudocereals, less is known about the range of bioactivities of peptides [20]. The study concludes that pseudocereal peptides have noteworthy nutritional advantages and hold promise as functional meals. While there have been many noteworthy advancements in the bioactivities of pseudocereal peptides, there are still certain opportunities and obstacles that should be taken into account for further research.

4. Value added products from pseudocereals

Pseudocereals are frequently utilized to make nutrient-dense gluten-free goods such as bread, pasta, and confections. Urquizo et al. [21] developed a fermented quinoa-based beverage in order to expand the traditional uses of quinoa and to provide new, healthier, and more nutritious food products. Gambus et al. [22] utilized amaranth as an alternative gluten-free ingredient to increase the nutritional quality of gluten-free bread. Bread with higher levels of fiber, protein, and minerals had an acceptable amount of amaranth flour.

5. Perspectives for the future

A lot of work needs to be done before pseudocereals can produce the intended results because their economic potential has not yet been completely understood and acknowledged. Because they are a good source of important nutrients that help reduce oxidative stress in the body, adding pseudocereals to staple diets, either whole or in combination with true cereals, can improve overall quality and lengthen life expectancy. There is still more potential to be discovered, and the industrial method to growing and processing pseudocereals needs to be addressed. The value-added products on an industrial level can be prepared using pseudocereals, and the market may be developed to combat nutrient-related malnutrition even in developed countries where the diet appears to be mostly calorie-dense.

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References

[1] Ciudad-Mulero M, Fernández-Ruiz V, Matallana-González MC, Morales P. Dietary fiber sources and human benefits: The case study of cereal and pseudocereals. Advances in Food and Nutrition Research. 2019;**90**:83-134. DOI: 10.1016/bs.afnr.2019.02.002. Epub 2019 Mar 7. PMID: 31445601

[2] Schoenlechner R, Siebenhandl S, Berghofer E. Pseudocereals. In: Arendt EK, Dal Bello F, editors. Gluten-Free Cereal Products and Beverages. New York, USA: Academic Press; 2008. pp. 149-190

[3] Food and Agriculture Organization of the United Nations (FAOSTAT). FAOSTAT Online Database. 2023. Available from: http://www.fao.org/faostat/en/#data/QC/

[4] Food and Agriculture Organization of the United Nations (FAOSTAT). Food Security and the Right to Food. 2015. Available from: http://www.fao.org

[5] FAO. Food and Agriculture Organization Regional Office for Latin America, and the Caribbean PROINPA. Quinoa: An Ancient Crop to Contribute to World Food Security. Santiago: FAO Regional Office for Latin American and the Caribbean; 2011. Available from: http://www.fao.org/alc/file/media/pubs/2011/cultivo_quinua_en.pdf

[6] Morales D, Miguel M, Garcés-Rimón M. Pseudocereals: A novel source of biologically active peptides. Critical Reviews in Food Science and Nutrition. 2021;**61**(9):1537-1544. DOI: 10.1080/10408398.2020.1761774

[7] Thakur P, Kumar K. Nutritional importance and processing aspects of pseudo-cereals. Journal of Agricultural Engineering and Food Technology. 2019;**6**(2):155-160

[8] Brennan CS. Dietary fibre, glycaemic response, and diabetes. Molecular Nutrition & Food Research. 2005;**49**(6):560-570

[9] Johns T, Eyzaguirre PB. Biofortification, biodiversity and diet: A search for complementary applications against poverty and malnutrition. Food Policy. 2007;**32**(1):1-24

[10] Stikic R et al. Agronomical and nutritional evaluation of quinoa seeds (Chenopodium quinoa Willd.) as an ingredient in bread formulations. Journal of Cereal Science. 2012;**55**(2):132-138

[11] Dini I, Tenore GC, Dini A. Antioxidant compound contents and antioxidant activity before and after cooking in sweet and bitter Chenopodium quinoa seeds. LWT-12. Food Science and Technology. 2010;**43**(3):447-451

[12] Klimczak I, Małecka M, Pachołek B. Antioxidant activity of ethanolic extracts of amaranth seeds. Food/Nahrung. 2002;**46**(3):184-186

[13] Moghadasian MH, Frohlich JJ. Effects of dietary phytosterols on cholesterol metabolism and atherosclerosis: Clinical and experimental evidence. The American Journal of Medicine. 1999;**107**(6):588-594

[14] Kozioł M. Chemical composition and nutritional evaluation of quinoa (Chenopodium quinoa Willd.). Journal of Food Composition and Analysis. 1992;**5**(1):35-68

[15] Pongrac P et al. The effects of hydrothermal processing and

germination on Fe speciation and Fe bioaccessibility to human intestinal Caco-2 cells in Tartary buckwheat. Food Chemistry. 2016;**199**:782-790

[16] FAOSTAT. FAOSTAT Gateway. 2013. Available from: http://faostat3.fao [Accessed: 11 December 2023]

[17] FAOSTAT. FAO Statistics Division. 2007. Available from: http://www.faostat.fao.org

[18] Chen K, Wang Y, Zhang R, Zhang H, Gao C. CRISPR/Cas genome editing and precision plant breeding in agriculture. Annual Review of Plant Biology. 2019;**70**:667-697

[19] Pirzadah TB, Malik B, Tahir I, Ul Rehman R. Buckwheat journey to functional food sector. Current Nutrition & Food Science. 2020;**16**(2):134-141

[20] Zhu F. Buckwheat proteins and peptides: Biological functions and food applications. Trends in Food Science & Technology. 2021;**110**:155-167

[21] Ludena Urquizo FE et al. Development of a fermented quinoa-based beverage. Food Science & Nutrition. 2017;**5**(3):602-608

[22] Gambus H, Gambus F, Sabat R. The research on quality improvement of gluten-free bread by amaranthus flour addition. Zywnosc. 2002;**9**(2):99-112

Chapter 2

Buckwheat: Potential Stress-Tolerant Crop for Mid-Hills of Eastern Himalaya under Changing Climate

Krishnappa Rangappa, Amit Kumar, Burhan U. Choudhury, Prabha Moirangthem, Jayanta Layek, Dipjyoti Rajkhowa, Anjan Kumar Sarma, Ng. Kunjarani Chanu, Supriya Debnath, Gangarani Ayam, Bijoya Bhattacharjee and Vinay K. Mishra

Abstract

Under changing climate, identification and diversification of cropping systems having higher stress resilience and adaptability for fragile mountain ecosystems of Eastern Himalayan Region (EHR) are paramount. Lesser known and underutilized crop like buckwheat (BW) with year-round cultivation potential and having higher stress tolerance to prevailing stresses (low pH, low moisture) could be a crop of choice for abating malnutrition among hill inhabitants. Proper time of sowing of the crop is between mid-September and mid-December seemingly essential for better grain yield to the tune of 15.0–18.0 q ha^{-1}, and the crop is found suitable to be grown all through the year for higher green biomass (12.6–38.4 q ha^{-1}). Enhanced exudation of low-molecular-weight organic acids (LMWOA) like oxalic acid by buckwheat increased the solubilization of fixed forms of free phosphorus (P) to the extent of 35.0 to 50.0 micro gram per plant in ideal acid soil of the region (P) in acid soil. In addition, relatively increased resilience to moisture stress with improved stress physiological attributes adds more potentiality for enhancing cropping intensity of hill slopes of EHR. Few genotypes namely IC377275 (18.97q ha^{-1}), IC26591 (17.1 qt ha^{-1}), IC14890 (16.32q ha^{-1}), and Himapriya (15.27q ha^{-1}) are emerging as high-yielding types for productive cultivation in acid soils. Studies on the combined effects of acid soil and moisture stress would aid in novel crop improvement of buckwheat in EHR.

Keywords: acid soil, leaf traits, moisture stress, mountain ecosystem, root architecture, root exudation, stomatal attributes, yield

1. Introduction

Eastern Himalayan Region (EHR) of India being one of the hot spots of biodiversity comprises ≈56% of the area under low altitude and 33% mid-altitude, and rest under high altitude is distinctly characterized by diverse edapho-climatic constraints and distress-ridden geography. Farming in this region of India is primarily rainfed and uniquely represented by complex diverse risk (CDR) prone type [1]. Presently, the cropping intensity is only 120% indicating that about 80% of that area remains vacant during the rabi season due to severe water scarcity as most of the rainwater received during the rainy season is lost as runoff through sloppy land. The region receives an average annual rainfall of 220–250 cm out of which large part (70–80%) is received during rainy season. The major lands of the region being sloppy terrain has been suffering from various degrees of degradation [1]. Wide spread soil erosion, soil acidity, nutrient mining, eroding biodiversity, acute moisture stress during winter season are some of the major concerns threatening the food and livelihood security of the region [1, 2].

Buckwheat (BW) is one of the lesser-known alternative gluten-free pseudo-cereal crops, which is having immense potential to act as life support for tribal inhabitants with multipurpose utility in the Himalayas (**Figure 1**). Its short duration (80–100 days) with early maturity makes it suitable for cultivation under marginal and degraded lands of mountain ecosystem on sustainable basis, which holds a great promise for increasing production in the hilly regions of India through its inherent potential for sustainable yield [2, 3].

Buckwheat (*Fagopyrum esculentum*) is an herbaceous crop with round and hollow knotted stem, generally green but sometimes tinged with red. The leaves are heart-shaped with reticulate venation, and inflorescence is a compound raceme that produces laterally flowered cymose clusters. The flowers are usually dimorphic with two forms of flowers, one with long style and short stamens and the other with short style and long stamen and their color varies from white or light green to pink or red. Buckwheat is necessarily cross-pollinated. The seeds have dark brown, tough rind, enclosing the kernel of seed. It is three-sided to form triangular because of which the name of the crop is known as "buckwheat" (**Figure 2**). The seed of buckwheat (achene) is a fruit and not a grain. Therefore, botanically, buckwheat is not a member of the family *Gramineae* or *Poaceae*, even though it is looking similar to the grains of cereals [4]. The root system is dense, fibrous with a deep taproot. Most of its roots are concentrated in the top 10 inches of the soil.

Figure 1.
Buckwheat (Fagopyrum esculentum) cultivation at mid-hill slopes of EHR.

Figure 2.
Whole grains of buckwheat having unprecedented nutritional value.

The crop is reported to help in soil binding and check erosion during the rainy season. Buckwheat is used for both grain and greens. The tender shoots are used as a leafy vegetable, and the flowers and green leaves are also used for extraction of rutin which is used in medicines. The presence of a high content of the metabolite rutin in their foliage has substantial medical importance for increased capillary fragility for hypertension, leading to hemorrhage, purpurea, and bleeding from kidney. The crop is also used as green fodder. The pericarp of the buckwheat seed is used as suitable stuffing material for pillows [5], packaging material, as base material for heating pad and as raw material for mattresses. The buckwheat is used in a number of culinary preparations, alcoholic drinks, etc. Buckwheat flowers are also an excellent source of nectar for honey. Because of its fast-growing ability, it can escape weed competition (**Figure 3**). It is reported to be used as staple food among the Monpas and Sherdukpen tribes of Tawang district of Arunachal Pradesh since rice cannot be grown (because of agro-physiological constraints) in this region due to high altitude.

Figure 3.
Buckwheat (F. esculentum (L.) Moench) crop with full canopy foliage before its flowering at mid altitudes of Meghalaya.

1.1 Types of Buckwheat

Fagopyrum Moench is an annual or perennial herb, belonging to the family *Polygonaceae*. *Fagopyrum* is derived from the Latin word *fagus* (beech) and the Greek word *pyrus* (wheat) as the achene resembles beechnut and is used like wheat. The common name buckwheat refers to two cultivated species of *Fagopyrum* namely Common buckwheat (*F. esculentum* Moench) and Tartary buckwheat (*Fagopyrum tataricum* Gaertn). One of the most important distinguishing characters between *F. tartaricum* and *F. esculentum* is in their achene morphology. Achenes of *F. tartaricum* are grooved with angles rounded below and sharply acute above, while achenes of *F. esculentum* are not grooved with sharply acute angles (**Table 1**). The growth characteristics of Common and Tartary also differ in their physiological responses to cold and drought. The epigenetic regulation due to DNA methylation in Tartary buckwheat confers resistance to the effects of cold weather [6]. Tartary buckwheat is also more resistant to drought than Common buckwheat. Due to their ability to adapt to different climatic variables and water-stress regimes, cold temperature, and nutrient-deficient acid soil of EHR, the buckwheat is considered potential crop for cultivation at higher altitude. The examples for common varieties for Tartary buckwheat are Himgiri, Sangla B-1, whereas for common buckwheat varieties are Himapriya VLVgal-7 and PRB-1.

1.2 Origin and distribution

The center of origin of buckwheat is the Himalayan region, which stretches across western China to northern India. It was first cultivated in inland Southeast Asia.

Type of cultivar	Plant Height (cm)	Leaf type	Inflorescence	Achene type	Flowering time
F. esculentum Moench	30–90 cm	Leaf is simple, and leaf blade is triangular, having papillate veins on both surfaces. Leaf base is cordate or nearly truncate.	Racemose/ corymbose and axillary/terminal white or pink flowers with heterostylous.	Dark brown in color, ovoid shaped, and sharply trigonous.	September to March
Fagopyrum tataricum (L.) Gaertn	30–70 cm	Petioles has long blade, leaf blade is broadly triangular, both surfaces papillate along veins, and leaf base is cordate or truncate.	Racemose and axillary/terminal in position. Each inflorescence consists of white or greenish flowers.	Blackish-brown in color, narrowly ovoid in shape, trigonous with grooved surfaces with acute angles rounded below middle.	May to October

Table 1.
Distinct characteristics of different types of buckwheat.

Grain or byproduct	Moisture (%)	Protein (%)	Fat (%)	Fiber (%)
Whole grain	10.0	11.2	2.4	10.7
Flour	12.1	7.8	1.5	0.7
Groats	10.6	11.2	2.4	0.6
Hulls	8.0	4.5	0.9	47.6

Table 2.
Nutrient composition of buckwheat grain.

From there, it has spread to Central Asia and Tibet, and then to the Middle East and Europe [7] and southwest to North China, then further to the Korean Peninsula and to Japan. In Japan, buckwheat was one of the most important foods since around 800 AD. Buckwheat is believed to have been introduced to Europe around 1200 to 1300 AD particularly in Ukraine, Germany, and Slovenia, which later spread to Belgium, France, Italy, and Britain. According to FAO, in 2017, buckwheat was cultivated in 25 countries with the total cultivated acreage of 3,940,526 ha with the total production was 2,056,585 t. Russia and China have the highest area under buckwheat cultivation [8]. In India, buckwheat is cultivated at high altitude regions of Jammu and Kashmir *viz.* Sonamarg, Baktour, Kupwara, Machil, Dawar, Nilnag, Gogjipathar Sind Valley, Ladakh and Zanskar, Kargil and Drass sectors, and Gurez Valley and in other states of India namely Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, West Bengal, Meghalaya, Assam, Manipur, and Nagaland. In southern parts of India, buckwheat is also cultivated in parts of Nilgiris and Palani hills.

1.3 Nutritional value

The buckwheat seeds are rich in protein, amino acids, and minerals (≈11–12%). The crop possesses higher content of lysine, tryptophan, arginine that are not present in cereals, and it is enriched with polyphenols, sterols, vitamins, and flavonoids (**Table 2**). It is reported that buckwheat sprouts could be used as a fresh vegetable in salads and be used for various other purposes including natural vegetable juice material. The biological value of buckwheat seed proteins is very high (93), as compared to pork (84), soybean meal (68), and wheat (63). The slowly digested or non-digested starch of buckwheat groats is important to diabetics, as it helps to flatten the glycemic response curve. A slow release of glucose from starch could prolong endurance during physical activities, and the duration of satiety is prolonged as well. The economic importance of buckwheat rests mainly with the high nutritive value of their grains (**Table 2**). The buckwheat has a long flowering period and thus served as the source of nectar for honey.

2. Agroclimatic suitability of Buckwheat for hill slopes of EHR

Buckwheat can be grown on a wide range of soil types. But it is best suited to light- and medium-textured soils, such as sandy loam, loam, and silt loam of EHR. Moreover, buckwheat is acid soil-tolerant crop. Generally, the moisture content of

Figure 4.
Buckwheat cultivation at mid-hills of Meghalaya following standardized agronomic practices [2].

the soil in winter season is less due to water scarcity, which can adversely affect the productivity of any crop in this geographically significant bio-diverse region. But buckwheat is a plant which can grow under such adverse moisture stress condition due to its extensive root networking system (**Figures 4** and **5**). During the moisture-stress conditions, the root of buckwheat go dipper and explore for water *vis a vis* essential nutrients.

Buckwheat is frequently used as catch or emergency crop because it grows rapidly and matures early. For the cultivation of buckwheat, winter months are preferred. It was recorded that when the crop was cultivated in October/November, it gave a potential yield of 9.7 and 11.0 q/ha, respectively (**Table 3**). As the crop showed potential yield during this period irrespective of adverse moisture stress condition, buckwheat was found to be a promising crop during this period as most of agricultural land in this region becomes fallow due to water scarcity and has low moisture content in the soil. In addition, a fast-growing cover crop such as buckwheat is most useful for reduced chemical or nonchemical weed suppression. Buckwheat will shade and smother weeds or outcompete them for soil moisture and nutrients. Moreover, both living buckwheat plants and buckwheat residues have an allelo-pathic effect on weed germination. Research shows that the allelo-pathic effects of buckwheat can last about 30–60 days. Buckwheat is used not only for human but also for livestock and poultry. The crop is also suitable as green manure. On incorporation, the buckwheat biomass rapidly decomposed in soil and adds N, P and organic matter to the soil. Incorporating buckwheat into the soil improves soil health by enhancing the soil structure of the topsoil, making it more friable and increasing the water infiltration rate.

Buckwheat can be grown on soils poor in nutrients and sandy soils, and on stony fields. It is a low-input crop not sensitive to disease and pest, and there is normally no need for application of insecticide, fungicide, herbicides, and does not require any irrigation for the successful cultivation. The farmers of EHR are basically small and marginal. Therefore, farmers of this region can easily adopt the crop because of low-input cost and get maximum benefit within a small period of time. In EHR, 3923.6 sq km areas is under shifting cultivation. As buckwheat requires less input,

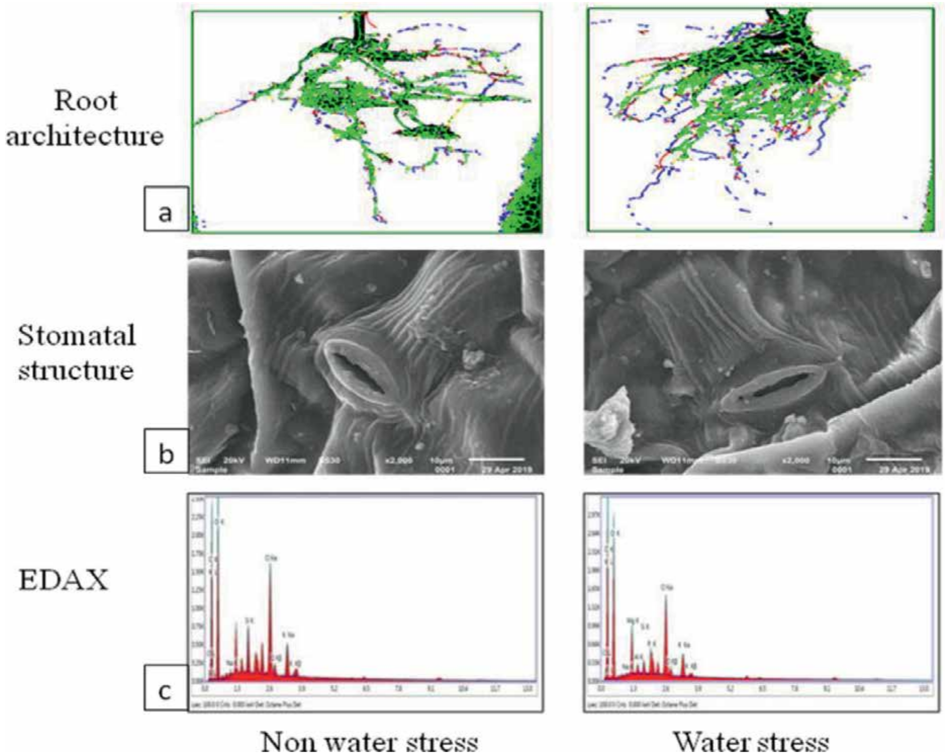

Figure 5.
Root architecture, stomatal structure, and energy-dispersive x-ray analysis (EDAX) of high-yielding buckwheat under water stress and non-water stress conditions [2].

Sowing time	Plant height (cm)	Duration (day)	Grain yield (q/ha)	Straw yield (q/ha)
October	87.8	142	9.73	10.2
November	54.6	163	11.0	10.2

Table 3.
Performance of buckwheat at hill slopes of Meghalaya.

abandoned areas due of shifting cultivation can be utilized effectively to grow the crop in large scale in this region. The prevailing agro-ecological condition of EHR region is suitable to producing buckwheat, and therefore, the crop is a potential crop for the farmers of this region. Therefore, buckwheat is becoming a potential contingency crop with substantial stress tolerance. Generally, in the upland conditions of EHR, the moisture content of the soil is more likely to reach its critical level of 7.0–10.0% compared to lowland condition (9.0–23.0%). Cool and moist climate favor the growth of buckwheat. Heavy soil with excessive moisture is not suitable for buckwheat. Higher income from buckwheat cultivation makes the crop more remunerative and is found suitable for preventing soil erosion across hill slopes, restoration of soil fertility as well as better alternative source of green fodder under stressful environments of hill ecosystem. Appropriate technology transfer with needful policy interventions for adequate value addition and marketing might help in popularizing this crop in Eastern Himalayan conditions. Buckwheat could be robust non-cereal crop because it is more productive than other cereals with better nutrient content in the grain and green leaves under abiotic stress conditions of marginal hill environments [9].

In one of the field experiments carried out at mid-hills of Meghalaya during 2014–2015, it was found that the highest mean yield of buckwheat was recorded for the month of sowing in October (9.83 q ha^{-1}) followed by sowing in November (9.45 q ha^{-1}) and December (9.09 q ha^{-1}) [10]. The lowest yield was recorded for sowing in the months of May (1.23 q ha^{-1}) and April (1.32 q ha^{-1}). As buckwheat needs cold and dry weather during maturity, sowing in October to December results in high yield as harvesting coincides with dry weather. High intensity rain in EHR during kharif has resulted in significantly lower yield of buckwheat as compared to yield of the crop sown in winter months. Among the months of sowing, significantly the highest HI was recorded in the month of November (34.0%) followed by December (33.5%) and October (32.6%). Meanwhile, the soil moisture measured was found to be highest (44.0%) during July and reached lowest during the months of January (14.5%) and February (15.1%) (**Figure 6**). Buckwheat production is influenced by various biotic and abiotic stress factors under fragile hilly ecosystems of Eastern Himalaya. In our study of higher grain production of the crop sown during the months of September to December, it was attributed to increased biomass production, favorable temperate climate, and relatively shorter days during rabbi season and also due to higher partitioning efficiency of the crop, even at the soil moisture status of 14.5–15.1% which is a common phenomenon during winter in the region (**Figure 6**) [10]. The standardized package of practice followed for cultivation of buckwheat at EHR is presented in **Table 4** [11].

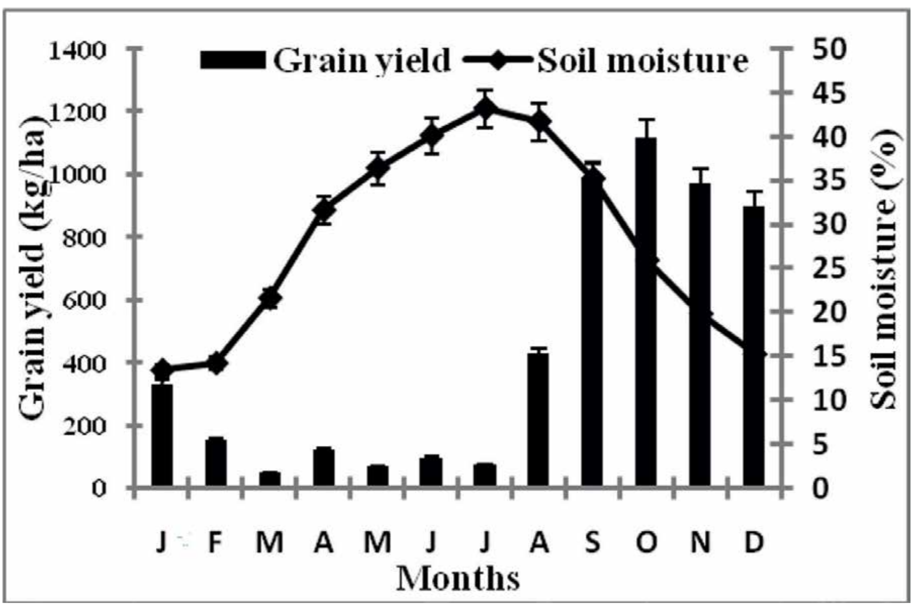

Figure 6.
Monthwise soil moisture regime and BW yield at mid-hills of Meghalaya.

Sl No	Type of practice	Description
1	Climate and soil requirements	Buckwheat favors cool and temperate climate and is best suited to light-to-medium textured, well-drained soils such as sandy loamy, loamy, and silt loamy. It shows a higher degree of tolerance to low-fertile acidic soils and low soil moisture conditions, but does not tolerate water logging. In case of water logged or high moisture in low land area, it can be successfully grown on raised beds. It will produce a crop on newly cleared land, drained marshland, or on other marginal land.
2	Field preparation	As the buckwheat has very fine root system, fine tilth is necessary to get an optimum plant stand. Buckwheat can grow well after one plowing or field could be prepared by one deep plowing followed by two harrowing/tilling and planking, which results in good germination and uniform stand of the crop. Being a cover crop, it does not require extensive land preparation and can grow well on poorly tilled soil.
3	Sowing and seed rate	The growing season varied with altitudes and rainfall pattern in EHR of India. The crop can be sown in mid-altitude after harvesting of *kharif* crops (rice or maize) particularly during the beginning of winter months like September to December. Healthy and disease-free quality seed @ seed rate of 25–30 kg/ha is sufficient for growing buckwheat as a grain crop. Seed rate of about 50 kg/ha is required when buckwheat is grown as a cover crop/fodder crop/vegetable crop. Sowing should be done in rows of 30–35 cm apart and 10–15 cm from plant to plant spacing, depending upon varieties. In buckwheat, higher seed rate is generally used to promote faster canopy development and higher population for better weed control. The seeds should be placed in 3–5 cm depths. Thinning may start at 15–20 days after sowing to maintain optimum population.
4	Nutrient management	Buckwheat generally grown by farmers in residual fertility after harvesting maize or rice in upland areas without adding other nutrients input. However, for getting a good yield, recommended dose of nutrients, that is, 40 kg N, 40 kg P_2O_5, and 25 kg K per hectare should be applied through organic manure. FYM @ 5 ton along with 1 ton VC, 150 kg oilcake, and 150 kg rock phosphate is recommended for growing buckwheat in one-hectare area. Application of bio-fertilizers such as *Azospirillum* spp. and *Azotobacter* spp. also resulted in improving buckwheat productivity and soil fertility.
5	Water management	Generally buckwheat is grown in hill slopes as a rainfed crop. If there is severe water stress, irrigation should be given at critical stages of crop growth in buckwheat like pre-flowering and fruit formation stage.
6	Intercultural operations and weeding	Although buckwheat plants are very good competitors for weeds and generally their fast-growing capacity make them a smother crop. Under such conditions, one weeding and hoeing at 20–25 days after sowing is helpful for raising a good crop.
7	Pests and diseases	Buckwheat is not attacked heavily by diseases or pests. However, some diseases like leaf spot (*Septoria polygonicola*), root and stem rot (*Phytophthora jagopyri*), powdery mildew (*Erysiphe polygoni*), rust (*Puccinia jagopyri*), etc., were observed. Selection of seeds from disease-free plants is a pre-requisite to prevent the diseases. Seed treatment using *Trichoderma viride* at the rate of 4 gm/kg of seeds and soil application of *Trichoderma viride*@ 2.5 kg mixed with 50 kg sand or well-rotten FYM is recommended to control the diseases. Major pests of buckwheat includes bruchids (*Acanthe celidsobtectus*), grain moth (*Cephitinea* sp.), cut worm (*Cirphis* spp.), and storage beetles (*Mycetophagus* spp.). Bird damage, particularly by doves, has been observed in this crop. Prevention is the best strategy to avoid insect problems in storage of buckwheat grains. Proper drying of grains is necessary to reduce infestation. In case of heavy infestation, neem oil (1500 ppm) @ 3 ml/liter water can be sprayed for effective management of pests.

Sl No	Type of practice	Description
8	Harvesting	To avoid shattering, the crop should be harvested when 75% of the grains turn brown or dull gray in color. Being of indeterminate growth habits, the plant shows irregular time of maturity. If the harvesting is delayed, shattering will start which may cause huge loss. After harvest, the crop should be allowed to dry for 2–3 days and then threshed. The seeds must be well-dried and kept at about 14% or less moisture for the safe storage of buckwheat grains.

Table 4.
Standardized agronomic package of practices for cultivation of buckwheat at EHR.

3. Increased P efficiency of Buckwheat suits to acid soils of EHR

Phosphorus (P) is a major soil nutrient limiting crop production in acid soils of EHR because of its high P fixation and its very low diffusion coefficient reducing soil solution P concentration to less than plant absorption thresholds. When phosphate fertilizer is applied in soil, adsorption and precipitation processes potentially result in precipitating cation concentrations in soil solution, leading generally into sesqui-oxides, following the dissolution of clay minerals and the release of Al ions (Al^{3+}) in acidic soils (pH<5.5), and hydroxyl-apatite in high pH and alkaline (pH>7.3) soils. About 99% of P absorbed by plants is primarily buffered phosphates into soil solution from adsorption sites of mineral and organic complexes. This means that almost all plant P uptake comes from the soluble soil Pi pool, suggesting that Po must first be converted to the Pi forms for plant uptake. In addition to white lupin, buckwheat (BW) has been classified as P uptake efficient [12]. Even when total soil P may be high, >80% still exists in forms that are unavailable to plants, with inorganic phosphorus (Pi) in most top soils between 25 and 75% and organic P (P_o) within the same range (**Figure 6**). Various mechanisms are involved in the efficient P uptake by plants such as white lupin (*Lupinus albus* L.) and buckwheat under P stress including changes in plant root morphology and plant physiology, whereby root exudates, for example, flavonoids by white lupin and low molecular weight organic acids (LMWOAs) by buckwheat are released [13] to hydrolyze a range of Pi and Po compounds in soil (**Figure** 7).

In the study conducted by Jasper and David [14], it was shown that Buckwheat (BW) could solubilize phosphorus (P) from fixed forms of soil P to subsequent crops. Calcium-bound P could solubilize more to enhance the free P (72% of inorganic pool) to the available fraction, and P uptake by BW (40 kg ha^{-1}) was remarkably higher than wheat (WHT) (16 kg ha^{-1}) from the inorganic pools. Following the cultivation, more P was added to available P pools after BW was compared to WHT, suggesting potential solubilization of P to subsequent crops. Buckwheat is often called a P scavenger because it can solubilize and take up soil P more efficiently than other plants. In its growing stage, the roots of buckwheat exude substances that help to solubilize P to the tune of 35.0-50.0 microgram per plant that may otherwise be unavailable to plants. The roots of buckwheat were also found to have a high storage capacity for inorganic P. As a result, when buckwheat plants are incorporated in the soil, they decay quickly, making phosphorus and other nutrients available to the succeeding crop [14].

The ability of buckwheat (*F esculentum*) roots to acquire P was characterized by morphological features and chemical changes in the rhizosphere (**Figures 8** and **9**). Jasper and David [14] have shown that higher shoot growth was achieved with a P supply between 5 and 100 μmol/liter. Root biomass and root length with increased

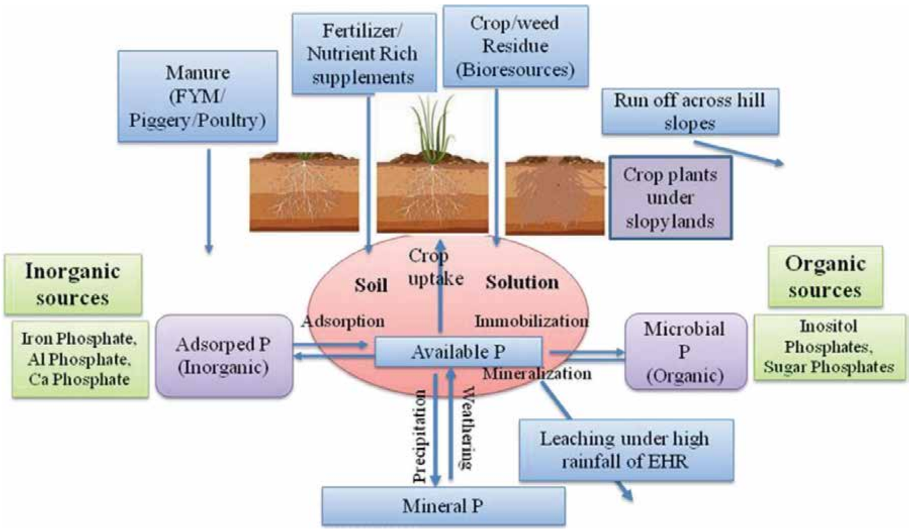

Figure 7.
Fate of added phosphorus in acid soil. P fixed either through adsorption, immobilization, and precipitation in low pH soils of EHR.

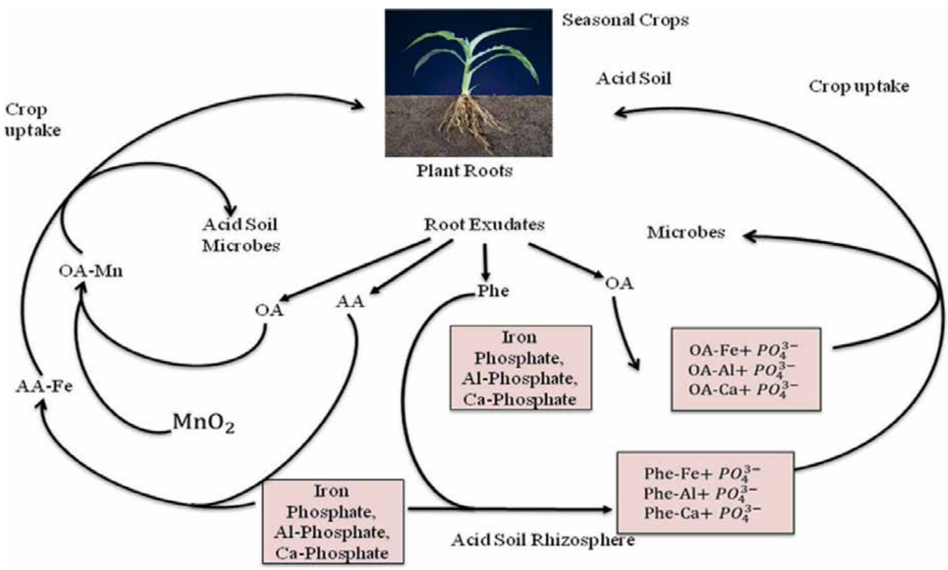

Figure 8.
Effects of root exudate components on nutrient availability and uptake by plants and rhizosphere microbes. OA = organic acids; AA = amino acids including phytosiderophores, Phe = phenolic compounds.

root hairs was found at low P levels. Root exudates of low-P plants have relatively lower pH values than exudates of high-P plants, and thereby they increased the solubility of $FePO_4$ and MnO_2 to a greater extent. Enhanced hydrolysis of glucose-6-phosphate by exudates from low-P plants was due to an increased "soluble" acid phosphatase activity (**Figure 9**) which was commonly enhanced with P deficiency. In the rhizosphere soil of buckwheat, some depletion of organic P forms was also observed (**Figure 9**).

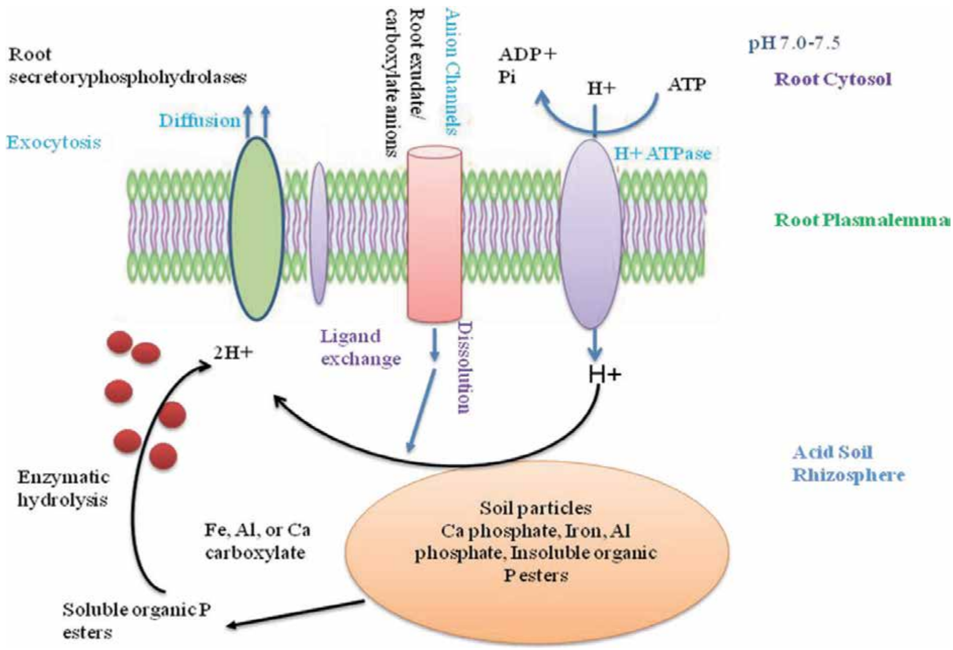

Figure 9.
P uptake by intact roots in acid soil. The ability of the roots to excrete organic acid is associated with several physiological mechanisms under low pH soils of Meghalaya.

The mechanisms conferring P efficiency have to be associated with either the acquisition of P nutrient from the environment or the movement and distribution within the plant or the utilization in metabolism. Efficient acquisition of P under insufficient supply like acid soils of EHR may be due to a higher ability of the buckwheat crop to explore the soil by a more extensive root system (with rapid development, higher root-to-shoot ratio, finer and longer roots and root hairs), or a greater ability to absorb P from a dilute solution (i.e., an efficient uptake mechanism) [2, 3, 10]. Exudation of reducing, chelating, and/or acidifying substances by the roots, resulting in solubilization of soil P, to the extent of 35.0-50.0 microgram per plant may also be of great importance.

Further as buckwheat is known for P solubilization, Aliyeh et al. (2018) have conducted extensive field studies to explore its potential in intercropping production systems. Intercropping of buckwheat can enhance the productivity of cropping systems through increased soil nutrient availability and thereby increasing plant nutrient use efficiency. One 2-year field study with different intercropping ratios of fenugreek and buckwheat and fertilizer types on nitrogen (N) and phosphorus (P) concentrations was undertaken at the research farm of Shahrekord University, Iran. The experiment comprised sole cropping of fenugreek (F), buckwheat (B), and three intercropping ratios fenugreek and buckwheat of 1:2, 1:1, and 2:1 under three fertilizer types: chemical fertilizer (CF), integrated fertilizer (IF), and broiler litter (BL). The results revealed that intercropping substantially increased total aboveground dry matter, total seed yield, N and P tissue content as well as their uptake. Efficiency of applied N use and applied N recovery in the intercropped plots was also higher as compared to the sole cropping. The intercropping ratio of F:B (2:1) emanated as the most suitable for improving nutrient use efficiency. The IF and BL have shown remarkable benefits in terms of increased total seed yield, tissue N and P contents, and their uptake in sole and intercrops. The intercropping of fenugreek–buckwheat in the ratio of 2:1 with the application of integrated fertilizer and broiled litter were emerged as promising for improving productivity under semiarid growing conditions of Iran or similar ecosystems elsewhere [15].

4. Buckwheat is potential moisture stress tolerant crop of EHR

Buckwheat is commonly cultivated under marginal and degraded lands of EHR with poor nutrients, lesser moisture regimes, and low-input agriculture [2]. Since moderate-to-severe moisture stress prevails during post-kharif season in the region, buckwheat cultivation is subjected to varied levels of moisture stress and invariable soil acidity that impacts at root and shoot level [2, 3]. Since crop growth largely depends on the ability of roots to acquire essential water and nutrients from the rhizosphere, the impediments at root system by toxic elements (Al and Fe) hamper the ability of the roots to support highly metabolizing shoot system especially under low soil moisture stress condition [16]. Under short-term water stress, plants increase their water use efficiency (WUE) by reducing stomatal aperture and thereby reducing transpiration rate; however, under conditions of prolonged water deficit, plants frequently produce leaves with reduced stomatal conductance resulting from altered stomatal density (SD) and size [17]. Under continued moisture stress, crop adaptability manifest to the extent of change in root growth, stomatal structure, and cuticle synthesis as major means of stomatal and nonstomatal barrier for reduced water loss through plant leaves [18]. Possible changes in root and shoot growth alterations, stomatal characteristics, and leaf surface features would be remarkably varied under lowest moisture stress levels of 10–15% that could be reached during winter months of Meghalaya. Since the root system is slowly explored as the key source for moisture stress tolerance and adaptation [19] with an array of optimum root traits or phenes, plant ability to alter the root system would increase the stress tolerance substantially. Buckwheat has unique advantage for modifying root in accordance with prevailing soil water status under soil moisture constraints as evident in our study indicating the versatile crop adaptability in terms of altering root plasticity [2, 10].

Differential and incremental increase in the leaf pigments especially protective pigments having antioxidant capacity such as chlorophyll b and carotenoids that are found as a suitable rescue system for the crop to thrive and impart stress adaptability under moisture stress conditions for balanced light absorption and reduced photo-inhibition at higher altitudes of Eastern Himalaya [20]. Chlorophyll a to b ratio decreased under moisture stress (3.07) compared to 5.5 under controlled conditions, substantiating the higher accumulation of secondary pigment chlorophyll b by buckwheat. Increased chlorophyll b and carotenoid content by buckwheat could be useful in two major photoprotection systems, *viz.*, (i) as antioxidant which can scavenge free radicals generated by excess solar radiation energy and (ii) through NPQ enhancement to emit excess solar radiation energy [3, 10]. Regulation of photosynthetic apparatus by inducing necessary changes in leaf pigments under fluctuating light conditions under hilly locations of Eastern Himalaya is important for onset of appropriate physiological mechanism and adaptation in stress-resilient crops like buckwheat [10, 18].

Stomatal index has reduced significantly both in abaxial and adaxial surfaces to the extent of 72.6 and 55.1% under moisture stress conditions compared to control [3].

The high-resolution SEM images show that under moisture stress, the stomatal size significantly decreased or closed partially in abaxial surface, whereas under controlled conditions stomatal aperture remains open to a greater extent (**Figure 5**). Gas exchange is regulated by controlling the stomatal aperture and density on the epidermis [21]. Stomatal size and stomatal density were considerably influenced by plant species and abiotic environmental perturbations such as changes in atmospheric CO_2 concentration, light intensity, temperature, soil water, and nutritional status [22]. Besides stomatal control, increased cuticle synthesis and accumulation are major means of non-stomatal regulation or barrier for free water loss through plant leaves that is a prime adaptive mechanism, which is able to amply prevent water loss under moisture stress conditions [23].

4.1 Genetic variability for physio-morphological and yield traits in Buckwheat under acid soils of Meghalaya

Another field experiment conducted during 2021–2022 with 44no of buckwheat germplasm under native acid soils of hill slopes in Meghalaya revealed significant genetic variability among buckwheat genotypes for various physio-morphological and yield traits. The levels of leaf carotenoids were found higher in high yielders to the tune of 32.6 and 27.2% compared to moderate and low yielders, respectively. High yielders have shown reduced chl a/b ratio compared to moderate and low yielders possibly owing to their increased chl b synthesis, which is known to act as both stress pigment and antioxidant [2, 3]. Total root length (TRL) and root surface area (RSA) had the range of 18.7–123.3 cm and 5.69–48.0 cm^2 per plant. High yielders have reduced TRL than moderate and low yielders to the tune of 30.9 and 28.2% implying that high yielders possibly harbor other rescuing physiological mechanisms under acidic soil. Shoot length and number of leaves had mean values of 32.7 cm and 21.8 and within the range of 12.5–50.3 cm and 11 to 38.7, respectively. High yielders have shown increased shoot length and more number of leaves to the tune of 30.8 and 32.7% and 52.2 and 76.3% as compared to moderate and low yielders. Seed yield in high yielders was found higher to the tune of 163 and 688%, respectively. High yielders *viz.*, IC377275 (18.97 qt/ha), IC26591 (17.1 qt/ha), Shimla (16.4 qt/ha), IC14890 (16.32 qt/ha), IC37288 (15.5 qt/ha), and Himapriya (15.27 qt/ha) were emerged as promising buckwheat genotypes for cultivation in acid soils of Meghalaya (Unpublished data).

5. Possible response of Buckwheat for combined acid soil and moisture stress (drought stress) conditions of EHR

Abiotic stresses commonly prevailing in fragile ecosystems of EHR such as drought, heat, and soil acidity could potentially cause extensive losses to hill agricultural productivity and thereby impact food security. Under changing climate, resource-poor farmers are exposed to a range of challenges such as variability in weather patterns, soil acidity that manifested low soil fertility with nutrient depletion which might act solely or in combination to increasingly limit potential crop yield. As a result, crop plants are needed to be tolerant of both drought and acid soil stress as Asia has the second largest area of acid soils in the world with distinct interactions with seasonal drought across many countries [24]. Under such conditions, crop growth largely depends on the ability of roots to explore the soil for absorption of water and nutrients. To enhance cropping intensity and crop productivity development of the crops with resilient root system like buckwheat would remarkably enhance crop yields under low-moisture of acid soil conditions of hill slopes of EHR [25, 26].

Even though the use of lime, phosphate fertilizers, organic matter, and irrigation are highly productive in acid soils, as evident elsewhere, liming is not a realistic alternative economically in EHR because of geographical hill and logistic terrains, unfavorable climate, and due to the high cost for low-input resource-poor farmers. Extensive utilization of external inputs might cause undesirable side effects under fragile ecosystems practicing sustainable organic farming that would substantially threaten the environment. Moreover, liming can raise soil pH transiently and overcome toxicity problems only in the surface soil leaving the subsoil usually unaffected and deeper incorporation of lime is technically difficult and expensive. Therefore, holistic understanding of plant response to individual and combined stress factors are important in mountain ecosystems as they offer window of opportunities for novel crop improvement for enhanced crop adaptability and food security. As Al toxicity is the most important factor limiting plant growth on acid mineral soils, plant roots undergo rapid inhibition and damage that limits uptake of nutrients and water.

Root elongation is reduced under water stress with two distinct differences between acid soil Al stress and drought stress: (i) Under drought stress, shoot growth is affected more than root growth, whereas short- and medium-term acid soil Al strongly reduce root growth without affecting shoot growth [27]; (ii) Al toxicity reduces cell elongation along the entire elongation zone [28], whereas under water-deficit stress only basal and central elongation zones growth is inhibited, but maintained toward the distal and apical elongation zones. The maintenance of root elongation in the root apex is accomplished by some physiological mechanisms such as osmotic adjustment, alteration in cell-wall extension, and deposition of abscisic acid (ABA) [29]. The different response of root elongation under acid soil Al and drought stress in climate-resilient crop like buckwheat appears to give ecological advantage because of its versatile fibrous roots [2, 3]. Reduced inhibition of root growth by Al in the Al-toxic subsoil allows buckwheat to forage more nutrient-rich surface soil efficiently for nutrients and water, while the relative maintenance of root growth under drought allows the roots to grow into the subsoil for improved foraging for deficient nutrients like phosphorus [2, 30]. However, under field conditions, how declining soil moisture increased mechanical impedance to be overcome by resilient crops like buckwheat having potential to release organic acids need to be studied.

6. Conclusions

Specific stress-tolerant traits harbored by buckwheat substantially emulate it as suitable crop for higher grain productivity during stressful conditions of winter months (mid-September to October) in EHR but found better for producing higher green biomass all through the year. Root morphological traits, root exudation, stomatal attributes, and photo-protective pigments were significantly enhanced and emanated as efficient stress rescue mechanisms in buckwheat to overcome inimical moisture stress and soil acidity conditions of hill slopes in EHR under changing climate. In view of its increased resilience and sustained productivity by identified high-yielding genotypes *viz.* IC377275 (18.97q ha^{-1}), IC26591 (17.1 qt ha^{-1}), IC14890 (16.32q ha^{-1}), and Himapriya (15.27q ha^{-1}) under stressful and marginal hill environments, Buckwheat was found to be potential stress-resilient and remunerative crop for increased cropping intensity and food security with prevailing low-input agriculture in EHR.

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References

[1] Das A, Layek J, Idapuganti RG, Basavaraj S, Lal R, Rangappa K, et al. Conservation tillage and residue management improves soil properties under upland rice–rapeseed system in subtropical eastern Himalayas. Land Degradation & Development. 2020;**31**:1775-1791. DOI: 10.1002/ldr.3568

[2] Subarna H, Rangappa K, Dasaiah HG, Moirangthem P, Saikia US, Bhattacharjee B, et al. Genotypic variability and physio-morphological efficiency of buckwheat (*Fagopyrum* spp.) under moisture stress at mid-altitudes of Meghalaya (India). Crop & Pasture Science. 2022;**74**(3):204-218 DOI: 10.1071/CP22062

[3] Krishnappa R, Rajkhowa D, Saikia US, Moirangthem P, Sarma AK, Deshmukh NA, et al. Physiological responses of buckwheat (*Fagopyrum esculentum* L.) for stressful environments under fragile hill ecosystems of eastern Himalaya. In: Proceedings of 14th International Symposium on Buckwheat. North Eastern Hill University (NEHU): Shillong, India; 2019. pp. 146-147

[4] Gondola I, Papp PP. Origin, geographical distribution andphylogenic relationships of common buckwheat (*Fagopyrum esculentum* Moench.). In: The European Journal of Plant Science and Biotechnology. Global Science Book; 2010. Available from: www.globalsciencebooks.info

[5] Choi WS, Toyama S, Choi YJ, Woo BS. Preclinical efficacy examination on healing practices and experiences of users for pillows and mattresses of loess ball bio-products. Procedia Engineering. 2015;**102**:399-409. DOI: 10.1016/j.proeng.2015.01.173

[6] Song Y, Jia Z, Hou Y, Ma X, Li L, Jin X, et al. Roles of DNA methylation in cold priming in Tartary buckwheat. Frontiers in Plant Science. 2020;**11**:608540

[7] Ohnishi O. Search for the wild ancestor of buckwheat. I. Description of new Fagopyrum species and their distribution in China. Fagopyrum. 1998;**18**:18-28

[8] Zhou M, Tang Y, Deng X, Ruan C, Kreft I, Tang Y, et al. In: Zhou M, Kreft I, Suvorova G, Tang Y, Woo SH, editors. Overview of Buckwheat Resources in the World. In Buckwheat Germplasm in the World. London, UK: Elsevier Inc. 2018. p. 355

[9] Oettler G. Centenary review. The fortune of a botanical curiosity-triticale: Past, present and future. The Journal of Agricultural Science. 2005;**143**:329-346. DOI: 10.1017/S0021859605005290

[10] Krishnappa R, Layek J, Rajkhowa D, Das A, Saikia U, Mahanta K, et al. Year round growth potential and moisture stress tolerance of buckwheat (*Fagopyrum esculentum* L.) under fragile hill ecosystems of eastern Himalaya (India). Frontier in Sustainable Food Systems. 2023 (in Review)

[11] Das A, Layek J, Babu S, Ramkrushna GI, Baiswar P, Krishnappa R, et al. Package of practices for organic production of important crops in NEH region of India. In: ICAR Research Complex for North Easter Hill (NEH) Region, The President, Indian Association of Hill Farming Umiam-793103. Meghalaya, India; 2019. p. 228

[12] Arcand MM, Schneider KD. Plant- and microbial-based mechanisms to

improve the agronomic effectiveness of phosphate rock: A review. Anais da Academia Brasileira de Ciencias. 2006;**78**:791-807

[13] Raghothama KG, Karthikeyan AS. Phosphate acquisition. Plant and Soil. 2005;**274**:37-49

[14] Teboh JM, Franzen DW. Buckwheat (*Fagopyrum esculentum* Moench) potential to contribute solubilized soil phosphorus to subsequent crops. Communications in Soil Science and Plant Analysis. 2011;**42**:1544-1550

[15] Salehi A, Mehdi B, Fallah S, Kaul H-P, Neugschwandtner RW. Productivity and nutrient use efficiency with integrated fertilization of buckwheat–fenugreek intercrops. Nutrient Cycling in Agroecosystems. 2018;**2018**(110):407-425

[16] Yang Z-B, Eticha D, Albacete A, Rao IM, Roitsch T, Horst WJ. Physiological and molecular analysis of the interaction between aluminium toxicity and drought stress in common bean (*Phaseolus vulgaris*). Journal of Experimental Botany. 2012;**63**:3109-3125. DOI: 10.1093/jxb/ers038

[17] Franks PJ, Doheny-Adams TW, Britton-Harper ZJ, Gray JE. Increasing water-use efficiency directly through genetic manipulation of stomatal density. The New Phytologist. 2015;**207**:188-195. DOI: 10.1111/nph.13347

[18] Seki M, Umezawa T, Urano K, Shinozaki K. Regulatory metabolic networks in drought stress responses. Current Opinion in Plant Biology. 2007;**10**:296-302. DOI: 10.1016/j.pbi.2007.04.014

[19] Abenavoli MR, Leone M, Sunseri F, Bacchi M, Sorgona A. Root phenotyping for drought tolerance in bean landraces from Calabria (Italy). Journal of Agronomy and Crop Science. 2016;**202**(1):1-12. DOI: 10.1111/jac.12124

[20] Ashraf M, Mehmood S. Response of four *Brassica* species to drought stress. Environmental and Experimental Botany. 1990;**30**:93-100. DOI: 10.1016/0098-8472(90)90013-T

[21] Fayaz N, Arzani A. Moisture stress tolerance in reproductive growth stages in triticale (X *Triticosecale* Wittmack) cultivars under field conditions. Crop Breeding Journal. 2011;**1**(1):1-12

[22] Soltys-Kalina D, Plich J, Strzelczyk-Żyta D, Śliwka J, Marczewski W. The effect of drought stress on the leaf relative water content and tuber yield of a half-sib family of 'Katahdin'-derived potato cultivars. Breeding Science. 2016;**66**:328-331. DOI: 10.1270/jsbbs.66.328

[23] Schroeder JI, Kwak JM, Allen GJ. Guard cell abscisic acid signalling and engineering drought hardiness in plants. Nature. 2001;**410**:327-330. DOI: 10.1038/35066500

[24] von Uexküll HR, Mutert E. Global extent, development and economic impact of acid soils. Plant and Soil. 1995;**171**:1-15

[25] Krishnappa R, Narzari R, Layek J, Moirangthem P, Choudhury BU, Bhattacharjee B, et al. Harnessing root associated traits and rhizosphere efficiency for crop improvement. In: Mamrutha HM et al., editors. Translating Physiological Tools to Augment Crop Breeding. Vol. 2023. Singapore: Springer Nature; 2023. pp. 257-290. DOI: 10.1007/978-981-19-7498-4_12

[26] Trachsel S, Stamp P, Hind A. Effect of high temperatures, drought and aluminum toxicity on root growth of

tropical maize (*Zea mays* L.) seedlings. Maydica. 2010;**55**:249-260

[27] Yang ZB, You JF, Xu MY, Yang ZM. Interaction between aluminum toxicity and manganese toxicity in soybean (Glycine max). Plant and Soil. 2009;**319**:277-289

[28] Kollmeier M, Felle HH, Horst WJ. Genotypical differences in aluminum resistance of maize are expressed in the distal part of the transition zone. Is reduced basipetal auxin flow involved in inhibition of root elongation by aluminum? Plant Physiology. 2000;**122**:945-956

[29] Yamaguchi M, Valliyodan B, Zhang J, Lenoble ME, Yu O, Rogers EE, et al. Regulation of growth response to water stress in the soybean primary root. I. Proteomic analysis reveals region-specific regulation of phenylpropanoid metabolism and control of free iron in the elongation zone. Plant, Cell & Environment. 2010;**33**:223-243

[30] Whitmore AP, Whalley WR. Physical effects of soil drying on roots and crop growth. Journal of Experimental Botany. 2009;**60**:2845-2857

Section 2

Functional Properties

Chapter 3

Quinoa and Its Antioxidant and Nutritional Properties and Application in the Food Industry

Reza Esmaeilzadeh Kenari and Maryam Azizkhani

Abstract

Quinoa (*Willd quinoa Chenopodium*) is a pseudo-cereal. Quinoa seed is rich in antioxidants and also has a lot of carotenoids. Quinoa seed extract can be used as a natural antioxidant as well as a natural color in many food products, including food edible oils and high-fat dairy products, especially cream, can be used. One of the factors affecting the properties of quinoa seed extract is the extraction method, in which ultrasound and supercritical CO_2 extractions are more efficient than green extraction. Therefore, the use of the Carotenoid extract of quinoa has a significant role in stabilizing heat-sensitive oils, especially soybean oil, as well as cream as a new approach to increasing shelf life and reducing the consumption of synthetic antioxidants and synthetic colors in food products.

Keywords: quinoa seed, soybean oil, green extraction, antioxidant activity, oxidative stability

1. Introduction

Quinoa is a medicinal plant native to South America. The plant belongs to the *Chenopodiaceae* family. There are about 250 types of *chenopodium* plant species around the world. Quinoa seeds are the main edible parts of the product and are available in at least three colors, red, black, and white (**Figure 1**). They are rich in protein with essential amino acids and unsaturated fatty acids including linoleic acid, oleic acid, and palmitic acid, as well as micronutrients such as vitamins, polyphenols, and minerals. The total carotenoid content is in different parts including leaves and seeds [1]. In terms of composition, quinoa seed has 60–69% carbohydrates, 13–20% protein, 9–12.6% moisture, 4–10% fat, about 52–60% starch, and 3–4% minerals (including iron, calcium, magnesium, and zinc), are 10% fiber. Quinoa seeds are considered a source of vitamin E and tocopherols. Quinoa contains more protein than wheat, rye, oats, millet, corn, and rice. Quinoa seeds contain the amino acid lysine, which is an essential amino acid. Quinoa and soy have a similar composition of fatty acids. Therefore, it is considered a rich source of essential fatty acids such as linoleic acid and linolenic acid. The amount of oil in red quinoa is higher than in white and black types. Quinoa seeds contain polyphenols and flavonoids and have more riboflavin and alpha-tocopherol than rice, barley, and wheat [2]. Quinoa seeds have

Figure 1.
The seeds of white, red, black, and tricolor quinoa.

lipophilic carotenoid pigments, which include carotenes, such as lycopene and beta-carotene, which are composed only of carbon, and xanthophylls, such as lutein and zeaxanthin, which contain oxygenated functional groups such as epoxy, carbonyl, hydroxyl, and carboxylic acid groups [1]. Red quinoa contains a high amount of betacyanins, betaxanthins, and flavonoids [3]. Limited research has investigated the value of carotenoids in quinoa seeds. Some researchers have reported the presence of specific carotenoids, such as lutein and zeaxanthin, in quinoa seeds [1].

Consuming whole grains, such as wheat, is consistently associated with a reduced risk of cardiovascular disease, diabetes, and obesity due to its rich content such as protein and phenolic compounds. Meanwhile, it is estimated that about 2% and 5% of adults and children with food allergies such as celiac disease, respectively, have gluten intolerance. Cereals are nonherbaceous broad-leaved plants with seeds that can be milled like flour and replace regular gluten-containing flour. Quinoa, amaranth, chia, and buckwheat are gluten-free nutrients. Amaranth and quinoa are highly valued for their protein, dietary fiber, polyphenols, and rich minerals and are consumed as a common grain and vegetable in many cultures. A variety of effective hydrophobic plant substances such as lipids, vitamins, and carotenoids have been found in the leaves, stems, and seeds of both amaranth and quinoa plants [4]. In the food industry, quinoa seeds are prepared as flour mixed with the flour of pseudo-cereals such as buckwheat and amaranth as well as wheat or other grains and are used in the production of products such as bread, pasta, pancakes, biscuits, cakes, and crackers. Quinoa leaves are consumed similarly to spinach or as salad components [5]. The main bioactive compound in red quinoa is rutin (vitamin P), a part of flavonoids. Rutin has anti-inflammatory, antioxidation, and antitumor properties and protects the liver [3]. Due to the presence of essential amino acids such as leucine and isoleucine, quinoa seeds have high nutritional value and quality and are highly digestible. Quinoa proteins have antibacterial, antidiabetic, and blood pressure biological activity [6].

Carotenoids are pigments synthesized by photosynthetic organisms such as plants and some bacteria, algae, nonphotosynthetic fungi, and a small number of prokaryotes. Humans and most animals do not synthesize carotenoids. Therefore, they are included in the diet for physiological functions. The main source of plant carotenoids are mainly roots, flowers, fruits, and seeds [7]. In most plants, carotenoids are found in plastids, especially chloroplasts of photosynthetic tissues and chromoplasts [8]. Carotenoids are the most studied lipophilic natural pigments. They cause yellow, orange, and red colors in corn, carrot, papaya, tomato, watermelon, some fish, and crustaceans [9]. Beta-carotene is one of the most famous food carotenoids that are sometimes found together with alpha-carotene in red and yellow fruits and vegetables such as tomatoes, melons, carrots, mangoes, apricots, pumpkins, etc. Lutein is usually found in yellow or orange fruits and flowers, as well as green vegetables. Zeaxanthin is found naturally in corn, and egg yolk, as well as in some orange and yellow vegetables and fruits such as alfalfa and marigolds [8, 10]. Currently, more than 600 known carotenoids are found in nature, and about 40 carotenoids are regularly consumed in the human diet [11].

Synthetic colors are formulated colors that do not have a natural origin. Adding colored materials to products is required due to things like color replacement for those colors that have been lost during the production process and increasing the existing color. The effectiveness and economic factors provided by artificial colors have led to their widespread use in various industries, including the food industry. Unfortunately, the use of artificial coloring materials or color additives has a negative role in human growth and health, because their toxicity can lead to health problems [12]. Currently, carotenoids produced by chemical synthesis dominate the world market, but their acquisition from natural sources is growing. In fact, according to European Union directives, the importance of natural food additives as an alternative to artificial additives in food, cosmetics, and pharmaceuticals is increasing [13]. In recent years, natural biologically active compounds have received attention due to the interest in natural foods. To meet the demand of consumers all over the world, the food industry has focused on using natural ingredients instead of artificial ingredients. These biologically active substances, in addition to adding economic value, depending on the concentration used, improve the quality of food and even have therapeutic effects. In this sense, carotenoids are natural substances that are often added to food products. Yellow, orange, and red carotenoid dyes are the most common natural pigments used in the food industry as a complete or partial replacement for yellow and red synthetic dyes, which are widely used in beverages and food products due to their stability and high solubility are used [8]. Most carotenoids are derived from the 40-carbon tetraterpenoid phytoene. Phytoene is biosynthesized from two 20-carbon diphosphate molecules [14] (consisting of eight isoprene units with a 40-carbon skeleton) [10]. The central unit usually has 22 carbon atoms, which have nine double bonds and four side chain methyl groups, if they are rearranged by keeping two central methyl groups, it is still classified as a carotenoid [15].

The extraction process is very important in determining the final result of preparing the desired amount of bioactive compounds such as carotenoids. The most important parameters affecting the efficiency of extraction of bioactive compounds from plant sources include matrix properties of a plant part, type of solvent, temperature, pressure, time, solvent concentration, and liquid/solid ratio [16]. Today, there is an increasing demand for the development of green extraction processes, with reduced operating time, better results and extract quality, and a significant reduction in the use of organic solvents. To increase the total yield of plant materials, ultrasound extraction, microwave extraction, and supercritical CO_2 extraction are considered nonconventional methods [17]. Ultrasound is a nonthermal technology that shows a special effect for the extraction of heat-sensitive compounds. The effects of high-power ultrasound to improve extraction is related to acoustic cavitation, which includes: the formation, growth, and collapse of microbubbles in the liquid environment to transmit high-frequency sound waves. The mechanical effects of the ultrasound lead to the release of the desired compounds from the matrix, through the disruption of the cellular tissue and facilitate the penetration of the solvent into the cellular materials. Therefore, ultrasound leads to increased efficiency, increased extraction speed, reduced extraction time, reduced temperature, and the volume of the solvent used. Extraction with supercritical CO_2 is an advanced technology with a high potential for extracting molecules that require standards. The above is in terms of performance without any complications from solvents. They are especially important when extracts are used for nutrients. Extraction with supercritical CO_2 using carbon dioxide in supercritical conditions as an extraction solvent is an alternative to traditional extraction methods [18]. For the extraction of natural compounds, supercritical CO_2 has physicochemical properties between gas and liquid and these properties (such as density, viscosity, and permeability) can be adjusted by modifying the pressure and temperature (always above the critical point). This method is suitable due to the critical point (temperature 31.1°C, pressure 73 atm). It is widely used for its chemical stability, nonflammability, and nontoxicity. Supercritical carbon dioxide has a nonpolar characteristic and ethanol or methanol is added in a small amount (5–15%) to increase the polarity, so it has a significant effect on the extraction of polar and nonpolar compounds [18].

To maintain the safety and effectiveness of food, it is necessary to prevent the oxidation of lipids. In general, the oxidation of food can be inhibited by using natural and synthetic antioxidants. Antioxidants are a type of food additives that are used in the edible oil industry to increase shelf life and inhibit oxidation and degradation of edible oil, which include natural and synthetic antioxidants [19]. The most widely used synthetic antioxidants include Butylated hydroxytoluene, butylated hydroxyanisole, tert-butyl hydroquinone, and propyl gallate. Due to their low cost and high antioxidant activity, they are often used in the edible oil industry as a food additive to prevent the degradation of edible oil. But they have disadvantages including interfering with the synthesis and activity of enzymes, being toxic and carcinogenic, binding to nucleic acid and damaging it, and cell mutagenesis, which produces their effects over a long time and at high concentrations. While natural antioxidants are known as green antioxidants and include simple phenol compounds, phenolic acid, ascorbic acid, tocopherols, carotenoids, flavonoids, vitamins, and anthocyanins. Compared to synthetic antioxidants, natural antioxidants have greater antioxidant activity, increased thermal stability, and increased nutritional value of edible oils, and are more acceptable to consumers [20]. Oxidative stability of the oil is resistance to oxidation during processing and storage, which is an important parameter for determining the quality and durability of edible oil. The production of soybean oil has seen significant growth due to its availability and relatively low cost. One of the most common obstacles to using soybean oil is its level of unsaturation and its sensitivity to oxidation, which mainly leads to a change in taste. Singlet oxygen participates in the initiation stage of lipid oxidation so that it directly reacts with unsaturated fatty acids and creates a mixture of conjugated and nonconjugated hydroperoxides. Carotenoids are a group of fat-soluble pigments that can remove singlet oxygen with multiple conjugated double bonds. The quenching rate of singlet oxygen with carotenoids, lutein, zeaxanthin, and lycopene increases with the increase in the number of conjugated double bonds. Also, the antioxidant property of carotenoids is affected by their concentration, oxygen partial pressure, and environmental conditions. So that beta-carotene reduces the oxidation ion of soybean oil at any concentration and effectively at higher concentrations. However, in high concentrations, it also helps to improve the taste and color of soybean oil [21, 22].

2. Research, results and interpretation

2.1 Extracting quinoa seeds and adding extract to oil

It is possible to extract the bioactive compounds of quinoa seeds through an ultrasound bath, supercritical CO_2 methods. First, red quinoa seeds were powdered for extraction. Then, using ultrasound bath methods (solvent/solid) 50/1) f 100 W and 20 kHz and 45 ± 1°C for 3 min) [23] and supercritical CO_2 (flow rate 15 g/min, temperature 59°C, pressure 350 bar) with two ratios of 10% and 15% ethanol extraction was done by method [24]. The extract obtained from the ultrasound extraction process was purified to prepare carotenoids [25]. In continuation of these two studies, the average total carotenoid content in ultrasound and supercritical CO_2 extractions with 10% and 15% ethanol was determined as 128.568, 120.35, and 121.54 μg/g, respectively [26, 27]. In the following, purified carotenoid extract was added to investigate the effect of the antioxidant activity of carotenoid extract on stability in soybean oil without antioxidants [26, 27]. In ongoing research, quinoa extract was extracted with an ethanol-water solvent ratio (80:20 and 50:50) using the ultrasound-assisted extractionmethod [28].

The number of phenolic compounds was measured by the Folin-Ciocaltio method [29] and flavonoid compounds by the method [30] and antioxidant activity tests such as the ferric reducing antioxidant power by method [31] and DPPH radical inhibition by method [32] and also beta-carotene discoloration test were performed by method [32].

2.2 Oxidative stability of oil

The carotenoid obtained from ultrasound extraction was added to soybean oil with a concentration of 100, 200, and 300 ppm. To evaluate the oxidative stability and the effect of carotenoids on the color of soybean oil, tests such as peroxide value, conjugated diene value, thiobarbituric acid value, and color measurement were performed. 100, 200, and 300 ppm concentrations were compared and soybean oil without antioxidants was also investigated. The samples were kept at 60°C for 8 days [26].

In another study, carotenoid obtained from supercritical CO_2 was added to soybean oil with 10% and 15% ethanol with a concentration of 200 ppm. The tests mentioned in the previous research were also done in this research. Commercial beta-carotene samples with 200 ppm concentration and soybean oil without antioxidants were also examined and compared. The samples were kept at 60°C for 8 days [27].

In ongoing research, quinoa extract (with chitosan wall) was nano-encapsulated. The nano-encapsulated extract was added to the cream. Then, the cream oil was separated from the cream, and then to measure the oxidative stability of the cream oil, the tests of the peroxide value, the thiobarbituric value, and the release of phenolic compounds of the nano-encapsulated extract in the cream oil.

2.2.1 Peroxide value

Oil peroxide value was done by method [33]. The measurement method is based on iodometric titration, where iodine produced from potassium iodide was measured by peroxide in soybean oil. The results of this study showed that 200 mg/kg of commercial and natural carotenoids obtained by ultrasonic bath extraction had the best performance in reducing the PV of soybean oil samples during storage [26]. Concentrations higher than 100–200 mg/kg increase produced peroxide [34].

Samples containing carotenoid extract by supercritical CO_2 extraction with cosolvent ethanol of 10%, and 15% had significantly less peroxide content than samples containing commercial beta-carotene on most days of storage. With increasing storage time, the amount of peroxide increased in all samples containing antioxidants. All the samples on the first day of storage had significantly less peroxide than the samples on the last day of storage. The lowest amount of peroxide on the last day of storage with a value of 7.21 (mEq/kg of fat) was related to the sample containing carotenoid extract with supercritical CO_2 extraction with 15% ethanol solvent [27].

In the ongoing study of quinoa extract on cream oil, the amount of peroxide value was measured by method [35]. In this research, some sample was mixed with acetic acid-chloroform solution in the saturated potassium iodide phase and placed in a dark place. Then distilled water and finally, starch glue reagent were added to it and titration of the sample was done with sodium thiosulfate. Along with the titration of the samples, the titration of the control sample was also performed [35].

2.2.2 Conjugate diene value

For this purpose, soybean oil samples were diluted with hexane (1:600 g/ml). Then, the absorbance of the diluted samples was measured at a wavelength of 234 nm against hexane as a control. To determine the concentration of conjugated diene formed during oxidation, the method of [36] was used. The conjugate diene value of soybean oil samples containing commercial beta-carotene and natural carotenoids obtained from ultrasound extraction at 100, 200, and 300 mg/kg during 8 days of storage at 60°C was investigated. The results showed that the conjugate diene value of the samples containing 100, 200, and 300 mg/kg of commercial antioxidants had an increasing trend in the amount of conjugate diene, which showed that the conjugate diene value in these three concentrations increased during storage. Samples containing 100 mg/kg of commercial beta-carotene had the lowest conjugate diene value during 8 days of storage and showed the lowest conjugate diene value (18.53 mmol/L) on the eighth day. The sample containing 100 mg/kg of natural carotenoids obtained from ultrasound extraction had the lowest conjugate diene value throughout the storage period and it was significantly different from the samples containing 300 mg/kg of natural carotenoids on the first day to the eighth day. According to the findings, it can be concluded that natural carotenoids with a concentration of 100 mg/kg had the highest antioxidant power with the lowest conjugate diene value (16.972 mmol/L) on the eighth day. The sample without antioxidants had the highest conjugate diene value (22.3172 mmol/L) among all samples. Samples containing commercial beta-carotene at the rate of 100 mg/kg had the lowest conjugate diene value until the eighth day. Similarly, those containing 100 mg/kg of natural carotenoids had the lowest conjugate diene value on day 8, that is, the lowest concentration of carotenoids had the greatest antioxidant effect in reducing conjugate diene value on the last day of storage [26].

In another study, oil samples containing commercial beta-carotene and carotenoid extract by supercritical CO_2 extraction method with auxiliary solvent ethanol 10%, 15% increased the amount of conjugated diene with increasing storage time and also in all samples on the first and last day. There was a significant difference in maintenance. Soybean oil containing carotenoid extract obtained from supercritical CO_2 extraction with 10% ethanol and 15% ethanol cosolvent had a significantly lower conjugated diene value in most days of storage, especially in the last days of storage, compared to soybean oil containing commercial beta-carotene. The reason for its higher carotenoid content. On the last day of storage, soybean oil containing natural carotenoid extract by supercritical extraction method with 15% ethanol auxiliary solvent and soybean oil containing commercial beta-carotene with the lowest value of 16.032 mmol/L and the highest value of 19.60 mmol/L, respectively. They had the amount of conjugated diene [27].

2.2.3 Thiobarbituric acid value

A portion of the sample was transferred to a volumetric flask and made up to volume with 1-butanol. Then, the contents of the balloon were stirred. Thiobarbutyric acid reagent was added to the stirred solution. Next, the samples were placed in a water bath and then cooled for 10 min. Then, the absorbance of the solution at a wavelength of 530 nm was read by a spectrophotometer against the control sample. Finally, the amount of TBA was determined in terms of millimoles of malondialdehyde per kilogram of soybean oil according to the method of [37].

Thiobarbituric acid value is widely used as an indicator for the second product of lipid oxidation (malondialdehyde) [38]. The thiobarbituric acid values of soybean oil samples containing different concentrations (100, 200, and 300 mg/kg) of natural antioxidants bath ultrasound extraction obtained from commercial, and were investigated during 8 days of storage at 60°C. The amount of thiobarbituric acid increased during storage with the increase in the concentration of commercial beta-carotene, and the highest antioxidant effect was related to the lowest concentration (100 mg/kg), which had the lowest amount of thiobarbituric acid. On the eighth day of storage, the amount of thiobarbituric acid of soybean oil samples containing different concentrations (100, 200, and 300 mg/kg) of natural carotene was similar to commercial beta-carotene, the sample without antioxidants had the highest amount of thiobarbituric acid. It can be seen that the lowest concentration (100 mg/kg) of both antioxidants was more efficient in reducing the amount of thiobarbituric acid [26]. This can be related to the pro-oxidant properties of carotenoids, including oxygen concentration, the chemical structure of carrot carotenoids, and the presence of other antioxidants such as polyphenols and tocopherols [39]. Not only carotenoids but also other antioxidants are beneficial in increasing the oxidative stability of oils up to a certain concentration above which the pro-oxidant effects of such compounds appear [40].

In another study, in the early days, the amount of thiobarbituric acid is low, but over time, the primary oxidation products increase and begin to decompose, and the amount of this index increases, and volatile aldehydes, the main cause of the bad taste of the oil, are formed. Although in samples containing carotenoid extract extracted with supercritical CO_2 with 10% ethanol from the sixth day and samples containing beta-carotene and carotenoid extract extracted with 15% ethanol on the last day, the amount of thiobarbituric acid was lower than the previous day, which could be due to the oxidation secondary autoxidation products and the formation of carboxylic acids [27].

In the ongoing study to measure thiobarbituric acid value, 1 mg of sample was mixed with 1 ml of thiobarbituric acid reagent and 3 ml of *n*-butanol and placed in a water bath at 95°C for 2 h. After cooling to room temperature (25°C), the absorbance was measured at a wavelength of 530 nm [41]. Likewise, the release of phenol in cream oil was also tested by the method [29] was measured.

2.3 Color measurement

The color of the oil samples containing antioxidants was evaluated using a colorimeter system using the *b*a*L method. *L* = parameters indicate brightness, **a* = indicates red/green, and **b* = indicates yellow/blue [33]. Samples containing commercial carotenoids had lower **a* values than samples containing natural carotenoids obtained from bath ultrasound. The highest value was related to the sample with 300 mg/kg of commercial beta-carotene on the eighth day, which was due to the use of this compound in the highest concentration Samples containing commercial carotenoids had lower **a* values than samples containing carotenoids obtained from natural bath ultrasound. Samples containing commercial antioxidants had higher **b* values than samples containing natural antioxidants. Because commercial beta-carotene was more yellow than natural carotenoid [26]. In all oils containing carotenoid extract obtained from supercritical CO_2 and commercial beta-carotene, the amount of **b* is higher than zero and positive and is in the range of yellow color. The amount of index **b* of a sample containing carotenoid extracts extracted by the supercritical CO_2 method was higher due to the yellowness of the carotenoid extract added to the oil compared to commercial beta-carotene. Samples containing commercial beta-carotene showed a significant difference during storage at 60°C. There was none between them. The amount of parameter **a* in most samples is lower than zero and negative, which can be due to the changes of carotenoid pigments in the oil during storage. The carotenoid extract extracted by the supercritical method with the help of 15%, and 10% ethanol solvents reduced the transparency of the oil samples due to its turbidity and yellowish color. Therefore, they had a significantly lower amount of **L* than the samples containing commercial beta-carotene [27].

3. Conclusion

In general, in these two studies, quinoa carotenoids were extracted by ultrasound and supercritical CO_2 methods with the help of 10%, and 15% ethanol solvents, and the total content of extracted carotenoids was measured. Since supercritical carbon dioxide is a suitable solvent for the extraction of carotenoids with low polarity and the selectivity of carotenoids with the supercritical CO_2 method is high and it produces a purer extract than the ultrasound method, as a result, the carotenoid content is higher with the supercritical CO_2 method than with the supercritical CO_2 method. Obtained by ultrasound method. In this sense, the supercritical CO_2 method showed very good performance compared to the ultrasound method. On the other hand, the supercritical CO_2 with the help of 15% ethanol solvent obtained more carotenoid content due to more interaction with the sample matrix than with the help of 10% solvent. Today, in the edible oil industry, synthetic antioxidants such as commercial beta-carotenes are used to improve oil color and strengthen oil to delay oxidation reactions. However, due to the bad nutritional effects of these synthetic antioxidants and consumers' preference for natural antioxidants, their use as a substitute for synthetic antioxidants has attracted the attention of researchers. Therefore, there is the extraction of carotenoids from red quinoa and its use as a natural antioxidant in soybean oil. The extracted carotenoid extract was purified by ultrasound method and the extracted carotenoid extract by the supercritical CO_2 method as natural antioxidants and commercial beta-carotene as artificial antioxidant were added to soybean oil and all in the same conditions in the oven with a temperature of 60°C for 8 days. To check the oxidation stability of soybean oil by adding the desired antioxidants and to check their antioxidant properties in preventing the formation of primary and secondary oxidation products, the methods of measuring the amount of peroxide, conjugated diene, and thiobarbituric acid were used. The antioxidant showed the highest oxidation rate on most days of storage compared to samples containing antioxidants. Therefore, commercial and natural carotenoids had similar efficiency and there was no direct relationship between carotenoid concentration and its antioxidant effect. As a result, red quinoa carotenoid can be a good substitute for commercial beta-carotene in soybean oil. The extraction of the carotenoid extract with the help of ultrasound and supercritical CO_2 is an alternative based on the principles of green and efficient chemistry in obtaining heat-sensitive natural pigments, which have the potential to be used in food and pharmaceutical fields.

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References

[1] Multari S, Marsol-Vall A, Keskitalo M, Yang B, Suomela JP. Effects of different drying temperatures on the content of phenolic compounds and carotenoids in quinoa seeds (Chenopodium quinoa) from Finland. Journal of Food Composition and Analysis. 2018;**72**:75-82. DOI: 10.1016/j.jfca.2018.06.008

[2] Sezgin AC, Sanlier N. A new generation plant for the conventional cuisine: Quinoa (Chenopodium quinoa Willd.). Trends in Food Science & Technology. 2019;**86**:51-58. DOI: 10.1016/j.tifs.2019.02.039

[3] Lin TA, Ke BJ, Cheng CS, Wang JJ, Wei BL, Lee CL. Red quinoa bran extracts protects against carbon tetrachloride-induced liver injury and fibrosis in mice via activation of antioxidative enzyme systems and blocking TGF-β1 pathway. Nutrients. 2019;**11**(2):395. DOI: 10.3390/nu11020395

[4] Tang Y, Li X, Chen PX, Zhang B, Liu R, Hernandez M, et al. Assessing the fatty acid, carotenoid, and tocopherol compositions of amaranth and quinoa seeds grown in Ontario and their overall contribution to nutritional quality. Journal of Agricultural and Food Chemistry. 2016;**64**(5):1103-1110. DOI: 10.1021/acs.jafc.5b05414

[5] Złotek U, Gawlik-Dziki U, Dziki D, Świeca M, Nowak R, Martinez E. Influence of drying temperature on phenolic acids composition and antioxidant activity of sprouts and leaves of white and red quinoa. Journal of Chemistry. 2019;**12**:2019. DOI: 10.1155/2019/7125169

[6] Piñuel L, Boeri P, Zubillaga F, Barrio DA, Torreta J, Cruz A, et al. Production of white, red and black quinoa (Chenopodium quinoa Willd Var. Real) protein isolates and its hydrolysates in germinated and non-germinated quinoa samples and antioxidant activity evaluation. Plants. 2019;**8**(8):257. DOI: 10.3390/plants8080257

[7] Rivera-Madrid R, Carballo-Uicab VM, Cárdenas-Conejo Y, Aguilar-Espinosa M, Siva R. Overview of carotenoids and beneficial effects on human health. In: Carotenoids: Properties, Processing and Applications. Academic Press; 2020. pp. 1-40. DOI: 10.1016/B978-0-12-817067-0.00001-4

[8] da Silveira VM, de Oliveira LM, Nunes-Pinheiro DC, da Silva Mendes FR, de Sousa FD, de Siqueira OL, et al. Analysis of tetraterpenes and tetraterpenoids (carotenoids). In: Recent Advances in Natural Products Analysis. Elsevier; 2020. pp. 427-456. DOI: 10.1016/b978-0-12-816455-6.00012-3

[9] Rodriguez-Amaya DB. Update on natural food pigments—A mini-review on carotenoids, anthocyanins, and betalains. Food Research International. 2019;**124**:200-205. DOI: 10.1016/j.foodres.2018.05.028

[10] Maoka T. Carotenoids as natural functional pigments. Journal of Natural Medicines. 2020;**74**(1):1-6. DOI: 10.1007/s11418-019-01364-x

[11] Cheng SH, Khoo HE, Kong KW, Prasad KN, Galanakis CM. Extraction of carotenoids and applications. In: Carotenoids: Properties, Processing and Applications. Academic Press; 2020. pp. 259-288. DOI: 10.1016/B978-0-12-817067-0.00008-7

[12] Hatta FA, Othman R. Carotenoids as potential biocolorants: A case study

of astaxanthin recovered from shrimp waste. In: Carotenoids: Properties, Processing and Applications. Academic Press; 2020. pp. 289-325. DOI: 10.1016/B978-0-12-817067-0.00009-9

[13] Del Mar C-GM, Gómez-Caravaca AM. Underutilized sources of carotenoids. In: Carotenoids: Properties, Processing and Applications. Academic Press; 2020. pp. 107-147. DOI: 10.1016/B978-0-12-817067-0.00004-X

[14] Saini RK, Keum YS. Carotenoid extraction methods: A review of recent developments. Food Chemistry. 2018;**240**:90-103. DOI: 10.1016/j.foodchem.2017.07.099

[15] Black HS, Boehm F, Edge R, Truscott TG. The benefits and risks of certain dietary carotenoids that exhibit both anti-and pro-oxidative mechanisms—A comprehensive review. Antioxidants. 2020;**9**(3):264. DOI: 10.3390/antiox9030264

[16] Ilaiyaraja N, Likhith KR, Babu GS, Khanum F. Optimisation of extraction of bioactive compounds from Feronia limonia (wood apple) fruit using response surface methodology (RSM). Food Chemistry. 2015;**173**:348-354. DOI: 10.1016/j.foodchem.2014.10.035

[17] D'Alessandro LG, Dimitrov K, Vauchel P, Nikov I. Kinetics of ultrasound assisted extraction of anthocyanins from Aronia melanocarpa (black chokeberry) wastes. Chemical Engineering Research and Design. 2014;**92**(10):1818-1826. DOI: 10.1016/j.cherd.2013.11.020

[18] Molino A, Mehariya S, Iovine A, Larocca V, Di Sanzo G, Martino M, et al. Extraction of astaxanthin and lutein from microalga Haematococcus pluvialis in the red phase using CO_2 supercritical fluid extraction technology with ethanol as co-solvent. Marine Drugs. 2018;**16**(11):432. DOI: 10.3390/md16110432

[19] Bera D, Lahiri D, Nag A. Studies on a natural antioxidant for stabilization of edible oil and comparison with synthetic antioxidants. Journal of Food Engineering. 2006;**74**(4):542-545. DOI: 10.1016/j.jfoodeng.2005.03.042

[20] Sharma S, Cheng SF, Bhattacharya B, Chakkaravarthi S. Efficacy of free and encapsulated natural antioxidants in oxidative stability of edible oil: Special emphasis on nanoemulsion-based encapsulation. Trends in Food Science & Technology. 2019;(91):305-318. DOI: 10.1016/j.tifs.2019.07.030

[21] Kaur D, Sogi DS, Wani AA. Oxidative stability of soybean triacylglycerol using carotenoids and y-tocopherol. International Journal of Food Properties. 2015;**18**(12):2605-2613. DOI: 10.1080/10942912.2013.803118

[22] Steenson DF, Min DB. Effects of β-carotene and lycopene thermal degradation products on the oxidative stability of soybean oil. Journal of the American Oil Chemists' Society. 2000;**77**:1153-1160. DOI: 10.1007/s11746-000-0181-7

[23] Macías-Sánchez MD, Mantell C, Rodriguez MD, De La Ossa EM, Lubián LM, Montero O. Comparison of supercritical fluid and ultrasound-assisted extraction of carotenoids and chlorophyll a from Dunaliella salina. Talanta. 2009;**77**(3):948-952. DOI: 10.1016/j.talanta.2008.07.032

[24] de Andrade LM, Kestekoglou I, Charalampopoulos D, Chatzifragkou A. Supercritical fluid extraction of carotenoids from vegetable waste matrices. Molecules.

2019;**24**(3):466. DOI: 10.3390/molecules24030466

[25] Mai HC, Truong V, Debaste F. Carotenoids purification from gac (Momordica cochinchinensis Spreng.) fruit oil. Journal of Food Engineering. 2016;**172**:2-8. DOI: 10.1016/j.jfoodeng.2015.09.022

[26] Abdolahi Alkami P, Esmaeilzadeh Kenari R, Farahmandfar R, Azizkhani M. Investigation of the antioxidant effect of red quinoa (Chenopodium formosanum Koidz) carotenoid extracted on the oxidative stability of soybean oil. Journal of Food Processing and Preservation. 2022;**46**(3):e16406. DOI: 10.1111/jfpp.16406

[27] Abdolahi P, Esmaeilzadeh Kenari R, Farahmandfar R, Azizkhani M. Antioxidant effect of red quinoa carotenoid extract obtained by supercritical fluid extraction on soybean oil stabilization. Journal of Food Research. 2023;**33**(1):83-96. DOI: 10.22034/fr.2022.50727.1827

[28] Arlene AA, Prima KA, Utama L, Anggraini SA. The preliminary study of the dye extraction from the avocado seed using ultrasonic assisted extraction. Procedia Chemistry. 2015;**16**:334-340. DOI: 10.1016/j.proche.2015.12.061

[29] Acquadro S, Appleton S, Marengo A, Bicchi C, Sgorbini B, Mandrone M, et al. Grapevine green pruning residues as a promising and sustainable source of bioactive phenolic compounds. Molecules. 2020;**25**(3):464. DOI: 10.3390/molecules25030464

[30] Shraim AM, Ahmed TA, Rahman MM, Hijji YM. Determination of total flavonoid content by aluminum chloride assay: A critical evaluation. LWT. 2021;**150**:111932. DOI: 10.1016/j.lwt.2021.111932

[31] Agregán R, Lorenzo JM, Munekata PE, Dominguez R, Carballo J, Franco D. Assessment of the antioxidant activity of Bifurcaria bifurcata aqueous extract on canola oil. Effect of extract concentration on the oxidation stability and volatile compound generation during oil storage. Food Research International. 2017;**99**:1095-1102. DOI: 10.1016/j.foodres.2016.10.029

[32] Saviz A, Esmaeilzadeh Kenari R, Khalilzadeh Kelagar MA. Investigation of cultivate zone and ultrasound on antioxidant activity of Fenugreek leaf extract. Journal of Applied Environmental and Biological Sciences. 2015;**4**(11S):174-181. DOI: 10.1006/abbi.1995.019

[33] Nour V, Corbu AR, Rotaru P, Karageorgou I, Lalas S. Effect of carotenoids, extracted from dry tomato waste, on the stability and characteristics of various vegetable oils. Grasas y Aceites. 2018;**69**(1):e238. DOI: 10.3989/gya.0994171

[34] Tsuchihashi H, Kigoshi M, Iwatsuki M, Niki E. Action of β-carotene as an antioxidant against lipid peroxidation. Archives of Biochemistry and Biophysics. 1995;**323**(1):137-147. DOI: 10.1006/abbi.1995.0019

[35] Deepika D, Vegneshwaran VR, Julia P, Sukhinder KC, Sheila T, Heather M, et al. Investigation on oil extraction methods and its influence on omega-3 content from cultured salmon. Journal of Food Processing and Technology. 2014;**5**(12):1-3. DOI: 10.4172/2157-7110.1000401

[36] Saguy IS, Shani A, Weinberg P, Garti N. Utilization of jojoba oil for deep-fat frying of foods. LWT-Food Science and Technology. 1996;**29**(5-6):573-577. DOI: 10.1006/fstl.1996.0088

[37] Ojagh SM, Rezaei M, Razavi SH, Hosseini SM. Effect of chitosan coatings enriched with cinnamon oil on the quality of refrigerated rainbow trout. Food Chemistry. 2010;**120**(1):193-198. DOI: 10.1016/j.foodchem.2009.10.006

[38] Razavi R, Maghsoudlou Y, Aalami M, Ghorbani M. Impact of carboxymethyl cellulose coating enriched with Thymus vulgaris L. extract on physicochemical, microbial, and sensorial properties of fresh hazelnut (Corylus avellana L.) during storage. Journal of Food Processing and Preservation. 2021;**45**(4):e15313. DOI: 10.1111/jfpp.15313

[39] Shixian Q, Dai Y, Kakuda Y, Shi J, Mittal G, Yeung D, et al. Synergistic anti-oxidative effects of lycopene with other bioactive compounds. Food Reviews International. 2005;**21**(3):295-311. DOI: 10.1080/FRI-200061612

[40] Moure A, Cruz JM, Franco D, Domínguez JM, Sineiro J, Domínguez H, et al. Natural antioxidants from residual sources. Food Chemistry. 2001;**72**(2):145-171. DOI: 10.1016/S0308-8146(00)00223-5

[41] Qiu H, Qiu Z, Chen Z, Liu L, Wang J, Jiang H, et al. Antioxidant properties of blueberry extract in different oleogel systems. LWT. 2021;**137**:110364. DOI: 10.1016/j.lwt.2020.110364

Chapter 4

Current Production Scenario and Functional Potential of the Whole Amaranth Plant: A Review

Nataly Peña, Sergio Minguez and Juan-David Escobar

Abstract

Amaranth grain is a pseudocereal that has been widely studied, standing out as a gluten-free seed and plant-based protein source. Amaranth seeds have been associated with functional properties and attractive medical benefits. Besides the seeds themselves, various other parts of the plant possess significant nutritional and functional value. Thus, on one hand, this chapter summarizes an overview of amaranth seeds, leaves, and flowers. Apart from this, recent research and studies have reported on amaranth's composition, its uses, and potential benefits for human health. This chapter also offers insight into the global socioeconomic scenario of farmers and producers. Possible strategies that include biotechnology, ingredient innovation, and ethical biotrade have been proposed here. These three fronts, acting synergistically, would exploit the considerable diversity of these species and promote programs to improve the value chain and, therefore, the life quality of their communities.

Keywords: amaranth, nutrition, pseudocereal, biotrade, functional ingredients

1. Introduction

Amaranth has been consumed throughout history as a staple food by the Inca, Maya, and Aztec civilizations like quinoa and chia seeds [1]. In the 1980s, an increase in interest in amaranth appeared as the US National Academy of Sciences conducted research on the grain and described its high nutritional value and agronomic potential [2]. Because of the growing demand for healthy foods, amaranth has gained recognition in countries where its consumption was not traditional. This recognition has been further supported by recent literature reviews focused on aspects such as the adaptation of amaranth to traditional cuisines [3, 4] as well as the functional and nutraceutical properties of this pseudocereal [5].

Amaranthus or amaranth comes from the Greek amarantos (Αμάρανθος or Αμάραντος), meaning the "one that does not wither," or the never-fading (flower) [6]. Several species of the genus are commonly referred to as weeds, while other species are used as leafy vegetables in many parts of the world [7]. Grain amaranth belongs to the order Caryophyllales, the amaranth family Amaranthaceae, which comprises 65 genera and 850 species, subfamily Amaranthoideae, genus *Amaranthus,* which includes 50–60 species cultivated for leaf (greens) and grains. It equally includes a few wild species. The important leaf amaranth species are *Amaranthus tricolor* (syn. *A. gangeticus, A. tristis, A. mangostanus, A. polygamous, and A. meloncholicus)*, *A. dubius*, and *A. lividus* (*Amaranthus blitum*). In recent years, *A. caudatus L., Amaranthus hypochondriacus L., and A. cruentus L.* are the species that have created a strong interest in seed production [8].

All the grain of amaranth's real origin is traced to Central and South America. Notwithstanding, with some species such as *Amaranthus tricolor* are believed to be a native of India or southern China; *A. lividus* is reported to be a native of south or Central Europe, whereas *A. dubius* is from Central America [9]. It makes sense that the key producers are mostly in several South American countries, along with China, India, Russia, and Kenya [10].

Although amaranth production is not registered by the UN's Food and Agriculture Organization (FAO), it is currently widely cultivated in several countries, including Nepal, Indonesia, Malaysia, Central America, Mexico, and Southern and Eastern Africa [11].

The data shows the strong influence of worldwide amaranth cultivation and the socioeconomic impact generated on farm families. This situation is overshadowed by the brightness of a food gem, which raises interest in its nutritional and functional properties. It should be noted that the leaves and flowers of amaranth have a high antioxidant activity compared with other parts of the plant and many other traditional leafy greens [12, 13].

This review begins with a summary of the composition, the functional properties, and the uses of the different anatomical parts of amaranth. Then, a comparative discussion among the results found in seeds, leaves, and flowers is presented. Finally, the current farmer scenario is analyzed.

2. Functional properties of different parts of the Amaranth plant

Overall, amaranth is a highly nutritious plant that can provide a range of important nutrients when consumed in its various forms. It is well known that the amaranth seed has been reporting outstanding nutritional and health properties. It is significant to note that other parts of the plant have also shown interesting functional potential. Therefore, the nutritional and functional aspects of the amaranth seed, leaves, and flowers are described separately below.

2.1 Amaranth seed

Amaranth seeds are a great source of plant-based protein, fiber, and several essential vitamins and minerals. They are high in lysine, an essential amino acid that is often lacking in grains. Amaranth seeds are also a good source of iron, calcium, magnesium, and phosphorus. Amaranth seeds contain antioxidants, such as vitamin E and phenolic compounds, which may help to protect against cellular damage.

Amaranth seed is a dicotyledonous pseudocereal that has been consumed for thousands of years. It is known for its many health benefits. The protein content of the amaranth seed is superior to that of cereals, making it a highly nutritious food.

Extensive research has shown that amaranth seeds are also well-balanced. They are rich in protein content of between 12% and 16% and have an excellent balance of essential amino acids in their peptides. These peptide-rich fractions exhibit various health benefits, including antioxidant, antihypertensive, hypocholesterolemic, anticoagulant, antidiabetic, anticancer, anti-inflammatory, and antiviral activities [12]. This leads to a reduction in plasma cholesterol levels. It also has antitumor effects, lowers blood sugar levels, and treats anemia [1].

In addition to being rich in protein, amaranth seeds are good sources of crude fiber, dietary fiber, and minerals, especially calcium, iron, and potassium [13]. This translates into a remarkable nutritional profile, and it can be used in a variety of dishes, including salads, soups, and baked goods, making it an excellent option as an additive to improve the nutritional profile of other foods [8]. Finally, as a gluten-free ingredient for people with coeliac disease or gluten intolerance, the flour obtained from milling amaranth seeds has become a great alternative.

Amaranth seeds have been shown to improve the antioxidant potential of baked cookies [14, 15], and they have been used to make functional cookies with antithrombotic and antihypertensive activities [16]. Even after thermal and enzymatic treatments, end-consumer products derived from amaranth showed antioxidant capacity, which further increased after *in vitro* digestion [17]. Altogether, amaranth seeds exhibit antioxidant activity attributed to their content of polyphenols, anthocyanins, flavonoids, and tocopherols [18], which can help to prevent damage to cells and reduce the risk of chronic diseases. This proves once again the high potential of amaranth seeds as a source of functional ingredients.

2.2 Amaranth leaves

Amaranth leaves are a highly nutritious vegetable that is commonly eaten in many parts of the world. They are rich in vitamins A, C, and K, with a higher content of vitamin C than spinach and cabbage. These essential vitamins are involved in the healthy functioning of the immune system and can help to prevent the spread of infectious diseases.

While amaranth leaves and stems contain high levels of several vitamins, they also contain riboflavin (vitamin B2), vitamin B6, folate, and niacin. Amaranth leaves also contain minerals such as calcium, iron, and magnesium [19]. Amaranth leaves are a nutritious vegetable with many health benefits when incorporated into a balanced diet, making it a healthy and nutrient-dense food [20].

It has been reported that amaranth leaves and their products are a valuable source of protein, calcium, iron, and ß-carotene [21]. Certain baked goods made with amaranth leaves were found to have significantly higher protein, fat, ash, and fiber content than their counterparts, while all fortified products had notably higher levels of calcium, magnesium, iron, and zinc [22].

Compared to other edible leaves, amaranth leaves are known for their high protein content. Furthermore, studies have shown that extracts derived from the leaves possess a superior antioxidant capacity compared to those obtained from the seeds [23]. This has been confirmed *in vitro* in both the leaves and flowers of the amaranth plant [24].

Specifically, high concentrations of hydroxycinnamic acid derivatives, such as caffeoylaldaric and -isocitric esters, have been found in amaranth leaves, although flavonoids and carotenoids were found in moderate concentrations compared to other leafy vegetables [25]. These unique compounds have been linked to potential health [26] and cosmetic benefits [27], including controlling lipids and obesity.

Additionally, tannins extracted from amaranth leaves have been identified as a promising source of antioxidants that may be used as food-preserving agents or as dietary supplements [28].

Concerning the unique antioxidant components found in amaranth vegetables, betalains (beta-cyanins and betaxanthins) and their physiological functions such as antioxidant, anti-lipidemic, anticancer, and antimicrobial activities are also emphasized [29].

Amaranth leaves are a versatile ingredient. They can be used in a variety of dishes, including soups, stews, and salads. Amaranth leaf infusions have also been used for treating anemia, chronic fatigue, diarrhea, coughing, and heavy menstrual bleeding, and even for soothing itchy, burning skin, and cleaning wounds [30]. The consumption of amaranth vegetables is also considered medicinal for young children, breastfeeding mothers, and patients suffering from constipation, fever, hemorrhage, anemia, and renal problems [31]. In this sense, some studies have proposed the incorporation of amaranth leaf flour in processed foods such as pasta, resulting in higher levels of iron, zinc, magnesium, potassium, and higher antioxidant capacity values after cooking [32]. Consumer acceptance of pasta made with amaranth leaf flour was found to be like that of pasta made with spinach. Once again, amaranth leaves have demonstrated their innate potential to increase the functional benefits of food and to improve human nutrition.

2.3 Amaranth flowers

Amaranth flowers are often used for ornamental purposes in gardens and floral arrangements. Furthermore, they are a good source of several important nutrients. They contain vitamin A, folate, and potassium, and they are particularly rich in vitamin C. Amaranth flowers also have certain health benefits due to their high antioxidant capacity. This depends on the flavonoid content.

Purple amaranth flowers contain higher levels of flavonoids than red amaranth flowers, which makes them particularly beneficial [33]. It is known that amaranth species are attractive sources of betalain because of the broad range of pigmentation [34]. Due to the global status of amaranth as a food, one of the major applications of amaranth flowers is as a natural food coloring agent.

Phenolic compounds found in the flowers include gallic acid, chlorogenic acid, protocatechuic acid, 2,4-dihydroxybenzoic acid, genistein, ellagic acid, feluric acid, and salicylic acid. Rutin, quercetin, and kaempferol-3-rutinoside are also found. It is worth noting that although all parts of the plant have been analyzed, chlorogenic acid is the only compound detected in flowers [35]. Moreover, even though the tannin content is higher in the leaves, the amounts of it found in the flower still represent a potential antitumor agent [28].

Similarly, although the inflorescence of amaranth contains only half the amount of rutin compared to the leaves, the amaranth plant could still be an excellent source of this antioxidant in the human diet [36]. Food additives with a high content of betacyanin, obtained from amaranth flowers, showed higher stability, even after they were incorporated into biscuits [37].

Despite its potential health benefits, the amaranth flower has not been widely used as a foodstuff, so its properties have been studied only to a limited extent. However, the flowers have been used as a remedy for diarrhea, dysentery, coughs, and bleeding [38].

An important finding is that extracts from the flower of the amaranth plant have a valuable potential as an antimicrobial agent. Amaranth stem and flower showed higher antimicrobial activity than root and leaves against five strains of bacteria including *Staphylococcus* sp., *Escherichia coli, Pseudomonas* sp., *Klebsiella* sp., *Paracoccus* sp., and three strains of fungi including *Fusarium* spp., *Aspergillus* spp., and *Alternaria* spp. [38]. Furthermore, the globe amaranth flower was reported to have antibacterial bioactivity against *P. aeruginosa* [39]. This indicates great potential for its use in medical applications and the food and agricultural industry.

3. Comparative discussion

Amaranth has been extensively employed in food products throughout history due to its favorable nutritional value, as shown in **Table 1**. Despite anatomical and species variations in the *Amaranthus* plant, numerous studies have consistently shown that it contains various bioactive compounds (as listed in **Table 2**) and functional properties (as described in **Table 3**) that support human health. Recent research has further reinforced these findings, providing additional evidence of the beneficial effects of amaranth on human health.

	Amaranth seeds d.b.	Scientific references	*Amaranth* leaves w.b.	Scientific references
Main nutrient (g/100 g)				
Proteins	13.5–17.5	[10, 15, 23, 39–53]	3.5–4.6	[23, 31, 43, 44, 54–56]
Carbohydrates	63.0–75.8	[10, 15, 39, 40, 42, 44–46, 49, 53, 57]	3.8–6.5	[23, 31, 44, 54]
Fiber	6.0–8.8	[10, 15, 23, 39, 40, 44–53, 57]	1.3–1.9	[23, 31, 44, 54–56]
Fat	5.8–10.2	[15, 23, 39, 40, 44–52, 58]	0.3–0.6	[23, 31, 44, 54, 55]
Minerals (mg/100 g)				
Calcium	159–240	[10, 39, 40, 44, 46, 47, 52, 53, 57]	140–350	[31, 43, 44, 55, 59]
Iron	760–1000	[10, 39, 40, 44, 46, 47, 52, 53, 57]	330–1000	[31, 44, 55, 56, 59]
Magnesium	235–303	[10, 39, 40, 46, 47, 52, 53, 57]	150–450	[31, 55, 59]
Phosphorus	455–580	[39, 44, 47, 52, 53, 57]	430–1000	[31, 55, 59]
Potassium	508–595	[10, 39, 40, 47, 52, 53, 57]	460–920	[31, 44, 55, 59]
Zinc	287–390	[10, 39, 40, 46, 47, 52, 53, 57]	0.67–2.0	[31, 43, 55, 59]
Vitamins (mg/100 g)				
Vitamin A	Unknown	—	1.70–5.7	[31, 43]
Vitamin C	298–705	[45, 53, 57]	36.0–78.0	[56, 59]
Thiamin (B1)	7.2–24	[45, 53]	0.03–0.06	[31]
Riboflavin (B2)	18–27	[45, 53, 57]	0.08–0.18	[31]
Niacin (B3)	89–100	[45, 57]	0.5–1.1	[31]

Table 1.
Nutritional value of Amaranth spp.

Plant part	Bioactive compounds	Scientific references
Seeds	1-Naphtalenol, 4-methyl	[23, 35, 45, 48–51, 53, 58, 60–68]
	2,4-Dihydroxybenzoic acid	
	3,4-Dihydroxybenzoic acid	
	24,25-Dihydroxyvitamin D	
	2H-1,2-Oxazine, 6-(4-chlorophenyl) tetrahydro-2-methyl	
	4-Hydroxybenzoic acid	
	9-Octadecenoic (2-phenyl-1,3-dioxolan-4-Yl)	
	Acid methyl ester	
	Alkaloids	
	Amaranthine	
	Betacyanins	
	Betanin	
	Caffeic acid	
	Caffeine	
	Ferulic acid	
	Flavonoids	
	Gallic acid	
	Gentistic acid	
	Isoamaranthine	
	Isobetanin	
	Isoquercitrin	
	Isorhametin	
	Kaempferol	
	Kaempferol dirhamnoside	
	Myricetin	
	Nicotiflorin	
	p-Coumaric acid	
	p-Hydroxybenzoic acid	
	p-OH-Benzoic acid	
	Phenolic acids	
	Protocatechuic acid	
	PUFAs	
	Quercetin	
	Quercetin 3-rutinoside	
	Rutin	
	Salicylic acid	
	Saponins	
	Sinapic acid	
	Squalene	
	Syringic acid	
	Tannins	
	Tocopherols	
	Tocotrienols	
	Triterpenes	
	Vanillic acid	
	Zeaxanthin	

Plant part	Bioactive compounds	Scientific references
Leaves	2-Methoxy-4-vinylphenol	[23, 24, 31, 35, 55, 59, 64, 69, 70]
	2-Propenoic, 3-(2,3-dimethoxyphenyl)-acid	
	2,4-Dihydroxybenzoic acid	
	24,25-Dihydroxyvitamin D	
	5-Methyl-2-(N-ethyl-p-chlorophenylamino)-2-thiazoline	
	Alkaloid	
	Carotenoid	
	Chlorogenic acid	
	Ferulic acid	
	Flavonoids	
	Gallic acid	
	Gentistic acid	
	Hydrocyanic acid	
	Kaempferol	
	Nitrates	
	Phenol-4-(2-(dimethylamino)ethyl)	
	Phenolic acids	
	Phytic acid	
	Protocatechuic acid	
	Quercetin	
	Retinoic acid, methyl ester	
	Rutin	
	Salicylic acid	
	Saponins	
	Steroids	
	Tannins	
	Terpenoids	
Flowers	2,4-Dihydroxybenzoic acid	[24, 35, 71–73]
	Betacyanins	
	Betalain (amaranthine, isoamaranthine)	
	Betaxanthins	
	Chlorogenic acid	
	Ferulic acid	
	Gallic acid	
	Gentistic acid	
	Isoquercetin and rutin	
	p-Coumaric acid	
	Protocatechuic acid	
	Salicylic acid	
	Syringic acid	
	Vanillic acid	

Table 2.
Biochemical studies validating bioactive compounds of Amaranthus spp.

Apart from the anatomical parts of the plant discussed earlier, studies have also investigated the functional properties of whole plant extracts. The entire plant has been found to possess numerous beneficial properties such as wound-healing

Plant part	Functionality	Scientific references
Seeds	Antibacterial	[46]
	Anti-inflammatory	[12, 45, 46, 62, 72, 74, 75]
	Antidiabetic	[12, 45, 46, 74, 76, 77]
	Antifungal	[12, 78]
	Antihypertensive	[12, 43, 46, 53, 60, 79, 80]
	Antimicrobial	[46, 81]
	Antioxidant	[1, 12, 15, 23, 35, 45, 46, 50, 53, 60, 62–64, 66–68, 74, 76, 79, 82–85]
	Antitumoral activities	[1, 12, 46, 53, 62, 72, 74, 79, 85]
	Cardiovascular disease	[43, 45, 46, 60, 72]
	Hepatoprotective	[46, 53, 74, 82, 86]
	Hypocholesterolemic	[1, 12, 45, 53, 60, 86]
	Immunomodulatory	[52, 53, 72, 79]
	Neuroprotective	[46]
Leaves	Antioxidant	[23, 24, 35, 44, 62, 64, 70, 82]
	Emollient	[44]
	Anti-inflammatory	[44, 74]
	Hepatoprotective	[74]
	Diuretic	[44]
Flowers	Antioxidant	[24, 35, 82]
	Antidiabetic	[72, 74]
	Anti-inflammatory	[72, 74]
	Hepatoprotective	[74]
	Immunomodulatory	[72]

Table 3.
Biochemical studies validating functional and health properties of Amaranthus spp.

acceleration and antimicrobial activities [81, 87] gut modulatory and bronchodilator effects [88], anti-inflammatory, analgesic, and anthelmintic activities [75, 89], and even anticancer properties [90], among others.

Although the current data suggests significant potential for functional properties in the seeds and leaves of the amaranth plant, additional research is needed to explore the potential antibacterial, antioxidant, and antifungal properties of the flower. These properties could have promising applications in fields such as phytosanitary and pharmaceuticals. Furthermore, while extensive research has been conducted on the nutritional potential of the grain and leaves, there are no available reports on the nutrient profile of the flower.

Amaranth, particularly the vegetable variety, is commonly consumed as a source of protein in sauces, soups, or cooked with other vegetables as a side dish or stand-alone meal [91]. It is also utilized in processed foods such as pasta [92], biscuits, and snacks [22]. Furthermore, extracts from the flower and leaves have been integrated into active and smart packaging films [22]. While traditionally consumed in infusions, flower extract has also been used as a food additive [37].

Amaranth seeds can be processed in various ways such as popping, flaking, extruding, and grinding into flour. The resulting flour can be combined with wheat or other flour to make a variety of baked goods [91]. Other interesting proposals include using amaranth as a food supplement [93], a binder for meat burgers, cream soups, and sauces [94], and as an alternative like cow's milk in beverages [94].

Further research is necessary to comprehensively explore the nutritional and functional properties of all parts of the amaranth plant, especially the flower, which remains relatively underexplored. Nonetheless, based on the available information, amaranth offers multiple health benefits and has various potential applications, notably in its leaves and seeds. Despite this, research on the flower has been limited, despite its potential health benefits that may rival those of the leaves.

4. Current scenario of amaranth farmers

The global situation of amaranth producers is diverse. While amaranth's high nutritional value and versatility in cooking are driving an increase in demand and production in some countries, there are also concerns regarding the sustainability of its production and its potential negative impact on the environment and small-scale farmers' livelihoods. The economic and social conditions of amaranth farmers differ based on the size and location of production.

Small-scale farmers operating in areas affected by migration, economic instability, and environmental degradation often belong to the rural poor. A 2008 report presented at the IFOAM Organic World Congress [95] indicated that amaranth was viewed as an alternative crop and livelihood that could provide valuable resources to these farmers in addressing these challenges. Amaranth is adaptable to extreme conditions such as drought and saline soils, making it particularly valuable for small farmers in the central and southern regions of Mexico. Nevertheless, the economic and social status of amaranth farmers varies depending on the region and the scale of production.

Small amaranth farmers face several limitations, one of which is the monopolization practices developed by certain associations. These practices include the transfer of knowledge and technology, seed distribution, and contact with potential national and foreign buyers. To support small-scale livelihoods, the government can take a more proactive role by establishing stricter requirements for cooperatives to ensure that small farmers are included as true partners or co-owners.

It is important to consider the entire value chain when promoting sustainable livelihoods in amaranth. Therefore, national consumer associations, particularly in European markets, can play a vital role by demanding more active and tangible participation of small farmers associated with cooperatives that control the amaranth value chain. This can ensure that small farmers are included as true partners or co-owners and can benefit from the knowledge, technology, and seed distribution practices developed by these cooperatives. By doing so, consumer associations can contribute to the promotion of fair and sustainable trade practices that benefit small-scale amaranth farmers and their communities.

According to a study carried out in Kenya, the production of amaranth faces several economic and environmental challenges. These challenges include droughts, limited awareness about crop utilization, inadequate seed supply, lack of market access, competition with other cereals, insufficient value-added equipment, low and unstable prices, limited knowledge about packaging, inadequate capital, and pest and disease pressure. The study indicated that farmers' knowledge, attitudes, and practices related to amaranth production, value addition, and utilization were relatively low due to insufficient technical support.

Studies have shown that crop diversification through intercropping can lead to yield increases in amaranth production, compared to monoculture. However, despite its benefits, only around half of Kenyan farmers practice intercropping [96]. Intercropping also serves other purposes such as medicinal, commercial, and animal feed purposes. Gender and education levels were found to have a significant positive effect on the adoption of intercropping in amaranth crops, with women being more likely to adopt the practice since they provide most of the agricultural labor for food production. However, women face several challenges in accessing key productive resources such as land, labor, and capital, and are often disadvantaged in terms of education and knowledge. Cultural factors also limit women's access to extension meetings and the transfer of knowledge.

In contrast to the previous study, a study conducted in Kampala found that more men were involved in the cultivation of amaranth than women, suggesting a potential shift in gender roles [97]. While female farmers primarily grew amaranth for personal consumption, male farmers focused on generating income. This study also highlighted the economic, employment, and social benefits of amaranth cultivation. Specifically, improved land use and increased empowerment of women were observed as potential social impacts. Social capital in the form of social groups is another way to empower women in agricultural production, leading to greater gender equality and increased income. It was noted that women have access to social capital, and households can acquire more assets such as land, livestock, and irrigation. Extension programs and services, such as training and mentoring, should consider the triple role that women play in creating equal opportunities.

Amaranth is a more competitive crop compared to others, primarily due to its short growth cycle, which enables farmers to obtain income quickly. The additional income generated is used for subsistence and to improve amaranth production by purchasing better agricultural inputs, resulting in greater capital obtained from the sale of products. The adoption of modern agronomic practices, including domestic agriculture and the use of small spaces, could promote sustainable and better land use. However, the overall observation shows that most households are growing amaranth using rudimentary technology [10]. This is combined with existing agricultural challenges in developing countries, such as limited land access, high labor costs, lack of irrigation facilities, fertilizer scarcity, poor transportation, poor market channels, and lack of financial support exacerbate the situation.

Various recent studies have come to a similar conclusion that amaranth can enhance household livelihoods owing to several benefits, including high productivity and stress tolerance, high nutritional and bioactive content, and significance for both household and industrial purposes. Nonetheless, the cultivation of amaranth grain confronts challenges such as inadequate availability of high-quality seeds, insufficient awareness of effective agronomic practices, and weak farmer organizations resulting in weak connections with political bodies, extension services, and research institutions.

The cultivation of protein crops and support for farmers is encouraged by the European Union (EU). The EU has implemented many initiatives including Protein2Food, the Green Deal, or the Common Agricultural Policy [98]. Protein2Food, for instance, aims to increase the production of selected protein crops such as quinoa, amaranth, buckwheat, lupin, fava beans, chickpeas, and lentils by improving their quality and quantity.

According to the report from MarketsandMarkets, the protein ingredients market offers several opportunities [99], including the following:

- Growing demand for protein ingredients from various end-use industries such as food & beverage, pharmaceutical, and animal feed.

- Increasing consumer interest in plant-based protein ingredients due to concerns over health, sustainability, and animal welfare.

- Rising demand for functional protein ingredients that offer health benefits beyond basic nutrition.

- Growing awareness about the benefits of protein-rich diets among consumers and athletes, driving demand for protein supplements.

- Emerging markets in Asia-Pacific, Latin America, and Africa offer significant growth potential for protein ingredient manufacturers.

- Technological advancements in protein extraction and processing led to improved efficiency and higher-quality products.

- Increasing focus on research and development to create innovative protein ingredients with enhanced functionality and nutritional profiles.

In this sense, the growing demand for plant-based ingredients in natural cosmetics and finished food products is expected to drive the amaranth grain market expansion. This growth is further enhanced by opportunities arising from the popularity of international cuisines, creating marketing opportunities for pulses, and promoting "new" ancient grains such as natural breakfast cereals, pasta, bakery, and healthy snacks [100]. However, research and development into industrial uses of underutilized crops are mainly taking place in developed countries, with the support of their policies, which may not be appropriate for developing countries. Therefore, there is an urgent need for the promotion of appropriate scales of development in line with local conditions in these countries.

Developing a network for stakeholders in grain amaranth is imperative. The goal of this network should be to facilitate knowledge and resource sharing and coordinate actions. One effective approach would be to include ethical biotrade practices [101], which promote good practices for companies and their suppliers in harvesting, collecting, or cultivating biodiverse ingredients in a way that is respectful of the local environment and communities. Moreover, in addition to generating new knowledge and technologies, researchers must also prioritize technology transfer, leveraging new knowledge and technology to enhance processes and empower stakeholders. Recognizing the crucial role of farmers in amaranth production, it is essential to involve them throughout the entire process.

Collaboration among all stakeholders involved in the production, marketing, and sale of amaranth products is crucial to fully realize the potential of this crop. This requires a joint effort from farmers, researchers, extension workers, processors, marketers, and policymakers to promote amaranth cultivation, develop value-added products, and create effective marketing channels to increase the demand and sale of amaranth products. By working together, they can maximize amaranth's economic, social, and health benefits, ultimately improving the livelihoods of those involved in its production and consumption. Moreover, it is important to establish unanimous policies and regulations to raise awareness and generate support for amaranth production and consumption, while aiming to achieve the Sustainable Development Goals.

5. Conclusions

During this review, we discussed the composition and functional properties of the different parts of the amaranth plant, including the seeds, the leaves, and the flowers. While most research has focused on the seeds due to their high nutritional content and versatility, recent studies have shown that the leaves and flowers exhibit even greater antioxidant activity. However, research on the flower has been limited in the past and should receive more attention in upcoming studies. Developing and promoting amaranth species that are both highly nutritious and resilient to environmental stress is essential for achieving sustainable agricultural systems.

To ensure the sustainability of amaranth farming and construct a resilient food system for future societies, it is crucial to consider the economic and social situation of amaranth farmers, which varies depending on the region and scale of production. However, initiatives to support and promote these farmers can positively impact their livelihoods and well-being. Achieving a sustainable food system requires ensuring the availability of high-quality and nutritious food for present and future generations, while also promoting the well-being of farmers and minimizing environmental impacts. This can be accomplished by distributing nutritious and healthy foods using ethical biotrade practices and through balanced and synergistic work among all stakeholders, including political and research entities.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Kumar Maurya N, Arya P. Amaranthus grain nutritional benefits: A review. Journal of Pharmacognosy and Phytochemistry. 2018;**7**(2):2258-2262

[2] National Research Council Amaranth. Modern Prospects for an Ancient Crop. Washington, D.C.: National Academies Press; 1984

[3] Dixit AA, Azar KM, Gardner CD, Palaniappan LP. Incorporation of whole, ancient grains into a modern Asian Indian diet to reduce the burden of chronic disease. Nutrition Reviews. 2011;**69**:479-488. DOI: 10.1111/j.1753-4887.2011.00411.x

[4] Boukid F, Folloni S, Sforza S, Vittadini E, Prandi B. Current trends in ancient grains-based foodstuffs: Insights into nutritional aspects and technological applications. Comprehensive Reviews in Food Science and Food Safety. 2018;**17**:123-136. DOI: 10.1111/1541-4337.12315

[5] Shahbaz M, Raza N, Islam M, Imran M, Ahmad I, Meyyazhagan A, et al. The nutraceutical properties and health benefits of Pseudocereals: A comprehensive treatise. Critical Reviews in Food Science and Nutrition. 2022:1-13. DOI: 10.1080/10408398.2022.2071205

[6] Kumari A, Arunabh J, S, R.M., Radheshyam, S. Assessment of the morphological and molecular diversity in Amaranthus Spp. Afr. Journal of Agricultural Research. 2013;**8**:2307-2311. DOI: 10.5897/AJAR12.1802

[7] Stallknecht GF, Schulz-Schaeffer JR. In: Janick J, Simon JE, editors. Amaranth Rediscovered. New York: Wiley; 1993. pp. 211-218

[8] Luis GM, Hernández Hernández BR, Peña Caballero V, Torres López G, Martínez Espinoza VA, Ramírez Pacheco L. Usos Actuales y Potenciales Del Amaranto (*Amaranthus* Spp.) current and potential uses of Amaranth (*Amaranthus* Spp.). JONNPR. 2018;**3**:423-436. DOI: 10.19230/jonnpr.2410

[9] Sreelathakumary I, Peter KV. 22 - Amaranth: Amarathus spp. In: Kalloo G, Bergh BO, editors. Genetic Improvement of Vegetable Crops. Pergamon; 1993. pp. 315-323. DOI: 10.1016/B978-0-08-040826-2.50026-6. ISBN 9780080408262

[10] Aderibigbe OR, Ezekiel OO, Owolade SO, Korese JK, Sturm B, Hensel O. Exploring the potentials of underutilized grain Amaranth (Amaranthus Spp.) along the value chain for food and nutrition security: A review. Critical Reviews in Food Science and Nutrition. 2022;**62**:656-669

[11] Soriano-García M, Saraid Aguirre-Díaz I. Nutritional Functional Value and Therapeutic Utilization of Amaranth. IntechOpen; 2020. DOI: 10.5772/intechopen.86897

[12] Zhu F. Amaranth proteins and peptides: Biological properties and food uses. Food Research International. 2023;**164**:112405

[13] Singh A, Punia D. Characterization and nutritive values of amaranth seeds. Current Journal of Applied Science and Technology. 2020;**39**(3):27-33. DOI: 10.9734/cjast/2020/v39i330511

[14] Alvarez-Jubete L, Wijngaard H, Arendt EK, Gallagher E. Polyphenol composition and in vitro antioxidant activity of Amaranth, quinoa buckwheat and wheat as affected by sprouting and baking. Food Chemistry.

2010;**119**:770-778. DOI: 10.1016/j.foodchem.2009.07.032

[15] Chauhan A, Saxena DC, Singh S. Total dietary fibre and antioxidant activity of gluten free cookies made from raw and germinated Amaranth (Amaranthus Spp.) flour. LWT. 2015;**63**:939-945. DOI: 10.1016/j.lwt.2015.03.115

[16] Sabbione AC, Suárez S, Añón MC, Scilingo A. Amaranth functional cookies exert potential antithrombotic and antihypertensive activities. International Journal of Food Science and Technology. 2019;**54**:1506-1513. DOI: 10.1111/ijfs.13930

[17] Pazinatto C, Malta LG, Pastore GM, Maria Netto F. Antioxidant capacity of Amaranth products: Effects of thermal and enzymatic treatments. Food Science and Technology. 2013;**33**:485-493. DOI: 10.1590/S0101-20612013005000076

[18] Escudero NL, Albarracín GJ, Lucero López RV, Giménez MS. Antioxidant activity and phenolic content of flour and protein concentrate of Amaranthus cruentus seeds. Journal of Food Biochemistry. 2011;**35**:1327-1341. DOI: 10.1111/j.1745-4514.2010.00454.x

[19] Ajuka Obasi N, Chinyere Chinyere G, Amadike Ugbogu E. Mineral and phytochemical contents in leaves of *Amaranthus hybridus* L and *Solanum nigrum* L. subjected to different processing methods. African Journal of Biochemistry Research. 2008;**2**:40-044

[20] Ebert AW, Wu T-H, Wang S-T. International Cooperators' Guide: Vegetable Amaranth (Amaranthus L.). Shanhua, Taiwan: AVRDC-The World Vegetable Center; 2011. pp. 1-9

[21] Darshan P, Yadav SK, Gupta M, Khetarpaul N. Nutrient composition of Amaranth (*Amaranthus tricolor*) and Kondhara (*Digera arvensis*) leaves and their products. Journal of Food Science and Technology (Mysore). 2004;**41**:563-566

[22] Singh S, Punia D, Khetarpaul N. Nutrient composition of products prepared by incorporating Amaranth (*Amaranthus tricolour*) leaf powder. Nutrition & Food Science. 2009;**39**:218-226. DOI: 10.1108/00346650910957465

[23] López-Mejía OA, López-Malo A, Palou E. Antioxidant capacity of extracts from Amaranth (*Amaranthus hypochondriacus* L.) seeds or leaves. Industrial Crops and Products. 2014;**53**:55-59. DOI: 10.1016/j.indcrop.2013.12.017

[24] Ozsoy N, Yilmaz T, Kurt O, Can A, Yanardag R. In vitro antioxidant activity of *Amaranthus lividus* L. Food Chemistry. 2009;**116**:867-872. DOI: 10.1016/j.foodchem.2009.03.036

[25] Schröter D, Baldermann S, Schreiner M, Witzel K, Maul R, Rohn S, et al. Natural diversity of Hydroxycinnamic acid derivatives, flavonoid glycosides, carotenoids and chlorophylls in leaves of six different *Amaranth* species. Food Chemistry. 2018;**267**:376-386. DOI: 10.1016/j.foodchem.2017.11.043

[26] Alam MA, Subhan N, Hossain H, Hossain M, Reza HM, Rahman MM, et al. Hydroxycinnamic acid derivatives: A potential class of natural compounds for the management of lipid metabolism and obesity. Nutrition & Metabolism (London). 2016;**13**:27. DOI: 10.1186/s12986-016-0080-3

[27] Taofiq O, González-Paramás A, Barreiro M, Ferreira I. Hydroxycinnamic acids and their derivatives: Cosmeceutical significance, challenges and future perspectives, a review.

Molecules. 2017;**22**:281. DOI: 10.3390/molecules22020281

[28] Jo H-J, Chung K-H, Yoon JA, Lee K-J, Song BC, An JH. Radical scavenging activities of tannin extracted from Amaranth (*Amaranthus caudatus* L.). Journal of Microbiology and Biotechnology. 2015;**25**:795-802. DOI: 10.4014/jmb.1409.09088

[29] Sarker U, Lin YP, Oba S, Yoshioka Y, Hoshikawa K. Prospects and potentials of underutilized leafy amaranths as vegetable use for health-promotion. Plant Physiology and Biochemistry. 2022;**182**:104-123

[30] Ruth ON, Unathi K, Nomali N, Chinsamy M. Underutilization versus nutritional-nutraceutical potential of the Amaranthus food plant: A mini-review. Applied Sciences. 2021;**11**:6879. DOI: 10.3390/app11156879

[31] Akubugwo IE, Obasi NA, Chinyere GC, Ugbogu AE. Nutritional and chemical value of *Amaranthus hybridus* l. leaves from Afikpo, Nigeria. African Journal of Biotechnology. 2007;**6**:2833-2839. DOI: 10.5897/AJB2007.000-2452

[32] Cárdenas-Hernández A, Beta T, Loarca-Piña G, Castaño-Tostado E, Nieto-Barrera JO, Mendoza S. Improved functional properties of pasta: Enrichment with Amaranth seed flour and dried Amaranth leaves. Journal of Cereal Science. 2016;**72**:84-90. DOI: 10.1016/j.jcs.2016.09.014

[33] Jo H-J, Kim JW, Yoon J-A, Kim KI, Chung K-H, Song BC, et al. Antioxidant activities of Amaranth (*Amaranthus* spp. L.) flower extracts. The Korean Journal of Food and Nutrition. 2014;**27**:175-182. DOI: 10.9799/ksfan.2014.27.2.175

[34] Howard JE, Villamil MB, Riggins CW. Amaranth as a natural food colorant source: Survey of germplasm and optimization of extraction methods for betalain pigments. Frontiers in Plant Science. 2022;**13**:932440. DOI: 10.3389/fpls.2022.932440

[35] Li H, Deng Z, Liu R, Zhu H, Draves J, Marcone M, et al. Characterization of Phenolics, Betacyanins and antioxidant activities of the seed, leaf, sprout, flower and stalk extracts of three *Amaranthus* species. Journal of Food Composition and Analysis. 2015;**37**:75-81. DOI: 10.1016/j.jfca.2014.09.003

[36] Kalinova J, Dadakova E. Rutin and Total quercetin content in Amaranth (*Amaranthus* spp.). Plant Foods for Human Nutrition. 2009;**64**:68-74. DOI: 10.1007/s11130-008-0104-x

[37] Roriz CL, Heleno SA, Carocho M, Rodrigues P, Pinela J, Dias MI, et al. Betacyanins from Gomphrena Globosa L. flowers: Incorporation in cookies as natural Colouring agents. Food Chemistry. 2020;**329**:127178. DOI: 10.1016/j.foodchem.2020.127178

[38] Baraniak J, Kania-Dobrowolska M. The dual nature of Amaranth—Functional food and potential medicine. Food. 2022;**11**:618. DOI: 10.3390/foods11040618

[39] Bressani R. AMARANTH. In: Caballero B, editor. Encyclopedia of Food Sciences and Nutrition (Second Edition). Academic Press; 2003. pp. 166-173. DOI: 10.1016/B0-12-227055-X/00036-5. ISBN 9780122270550

[40] Becker R, Wheeler EL, Lorenz K, Stafford AE, Grosjean OK, Betschart AA, et al. A compositional study of Amaranth grain. Journal of Food Science. 1981;**46**:1175-1180. DOI: 10.1111/j.1365-2621.1981.tb03018.x

[41] Abreu M, Hernández M, Castillo A, González I, González J, Brito O. Study on the complementary effect between the

proteins of wheat and Amaranth. Food/Nahrung. 1994;**38**:82-86. DOI: 10.1002/food.19940380114

[42] Joshi DC, Sood S, Hosahatti R, Kant L, Pattanayak A, Kumar A, et al. From zero to hero: The past, present and future of grain Amaranth breeding. Theoretical and Applied Genetics. 2018;**131**:1807-1823. DOI: 10.1007/s00122-018-3138-y

[43] Achigan-Dako EG, Sogbohossou OED, Maundu P. Current knowledge on Amaranthus Spp.: Research avenues for improved nutritional value and yield in leafy amaranths in sub-Saharan Africa. Euphytica. 2014;**197**:303-317. DOI: 10.1007/s10681-014-1081-9

[44] Rastogi A, Shukla S. Amaranth: A new millennium crop of nutraceutical values. Critical Reviews in Food Science and Nutrition. 2013;**53**:109-125. DOI: 10.1080/10408398.2010.517876

[45] Tang Y, Tsao R. Phytochemicals in quinoa and Amaranth grains and their antioxidant, anti-inflammatory, and potential health beneficial effects: A review. Molecular Nutrition & Food Research. 2017;**61**:1600767. DOI: 10.1002/MNFR.201600767

[46] Jan N, Hussain SZ, Naseer B, Bhat TA. Amaranth and Quinoa as potential nutraceuticals: A review of anti-nutritional factors, health benefits and their applications in food, medicinal and cosmetic sectors. Food Chem X. 2023;**18**:100687. DOI: 10.1016/J.FOCHX.2023.100687

[47] Nascimento AC, Mota C, Coelho I, Gueifão S, Santos M, Matos AS, et al. Characterisation of nutrient profile of quinoa (*Chenopodium quinoa*), Amaranth (*Amaranthus caudatus*), and purple corn (*Zea mays* L.) consumed in the north of Argentina: Proximates, minerals and trace elements. Food Chemistry. 2014;**148**:420-426. DOI: 10.1016/j.foodchem.2013.09.155

[48] Barba de la Rosa AP, Fomsgaard IS, Laursen B, Mortensen AG, Olvera-Martínez L, Silva-Sánchez C, et al. Amaranth (*Amaranthus hypochondriacus*) as an alternative crop for sustainable food production: Phenolic acids and flavonoids with potential impact on its nutraceutical quality. Journal of Cereal Science. 2009;**49**:117-121. DOI: 10.1016/j.jcs.2008.07.012

[49] Repo-Carrasco-Valencia R, Hellström JK, Pihlava J-M, Mattila PH. Flavonoids and other phenolic compounds in Andean indigenous grains: Quinoa (*Chenopodium quinoa*), Kañiwa (*Chenopodium pallidicaule*) and Kiwicha (*Amaranthus caudatus*). Food Chemistry. 2010;**120**:128-133. DOI: 10.1016/j.foodchem.2009.09.087

[50] Schoenlechner R, Siebenhandl S, Berghofer E. 7 - Pseudocereals. In: Arendt EK, Bello FD, editors. Food Science and Technology, Gluten-Free Cereal Products and Beverages. Academic Press; 2008. p. 149-VI. DOI: 10.1016/B978-012373739-7.50009-5. ISBN 9780123737397

[51] Escudero NL, de Arellano ML, Luco JM, Giménez MS, Mucciarelli SI. Comparison of the chemical composition and nutritional value of Amaranthus Cruentus flour and its protein concentrate. Plant Foods for Human Nutrition. 2004;**59**:15-21. DOI: 10.1007/s11130-004-0033-3

[52] D'Amico S, Schoenlechner R. Chapter 6 - Amaranth: Its unique nutritional and health-promoting attributes. In: Taylor JRN, Awika JM, editors. Woodhead Publishing Series in Food Science, Technology and Nutrition, Gluten-Free Ancient Grains. Woodhead

Publishing; 2017. pp. 131-159. DOI: 10.1016/B978-0-08-100866-9.00006-6. ISBN 9780081008669

[53] Caselato-Sousa VM, Amaya-Farfán J. State of knowledge on Amaranth grain: A comprehensive review. Journal of Food Science. 2012;**77**:R93-R104. DOI: 10.1111/j.1750-3841.2012.02645.x

[54] Sarker U, Hossain MM, Oba S. Nutritional and antioxidant components and antioxidant capacity in green morph Amaranthus leafy vegetable. Scientific Reports. 2020;**10**:1336. DOI: 10.1038/s41598-020-57687-3

[55] Ngugi CC, Oyoo-Okoth E, Manyala JO, Fitzsimmons K, Kimotho A. Characterization of the nutritional quality of Amaranth leaf protein concentrates and suitability of fish meal replacement in Nile tilapia feeds. Aquaculture Reports. 2017;**5**:62-69. DOI: 10.1016/j.aqrep.2017.01.003

[56] Funke OM. Evaluation of nutrient contents of Amaranth leaves prepared using different cooking methods. Food and Nutrition Sciences. 2011;**2**:249-252. DOI: 10.4236/fns.2011.24035

[57] Gamel TH, Linssen JP, Mesallam AS, Damir AA, Shekib LA. Effect of seed treatments on the chemical composition of two *Amaranth* species: Oil, sugars, Fibres, minerals and vitamins. Journal of the Science of Food and Agriculture. 2006;**86**:82-89. DOI: 10.1002/jsfa.2318

[58] Ayorinde FO, Ologunde MO, Nana EY, Bernard BN, Afolabi OA, Oke OL, et al. Determination of fatty acid composition of *Amaranthus* species. Journal of the American Oil Chemists' Society. 1989;**66**:1812-1814. DOI: 10.1007/BF02660754

[59] Jiménez-Aguilar DM, Grusak MA. Minerals, vitamin C, Phenolics, flavonoids and antioxidant activity of Amaranthus leafy vegetables. Journal of Food Composition and Analysis. 2017;**58**:33-39. DOI: 10.1016/j.jfca.2017.01.005

[60] Martirosyan DM, Miroshnichenko LA, Kulakova SN, Pogojeva AV, Zoloedov VI. Amaranth oil application for coronary heart disease and hypertension. Lipids in Health and Disease. 2007;**6**:1. DOI: 10.1186/1476-511X-6-1

[61] Estivi L, Pellegrino L, Hogenboom JA, Brandolini A, Hidalgo A. Antioxidants of Amaranth, quinoa and buckwheat Wholemeals and heat-damage development in Pseudocereal-enriched einkorn water biscuits. Molecules. 2022;**27**:7541. DOI: 10.3390/MOLECULES27217541

[62] House NC, Puthenparampil D, Malayil D, Narayanankutty A. Variation in the polyphenol composition, antioxidant, and anticancer activity among different *Amaranthus* species. South African Journal of Botany. 2020;**135**:408-412. DOI: 10.1016/j.sajb.2020.09.026

[63] Gamel TH, Mesallam AS, Damir AA, Shekib LA, Linssen JP. Characterization of amaranth seed oils. Journal of Food Lipids. 2007;**14**:323-334. DOI: 10.1111/j.1745-4522.2007.00089.x

[64] Adegbola PI, Adetutu A, Olaniyi TD. Antioxidant activity of *Amaranthus* species from the Amaranthaceae Family – A review. South African Journal of Botany. 2020;**133**:111-117. DOI: 10.1016/j.sajb.2020.07.003

[65] Gamel TH, Linssen JP, Mesallam AS, Damir AA, Shekib LA. Seed treatments affect functional and Antinutritional properties of Amaranth flours. Journal of the Science of Food and Agriculture. 2006;**86**:1095-1102. DOI: 10.1002/jsfa.2463

[66] Peiretti PG, Meineri G, Gai F, Longato E, Amarowicz R. Antioxidative

activities and phenolic compounds of pumpkin (*Cucurbita pepo*) seeds and Amaranth (*Amaranthus caudatus*) grain extracts. Natural Product Research. 2017;**31**:2178-2182. DOI: 10.1080/14786419.2017.1278597

[67] Tikekar RV, Ludescher RD, Karwe MV. Processing stability of squalene in Amaranth and Antioxidant potential of Amaranth extract. Journal of Agricultural and Food Chemistry. 2008;**56**:10675-10678. DOI: 10.1021/jf801729m

[68] Klimczak I, Małecka M, Pachołek B. Antioxidant activity of Ethanolic extracts of Amaranth seeds. Nahrung. 2002;**46**: 184-186. DOI: 10.1002/1521-3803(20020501)46:3<184::AID-FOOD184>3.0.CO,2-H

[69] Barku VYA, Opoku-Boahen Y, Owusu-Ansah E, Mensah EF. Antioxidant activity and the estimation of Total phenolic and flavonoid contents of the root extract of *Amaranthus spinosus*. Asian Journal of Plant Science & Research. 2013;**3**(1):69-74

[70] Ishtiaq S, Ahmad M, Hanif U, Akbar S, Mehjabeen K, S.H. Phytochemical and in vitro antioxidant evaluation of different fractions of *Amaranthus graecizans* Subsp. *silvestris* (Vill.) Brenan. Asian Pac. Journal of Tropical Medicine. 2014;**7**:S342-S347. DOI: 10.1016/S1995-7645(14)60256-X

[71] Khanam UKS, Oba S. Bioactive substances in leaves of two *Amaranth* species, *Amaranthus tricolor* and *A. hypochondriacus*. Canadian Journal of Plant Science. 2013;**93**:47-58. DOI: 10.4141/CJPS2012-117

[72] Madadi E, Mazloum-Ravasan S, Yu JS, Ha JW, Hamishehkar H, Kim KH. Therapeutic application of Betalains: A review. Plants. 2020;**9**:1-27. DOI: 10.3390/PLANTS9091219

[73] Spórna-Kucab A, Kumorkiewicz A, Szmyr N, Szneler E, Wybraniec S. Separation of Betacyanins from flowers of *Amaranthus cruentus* L. in a polar solvent system by high-speed counter-current chromatography. Journal of Separation Science. 2019;**42**:1676-1685. DOI: 10.1002/jssc.201801172

[74] Peter K, Gandhi P. Rediscovering the therapeutic potential of *Amaranthus* species: A review. Egyptian Journal of Basic and Applied Sciences. 2017;**4**:196-205. DOI: 10.1016/j.ejbas.2017.05.001

[75] Baral M, Chakraborty S, Chakraborty P. Evaluation of anthelmintic and anti-inflammatory activity of *Amaranthus spinosus* Linn. International Journal of Current Pharmaceutical Research. 2010;**2**:44-47

[76] Kim HK, Kim MJ, Cho HY, Kim E-K, Shin DH. Antioxidative and anti-diabetic effects of Amaranth *(Amaranthus esculantus*) in Streptozotocin-induced diabetic rats. Cell Biochemistry and Function. 2006;**24**:195-199. DOI: 10.1002/cbf.1210

[77] Valenzuela Zamudio F, Hidalgo-Figueroa SN, Ortíz Andrade RR, Hernández Álvarez AJ, Segura Campos MR. Identification of antidiabetic peptides derived from in Silico hydrolysis of three ancient grains: Amaranth, quinoa and chia. Food Chemistry. 2022;**394**:133479. DOI: 10.1016/j.foodchem.2022.133479

[78] Giuseppe Rizzello C, Coda R, De Angelis M, Di Cagno R, Carnevali P, Gobbetti M. Long-term fungal inhibitory activity of water-soluble extract from Amaranthus spp. seeds during storage of gluten-free and wheat flour breads. International Journal of Food Microbiology. 2009;**131**:(2-3):189-196. DOI: 10.1016/j.ijfoodmicro.2009.02.025. ISSN: 0168-1605

[79] Añón MC. Health benefits of Amaranth. In: Reference Module in Food Science. Elsevier; 2023

[80] Ontiveros N, López-Teros V, de Vergara-Jiménez MJ, Islas-Rubio AR, Cárdenas-Torres FI, Cuevas-Rodríguez EO, et al. Amaranth-Hydrolyzate enriched cookies reduce the systolic blood pressure in spontaneously hypertensive rats. Journal of Functional Foods. 2020;**64**:103613. DOI: 10.1016/j.jff.2019.103613

[81] Paswan SK, Srivastava S, Rao CV. Wound healing, antimicrobial and antioxidant efficacy of *Amaranthus spinosus* Ethanolic extract on rats. Biocatalysis and Agricultural Biotechnology. 2020;**26**:101624. DOI: 10.1016/j.bcab.2020.101624

[82] Kongdang P, Dukaew N, Pruksakorn D, Koonrungsesomboon N. Biochemistry of Amaranthus polyphenols and their potential benefits on gut ecosystem: A comprehensive review of the literature. Journal of Ethnopharmacology. 2021;**281**:114547. DOI: 10.1016/J.JEP.2021.114547

[83] Paśko P, Bartoń H, Zagrodzki P, Gorinstein S, Fołta M, Zachwieja Z. Anthocyanins, Total polyphenols and antioxidant activity in Amaranth and Quinoa seeds and sprouts during their growth. Food Chemistry. 2009;**115**:994-998. DOI: 10.1016/j.foodchem.2009.01.037

[84] Tironi VA, Añón MC. Amaranth proteins as a source of antioxidant peptides: Effect of proteolysis. Food Research International. 2010;**43**:315-322. DOI: 10.1016/j.foodres.2009.10.001

[85] Zhu F. Dietary fiber polysaccharides of Amaranth, buckwheat and quinoa grains: A review of chemical structure, biological functions and food uses. Carbohydrate Polymers. 2020;**248**:116819. DOI: 10.1016/j.carbpol.2020.116819

[86] Berger A, Gremaud G, Baumgartner M, Rein D, Monnard I, Kratky E, et al. Cholesterol-lowering properties of Amaranth grain and oil in hamsters. International Journal for Vitamin and Nutrition Research. 2003;**73**:39-47. DOI: 10.1024/0300-9831.73.1.39

[87] Wekesa FS. Socio-Economic Analysis of Production and Response of Grain Amaranth (*Amarantlius Caudatus* L.) to Fertilizer Application and Inter-Cropping with Maize or Beans in Kisumu West District, Kenya. Kenya: University of Nairobi; 2010

[88] Chaudhary MA, Imran I, Bashir S, Mehmood MH, Rehman N, Gilani A-H. Evaluation of gut modulatory and bronchodilator activities of *Amaranthus spinosus* Linn. BMC Complementary and Alternative Medicine. 2012;**12**:166. DOI: 10.1186/1472-6882-12-166

[89] Zeashan H, Amresh G, Rao CV, Singh S. Antinociceptive activity of *Amaranthus spinosus* in experimental animals. Journal of Ethnopharmacology. 2009;**122**:492-496. DOI: 10.1016/j.jep.2009.01.031

[90] Baskar A-A, Al. Numair K-S, Alsaif M-A, Ignacimuthu S. In vitro antioxidant and Antiproliferative potential of medicinal plants used in traditional Indian medicine to treat cancer. Redox Report. 2012;**17**:145-156. DOI: 10.1179/1351000212Y.0000000017

[91] Das S. Amaranthus: A Promising Crop of Future. Singapore: Springer Singapore; 2016. DOI: 10.1007/978-981-10-1469-7. ISBN: 978-981-10-1468-0

[92] Borneo R, Aguirre A. Chemical composition, cooking quality, and consumer acceptance of pasta made with dried Amaranth leaves flour. LWT. 2008;**41**:1748-1751. DOI: 10.1016/j.lwt.2008.02.011

[93] Antonio T-G, Javier L-RF. Functional Value of Amaranth as Applied to Sports Nutrition. London, UK: InTechOpen; 2020

[94] Bender D, Schönlechner R. Recent developments and knowledge in pseudocereals including technological aspects. Acta Alimentaria. 2021;**50**(4):583-609. DOI: 10.1556/066.2021.00136

[95] Bjarklev A, Kjaer T, Kjaergård B. Amaranth farming rural sustainable livelihood of the future? In: Poster Session Presented at IFOAM Organic World Congress. Modena, Italy; 2008

[96] Malaba K, Otuya R, Saina E. Social factors influencing adoption of grain amaranth/maize intercrop among small holder farmers in Kiminini, Kenya. African Journal of Education, Science and Technology. 2018;**4**(4):48-57. DOI: 10.2022/ajest.v4i4.312

[97] Akoth B. Potential of Amaranthus in Improving Urban Farmers' Livelihoods in Kampala [Thesis]. Stellenbosch, South Africa: Stellenbosch University

[98] EU Research and innovation framework programme, H. PROTEIN2FOOD Aims & Objectives. Available from: https://www.protein2food.eu/about-protein2food/aims-objectives/ [Accessed: May 1, 2023]

[99] Protein Ingredients Market Share and Analysis-2028. [Internet]. 2023. Available from: https://www.marketsandmarkets.com/Market-Reports/protein-ingredients-market-114688236.html [Accessed: May 11, 2023]

[100] Escobar-García JD, García-Segovia P, Martínez-Monzó J, Igual M. Effect of enrichment with quinoa and amaranth on properties of extruded corn snacks

[101] Union for ethical bio trade Ethical Biotrade Standard Available from: https://uebt.org/resource-pages/standard [Accessed: May 1, 2023]

Chapter 5

Pseudocereals as Treasures of Nutritional and Nutraceutical Compounds

Nisha Singh, Megha Ujinwal and Debasish Paikray

Abstract

A diverse category of underutilized grains known as pseudocereals includes a wide range of species with varying nutritious and nutritional contents such as phytochemicals (saponins, polyphenols, phytosterols, phytosteroids, Protein, vitamins and essential micronutrients. Global dietary changes, rapid urbanization, and increased sedentary behavior pseudocereal is considered as “super food” as it helps in reduction of several diseases such as inflammatory-related diseases, cancer, cardiovascular disorders, diabetes, and obesity. Here, we discuss about the nutritional composition and the content of bioactive compounds present in pseudocereals for potential health benefit and application for breeding purposes, to enhance agronomic traits and improve the product development in the food and pharmacological industries. This chapter provides a concise overview on the potential of diverse nutritional and nutraceutical compounds present across different pseudocereals and its impact on human health.

Keywords: bioactives, nutraceutical, nutritional, pseudocereals, phytochemicals

1. Introduction

Major cereal crops including wheat, rice, and maize is essential for feeding the world’s expanding population. Even though they are a good source of energy, the population as a whole is suffering from malnutrition and “hidden hunger” as a result of their lack of vital micronutrients. The development of underutilized but nutritious grains over the past few decades is related to their usefulness and functioning [1]. Grains functionality is determined mainly by their genetic make-up and the impact of environmental conditions on their primary components, which include carbohydrates, proteins, vitamins, minerals, and phenolic phytochemicals [2]. For the human diet, several trends have evolved, such as wholegrain, gluten-free, high in dietary fiber or resistant starch, reduced carbohydrate, or digestibility. In this context, pseudocereals are well-known grains that are prized for their nutritional characteristics. Aside from such health-related objectives, consumers are concerned about environmental issues; the continuous climate change is another motivation for people to reconsider their nutritional activities [3]. As a result, the development of food products with a variety of health benefits derived from such plant species might provide a tremendous chance to improve public health. Such foods are gaining favor among the scientific community, consumers, and food manufacturers [4].

In this context, Pseudocereals are more prominent among other major crops. Pseudocereals (also known as Andean grains) are edible seeds from dicotyledonous plants that resemble cereals (monocotyledonous *Poaceae* family) in physical appearance and starch content [5, 6]. Whole pseudocereal grains like buckwheat (*Fagopyrum esculentum and Fagopyrum tataricum*), amaranth (*Amaranthus caudatus, Amaranthus cruentus*, and *Amaranthus hypochondriacus*), chia (*Salvia hispanica*), quinoa (*Chenopodium quinoa*), Wattleseed (*Acacia victoriae*), Kaniwa (*Chenopodium pallidicaule*), acron (Quercus), breadnut (Artocarpus camansi) and Pitseed goosefoot (*Chenopodium berlandieri*) are also high in compounds with known health benefits like prevention and reduction of many degenerative diseases [2]. They give nutritious properties in food items, hence meeting various goals of the United Nations (UN) Agenda 2030 (https://www.un.org/sustainabledevelopment/sustainable-development-goals), also demonstrate their potential in attaining United nation Sustainable Goal-2 (SDG-2) for Zero hunger [7] Pseudocereals are high in protein and have a strong nutritional, phytochemical, and phenolic profile. The amino acid profile and nutritional qualities of pseudocereals are superior to wheat, rice, and maize in terms of essential amino acid index, biological value, protein efficiency ratio, and nutritional index. Furthermore, pseudocereal grains have a significant amount of lysine, threonine, valine, phenylalanine, isoleucine, leucine, methionine, and tryptophan, an important amino acid that may not be present in other cereals [8, 9]. Quinoa has more protein concentration than cereals, ranging from 14 to 18% of the seed, compared to maize (10%), rice (8%), and wheat (14%). Amaranth contains more protein (14.0–15.5%) than maize, wheat, and sorghum, as well as less fat (7.5%), more carbohydrate (60–68%), and less ash (2.5–3.1%) [3]. Buckwheat has a high protein content ranging from 8.5 to 18.8% depending on cultivar, supply, and climate conditions [10]. As per Osbourne classification, Janssen et al. reported that 18–44% albumins, 5–70% globulins, 4–37% glutelin and 0–11% prolamins can be found in buckwheat [11]. Pseudocereals are becoming more widespread in human diets because they are gluten-free (GF) grains with high nutritional and nutraceutical value, as well as saponins, which have various agro-pharmacological and industrial applications [9, 12].

Because of the starch content in the seeds, pseudocereals have been used as a nutritious component in a range of bread products, beverages, and gluten-free products [6]. Pseudocereals have a high viscosity, high water binding capacity, swelling, and good freeze-thaw stability. Cooking, popping, roasting, and fermenting are typical pseudocereal culinary techniques used to make porridges, soups, stews, and sweet desserts. Pseudocereal-derived products do not necessitate significant adjustments to cereal-derived manufacturing procedures [11]. Bakery items and pasta are created with flour blends of pseudocereals and cereals to improve nutritional characteristics, or with 100% pseudocereal flour for the gluten-free foods industry, which has been one of the key drivers of rising pseudocereal use [13]. Pseudocereals are being exploited to develop new food products, especially ones with higher nutrient and mineral content. As a result, it contributes to the growing popularity of grains among consumers [14–17].

As a result, including any of these pseudocereals in the diet has a high nutritional potential, resulting in the implementation of a sustainable diet in marginalized rural areas (**Figure 1**). The objective of this chapter is to assess the nutritional composition and bioactive chemical content of pseudocereals for potential health benefits. Furthermore, it will help breeding initiatives improve agronomic traits and product development in the food and pharmaceutical industries.

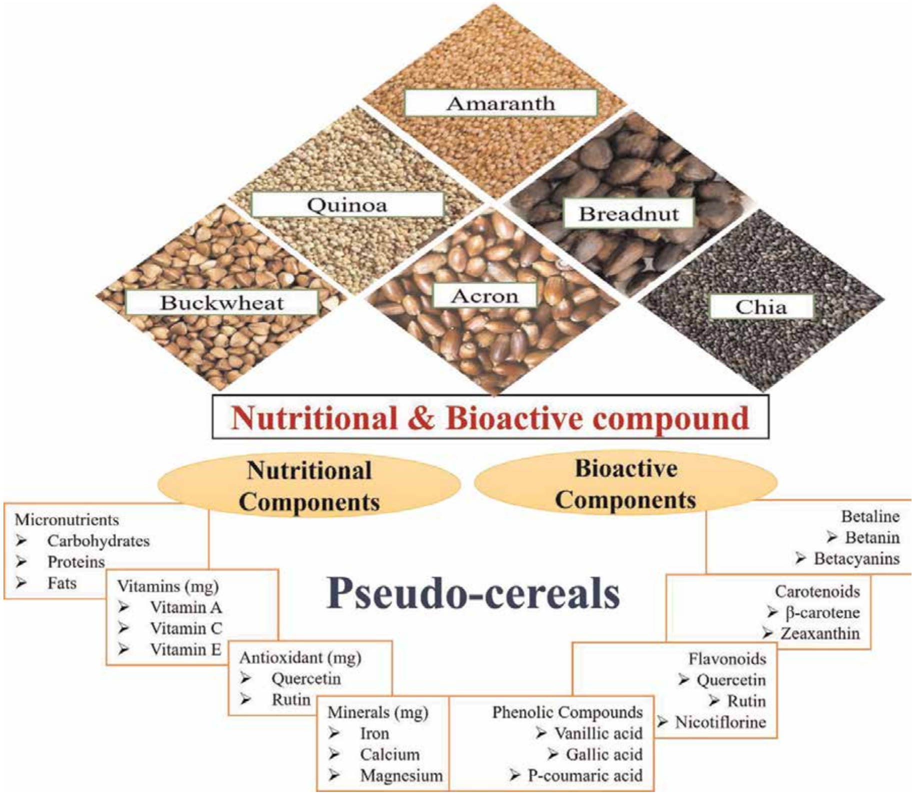


Figure 1.
Different pseudocereals which governs important nutritional and bioactive compounds.

2. Nutritional value and bioactive components in pseudocereals

Pseudocereals are non-grassy, wild plants that belong to the dicotyledonous family, Amaranth (*Amaranthus* sp.), buckwheat (*Fagopyrum esculentum Moench*), and quinoa (*Chenopodium quinoa Willd*.) are the major pseudocereals [18, 19]. Pseudocereals are so marked because they resemble cereals in terms of carbohydrate, mineral, protein content, and other nutritional components (**Table 1**) [1]. Furthermore, pseudocereal seeds are digested in the same way as cereal seeds but are underutilized due to cereals' relative dominance and pseudocereals' limitations in practise [18]. Considering their higher nutritious value and presence of micro and macronutrients, pseudocereals are termed as "future superfoods and rich food" [21]. Because of its great nutritional potential and genetic diversity, the FAO designated quinoa, a pseudocereal, as one of humanity's promising crops destined to contribute to food security in the twenty-first century [Food and Agriculture Organization Regional Office for Latin America and PROINPA]. Quinoa and amaranth have soft leaves that can be used in cooking, but their grains are the most popular because of their high nutritional value. They contain a high concentration of proteins with a well-balanced essential amino acid composition that includes a sulfur-rich amino acids (**Table 2**) [24].

Despite the potential benefits of these underutilized grain crops, various constraints prevent their general acceptance into food systems and breeding programs. These factors could be agronomical (yield potential), technological (trait

Nutritive parameters	Amaranth	Buckwheat	Quinoa	Chia
Calories (kcal)	371	335	368	486
Carbohydrates (g)	65.25	70.59	64.16	42.12
Dietary Fiber (g)	6.7	10	7	34.4
Protein (g)	13.56	12.62	14.12	16.54
Total lipid (g)	7.02	3.1	6.07	30.74
Vitamin A, IU	2	0	14	54
Vitamin B-6 (mg)	0.591	0.582	0.487	—
Vitamin C (mg)	4.2	0	—	1.6
Vitamin E (mg)	1.19	0.32	2.44	0.5
Folate (μg)	82	54	184	54
Calcium (mg)	159	41	47	631
Iron (mg)	7.61	4.06	4.57	7.72
Magnesium (mg)	248	251	197	335
Phosphorus (mg)	557	337	457	860
Potassium (mg)	508	577	563	407
Zinc (mg)	2.87	3.12	3.1	4.58

IU = International unit.
Dashed line (—) indicates the unavailability of the information in the literature.

Table 1.
Nutrition value in pseudocereals (per 100 g grain or grain flour) [20].

Amino acid	Amaranth	Buckwheat	Quinoa	Chia
Alanine (ALA)	4.26	4.50	4.35	1.04
Arginine (ARG)	7.77	9.70	7.85	2.14
Aspartic acid (ASP)	12.57	11.30	8.40	1.69
Cystine (CYS)	1.60	1.60	1.85	0.41
Glutamic acid (GLU)	16.12	18.60	13.75	3.50
Glycine (GLY)	8.50	6.30	4.80	0.94
Histidine (HIS)	1.86	2.70	2.98	0.53
Isoleucine (ILE)	2.82	3.80	3.75	0.80
Leucine (LEU)	4.83	6.40	6.08	1.37
Lysine (LYS)	5.45	6.10	5.55	0.97
Methionine (MET)	1.86	2.50	2.24	0.59
Phenylalanine (PHE)	3.98	4.80	4.35	1.02
Proline (PRO)	3.76	3.80	5.67	0.78
Serine (SER)	7.79	4.70	4.56	1.05
Tyrosine (TYR)	2.85	2.10	1.98	0.56
Threonine (THR)	3.02	3.90	3.01	0.71

Amino acid	Amaranth	Buckwheat	Quinoa	Chia
Tryptophan (TRP)	1.05	2.00	1.25	0.44
Valine (VAL)	4.34	4.70	4.55	0.95

Table 2.
Amino acid profile in pseudocereals (g per 100 g protein) [22, 23].

FDC ID	Scientific name	Common name	Crop type	Form consumed	References
170,682	*Amaranthus ssp.*	Amaranth	Pseudo-cereal	Whole grain	[1, 5]
170,687	*Fagopyrum esculentum* Moench	Buckwheat	Pseudo-cereal	Whole-groat grain	[1, 5]
168,874	*Chenopodium quinoa* Willd.	Quinoa	Pseudo-cereal	Whole grain	[1, 5]
170,554	*Salvia hispanica L.*	Chia	Pseudo-cereal	Whole grain	[1, 5]
170,566	*Quercus spp.*	Acorn	Pseudo-cereal	Whole grain	[1, 5]
170,552	*Artocarpus camansi*	Breadnut	Pseudo-cereal	Fluor/Whole grain	[1, 5]
—	*Celosia argentea*	Quail grass/ Soko/ Cockscomb	Pseudo-cereal	Whole grain	[1, 5]
—	*Chenopodium berlandieri*	Pitseed goosefoot	Pseudo-cereal	Fluor/Whole grain	[1, 5]

FDC ID = Food Data Central identification number.
Dashed line (—) indicates the unavailability of the information in the literature.

Table 3.
List of eight underutilized pseudocereal.

improvement), social (knowledge diffusion) and economical [20, 25, 26]. Some of analyzed grain crop were listed in **Table 3**.

The production of novel foods with functional components is one of the main research lines in Food Science and Technology. Bioactive chemicals must be collected and identified before being added to foods, where they may give both biological activity and nutritional benefits [27]. Several scientific studies have determined that the antioxidant activity shown in pseudocereals, particularly quinoa, could support their intake in our daily diet [28]. As a result, recent research has discovered diverse domestic and agro-industrial uses of pseudocereals, allowing for the preservation of nutritional characteristics and boosting the appeal of these products to various populations. More research is needed, however, to support these findings, which reveal fresh scientific information about the bioactivities of pseudocereals.

3. Suitability and application of nutraceutical compounds

Pseudocereals include a wide range of bioactive substances, such as dietary fiber, unsaturated fatty acids, lignans, antioxidants, flavonoids, polyphenols, minerals, and

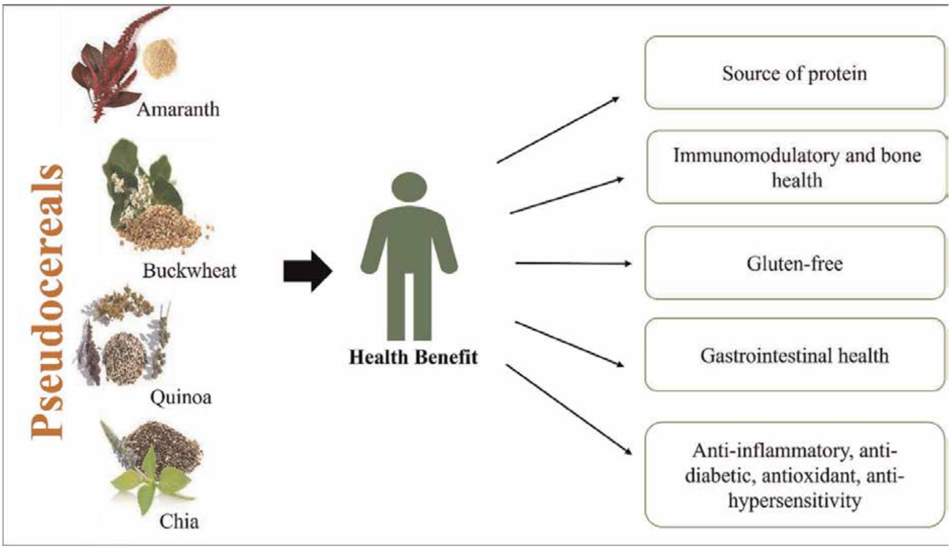
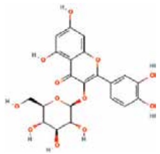
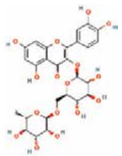
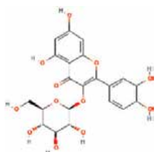
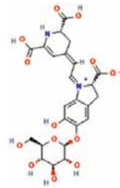
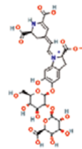
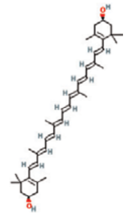
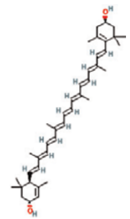
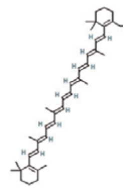
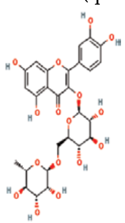
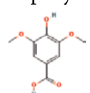
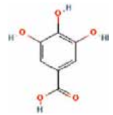
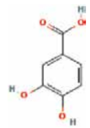
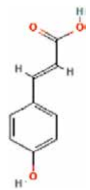
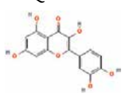
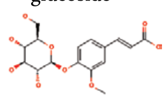
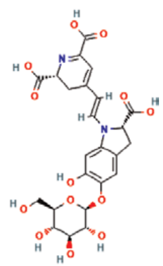


Figure 2.
Health benefit of different pseudocereals.

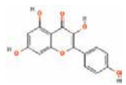
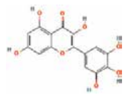
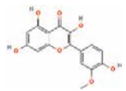
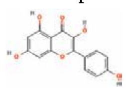
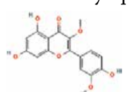
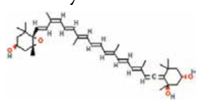
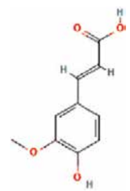
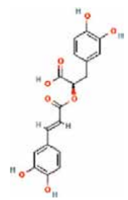
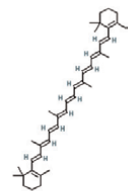
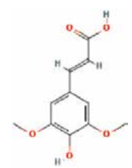
vitamins [29]. Plant proteins are becoming increasingly popular as a reliable and long-term source of protein for the global population due to their decreased environmental effect. Protein sources with an optimal amino acid (AA) composition, such as buck-wheat, quinoa, and amaranth, have gained attract as staple meals due to their health benefits (**Figure 2**) [30]. Pseudocereals prevent the occurrence of several noncommunicable infections by supplying the recommended daily allotment of all nutrients as well as a variety of bioactive substances (**Table 4**) [31]. Researchers have developed an interest in the bioactive components contained in pseudocereals and have investigated its preventative properties against several infectious diseases such as cardio-vascular disease, obesity, cancer, and diabetes. Significant amounts of fiber, iron, and omega-3 fatty acids were revealed when the key features of pseudocereals were studied. It also contains more calcium and magnesium than milk [32]. Some pseudocereals contain high levels of both the 11S and 7S globulin proteins, which are antihypertensive [33]. Several studies have shown that buckwheat has anti-diabetic, anti-tumor, antioxidant, hepatoprotective, and anti-inflammatory activities [34]. Quinoa has been shown to improve blood serum lipid profiles as well as lessen the risk of cardiovascular disease and type 2 diabetes [35]. Amaranth possesses antibacterial and antifungal properties, and amaranth protein-based diets have been proven to enhance glucose tolerance, increase plasma insulin, and reduce food consumption [5]. Hydrolysates of pseudocereals protein exhibit antioxidant action when exposed to hydrogen peroxide (H_2O_2) in an optimum environment, lowering lipid oxidation and increasing yeast viability [36].

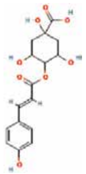
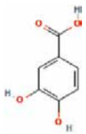
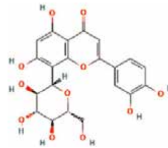
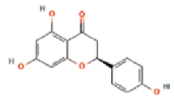
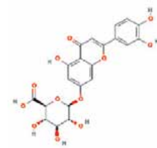
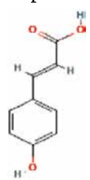
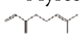
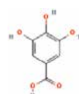
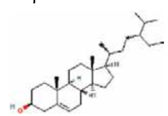
By inhibiting enzymes such as −amylase, −glucosidase, and −dipeptidyl peptidase-IV, pseudocereal proteins have been demonstrated to have powerful anti-diabetic activities. The same set of researchers showed that pseudocereals have antiproliferative and antioxidant properties against colon cancer cells [37, 38]. Carot-enoids, fatty acids, and other lipophilic antioxidants, such as tocopherols, are found in pseudocereals and contribute to their antioxidant activity. In terms of 2,2-diphenyl-1-picrylhydrazyl (DPPH), oxygen radical absorbance capacity (ORAC), and ferric

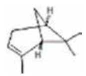
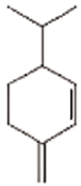
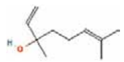
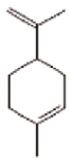
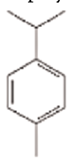
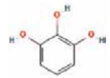
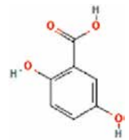
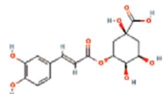
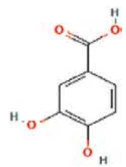
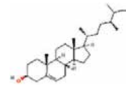
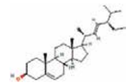
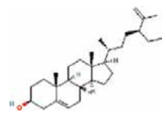
Pseudo-cereal	Major bioactive components			References
Amaranth	Flavonoids: • Isoquercetin  • Rutin  • Nicotiflorine 	Betaline: • Amaranthine  • Betacyanin 	Carotenoids: • Zeaxanthin  • Lutein  • β-carotene 	[10]
Buckwheat	Flavonoids: • Rutin (quercetin-3-rutinosid) 	Phenolic Components: • p–hydroxyl benzoic Syringic acid 		[10]

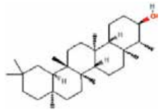
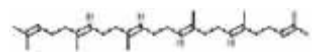
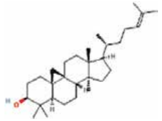
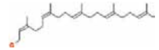
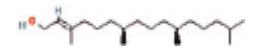
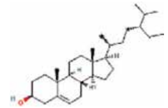
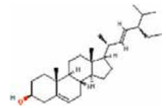
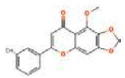
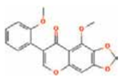
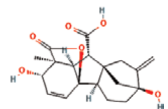
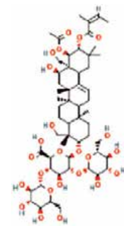
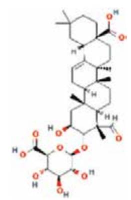
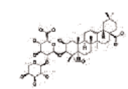
Pseudo-cereal	Major bioactive components			References
		• Vanillic acid  • Gallic acid  • Protocatechuic acid  • Ferulic acid p –coumaric acid 		
Quinoa	Flavonoids: • Quercetin 	Phenolics: • Ferulic acid-4–glucoside 	Betalains • Betanin 	[10]

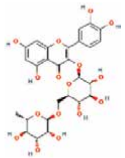
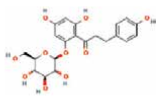
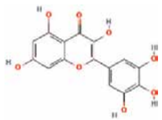
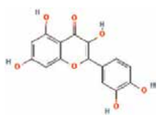
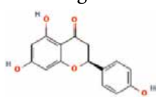
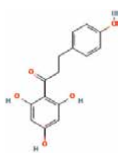
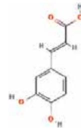
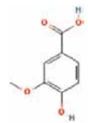
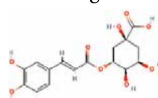
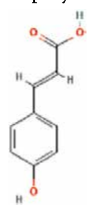
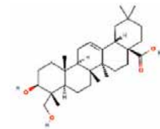
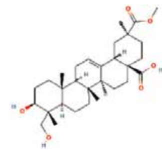
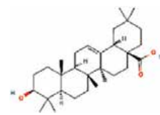
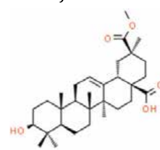
DOI: http://dx.doi.org/10.5772/intechopen.113369

Pseudo-cereal	Major bioactive components			References
	• Kaempferol  • Myricetin  • Isorhamnetin 			
Chia	Flavonoids: • Kaempferol  • Dimethyl quercetin (quercetin dimethyl ether)  • Acetyl orientin 	Phenolics: • Ferulic acid  • Rosmarinic acid 	Carotenoids: • β-carotene  Xanthophyll: • Neoxanthin 	[12]

Pseudo-cereal	Major bioactive components				References
	• Naringenin  • Luteolin-O-glucuronide 	• Sinapic acid  • Coumaroyl quinic acid  • Protocatechuic acid  • p-coumaric acid 			
Acorn	Terpenoids: • Myrcene 	Phenolics: • Gallic acid 	Sterols • β sitosterol 	Aliphatic alcohol • Tetracosanol 	[13]

Pseudo-cereal	Major bioactive components	References
	• Alpha- pinene  • Beta- phellandrene  • Linalool  • Limonene  • p-cymene  • Pyrogallol  • Gentisic acid  • Chlorogenic acid  • Protocatechuic acid  • Campesterol  • stigmasterol  • Clerosterol  • Hexacosanol • Octacosanol • Docosanol 	

Pseudo-cereal	**Major bioactive components**				**References**
Breadnut	Terpenoids • Friedelinol  • squalene  • cycloartenol 	Alcoholic compounds • Polyprenol  • Phytol 	Sterols • β sitosterol  • stigmasterol 		[6]
Quail grass/ Soko/ Cockscomb	Flavonoids: • 5-Methoxy-6,7-methylenedioxy-2′-hydroxyisoflavone  • Tlatlancuayin 	Phenolics: • Stilbenes • Tannins • Lignans • Anthocyanins • Coumarins	Diterpenes: • Gibberellic acid 	Steroids: • Steroidal saponins  • Cristatain  • Celosin A, B, C, and D 	[14]

Pseudo-cereal	Major bioactive components	References
Pitseed goosefoot	Flavonoids: • Rutin  • Phloridzin  • Myricetin  • Quercetin  • Naringenin  • Phloretin  Phenolics: • Caffeic acid  • Gallic acid  Vanillic acid  • Chlorogenic acid  • p-hydroxybenzoic acid  Saponins: • Hederagenin  • Phytolaccagenic acid  • Oleanolic acid  • Sarjenic acid 	[15–17]

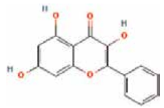
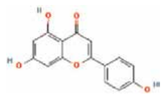
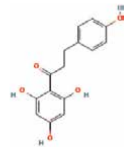
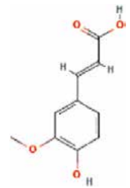
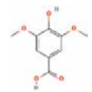
Pseudo-cereal	Major bioactive components	References
	• Galangin  • Apigenin  • p-coumaric acid  • Ferulic acid  • Syringic acid 	

Table 4.
Major bioactive components in different pseudocereals with their 2D protein structure.

reducing antioxidant power (FRAP), the antioxidant activities of the lipophilic extracts from the quinoa seed were higher than those of the amaranth seed; however, total carotenoid index (TCI), unsaturated fatty acids (UFAs), and total tocopherol index (TTI) measurements were highly correlated. The balance between the generation of reactive oxygen species (ROS) and antioxidant defense is off, resulting in oxidative stress [39, 40]. Furthermore, pseudocereal seeds have recently been revealed to have significant levels of phytosterols, which have been shown to have antibacterial, antioxidant, and anticancer characteristics as well as cardiovascular disease (CVD) prevention effects [40]. Pseudocereal proteins are rich in bioactive peptides. A study using simulated gastrointestinal digestion produced Pseudocereals protein hydrolysate. According to the findings of the study, pseudocereal protein hydrolysates have an exceptional potential to manage hypertension, and quinoa protein can be used to create foods with functional qualities that lower blood pressure [41]. It has been discovered that *A. mantegazzianus* hydrolytically releases antihypertensive encrypted peptides [42]. The study found that tartary buckwheat extract (TBE) supplemented with D-ChiroInositol (DCI) could prevent rats from liver damage and hyperglycemia caused by high fructose diet supplementation. TBE ingestion, according to these data, may be a good prophylactic or therapeutic strategy for hepatic steatosis, oxidative damage, and high-fat diet-induced hyperglycemia [43]. In cultured colonic epithelial Caco-2 cells, quinoa polyphenols have been found to reduce inflammation and improve gastrointestinal health in experimental mice by downregulating the cytokines interleukin-8 (IL-8), interleukin-1 (IL-1), and tumor necrosis factor (TNF) [44]. Furthermore, quinoa seed saponins have been demonstrated to lower IL-6, TNF, and nitric oxide (NO) overproduction, suggesting that they could be used as a functional dietary element for inflammation control and prevention [45]. Cooked quinoa polyunsaturated fatty acids (PUFA) and phenolics significantly lowered pro-inflammatory factor IL-8 synthesis, expression of IL-8, IL-6, TNF, COX-2, and IL-1, and expression of anti-inflammatory cytokines like IL-10 [46]. Burlacu et al. [47] present results on phytoconstituents obtained from oak extracts (*Quercus*) and their biological value as antioxidants, antimicrobials, and anticancer agents. The phenolic chemicals flavonoids, stilbenoids, and arylbenzofurons are said to be abundant in breadnut (*Artocarpus*) plants [48]. The usage of pseudocereals in food has grown significantly, and research has even spread into the non-food sector. Buckwheat, for example, has been used to make yoghurt, vinegar, black sauce, tea, and alcoholic beverages [49]. Fiber-rich quinoa milling fractions have been used as binders in the production of bologna-style sausages. In the sausage, the fiber-rich quinoa fraction increased emulsion stability while lowering lipid oxidation and water activity. Because the quinoa fractions already contributed enough color to the product, it was determined that nitrite addition was unnecessary [50]. Buckwheat has been the most studied pseudocereal in the non-food domain. Buckwheat protein derived from distillers dried grains has been utilized to create composite edible films for food packaging, and buckwheat peptides could be employed as a functional ingredient in the development of nutraceuticals [51, 52].

4. Conclusion and way to forward

All pseudocereals are plants that can be easily adapted to and cultivated in a variety of environments. They are particularly resistant to drought and high temperatures, making them important food security plants. Pseudocereals are popular due to their great commercial worth as well as their unique functional and nutritional properties. Non-phenolic compounds such as ascorbic acid, phytic acid, tocopherols, sterols, carotenoids, and saponins, among others, may be the most likely antioxidant donors despite the high fraction of total phenols. Anti-inflammatory, anticancer, hepatoprotective, antioxidant, wound healing, antimitotic (antitumor), antiviral, anti-microbial activity and skin depigmentation, antidiabetic, antinociceptive effect, and antibacterial activities have been reported in various parts of the plant extracts. As a result, understanding the qualities of pseudocereals is critical. This will help people with gluten-related disorders improve their quality of life. However, there is a tremendous possibility for further scientific research into pseudocereals to demonstrate therapeutic efficacy and commercial application. Pseudocereals are gaining popularity among consumers and small enterprises worldwide, particularly in poor countries. A recent study clearly shows that non-essential components such phytochemicals found in pseudocereals may be advantageous to health. This characteristic has prompted the development of a number of processing methods that may improve the biological value of pseudocereals. Despite their nutritional and physiological value, these grains are currently underutilized in the market. Exploiting pseudocereals' bioactive potential by hydrolyzing anti-nutrient components and boosting the number of health-beneficial chemicals has emerged as a critical technique. High cost (imported grain as quinoa), and the majority of people are unaware of its benefits. Pseudocereals also have functional properties such a high nutritional profile, bioactive compounds, and are gluten-free. Food Science and Technology plays a vital role in investigating and sharing information on these grains in this situation. Pseudocereals are popular because they have a high commercial value as well as unique functional and nutritional features. As a result, it is necessary to have a complete understanding of the properties of pseudocereals, as well as their benefits and drawbacks. This will help to improve the quality of life for persons suffering from gluten-related disorders. Pseudo-cereals have limitless possibilities; the only task is to see them.

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Author contributions

NS: conceived the study, edit the manuscript. M: contributed to the writing and editing of the DP: contributed to the writing manuscript and table preparation. All authors contributed to the writing, editing, and approved the manuscript.

Conflicts of interest

We have no conflicts of interest to disclose.

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References

[1] Perez-Rea D, Antezana-Gomez R. The functionality of pseudocereal starches. In: Woodhead Publishing Series in Food Science, Technology and Nutrition. Starch in Food. Woodhead Publishing; 2018. pp. 509-542

[2] Mir NA, Riar CS, Singh S. Nutritional constituents of pseudo cereals and their potential use in food systems: A review. Trends in Food Science & Technology. 2018;**75**:170-180

[3] Jan N, Hussain SZ, Naseer B, Bhat TA. Amaranth and quinoa as potential nutraceuticals: A review of anti-nutritional factors, health benefits and their applications in food, medicinal and cosmetic sectors. Food Chemistry. 2023; **X**:100687

[4] Gul K, Singh AK, Jabeen R. Nutraceuticals and functional foods: The foods for the future world. Critical Reviews in Food Science and Nutrition. 2016;**56**(16):2617-2627

[5] Martínez-Villaluenga C, Peñas E, Hernández-Ledesma B. Pseudocereal grains: Nutritional value, health benefits and current applications for the development of gluten-free foods. Food and Chemical Toxicology. 2020;**137**: 111178

[6] Srichuwong S, Curti D, Austin S, et al. Physicochemical properties and starch digestibility of whole grain sorghums, millet, quinoa and amaranth flours, as affected by starch and non-starch constituents. Food Chemistry. 2017;**233**: 1-10

[7] Singh RK, Sreenivasulu N, Prasad M. Potential of underutilized crops to introduce the nutritional diversity and achieve zero hunger. Functional & Integrative Genomics. 2022;**22**(6): 1459-1465

[8] Bochetto A, Merino N, Kaplan M, Guiñez M, Cerutti S. Design of a combined microextraction and back-extraction technique for the analysis of mycotoxins in amaranth seeds. Journal of Food Composition and Analysis. 2021; **98**:103818

[9] Bhinder S, Kaur A, Singh B, Yadav MP, Singh N. Proximate composition, amino acid profile, pasting and process characteristics of flour from different Tartary buckwheat varieties. Food Research International. 2020;**130**: 108946

[10] Sofi SA, Ahmed N, Farooq A, Rafiq S, Zargar SM, Kamran F, et al. Nutritional and bioactive characteristics of buckwheat, and its potential for developing gluten-free products: An updated overview. Food Science & Nutrition. 2023;**11**(5):2256-2276

[11] Janssen F, Pauly A, Rombouts I, Jansens KJA, Deleu LJ, Delcour JA. Proteins of amaranth (Amaranthus spp.), buckwheat (Fagopyrum spp.), and quinoa (Chenopodium spp.): A food science and technology perspective. Comprehensive Reviews in the Food Science and Food Safety. 2017;**16**(1): 39-58

[12] Saturni L, Ferretti G, Bacchetti T. The gluten-free diet: Safety and nutritional quality. Nutrients. 2010;**2**(1): 00016-00034

[13] Schoenlechner R, Bender D. Pseudocereals for global food production. Cereal Foods World. 2020; **65**(2)

[14] Kahlon TS, Avena-Bustillos RJ, Chiu MM. Sensory evaluation of gluten-free quinoa whole grain snacks. Heliyon. 2017;**3**:1-12

[15] Peksa A, Kita A, Carbonell-Barrachina AA, et al. Sensory attributes and physicochemical features of corn snacks as affected by different flour types and extrusion conditions. LWT-Food Science Technology. 2016;**72**:26-36

[16] Lorusso A, Verni M, Montemurro M, et al. Use of fermented quinoa flour for pasta making and evaluation of the technological and nutritional features. LWT – Food. Science and Technology. 2017;**78**:215-221

[17] Kerpes R, Fischer S, Becker T. The production of gluten-free beer: Degradation of hordeins during malting and brewing and the application of modern process technology focusing on endogenous malt peptidases. Trends in Food Science and Technology. 2017;**67**: 129-138

[18] Nagar P, Engineer R, Rajput K. Review on Pseudo-cereals of India. IntechOpen. 2022. DOI: 10.5772/intechopen.101834

[19] Fletcher RJ. Pseudocereals: Overview; 2015. DOI: 10.1016/B978-0-08-100596-5.00039-1

[20] Bekkering CS, Tian L. Thinking outside of the cereal box: Breeding underutilized (pseudo) cereals for improved human nutrition. Frontiers in Genetics. 2019;**10**:1289

[21] Ram A, Thattantavide A, Kumar A. Re-emergence of pseudocereals as superfoods for food security and human health: Current Progress and future prospects. Wild Food Plants for Zero Hunger and Resilient Agriculture. 2023; **2023**:207-236

[22] Rodríguez JP, Rahman H, Thushar S, Singh RK. Healthy and resilient cereals and pseudo-cereals for marginal agriculture: Molecular advances for improving nutrient bioavailability. Frontiers in Genetics. 2020;**11**:49

[23] Agarwal A, Rizwana T, AD, Kumar T, Sharma KP, Patel SKS. Nutritional and functional new perspectives and potential health benefits of quinoa and chia seeds. Antioxidants. 2023;**12**(7): 1413

[24] Rollán GC, Gerez CL, LeBlanc JG. Lactic fermentation as a strategy to improve the nutritional and functional values of pseudocereals. Frontiers in Nutrition. 2019;**6**:98

[25] Drzewiecki J, Martinez-Ayala AL, Lozano-Grande MA, Leontowicz H, Leontowicz M, Jastrzebski Z, et al. In vitro screening of bioactive compounds in some gluten-free plants. Applied Biochemistry and Biotechnology. 2018; **186**:847-860

[26] Inglett GE, Chen D, Liu SX. Antioxidant activities of selective gluten free ancient grains. Food and Nutrition Sciences. 2015;**6**:612-621

[27] Rocchetti G, Chiodelli G, Giuberti G, Masoero F, Trevisan M, Lucini L. Evaluation of phenolic profile and antioxidant capacity in gluten-free flours. Food Chemistry. 2017;**228**: 367-373

[28] Ciudad-Mulero M, Fernandez-Ruiz V, Matallana-Gonzalez MC, Morales P. Dietary fiber sources and human benefits: The case study of cereal and pseudocereals. Advances in Food and Nutrition Research. 2019;**90**:83-134. In Press, Corrected Proof

[29] Pirzadah TB, Malik B, Tahir I, Hakeem KR, Alharby HF, Rehman RU. Lead toxicity alters the antioxidant defense machinery and modulate the biomarkers in Tartary buckwheat plants.

International Biodetergent and Biodegradation. 2020;**151**:104992

[30] Usman M, Patil PJ, Mehmood A, Rehman A, Shah H, Haider J, et al. Comparative evaluation of pseudocereal peptides: A review of their nutritional contribution. Trends in Food Science & Technology. 2022;**122**:287-313

[31] Shahbaz M, Raza N, Islam M, Imran M, Ahmad I, Meyyazhagan A, et al. The nutraceutical properties and health benefits of pseudocereals: A comprehensive treatise. Critical Reviews in Food Science and Nutrition. 2022:1-13

[32] Jeelani PG, Sinclair BJ, Perinbarajan GK, Ganesan H, Ojha N, Ramalingam C, et al. The therapeutic potential of chia seeds as medicinal food: A review. Nutrire. 2023;**48**(2):39

[33] Razzeto GS, Uñates MA, Moreno JER, Lucero López RV, Aguilar EG, Sturniolo H, et al. Evaluation and comparative study of the nutritional profile and antioxidant potential of new quinoa varieties. Asian Journal of Agricultural and Horticultural Research. 2019;**3**(3):1-11

[34] Jing R, Li HQ, Hu CL, Jiang YP, Qin LP, Zheng CJ. Phytochemical and pharmacological profiles of three Fagopyrum buckwheats. International Journal of Molecular Science. 2016;**17**(4): 589

[35] Karimian J, Abedi S, Shirinbakhshmasoleh M, Moodi F, Moodi V, Ghavami A. The effects of quinoa seed supplementation on cardiovascular risk factors: A systematic review and meta-analysis of controlled clinical trials. Phytotherapy Research. 2021;**35**(4):1688-1696

[36] Marques-Coelho M et al. Emerging opportunities in exploring the nutritional/functional value of amaranth. Food & Function. 2018;**9**: 5499-5512

[37] Vilcacundo R, Martínez-Villaluenga C, Hernández-Ledesma B. Release of dipeptidyl peptidase IV. α-amylase and α-glucosidase inhibitory peptides from quinoa (*Chenopodium quinoa* willd.) during in vitro simulated gastrointestinal digestion. Journal of Functional Foods. 2017;**35**:531-539

[38] Vilcacundo R, Miralles B, Carrillo W, Hernández-Ledesma B. In vitro chemopreventive properties of peptides released from quinoa (*Chenopodium quinoa* willd) protein under simulated gastrointestinal digestion. Food Research International. 2018;**105**:403-411

[39] Tang Y et al. Assessing the fatty acid composition, carotenoid, and tocopherol compositions of amaranth and quinoa seeds grown in Ontario and their overall contribution to nutritional quality. Journal of Agricultural and Food Chemistry. 2016;**64**:1103-1110

[40] Alonso-Miravalles L, Zannini E, Bez J, Arendt EK, O'Mahony JA. Physical and flow properties of pseudocereal-based protein-rich ingredient powders. Journal of Food Engineering. 2020;**281**: 109973

[41] Guo H, Hao Y, Richel A, Everaert N, Chen Y, Liu M, et al. Antihypertensive effect of quinoa protein under simulated gastrointestinal digestion and peptide characterization. Journal of the Science of Food and Agriculture. 2020;**100**(15): 5569-5576

[42] Fritz M, Vecchi B, Rinaldi G, Añón MC. Amaranth seed protein hydrolysates have in vivo and in vitro antihypertensive activity. Food Chemistry. 2011;**126**(3):878-884

[43] Hu Y, Zhao Y, Ren D, Guo J, Luo Y, Yang X. Hypoglycemic and hepatoprotective effects of d-chiro-inositol-enriched tartiary buckwheat extract in high fructose-fed mice. Food & Function. 2015;**6**(12): 3760-3769

[44] Noratto G, Carrion-Rabanal R, Medina G, Mencia A. Quinoa protective effects against obesity-induced intestinal inflammation. FASEB Journal. 2015;**29** (Supplement):602

[45] Yao Y, Yang X, Shi Z, Ren G. Anti-inflammatory activity of saponins from quinoa (*Chenopodium quinoa* Willd.) seeds in lipopolysaccharide-stimulated RAW 264.7 macrophages cells. Journal of Food Science. 2014;**79**(5):H1018-H1023

[46] Tang Y, Li X, Chen PX, Zhang B, Hernandez M, Zhang H, et al. Characterisation of fatty acid, carotenoid, tocopherol/tocotrienol compositions and antioxi-dant activities in seeds of three *Chenopodium quinoa* willd. Food Chemistry. 2015;**174**:502-508

[47] Burlacu E, Nisca A, Tanase C. A comprehensive review of phytochemistry and biological activities of Quercus species. Forests. 2020;**11**(9):904

[48] Buddhisuharto AK, Pramastya H, Insanu M, Fidriann I. An updated review of phytochemical compounds and pharmacology activities of *Artocarpus* genus. Biointerface Research Applied Chemistry. 2021;**11**:14898-14905

[49] Cai YZ, Corke H, Wang D, Li WD. Buckwheat: Overview. In: Wrigley CW, Corke H, Seethamaran K, Faubion J, editors. Encyclopedia of Food Grains. 2nd ed. Amsterdam: Elsevier; 2015. pp. 307-315

[50] Fernández-López J, Lucas-González R, Viuda-Martos M, Sayas-Barberá E, Ballester-Sánchez J, Haros CM, et al. Chemical and technological properties of bologna-type sausages with added black quinoa wet-milling coproducts as binder replacer. Food Chemistry. 2020;**310**:125936

[51] Liu S, Chen D, Xu J. Characterization of amaranth and bean flour blends and the impact on quality of gluten-free breads. Journal of Food Measurement and Characterization. 2019;**13**(2): 1440-1450

[52] Wang X, Ullah N, Sun X, Guo Y, Chen L, Li Z, et al. Development and characterization of bacterial cellulose reinforced biocomposite films based on protein from buckwheat distiller's dried grains. International Journal of Biological Macromolecules. 2017;**96**:353-360

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Although they are neither technically classified as grasses nor as actual cereal grains, pseudocereals are plants that yield fruits or seeds that are utilized and consumed like grains. Pseudocereals are complete grains that are usually high in protein and free of gluten. Supposedly many of the "ancient grains" are actually pseudocereals. The Food and Agricultural Organization (FAO) has also noted that pseudocereals greatly improve health and nutrition, as well as an individual's food supply and standard of living, all of which can contribute to future food security and sustainability. Their protein-derived peptides have been shown in previous investigations to possess antioxidant, anti-inflammatory, anti-hypertensive, anti-cancerous, and hypocholesterolemic qualities. Because pseudocereals have these intriguing qualities, more research is required to determine how best to incorporate them into the diet and what health benefits they may offer, which is exactly what this book is about. It provides essential information to scientific and non-scientific communities alike to keep interest in pseudocereals alive for the overall health and wellness of the planet.

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