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REVIEW

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Quinoa as a functional crop with emphasis on distribution, nutritional composition, and biological effects

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Abstract
Native to the Andes, quinoa (*Chenopodium quinoa* Willd.) is a pseudocereal that has become well-known around the world for its remarkable nutritional profile and possible health advantages. The distribution, content, nutritional value, and biological activity of quinoa are all examined in this thorough analysis. We look at how it is grown in different parts of the world, including its historical origins in South America and its growing appeal in a variety of climates throughout the globe. According to the composition study, quinoa is a better option than regular grains because of its abundance of excellent quality protein, vital essential amino acids, fiber from food, nutrition, and minerals. Also covered in depth how quinoa can help with nutritional deficits, especially those related to protein and micronutrient consumption. The review also explores the plant's active compounds, such as phenolic acids, flavonoids, and saponins, which support its antibacterial, anti-inflammatory, and antioxidant qualities. Furthermore, quinoa's possible therapeutic benefits for long-term conditions including cancer, heart disease, and diabetes are evaluated cautiously. To highlight the significance of quinoa in advancing global food security and improving human health, this study ends by talking about the difficulties in producing grain, such as environmental considerations and environmentally friendly farming techniques. Quinoa is a highly functional food with considerable room for further study and application due to its numerous biological activities.

Keywords Pseudocereals, Nutritional value, Saponins, Flavonoids

1 Introduction

Quinoa (*Chenopodium quinoa* Willd.) is an herbaceous, tetraploid, halophytic crop belonging to the Chenopodiaceae family and the *Chenopodium* genus. Native to the Andean region of South America, its cultivation dates to 5000–3000 BC, where the Inca civilization revered it as a sacred food.

Interest in quinoa resurged significantly in recent decades, culminating in the United Nations declaring 2013 the "International Year of Quinoa" [1]. This renewed global attention is largely attributed to its exceptional nutritional value, environmental resilience, and ability to thrive under conditions of drought, salinity, frost, and nutrient-poor soils, making it highly relevant for regions facing food insecurity [2].

Quinoa adapts through morphological, physiological, and molecular traits, such as genetic plasticity and the activation of stress-related proteins. These features contribute to its ability to grow in diverse and often adverse climates. Moreover, quinoa is rich in high-quality plant-based protein (16–18%), dietary fibre, and essential micronutrients such as magnesium, potassium, zinc, and B vitamins [3]. Its nutritional composition makes it an attractive dietary option for managing and preventing chronic conditions such as type 2 diabetes, obesity, and metabolic syndrome. Quinoa's low glycaemic index, complex carbohydrates, and bioactive compounds—including flavonoids and polyphenols—are known to promote satiety, enhance insulin sensitivity, and support glycaemic control [4]. Furthermore, minerals such as selenium and zinc, present in quinoa, are critical for thyroid health, playing roles in the conversion of T4 to T3 and the maintenance of hormonal balance [5].

Therefore, the aim of this review is to explore the phytochemical composition of quinoa, with a specific focus on its bioactive compounds and their molecular mechanisms in antihypertensive, anti-inflammatory, and antioxidant activity. The review also aims to highlight its nutritional value and therapeutic potential, particularly within the context of chronic disease prevention and management.

The following sections will cover quinoa's botanical features, phytoconstituents, traditional uses, and recent experimental findings, with a special emphasis on species cultivated in North Africa.

2 Botanical description and distribution

Growing mostly for its delicious seeds, quinoa is an annual herbaceous plant that is very nutrient-dense. Quinoa (*Chenopodium quinoa* Willd.) is an annual herbaceous crop recognized for its exceptional nutritional profile and cultivated primarily for its edible seeds. Indigenous to the Andean highlands of South America—specifically Peru, Bolivia, Ecuador, and Colombia—it has undergone domestication over a period exceeding 5,000 years. Although traditionally associated with high-altitude environments, quinoa exhibits remarkable adaptability to a wide range of agroecological conditions, a characteristic that has facilitated its increasing cultivation on a global scale [6]. Botanically, *Chenopodium quinoa* typically attains a height ranging from 1 to 3 m (approximately 3 to 10 feet). The plant features a sturdy, erect stem that may be either branched or unbranched, with pigmentation that transitions from green to shades of red, purple, or yellow during maturation. Its alternate leaves exhibit considerable morphological variability, ranging from triangular to lanceolate or rhomboid forms, frequently with serrated margins. Leaf coloration is also diverse—spanning green, crimson, and purple hues—depending on the plant's genotype and exposure to environmental stressors. The inflorescence consists of dense, racemose panicles composed of minute, inconspicuous flowers, which are predominantly bisexual or pistillate, and exhibit a pronounced tendency for self-pollination. Flowering generally occurs from late summer to early fall, with blooms showing green to yellowish hues [7].

The seeds are small, spherical grains measuring approximately 2 mm in diameter—exhibit a diverse color palette including white, red, yellow, purple, brown, and black [8]. These seeds are protected by a natural coating rich in saponins, which must be removed during processing to eliminate bitterness [9]. Furthermore, the plant may flourish in suboptimal soil conditions due to its tolerance to salt and cold [1].

2.1 Morphological characteristics

Height Although certain types can reach greater heights, quinoa plants often grow between 1 and 2 m (3 and 6.5 feet) in height.

Stems The plant features upright stems with branches that, depending on the type, can be either purple, red, or green. The stems are frequently robust and branch out to resemble bushes.

Leaves Quinoa leaves are wide and shaped like an oval or rhombus. They might have a purple, crimson, or green colour. The leaves frequently have edges that are serrated (Fig. 1).

Flowers Quinoa plants have tiny, hardly noticeable flowers in close-packed clusters. Late summer to early fall is when the blooms may develop; they are usually green or yellowish [7].

Quinoa seeds are tiny, spherical, and come in a range of colours, including white, red, black, and golden. To make the seeds edible, they must be cleaned or processed to remove their bitter saponin-rich covering. The portion of the plant that is picked and eaten are these seeds [8].

2.2 Distribution

Quinoa (*Chenopodium quinoa* Willd.) is native to the Andean highlands of South America, particularly in Peru, Ecuador, Colombia, and Bolivia. It has been cultivated by Indigenous peoples for thousands of years in these high-altitude regions, where it thrives under extreme environmental conditions, including low temperatures, strong winds,

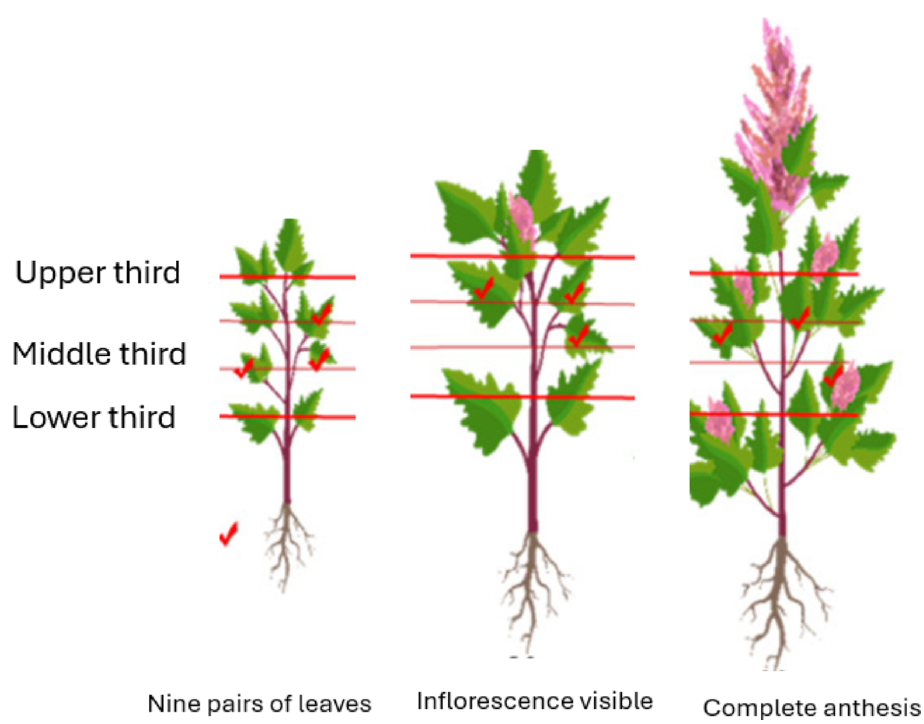


Fig. 1 Modified three leaves of quinoa [10]

and frequent drought. As noted by Jacobsen (2003), traditional quinoa cultivation typically occurs at elevations between 2.500 and 4.000 m (approximately 8.200 to 13.100 feet) above sea level [7].

In recent decades, the global demand for quinoa has increased substantially, largely due to its gluten-free status, high nutritional value, and adaptability to marginal environments. As a result, its cultivation has expanded far beyond South America. Today, quinoa is grown in diverse agroclimatic regions, including North America (notably in the United States and Canada), Europe (particularly in Spain and France), and Asia (notably in China and India), where it is being adapted to local soil and climate conditions for both commercial and research purposes [1]. The plant's capacity to thrive in a range of locations outside of its natural habitat is a result of its adaptability to several climatic circumstances, including drought, frost resistance, and soil tolerance.

Because to the favourable growing circumstances, quinoa is cultivated in places like Colorado, California, and Idaho in the United places. To accommodate the growing demand for the grain and diversify worldwide supply, quinoa is also being grown in places like Canada and Australia [7]. While the global rise in quinoa cultivation reflects its growing appeal as a nutritious and climate-resilient crop, it has also raised concerns regarding its impact on traditional Andean communities and local ecosystems. In its native regions, particularly in Bolivia and Peru, quinoa has deep cultural, economic, and dietary significance. However, the surge in international demand has led to shifts toward industrial-scale farming, which may threaten smallholder livelihoods, alter land use patterns, and potentially harm fragile Andean ecosystems. Despite these challenges, quinoa's nutritional profile and agronomic resilience continue to drive its global dissemination. Its ability to tolerate drought, salinity, and cold temperatures, as well as grow in low fertility soils, makes it a promising alternative to conventional grains in areas facing climate stress and declining soil productivity. Given its adaptability, quinoa is increasingly viewed as a strategic crop for enhancing food security in regions prone to extreme weather events, desertification, or resource scarcity [1]. Furthermore, interest in cultivating quinoa beyond conventional growing regions has increased because of its popularity. For example, there has been some success with quinoa cultivation efforts in southern Europe and the mountainous regions of the United States [7]. In addition, interest in cultivating quinoa outside of conventional growing regions has increased because to its popularity. For example, there has been some success with quinoa cultivation efforts in southern Europe and the high plains of the United States [7]. Quinoa's adaptability to diverse climates and its nutritional value have fuelled its rapid expansion in the global market, leading to its widespread availability in both mainstream grocery outlets and health food stores. However, this growing international demand has introduced a range of challenges for Andean producers, particularly in Bolivia and Peru, where the crop has deep-rooted cultural and economic importance. One major concern is the rising cost of quinoa, which—though beneficial for export-driven economies—has made it less affordable and accessible to local populations who have relied on it as a dietary staple for generations. This economic shift risks disrupting traditional agricultural practices and exacerbating food insecurity in the very regions where quinoa originated.

In addition, the expansion of large-scale quinoa monocultures to meet global export demands has been associated with environmental degradation in some areas. Over-exploitation of land, loss of soil fertility, and pressure on natural resources are among the unintended consequences of industrialized production, raising questions about the long-term sustainability of current cultivation practices [11].

However, because of its nutritional composition and capacity to flourish in poor soils, quinoa remains a crucial crop for sustainable agriculture. Its high protein content, necessary amino acids, and plenty of fibre, vitamins, and minerals make it a nutritional powerhouse. As a result, quinoa has become increasingly well-liked as a nutritious food item worldwide [1]. The *Chenopodium* genus comprises more than 200 species, but *Chenopodium quinoa* is by far the most widely cultivated and well-known for its nutritious, edible seeds. Other related species, such as *Chenopodium berlandieri*—which is native to North America—are often considered wild relatives of quinoa. While these species are not commonly grown as staple crops, some have been traditionally used for medicinal purposes or as leafy vegetables in local diets.

The increasing global interest in quinoa is largely driven by the remarkable nutritional value, desiccation tolerance, and climatic adaptability of *C. quinoa*. These traits make it a valuable crop for addressing food security in regions facing climate variability, poor soil conditions, and limited water resources. However, it is important to recognize that the rapid expansion of quinoa cultivation—particularly in its native Andean regions—has brought with it socioeconomic and ecological challenges. Rising global demand has contributed to shifts in local farming practices, increased land pressure, and elevated grain prices, which can undermine the food security of the very communities that have traditionally depended on quinoa [1].

3 Nutritional value

The Incas, Quechua, and Aymara peoples have used quinoa, a broadleaf plant native to the Andes, as a major source of sustenance in rural areas [12]. Originating more than 5000 years ago, it was a key crop in pre-Columbian communities in Latin America and was revered by the Incas. Quinoa seeds have great nutritional value in their different species (red, black, white, and kaniwa) as shown in Table 1, and are abundant in protein, lipids, carbohydrates, minerals, and saponin. Quinoa grains are also of excellent nutritional quality. They contain flavonoids, phenolic chemicals, and antioxidant capacity [12]. Micronutrients like potassium, phosphorus, and magnesium are abundant in quinoa, meeting daily requirements [13]. When creating and manufacturing food products, their functional qualities are essential.

3.1 Protein

In light of the allergies and intolerances related to protein ingestion. Scientists are replacing animal-based proteins like milk and egg with legumes and plant-based proteins like quinoa, which have lower gluten and high protein content [19]. Quinoa is isolated by centrifuging, solvents, and pH modification. As the pH rises, the protein

Table 1 Nutritional value of Quinoa species (g per 100 g of dry substance)

	Protein	Fat	Fiber	Ash	Carbohydrate	Moisture	References
White Quinoa	14.1–14.4	6.0-9.7	2.8–11.7	2.6–3.4	72.5–77	9.3–12.0 ± 0.11	[14, 15, 16, 17, 18]
Kaniwa	14.4–18.8	7.6–9.7	6.1	3.4–4.1	63.4–72.5	n.r.	[14, 15]
Red Quinoa	15.6 ± 0.4	6.4 ± 0.3		2.8 ± 0.2	75.3 ± 0.5	9.6 ± 0.2	[16]
Black Quinoa	14.6 ± 0.4	6.8 ± 0.3		2.7 ± 0.2	76.1 ± 0.5	9.7 ± 0.3	[16]

n.r. = not reported

Table 2 Protein fractions from Kaniwa and Quinoa (percentage of total protein)

	Albumins & globulins	Prolamins	Glutelins & insoluble proteins	References
Quinoa	45	23	32	[14].
Kaniwa	41	28	31	[14].

Table 3 Quinoa's amino acid content (mg amino acid/g protein) following acid hydrolysis

Amino Acid	Quinoa dry	Quinoa washed	References
1. Arginine	70	78	[15]
2. Tryptophan	15	19	[15]
3. Cystine	16	21	[15]
4. Methionine	18	28	[15]
5.Aspartic acid	70	81	[15]
6. Threonine	38	40	[15]
7.Serine	39	45	[15]
8.Glutamic acid	131	147	[15]
9.Proline	32	21	[15]
10.Glycine	47	42	[15]
11.Alanine	37	47	[15]
12.Valine	39	59	[15]
13.Isoleucine	32	52	[15]
14.Leucine	79	77	[15]
15. Tyrosine	29	26	[15]
16. Phenylalanine	34	36	[15]
17. Lysine	51	57	[15]
18.Histidine	24	21	[15]

becomes more extractable, making it a viable substitute for people allergic or intolerant to conventional animal proteins [20]. A study found that quinoa's nutrient content varied significantly, with the highest value double or triple the lowest. The highest protein content was 15.7 g/100 g EP, 70% higher than the lowest variety. It also has a balanced pattern of essential amino acids, with all essential amino acids present in quinoa. Quinoa proteins are high in lysine and threonine, generally the limiting amino acids in conventional cereals like wheat and maize [21]. Quinoa (*Chenopodium quinoa* Willd.) and kaniwa (*Chenopodium pallidicaule* Aellen) have a lower protein content than other grains. The Andean species' proteins are mainly composed of albumin and globulin, similar to casein as shown in Table 2. Quinoa's principal protein, chenopodina, has higher molecular weights than casein [14]. Quinoa seeds are a high-quality protein source with 8–22% protein content, high in essential amino acids like lysine, cysteine, and methionine, and low in prolamine, as shown in Tables 3 and 4, their structures are illustrated in Fig. 2. Its biological value is 73% similar to beef [22].

3.2 Carbohydrates

Starch and other carbohydrates are necessary for energy, signaling, and structural elements. Quinoa, a significant energy source, has a high D-xylose and maltose content, 58.1–64.2% starch, and 11% amylose [17]. Quinoa polysaccharides are antioxidants that contribute to a nutritious diet. Carbohydrates are classified into three main groups: sugars, oligosaccharides, and polysaccharides [25]. Quinoa carbohydrates have a high starch content, ranging from 32 to 69.2% [12]. Starch is found in two forms Amylose 3.5–22.5, and Amylopectin 77.5 [12]. Quinoa contains maltose, D-galactose, D-ribose, fructose,

Table 4 Quinoa's amino acid content (g/100 g protein)

Amino Acid	Quinoa protein	References
Histidine	3.2–2.9	[19, 23]
Leucine	5.9–6.6	[19, 23]
Isoleucine	3.6–4.9	[19, 23]
Lysine	2.4–7.8	[18, 19, 23]
Methionine	5.3	[23]
Methionine + Cysteine	3.6	[19]
Phenylalanine	6.9	[23]
Phenylalanine + tyrosine	6.1	[19]
Threonine	2.1–8.9	[18, 19, 23]
Valine	4.2–4.5	[19, 23]
Tryptophan	0.9–1.2	[19, 23]
Alanine	4.2	[19]
Glycine	4.9	[19]
Proline	5.5	[19]
Serine	4.0	[19]
Glutamic acid	13.2	[19]
Aspartic acid	8.0	[19]
Arginine	7.7	[19]

and glucose as shown in Table 5, and their structures are illustrated in Fig. 3. Carbohydrates have various physiological health effects, including energy provision, satiety, blood glucose and insulin metabolism control, protein glycosylation, cholesterol, and triglyceride metabolism. Quinoa carbohydrates can be considered nutraceutical due to their beneficial hypoglycemic effects and lowering of free fatty acids [12]. The chemical composition of sugars in 39 quinoa samples was analyzed, with sucrose being the principal sugar in all types (black, red, and white) as shown in Table 6. No significant differences between sucrose concentrations, Arabinose, fructose, and glucose were found [16].

3.3 Lipids

Quinoa seed oil's high oil quality and quantity make it a desirable alternative oil source. Linoleic (23), oleic, and linolenic acids (24) are the primary sources of 55–63% fatty acid content. About 50.2–56.1% linoleic acid (23), 22.0-24.5% oleic acid (25), 9.9–11.0% palmitic acid (26), and 5.4-7.0% linolenic acid (24) are among the many polyunsaturated fatty acids found in quinoa oil [22]. Quinoa seeds' lipids contain high amounts of neutral lipids, with triglycerides accounting for over 50%. The fatty acid composition of Quinoa seeds consists of total saturated (19-12.3%), monounsaturated (25-28.7%), and polyunsaturated (58.3%), mainly linoleic acid (about 90%) [12]. At 10% of total fatty acids, palmitic acid (26) is the primary saturated fatty acid [22]. The main unsaturated fatty acids are oleic, linoleic (23), and linolenic acids (24), which account for 87.2–87.8% of total fatty acids. Quinoa oil contains vitamin E, which prevents the oxidation of these unsaturated fatty acids [22]. Structures of these fatty acids are presented in Fig. 4.

3.4 Fibers

Dietary fiber from plants is divided into soluble and insoluble components. Soluble fib0ers are easily fermented and have prebiotic properties, while water-insoluble fibers provide bulking mass. Quinoa seeds are an excellent source of dietary fiber, accounting for 2.6–10% of total fiber weight. Of this, 22% of the quinoa fiber is soluble, and the

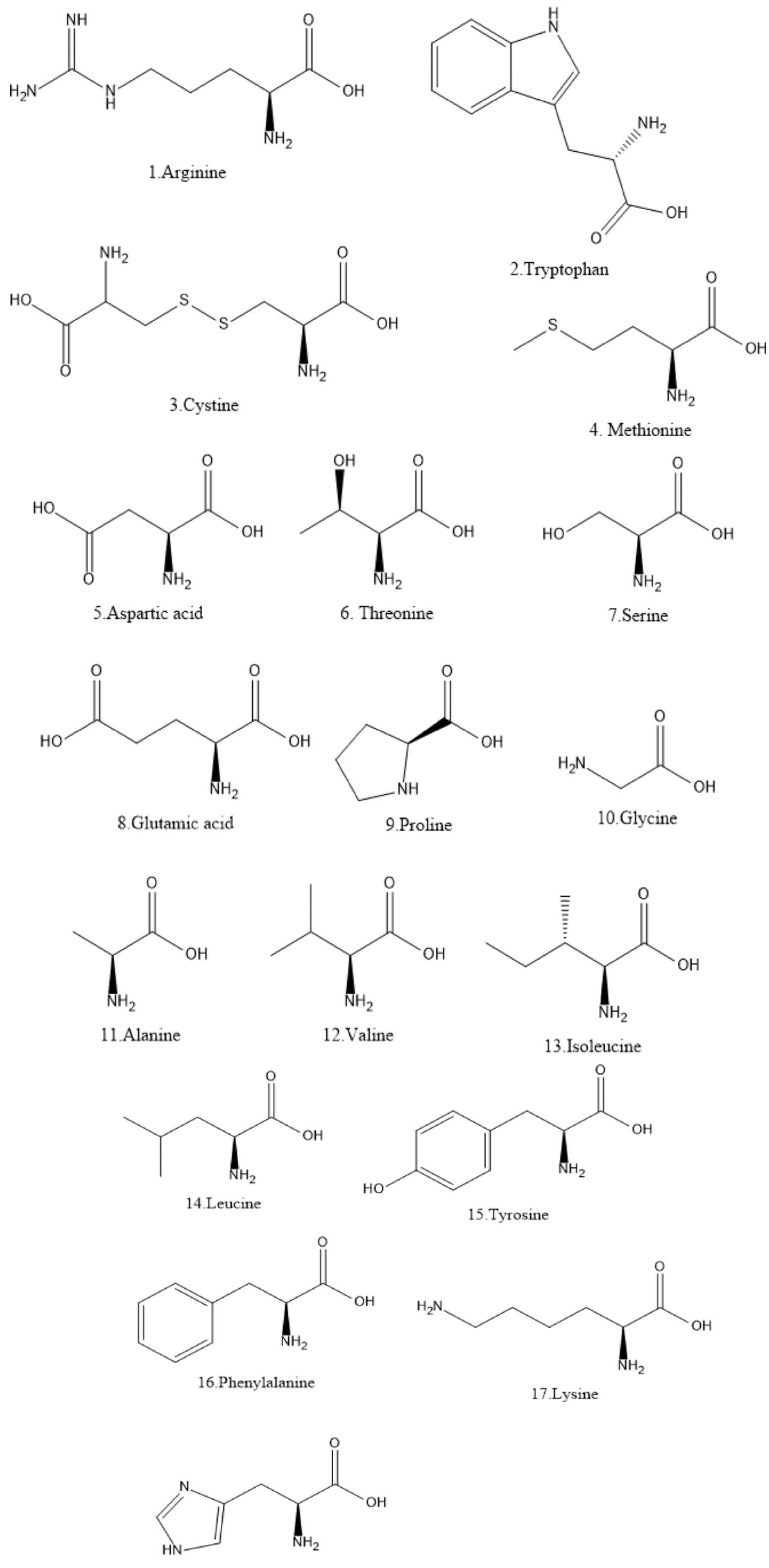


Fig. 2 Structures of amino acids found in Quinoa [24]

Table 5 Carbohydrates found in 100 g of Quinoa

	19. Glucose	20. Fructose	21. Maltose	22. Sucrose	Xylose	References
Quinoa	1.70–19 mg	0.20–19.6 mg	1.40–101 mg	2.90 mg	120 mg	[17, 26]

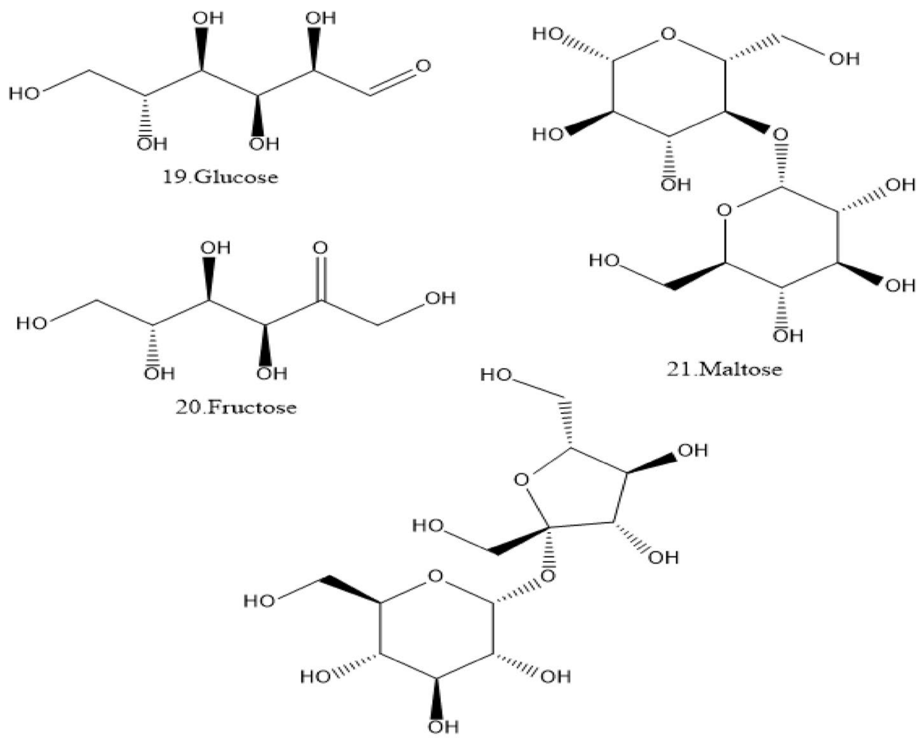


Fig. 3 Structures of carbohydrates found in Quinoa [27]

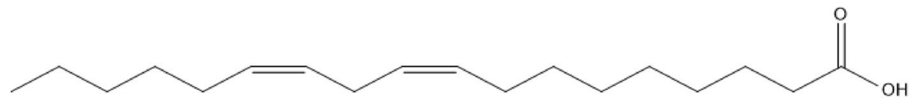
Table 6 Sugar composition of three types of Quinoa (*Chenopodium Quinoa* Willd.) presented in g/100 g mean ± se

	Arabinose	Fructose (20)	Glucose (19)	Sucrose (22)	Total	References
Black	0.50 ± 0.05	0.27 ± 0.05	0.64 ± 0.08	1.7 ± 0.3	3.1 ± 0.3	[16]
Red	0.63 ± 0.04	0.20 ± 0.05	0.47 ± 0.09	1.3 ± 0.2	2.6 ± 0.2	[16]
White	0.62 ± 0.03	0.0002-0.25 ± 0.04	0.007–0.61 ± 0.07	0.0029-1.4 ± 0.2	0.0062-2.9 ± 0.1	[16, 17]

remaining 78% is insoluble [22]. Quinoa is a significant fiber source, with no significant impact on fiber content. Animal studies have shown the presence of arabinans and rhamnogalacturonan-I in quinoa [25]. Quinoa contains a high total dietary fiber with soluble fiber content ranging from 1.3 to 6.1 g/100 g edible matter [18].

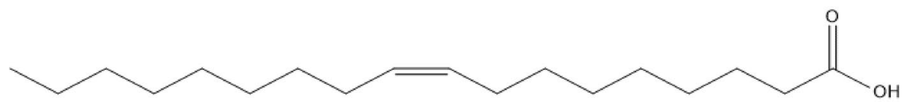
3.5 Vitamins

Quinoa was shown to have high levels of thiamine (29) (0.4 mg/100 g), folic acid (30) (78.1 mg/100 g), vitamin C (27) (16.4 mg/100 g), vitamin B6 (28) (0.20 mg/100 g), and pantothenic acid (0.61 mg/100 g) structures are illustrated in Fig. 5 [22]. Folate, particularly folic acid, is recommended for pregnant women to prevent neural tube defects.

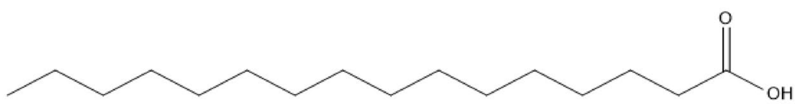


23.Linoleic acid

24.Linolenic acid

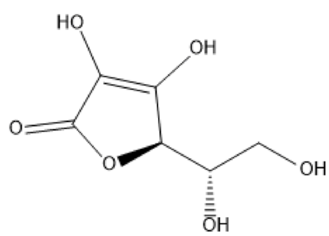


25.Oleic acid

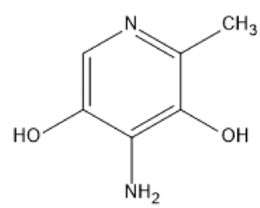


26.Palmitic acid

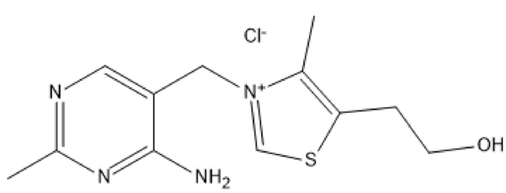
Fig. 4 Structures of fatty acids found in Quinoa [26]& [28]



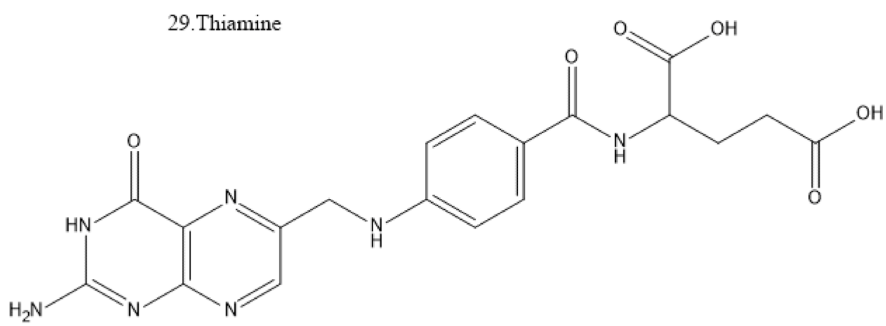
27.Vitamin C



28.Vitamine B6
Pyridoxine



29.Thiamine



30.Folic acid

Fig. 5 Structure of vitamins found in Quinoa [29]

3.6 Minerals

Inorganic micro and macronutrients, such as calcium, iron, potassium, magnesium, and phosphorus, are crucial for human nutrition. These minerals are required for a balanced diet and are found in biologically usable forms. Quinoa seeds also contain higher calcium, iron, fiber, and zinc [22]. As shown in Table 7 the mineral constituents of quinoa species.

4 Phytochemical composition

The desire for native and naturalized plant phytochemicals for pharmacological and nutritional uses has regained focus. Numerous chemical molecules with antibacterial, anti-obesity, antidiabetic, and antioxidant properties are produced by plants. These substances, which include phenolic compounds, Phyto steroids, flavonoids, and terpenoids, are present in a variety of plant components, including stems, roots, leaves, bark, flowers, fruits, and seeds. Among dietary phenolic compounds, flavonoids and phenolic acids represent the most prevalent subclasses and have been extensively characterized in quinoa (*Chenopodium quinoa*) seeds. These bioactive constituents, classified as functional compounds, encompass a diverse array of molecules capable of modulating various metabolic pathways within the human body, thereby exerting a broad spectrum of potential physiological effects. Functional compounds may be categorized based on their solubility properties, including hydrophilic compounds such as phenolics and betalains, as well as lipophilic constituents like carotenoids and phytoecdysteroids. Tannins, alongside saponins, are recognized as anti-nutritional compounds in quinoa due to their capacity to form insoluble complexes with proteins and polysaccharides, thereby diminishing nutrient bioavailability and sensory quality. Their presence contributes to an astringent taste, reducing consumer acceptability. Despite their potential impact, the tannin composition of quinoa seeds remains insufficiently characterized. Hydrolyzable tannins, including gallotannins and ellagitannins, can be enzymatically degraded into gallic and ellagic acids, respectively. These substances most likely serve to shield seeds from microbial deterioration until germination-friendly circumstances are met.

4.1 Phenolic acids

Quinoa leaves' cell walls contain both free and chemically bound phenolic acids. Different kinds of phenolic acids, including thirteen cinnamic acid analogs like cinnamic acid (30), ortho and para coumaric acid (31), rosmarinic acid (34), sinapinic acid (35), caffeic acid (32), chlorogenic acid (36) as seen in Table 7; Fig. 5. The most common phenolics

Table 7 Mineral constituents of Quinoa species (mg per 100 g of dry substance)

Minerals	Quinoa	Kaniwa	References
Calcium	27.5-148.7	110	[14, 26, 30]
Magnesium	26–502	n.r.	[14, 26, 30]
Sodium	5–31	n.r.	[14, 26]
Phosphorus	140–530	375	[14, 26, 30]
Iron	1.4–16.8	15.0	[14, 26, 30]
Copper	0.6–9.5	n.r.	[14, 26]
Zinc	2.8–4.8	n.r.	[14, 26, 30]
Potassium	511.9–1475	n.r	[26, 30]
Manganese	2-21.9	n.r	[26]

n.r. = not reported

found in quinoa seeds in bound form were ferulic acid and its derivatives [31]. Benzoic acid analogues like Benzoic acid (37) and its derivatives including 4-Hydroxybenzoic acid (38), gallic acid (39), protocatechuic acid (40), syringic acid (41), vanillic acid (42) and its derivatives like vanillic acid glucosyl ester (43) and vanillin (44) as seen in Table 8 and Fig. 6. They are abundant in quinoa seeds and leaves. These compounds provide significant health benefits, including antihypertensive, antioxidative, antidiabetic, anti-inflammatory, and anticarcinogenic properties. quinoa varieties are essential for reducing obesity and diabetes. The conjugated forms of bound phenolic acid derivatives were unaffected by environmental stressors. Stronger antioxidant and pancreatic lipase and α-glucosidase inhibitory activity were observed with higher phenolic acid concentration [32]. When measuring the total phenolic compounds showed the highest value in the quinoa seeds and the lowest value in the quinoa sprout [33].

4.2 Flavonoids

The fifteen-carbon skeleton of flavonoids is made up of two benzene rings connected by a heterocyclic pyrene ring. Different flavonoids classes have been reported in quinoa including flavones (45–48), flavonols (49–54), flavanones (55–57), dihydroflavones (), flavanols (58–60), and isoflavones (61–65) based on their structural characteristics. Plants contain flavonoids, which help protect them from herbivores and insects. Quinoa has been shown to contain four flavones: acacetin (45), isovitexin (46), orientin (47), and vitexin (48) as shown in Table 8 and Fig. 7. Compared to other quinoa sections, sprouts have a noticeably higher flavonoid content [26]. Vitexin was present in quinoa sprouts that were cultivated in the dark. Other plant species also yielded acetin, isovitexin, orientin, and vitexin which exhibited a range of biological activities [31]. The most prevalent flavonoids found in quinoa leaves and seeds are flavonol glycosides. The average individual concentration of the 12 distinct flavonol glycoside types found in quinoa, which are made up of derivatives of kaempferol (49) as Kaempferol3-O-(2,6-di-α-l-rhamnopyranosyl)-β-d-galactopyranoside (50) mainly in Japanese quinoa and quercetin (52) as quercetin-3-glucoside (52) and its derivatives like isorhamnetin (51) and rutin (54) as shown in Table 8 and Fig. 7. Mainly three flavanols found in quinoa seeds are hesperidin (55), neohesperidin (56), and naringin (57) as shown in in Table 8; Fig. 7. In a previous study [12] explained that values were higher in yellow quinoa sprouts than red quinoa sprouts. Quinoa seeds contained three flavanols: epicatechin (59), epigallocatechin (60), and catechin (58) as shown in Table 8; Fig. 7. Also, quinoa seeds have five isoflavones including biochanin (61), daidzein (62), genistein (63), prunetin (64), and puerarin (65) as shown in Table 8; Fig. 7.

4.3 Terpenoids

Different classes of terpenoids in quinoa seeds contain at least 15 monoterpenoids such as Camphene (66), Camphor (67), γ-Terpinene (68), and p-Cymene (69) as shown in Table 7; Fig. 7. Triterpenoids have two classes including their aglycones (sapogenins) and glycosides (saponins) [33]. Tetracycles or pentacycles are found in the core structures of the quinoa triterpenoids. The majority of them are saponins, which are pentacyclic triterpenoids. The saponins were categorized as mono-, di-, and tridesmosides based on the number of saccharide chains in their structures, which include an aglycone (sapogenin) and one to three saccharide chains. The primary saponins and aglycones could be fully

Table 8 Phytoconstituents which were reported in different organs of Quinoa species

Name	Organ	References
Phenolic acids and derivatives		
Cinnamic acid	Sprouts and seeds	[31, 33]
Ortho and para coumaric acid	Leaves and seeds	[31, 35, 33]
Rosmarinic acid	Seeds	[36, 35]
Sinapinic acid	Leaves and seeds	[31, 33]
Caffeic acid	Seeds	[36, 31, 35]
Chlorogenic acid	Leaves and seeds	[36, 31]
Ferulic acid	Leaves, sprouts and seeds	[25, 33]
Benzoic acid	Leaves and flour	[36, 31]
4-Hydroxybenzoic acid	Seeds	[31]
2,4-Dihydroxybenzoic acid	Seeds	[31]
Gallic acid	Leaves, sprouts and seeds	[31]
Protocatechuic acid	Sprouts and seeds	[36, 33]
Syringic acid	Leaves and seeds	[36, 31, 33]
Vanillic acid	Seeds	[36, 31, 33]
Flavonoids		
Acacetin	Flour	[35, 26, 37]
Isovitexin	Sprouts	[31, 35, 37]
Orientin	Seeds	[31, 35, 37]
Vitexin	Sprouts and seeds	[35, 33, 37]
Kaempferol	Leaves and seeds	[35, 33, 37]
Kaempferol3-O-(2,6-di-α-l-rhamnopyranosyl)-β-d-galactopyranoside	Seeds	[31, 35, 33]
Quercetin	Leaves and seeds	[31, 35, 37]
Quercetin-3-glucoside	Seeds	[31, 35, 37]
Isorhamnetin	Leaves	[31]
Rutin	Leaves, sprouts and seeds	[35, 33]
Hesperidin	Seeds	[35, 33]
Neohesperidin	Seeds	[31, 35]
Naringin	Seeds	[31, 35]
Epicatechin	Seeds	[31, 37]
Epigallocatechin	Seeds	[31, 37]
Catechin	Seeds	[31, 37]
Biochanin A	Seeds	[31, 37]
Daidzein	Seeds	[31]
Genistein	Seeds	[31, 37]
Prunetin	Seeds	[31, 37]
Puerarin	Seeds	[31]
Terpenoids		
Camphene	Leaves	[31]
Camphor	Leaves	[31, 38]
Γ-Terpinene	Leaves	[31, 38]
P-Cymene	Flours	[31, 38]
Oleanolic acid	Seeds and brain	[31, 38]
Hederagenin	Seeds and brain	[33, 38]
Spergulagenic acid	Seeds and brain	[31, 33, 38]
Serjanic acid	Flowers, fruits, seeds and bran	[31]
Phytolaccagenic acid	Bran	[31, 35]
Gypsogenin	Flowers, fruits, seeds and bran	[31]
A-tocotrienol	Seeds	[31, 35]

Table 8 (continued)

Name	Organ	References
B-tocotrienol	Seeds	[31, 35]
Sesquiterpene	Seeds	[31, 35]
Phyto steroids		
Cholesterol	Seeds	[31, 38]
Campestanol	Seeds	[31]
Makisterone	Seeds	[39, 33]
Δ5-Avenasterol	Seeds	[39, 33]
β-Sitosterol	Seeds	[39, 31]
Nitrogen compounds	Seeds	[39, 25]
Betanin	Seeds	[25]

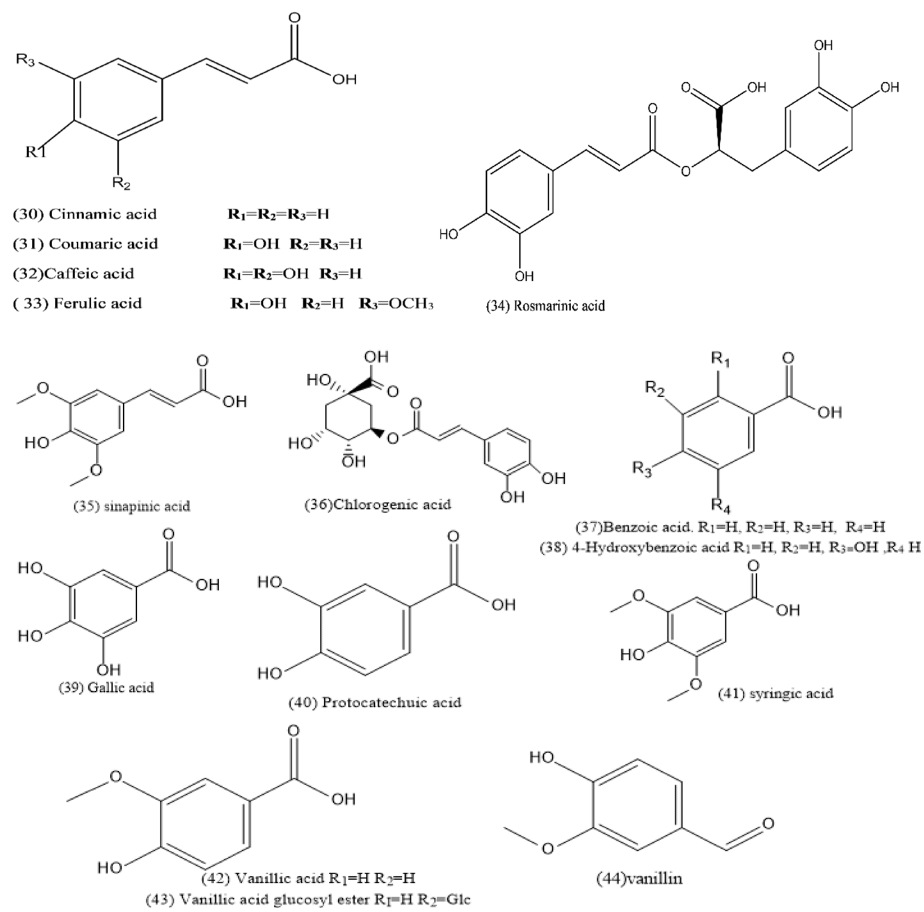


Fig. 6 Structures of phenolic acids and derivatives (30–44) from quinoa [36, 39, 35]

identified and preassigned thanks to liquid chromatography-tandem mass spectrometry (LC-MS/MS) [26]. Oleanolic acid (70), hederagenin (71), spergulagenic acid (72), serjanic acid (73), phytolaccagenic acid (74), and gypsogenin (75) are the primary aglycones as shown in Table 8; Fig. 8. Both α-tocotrienol (76) and β-tocotrienol (77) were also identified in quinoa seeds as meroterpenoids. They were the members of the vitamin E family to show antioxidant and anti-inflammatory properties. Only one sesquiterpene, namely caryophyllene (78) was identified in quinoa.

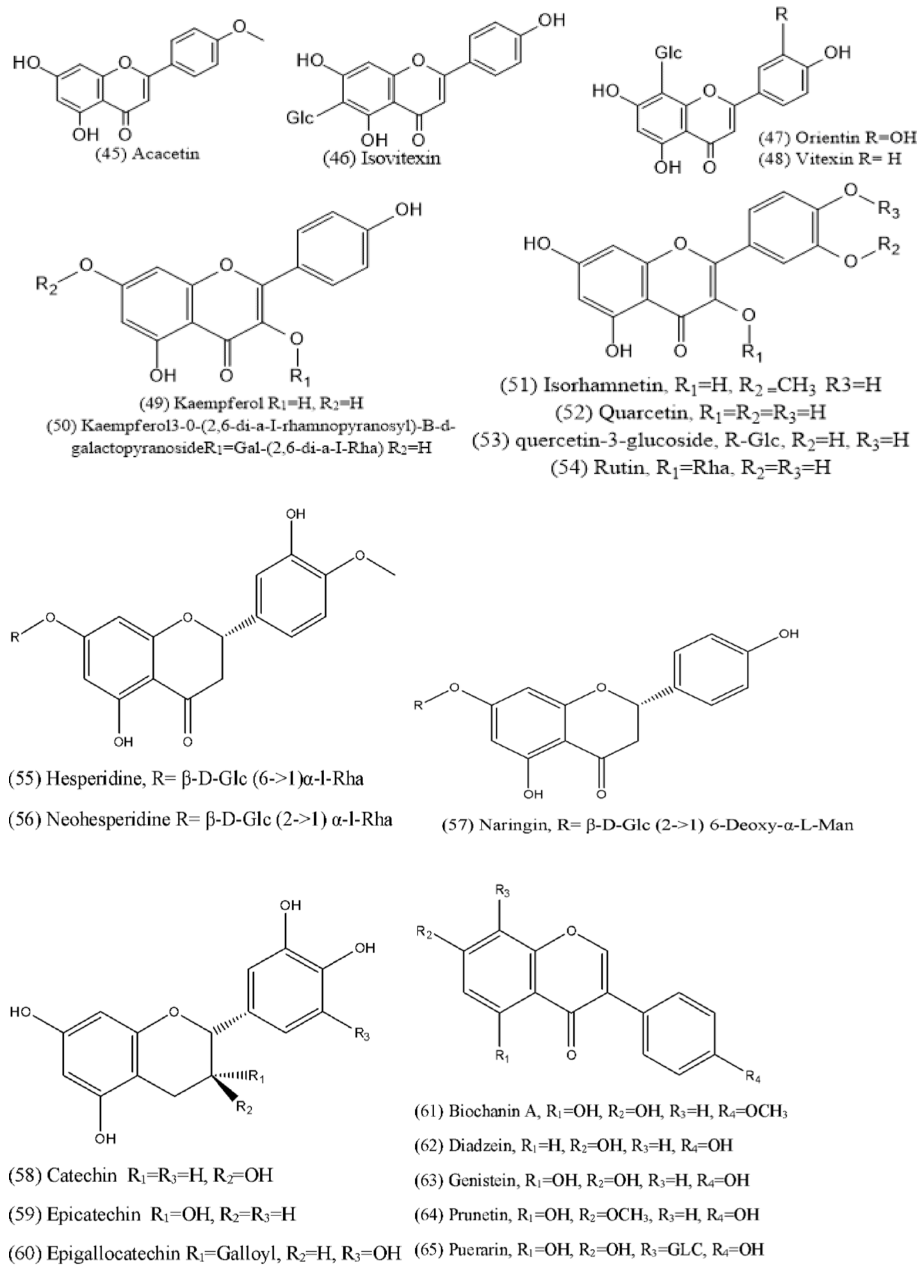


Fig. 7 Structures of flavones (45–48), flavonols (49–54) and flavanones (55–57), flavanols (58–60), isoflavones (61–65), from quinoa [37, 39, 35]

4.4 Phytosteroids

Based on the amount of carbon atoms in their structure, and they are mostly found in the bran region of the grain as free, polar/non-polar conjugated compounds. Only quinoa has a substantial amount of phytoecdysteroids (138–570 μg/g), making it a pseudo-cereal [25]. Quinoa has been shown to have over 36 different steroids. Among the quinoa lipids, seven sterols were found as cholesterol (79), campestanol (80), Makisterone (81), Δ5-avenasterol (82) and β-sitosterol (83), Table 8; Fig. 9, were the most prevalent in quinoa sterols [31].

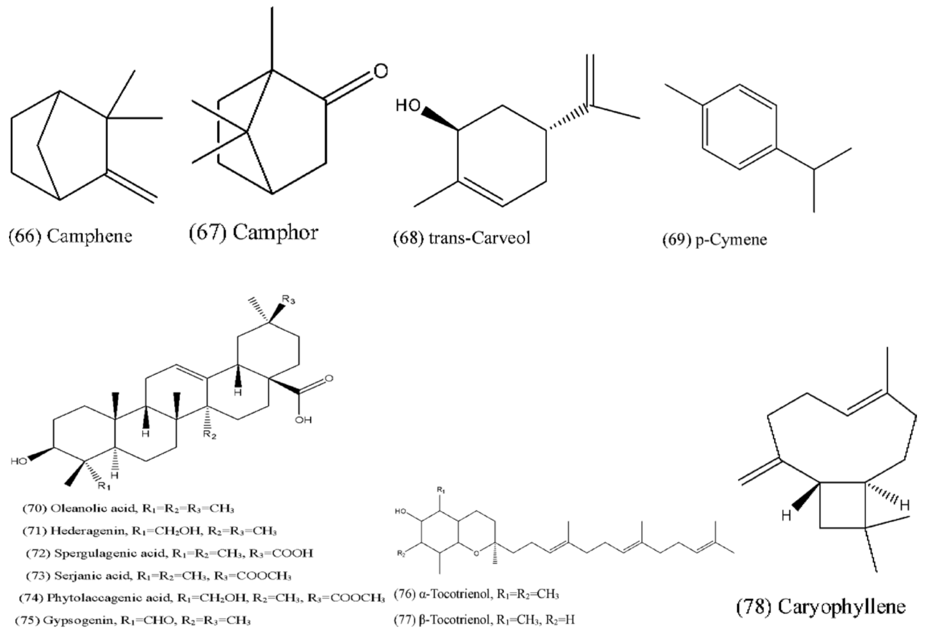


Fig. 8 Structures of monoterpenoids (66–69), triterpenoids (saponins) (70–75), meroterpenoids (76–77) and sesquiterpenoids (78) from Quinoa [35, 38].

4.5 Betalain

Quinoa has a water-soluble phytochemical called betalain, which acts as a natural antioxidant and helps prevent cancer. The red, black, or yellow colours seen in quinoa seeds and their vegetative sections are caused by this pigment. Red-violet and orange-red betaxanthins, nitrogen-aromatic indole compounds made from tyrosine, make up the betalain pigment [34]. Betalain is present in several types of quinoas. The use of microencapsulation to stabilise betalain and related compounds has been investigated recently. Microencapsulations with a high betacyanin concentration and a low saponin content have unique health-promoting qualities. One example of betalain is betanin (84), Table 8; Fig. 9.

5 The biological activities of Quinoa

There is a wide spectrum of biological activities like: cancer cell apoptosis, antidiabetic, antimicrobial, anti-obesity anti-oxidant, anti-inflammatory, and anti-hypertension. All of these are due to containing saponin, flavonoids, phytosterols, and polyphenols [31].

5.1 Induction of cancer cells apoptosis

It is done through the mitochondrial intrinsic route by saponin and polyphenols like: quercetin and apigenin in quinoa including the inhibition of antiapoptotic protein (Bcl-2) besides the activation of the pro apoptotic protein caspase 3 and caspase 9 (Fig. 10). Bcl2 protein is located on the site of outer membrane of mitochondria and has a role in the prevention of cytochrome c and caspase activation [40].

Quinoa-derived polyphenols have been implicated in the modulation of the extrinsic apoptotic pathway through their regulatory effects on death receptors. Specifically, these compounds have been shown to upregulate the expression of key death receptors, including Fas, DR4, and DR5, thereby enhancing cellular sensitivity to apoptotic ligands such as TRAIL (TNF-related apoptosis-inducing ligand) and FasL (Fas ligand), which

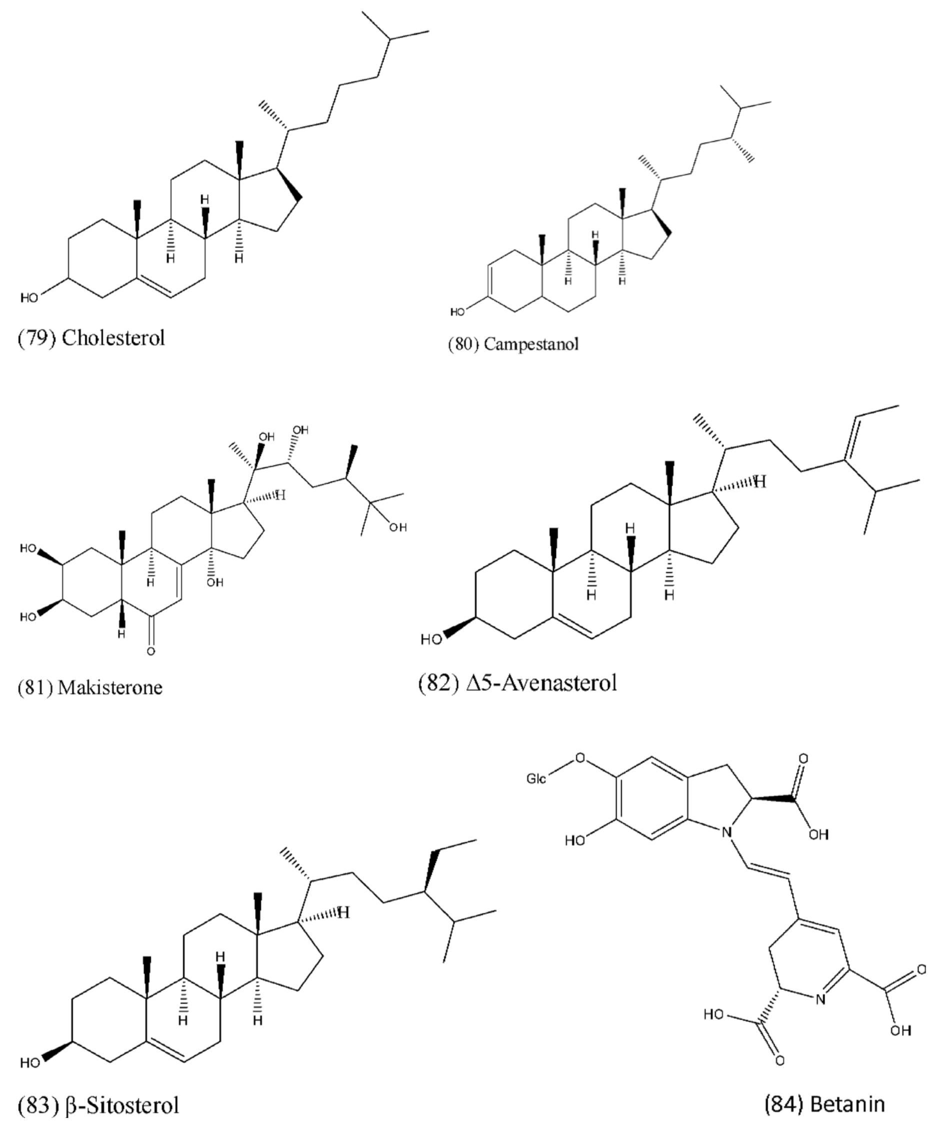


Fig. 9 Structures of phyto steroids (79–83) and betanin (84) in Quinoa [39].

initiate apoptotic signaling cascades [41]. Mechanistically, polyphenols such as epigallocatechin gallate (EGCG) act by promoting Fas/FasL interactions, leading to the activation of caspase-8, which subsequently triggers the effector caspase-3, culminating in programmed cell death.

5.2 Antidiabetic effect

Saponins in quinoa lower glucose in the body through different mechanisms at different sites [42]. Figure 11 shows the different mechanisms by which quinoa saponins can lower the blood glucose level.

Polyphenolic compounds, including flavonoids such as quercetin and phenolic acids like ferulic acid, exert significant anti-diabetic effects through multiple biochemical mechanisms:

1. Inhibition of carbohydrate-digesting enzymes

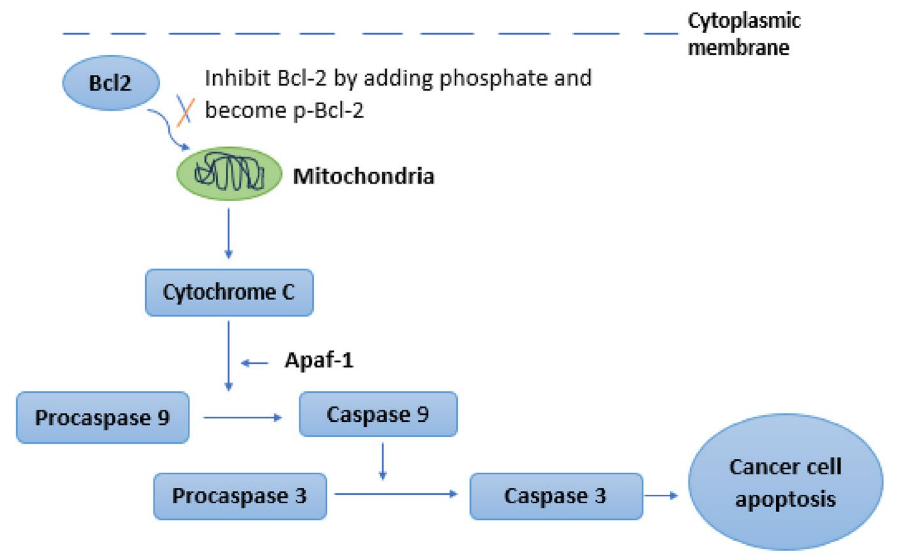


Fig. 10 Represents the detailed mechanism of quinoa in cancer cell apoptosis

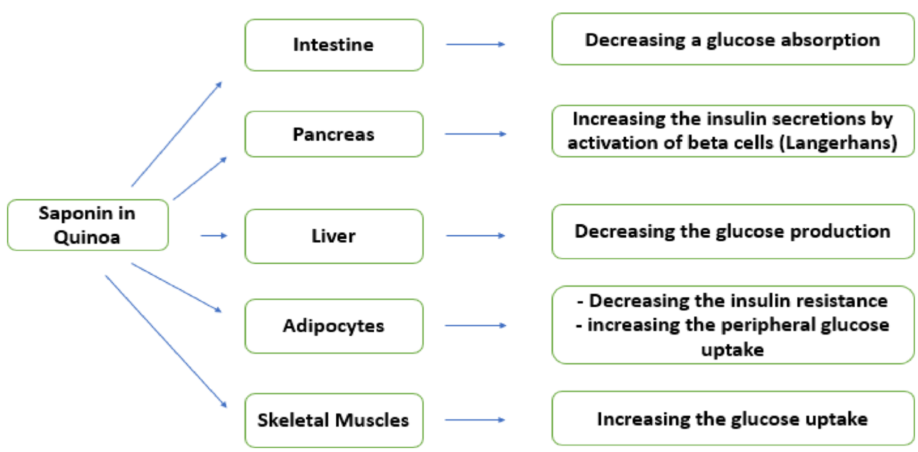


Fig. 11 The mechanisms of Quinoa on the treatment of diabetes

- ***α-Amylase Inhibition***: This impedes the hydrolysis of starch into oligosaccharides in the oral cavity and small intestine, thereby slowing the rate of glucose absorption.
- ***α-Glucosidase Inhibition***: This enzyme is responsible for the final step in carbohydrate digestion, breaking down disaccharides into monosaccharides. Its inhibition limits glucose release at the intestinal brush border.

These enzymatic modulations collectively contribute to attenuated postprandial hyperglycemia and improved glycemic control [41].

2. Enhancement of glucose uptake via insulin signaling pathways

Flavonoids improve cellular glucose uptake through both insulin-dependent and insulin-independent mechanisms as they stimulate the PI3K/Akt signaling pathway, leading to the translocation of GLUT4 glucose transporters to the plasma membrane in skeletal muscle and adipose tissue. They also activate AMP-activated protein kinase (AMPK), which enhances insulin sensitivity and promotes glucose uptake independent of insulin signaling [43].Quercetin, in particular, has been shown to facilitate glucose transport in adipocytes and myocytes, further supporting its insulin-mimetic properties.

3. Protection of pancreatic β-cells

Polyphenols and flavonoids exert cytoprotective effects on pancreatic β-cells by Scavenging reactive oxygen species (ROS), thereby mitigating oxidative stress–induced cellular damage. In addition to downregulating pro-inflammatory cytokines such as TNF-α and IL-6, reducing inflammatory responses that contribute to β-cell dysfunction and apoptosis [44].

5.3 Anti-obesity

The quinoa has a great role in the treatment of patients with obesity due to the presence of saponins. Saponins reduce the accumulation of triglycerides by activating the phosphorylation of AMPK which cause B-oxidation of lipids instead of forming free fatty acids or causing lipogenesis [45]. Furthermore, it suppresses the appetite signals in the hypothalamus either by stimulation of 5 HT releasing from ilea or by activation of capsaicin-sensitive sensory (Fig. 12) [45].

5.4 Anti- obesity effect of flavonoid and polyphenols in Quinoa

Firstly: inhibition of adipogenesis by suppressing the expression of genes which involved in fat cell differentiating like: (C/EBP alpha, PPAR gamma). Moreover, it inhibits the lipid accumulation in preadipocytes which considered as fat precursor cells. All of this results in decreasing the formation of new fat cells and reduction of fat mass [46].

Secondly: flavonoids can apply modulation of appetite and satiety hormones and that is done by modulating leptin and ghrelin which control appetite and satiety and this potentiate the reduction of calorie intake and promote weight loss [46].

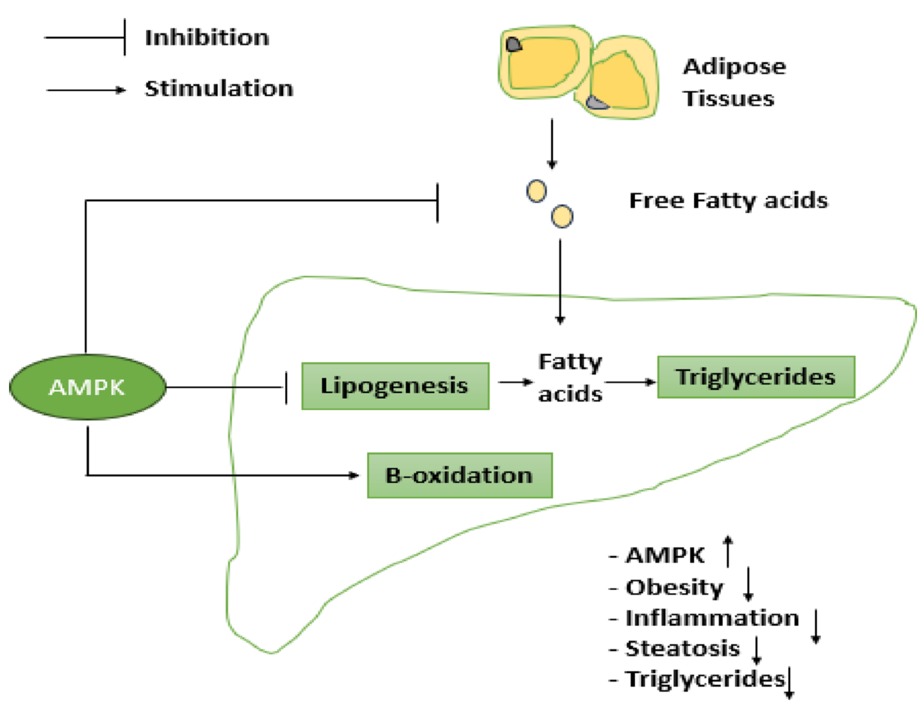


Fig. 12 Represents the role of Quinoa on decreasing the accumulation of triglycerides and treating the obesity

5.5 Antimicrobial effect

The polyphenols and saponins have a good role as antimicrobials. By examining the antimicrobial effect of Quinoa saponins on foodborne pathogenic bacteria [47]. We observed that saponin like: triterpenoid glycosides in quinoa caused severe damage to the bacteria by degradation of the cell wall and then, disruption of the membrane protein and cytoplasmic membrane which led to cell contents leakage. Moreover, it shows a potent effect against S. aureus and S. epidermidis. We determined that by the estimation of MIC minimum inhibitory concentration and MBC minimum bactericidal concentration [47]. Polyphenols has a role as antioxidant which induce oxidative stress and generate ROS in bacterial cells which cause DNA and protein damage [48]. Furthermore, inhibit microbial DNA gyrase and topoisomerase. Phytosterols like B-sitosterols which is abundant in quinoa, interfere with bacterial quorum sensing [49].

5.6 Antioxidant effect

Flavonoids and polyphenols in quinoa have a great role as an anti-oxidant by inhibition of ROS generation or scavenging of ROS and that's done through the inhibition of free radical generating enzymes like: xanthine oxidase, lipoxygenases and cyclooxygenases which produce the reactive oxygen species ROS through enzymatic reactions [42].

5.7 Free radical scavenging via electron or hydrogen atom transfer

Quinoa (Chenopodium quinoa Willd.) exhibits potent antioxidant activity primarily due to its high content of phenolic compounds, notably ferulic acid, quercetin, and kaempferol glycosides. These compounds exert their effects through both direct radical scavenging and indirect modulation of antioxidant pathways.

1. Direct ROS scavenging via electron and hydrogen atom transfer

Phenolic compounds neutralize reactive oxygen species (ROS)—including hydroxyl radicals (•OH), superoxide anions ($O_2•^-$), and peroxynitrite ($ONOO^-$)—by donating electrons or hydrogen atoms. This process converts harmful radicals into stable species, preventing oxidative damage to lipids, proteins, and nucleic acids. The resulting phenoxyl radicals are resonance-stabilized, halting propagation of lipid peroxidation chains, particularly in cellular membranes [50].

2. Kaempferol-specific antioxidant actions

Kaempferol, a major flavonoid in quinoa, contributes to antioxidant defense through:

- Direct scavenging of ROS, thereby reducing lipid peroxidation, protein oxidation, and DNA damage [51].
- Indirect activation of the Nrf2–ARE signaling pathway, leading to upregulation of antioxidant and cytoprotective enzymes such as SOD, CAT, GPx, HO-1, and NQO1. This enhances endogenous antioxidant capacity and supports cellular redox balance [52].

Quinoa's antioxidant activity is partly mediated through metal ion chelation, a mechanism by which its polyphenols—particularly quercetin, kaempferol, and ferulic acid—bind and sequester transition metals such as Fe^{2+} and Cu^{2+}, thereby preventing metal-catalyzed oxidative reactions. These compounds contain structural features such as catechol groups, carbonyls, and hydroxyl groups that allow them to form stable complexes with metal ions, inhibiting key oxidative enzymes like lipoxygenases (LOXs). Since LOXs require Fe^{2+} for the oxidation of polyunsaturated fatty acids into pro-inflammatory lipid mediators (e.g., leukotrienes, HETEs), metal chelation by quinoa phenolics disrupts this catalytic cycle, reducing inflammation and oxidative damage. In vitro studies demonstrate up to 70–85% inhibition of LOX activity by quinoa extracts, an effect reversed upon addition of excess Fe^{2+}, confirming a chelation-based mechanism. This process not only attenuates lipid peroxidation but also limits chronic inflammation associated with various diseases [37, 52].

5.8 Anti-inflammatory effect

Quinoa has two mechanisms in the treatment as an anti-inflammatory. The first one is done by flavonoids via the inhibition of lipopolysaccharide which induce the inflammation. Moreover, the inhibition of interleukin-6. The second is done by flavonoids either kaempferol or quercetin by the inhibition of proinflammatory cytokines which induce the inflammation [furthermore, Inhibition of PI3K/Akt/NF-κB Signalling by Quinoa Saponins.

The PI3K/Akt/NF-κB signalling pathway is a key regulator of inflammatory responses, cell proliferation, and immune activation. When activated by stimuli such as lipopolysaccharides (LPS), reactive oxygen species (ROS), or metabolic stress, PI3K phosphorylates and activates Akt (Protein Kinase B). Akt, in turn, activates IκB kinase (IKK), which phosphorylates the inhibitory molecule IκBα. This leads to the nuclear translocation of NF-κB, a transcription factor that promotes the expression of numerous pro-inflammatory cytokines and mediators, including TNF-α, IL-6, IL-1β, COX-2, and iNOS.

Quinoa saponins have demonstrated potent anti-inflammatory and antioxidant effects through modulation of key molecular pathways in both in vivo and in vitro models. In hyperuricemic mice, oral administration of quinoa bran-derived saponins significantly lowered serum uric acid levels, ameliorated renal histopathological damage, and suppressed the expression of pro-inflammatory cytokines (TNF-α, IL-1β, IL-6) [31]. These effects were mechanistically linked to the inhibition of the PI3K/Akt/NF-κB signaling axis, where saponins reduced PI3K activation, Akt phosphorylation, and NF-κB nuclear translocation, thereby attenuating the transcription of inflammatory mediators. Concurrently, saponins enhanced renal antioxidant defenses by increasing activities of SOD, CAT, and GPx, and reducing lipid peroxidation markers such as MDA. In RAW264.7 macrophages, quinoa saponins (notably the Q50 fraction) inhibited LPS-induced production of NO, TNF-α, and IL-6 by interfering with TLR4-mediated signaling, downregulating iNOS expression, and preventing NF-κB activation and nuclear translocation [53]. These effects were confirmed by ELISA, Western blotting, RT-qPCR, and immunofluorescence. Overall, quinoa saponins exert systemic anti-inflammatory and antioxidant actions by disrupting PI3K/Akt/NF-κB and TLR4 signaling pathways, making them promising candidates for managing inflammatory and metabolic disorders such as gouty nephropathy and chronic kidney disease [37].

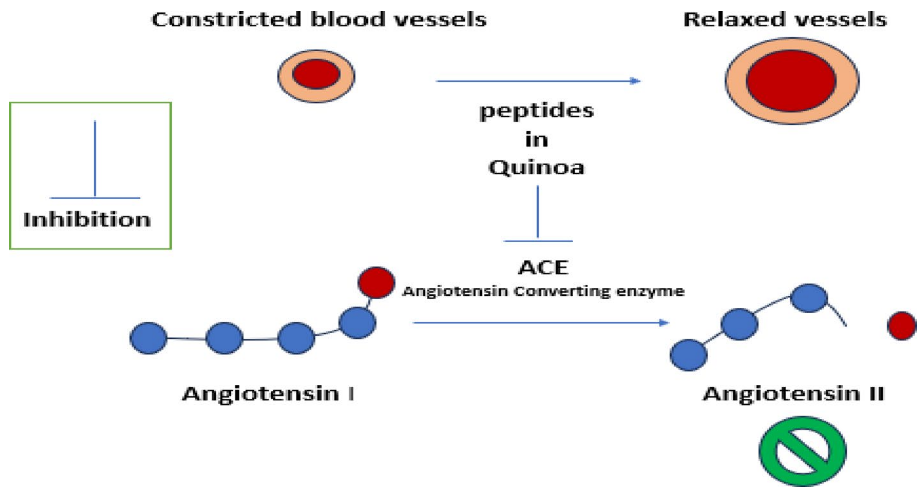


Fig. 13 The role of quinoa as ACE inhibitor in the treatment of hypertension

5.9 Anti-hypertension effect

The huge content of peptides prevents the angiotensin-converting enzyme in the body from converting angiotensin-I into angiotensin-II (Fig. 13), which leads to the relaxing of blood vessel walls and lowers the blood pressure [54].

5.9.1 Peptides derived from Quinoa fermentation exhibit potent ACE inhibitory activity

Fermentation of quinoa with *Lactobacillus paracasei* CICC 20,241 has been found to produce bioactive peptides with significant inhibitory effects on angiotensin-converting enzyme (ACE), a key regulator in the renin–angiotensin system and a pharmacological target for hypertension management. Two peptides isolated from the fermentation process—NIFRPFAPEL and AALEAPRILNL—exhibit distinct modes of ACE inhibition. NIFRPFAPEL functions as a competitive inhibitor, while AALEAPRILNL acts through a non-competitive mechanism. Both peptides demonstrated strong inhibitory potency, with IC_{50} values of 49 μM and 80 μM, respectively, indicating their effectiveness in attenuating ACE activity and their potential as functional components in antihypertensive nutraceutical formulations [54].

5.9.2 Mechanistic insights into ACE Inhibition by quinoa-derived peptides

Quinoa-derived peptides exhibit antihypertensive potential by targeting angiotensin-converting enzyme (ACE), a critical enzyme in the renin–angiotensin system responsible for the conversion of angiotensin I to the vasoconstrictor angiotensin II. Enzyme kinetics using Lineweaver–Burk plots revealed distinct modes of inhibition: the peptide NIFRPFAPEL acts as a competitive inhibitor, binding directly to the active site, while AALEAPRILNL exhibits non-competitive inhibition by interacting with an allosteric site, inducing conformational changes that impair enzymatic activity. Molecular docking studies confirmed these interactions, with NIFRPFAPEL forming strong hydrogen bonds with key active-site residues (Tyr523, Glu384, His513) and additional stabilization via hydrophobic interactions and salt bridges. Moreover, these peptides may interfere with ACE's zinc-binding domain, which is essential for catalysis. Their demonstrated binding affinity, stability under physiological conditions, and multimodal inhibition support their role as promising natural ACE inhibitors for blood pressure regulation [55].

6 Limitations and future research directions

Although *Chenopodium quinoa* exhibits promising health benefits, current research is limited by several factors that hinder its full scientific and clinical validation.

1. **Reliance on In Vitro and Animal Studies**: Most evidence stems from laboratory and rodent models, which do not accurately reflect human physiology. Translation to human health outcomes requires further validation.
2. **Lack of Human Clinical Trials**: Few well-controlled clinical studies exist. Data on effective doses, long-term safety, and population-specific outcomes are lacking, highlighting the need for randomized controlled trials.
3. **Limited Bioavailability and Metabolism Data**: The absorption, metabolism, and biological activity of quinoa's phytochemicals in humans remain poorly understood. Identification of active metabolites and their systemic effects is essential.
4. **Variability in Composition**: Quinoa's nutritional and phytochemical content varies across cultivars, environments, and processing methods. Standardization in research is needed, and breeding programs should target improved phytochemical traits and reduced antinutritional factors like saponins.
5. **Incomplete Understanding of Mechanisms**: While pathways such as PI3K/Akt/NF-κB and Nrf2/ARE are involved, more studies are needed on synergistic effects, epigenetic regulation, and microbiome interactions.

6.1 Future research should focus on

- Conducting robust clinical trials.
- Studying ADME and metabolite activity in humans.
- Exploring gut microbiota interactions.
- Standardizing quinoa processing and phytochemical profiling.
- Using omics technologies to elucidate mechanisms.
- Applying precision nutrition approaches.
- Advancing breeding for enhanced bioactivity and stress resilience.

Addressing these gaps will support the safe and effective integration of quinoa into evidence-based nutritional and therapeutic strategies.

7 Conclusion

Chenopodium quinoa is a nutritionally dense and agronomically resilient crop with growing global interest due to its exceptional health-promoting properties and adaptability to diverse environmental conditions. It offers a complete protein profile with all essential amino acids, is rich in dietary fiber, unsaturated fatty acids, and essential micronutrients, and contains a wide array of phytochemicals, including flavonoids (e.g., quercetin, kaempferol), phenolic acids, and saponins. These compounds contribute to quinoa's documented antioxidant, anti-inflammatory, anti-diabetic, anti-obesity, antihypertensive, and antimicrobial activities through well-defined molecular mechanisms, such as modulation of redox signaling (Nrf2/ARE), inhibition of inflammatory mediators (PI3K/Akt/NF-κB), and enzyme inhibition (ACE, α-glucosidase, LOX).

However, while numerous in vitro and in vivo preclinical studies have established quinoa's pharmacological potential, there remains a critical need for well-designed human clinical trials to confirm its efficacy, safety, optimal dosage, and long-term effects in various populations. Moreover, factors such as bioavailability, digestive stability, and inter-individual variability in metabolic response must be better understood before quinoa-derived compounds can be reliably translated into therapeutic or preventive applications.

From an agricultural and food systems perspective, continued breeding efforts are essential to enhance desirable traits such as saponin content modulation (for reduced bitterness and enhanced palatability), bioactive compound enrichment, yield stability under abiotic stress, and resistance to pests and diseases. Advances in genomics, metabolomics, and precision breeding tools offer new opportunities to tailor quinoa varieties for both nutritional optimization and climate resilience.

In summary, quinoa stands at the intersection of nutrition, health, and sustainable agriculture, yet its full potential will only be realized through integrated efforts that include clinical validation, translational research, and targeted crop improvement programs.

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Author contributions
A.A.A. collected the data on the nutritional value and wrote this part. A.A.A. collected the data about the chemical composition and wrote these parts. M.A.N. wrote the introduction and distribution part. S.M.E. collected the data on the biological activity and wrote this part. S.M.E. suggested the idea, collected the written parts, and revised the manuscript draft. All authors read and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethical approval and consent to particpate
Not Applicable.

Consent for publication
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Competing interests
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