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Review

Nutrient composition, functional activity and industrial applications of quinoa (*Chenopodium quinoa* Willd.)

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ABSTRACT

Quinoa is one of the gluten-free crops that has attracted considerable interest. Quinoa contains functional ingredients such as bioactive peptides, polysaccharides, saponins, polyphenols, flavonoids and other compounds. It is very important to determine efficient methods to identify such functional ingredients, and to explain their possible health benefits in humans. In this review, the chemical structure and biological activity mechanisms of quinoa nutrient composition have been elaborated. In addition, the development of quinoa-based functional foods and feed is emerging, providing a reference for the development of functional products with quinoa as an ingredient that are beneficial to health. The active ingredients in quinoa have different health effects including antioxidant, antidiabetic, antihypertensive, anti-inflammatory, and anti-obesity activities. Further exploration is also needed to improve the application of quinoa within the functional food industry, and in the areas of feed, medicine and cosmetics.

1. Introduction

The drastic changes that are occurring to the world’s ecology are having a great impact on human life, especially restricting food supply by affecting the yield and quality of crops. Therefore, it is essential to find an alternative nutritious crop that can adapt to climate change. From a nutritional point of view, the usefulness or functionality of any grain as a food mainly depends on the quantity and quality of the protein that it contains. Natural plant protein has attracted much attention due to its safety, high biocompatibility, nutritional value and low cost. Therefore, finding new plant proteins rich in essential amino acids is very important for the food and pharmaceutical industries (Amanda, Moreno, & Carciofi, 2020). The functional component content of cereals mainly depends on genetic composition and environmental factors. In this case, quinoa seems to be a good choice that can meet almost all nutritional needs and provide compounds with health-promoting properties (Ruiz et al., 2014).

Quinoa is a pseudo cereal native to the Andes of South America. Quinoa has been grown as a new alternative crop in many places because of its high nutritional properties and environmental

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Abbreviations: 20E, pure 20-hydroxyecdysone; AF, abdominal fat; ALT, alanine aminotransferase; AP2, Apetala 2; AST, aspartate transaminase; BAPs, bioactive peptides; C/EBP α, CCAAT/enhancer binding protein α; C/EBP β, CCAAT enhancer binding protein β; C/EBP δ, CCAAT enhancer binding protein δ; CCK, cholecystokinin; DPP-IV, dipeptidyl peptidase-IV; DPPH, 1,1-diphenyl-2-picrylhydrazyl; FRAP, ferric ion reducing antioxidant power; GI, glycemic index; IGF-1, insulin-like growth factors -1; IL-6, interleukin-6; HFD, high-fat diet; LDL, low-density lipoprotein; LDL-C, low density lipoprotein cholesterol; MCF-7, Michigan Cancer Foundation-7 cell line; MDA, malondialdehyde; MICs, minimum inhibitory concentrations; NO, nitric oxide; ORAC, oxygen radical absorbance capacity; PPAR γ, peroxisome proliferator-activated receptor γ; QAP, quinoa alkaline-extract polysaccharide; QE, 20-hydroxyecdysone; QPN, quinoa protein nanoparticles; QWP, quinoa water-extract polysaccharide; ROS, reactive oxygen species; SQAP, separate quinoa alkaline-extract polysaccharide; SMMC 7721, human hepatoma cell line; SREBP1C, sterol regulatory element binding protein-1c; SQWP, separate quinoa water-extract polysaccharide; TGF-1, transforming growth factor-β1; TNF-α, tumor necrosis factor-α; TG, total triglyceride; TPC, total phenol content; VF, visceral fat.

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adaptability (Castro et al., 2019). For example, salt stress induces better absolute and relative growth rates, and quinoa can adapt to drought-affected environments through its high water use efficiency. At present, quinoa is grown in South America, North America, Asia, Europe and other places. Peru is the largest producer and exporter of quinoa, and Peru and Bolivia together account for 90 % of the world's production, with global increases in the past few years approaching a total of 160,000 metric tons (Fathi & Kardoni, 2020). Diverse studies have revealed that quinoa possesses a plethora of bioactive compounds, such as proteins, polysaccharides, saponins and flavonoids (James, 2009; Pereira, Cadavez, Barros, Encina-Zelada, & Ferreira, 2020). Therefore, these bioactive compounds have been identified as playing important roles in promoting health by serving as antioxidant (Daliri, Ahmadi, Pezeshki, Hamishehkar, & Ghorbani, 2021), hypolipidemic (Cao et al., 2020), antidiabetic (Mudgil, Kilari, Kamal, Olalere, & Maqsood, 2020; Tan, Chang, Liu, Li, & Zhao, 2020), anti-inflammatory (Yao et al., 2015), and anticancer (Mohamed, Fouda, & Mohamed, 2019; Stiki, Milini, Kosti, Jovanovi, & Pei, 2020). In addition, quinoa can be regarded as an important raw material for development as a functional ingredient and food to improve human health. Although many studies have confirmed that quinoa has the physiological activity of regulating chronic diseases, its mechanism and main biological components are not clear, which hinders the breeding of high-quality quinoa varieties and the development of high value products. The FAO has announced that the high nutritional value and genetic diversity of quinoa may contribute to food security in the 21st century, thus identifying quinoa as one of the promising plants for human food production.

In recent years, more in-depth research has been carried out on the nutritional value of quinoa and the development of quinoa products, with different processing methods resulting in a great impact on their nutritional quality and health benefits. Several challenges remain in optimizing the role of quinoa in promoting global human health and nutrition. Considering the development and innovation in the quinoa industry, this review focuses on the bioactive compounds in quinoa, their related biological activities and benefits to health, as well as the progress and future prospects for the commercialization of quinoa and its products. At the same time, this review provides insights for further development of the quinoa industry including precision nutritious foods.

2. Functional components

Quinoa is rich in functional ingredients, which are of great significance for improving human health. These functional ingredients mainly include polyphenols, flavonoids, carbohydrates, peptides and saponins. The bioactive compounds in quinoa and the methodologies for their identification are shown in Fig. 1 and Table 1, respectively.

2.1. Bioactive proteins and peptides

Quinoa is considered to be a nutritional grain mainly because of its high protein content and balanced proportion of amino acids, especially lysine and arginine (Comai et al., 2007). In a recent study, the protein content of six quinoa varieties was measured and found to range from 15.6 % to 18.7 % (Gómez, Prieto, Sobrado, & Magro, 2021). In another study, the composition and secondary structure of six different quinoa varieties from China were investigated (Wang, Zhao, & Yuan, 2020). The molecular weight of the quinoa protein isolate (QPI) ranged from 10.0 kDa to 50.0 kDa with β-sheets forming the main secondary structure and comprising 30.86 % to 36.88 % of the protein. Spectrum deconvolution techniques are often used to identify secondary protein structures. Using these methods, strong peak differences were identified in the protein secondary structure of different quinoa cultivars (García-Parra, Roa-Acosta, García-Londoño, Moreno-Medina, & Bravo-Gomez, 2021). Titicaca seed proteins had a larger ratio of β-sheet-1 and β-sheet-2 and contained β-turns-1, while Nariño mainly contained β-turns-2, β-turns-3 and α-helices. The secondary structure spectrum can also be used as a fingerprint for each variety. An improved spectral method could be used to identify genetic variation and control the quality of adulterated flour. According to Drzewiecki et al. (2018), the absorption bands of quinoa associated with —NH groups at 1657 cm-1 and 1549 cm-1 represent the amide I and amide II bands, respectively, and can be attributed to the aromatic C—H bend protein structure. This structural feature is also related to antioxidant activity of quinoa proteins. The protein in quinoa seeds is mainly composed of 11S globulin (37 %) and 2S albumin (35 %), both of which are stabilized by disulfide bonds (Drzewiecki et al., 2018). In addition, quinoa seeds contain low concentrations of gliadin (0.5–7 %), which is suitable for people with celiac disease (Dakhili, Abdolalizadeh, Hosseini, Shojaee-Aliabadi, & Mirmoghtadaie, 2019). Lunasin is a new anticancer peptide that exists widely in soybean and maize, and it has been detected in quinoa by

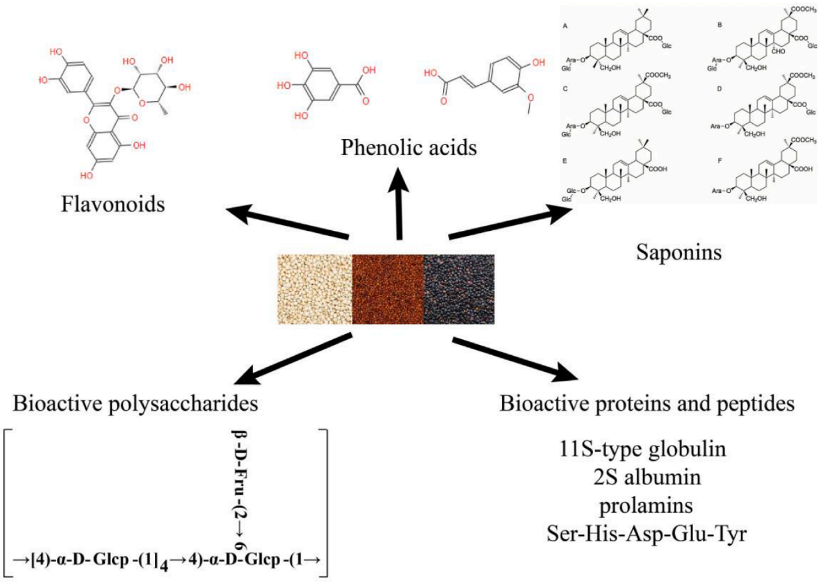

Fig. 1. The basic structures of some representative bioactive compounds isolated from quinoa.

Table 1
Bioactive compounds in quinoa and their methods of identification.

Family	Compounds	Identification methodology	References
Polyphenols	Rutin, vanillic acid, ferulic acid, kaempferol, quercetin derivatives, p-coumaric, daidzein, caffeine, caffeic acid, pinocembrin, apigenin, pinocembrin	HPLC-DAD-MS, LC-ESI-QTOF-MS, HPLC-DAD, UHPLC/ESI-Orbitrap MS	(Antognoni et al., 2021; Tang et al., 2015)
Flavone	Quercetin, kaempferol, myricetin, isorhamnetin, Quercetin glucuronide, Kaempferol glucuronide, Kaempferol 3-O-glucoside, Kaempferol pentosyl rhamnoside, Kaempferol, Quercetin-3-O-(2″-apiosyl)-rutinoside	HPLC-ESI-MS3 HPLC	(Balakrishnan & Schneider, 2020; Ritva, Hellstroem, Pihlava, & Mattila, 2010; Tang et al., 2015)
Saponins	Phytolaccagenic acid, Oleanolic acid, Serjanic acid, Hederagenin	HPLC, HPLC/MS, 1D and 2D NMR	(Yousif et al., 2020; Xue et al., 2020)
Bioactive polysaccharides	SQAP-1, SQAP-2, SQWP-1, SQWP-2, QWP-1, QWP-2, QAP-1, QAP-2	1D and 2D NMR, GC–MS	(Hu et al., 2017; Teng et al., 2020; Teng et al., 2021)
Bioactive proteins and peptides	QPH, BAPs, globulins, albumins, prolamins, QPN	HPLC, FTIR, IFS	(Daliri et al., 2021; Guo et al., 2021; Mudgil et al., 2020; Vilcacundo et al., 2018; Zhang, Zuo, Ma, Yu, & Wang, 2021)
Phytoecdysteroid	20-hydroxyecdysone	LC–UV–MS	(Graf et al., 2014)

HPLC, high-performance liquid chromatography; ESI, electrospray ionization; MS, mass spectrometry; NMR, nuclear magnetic resonance; GC, gas chromatography; IFS, intrinsic fluorescence spectroscopy; QAP, quinoa alkaline-extract polysaccharide; QWP, quinoa water-extract polysaccharide; SQAP, separate quinoa alkaline-extract polysaccharide; SQWP separate quinoa water-extract polysaccharide.

UPLC-ESI-MS, with the planting location affecting the quantity in the grain (ranging from 1.01 × 10–3 mg/g to 4.89 × 10–3 mg/g) (Ren, Zhu, & Shi, 2017). Lysine is described as the first limiting amino acid (Sheng, Xin, Wang, Peng, & Li, 2019) and it can promote human development and enhance immune function, making it an essential nutrient for children. Researchers have shown that quinoa is rich in lysine and it can promote the absorption and transport of calcium in the body (Stikic et al., 2012).

Many studies have confirmed that active peptides in quinoa have hypoglycemic, hypotensive and hypolipidemic activities. Indeed, quinoa protein hydrolysates treated with different food grade enzymes inhibited dipeptidyl peptidase-IV (DPP-IV) and α-glucosidase angiotensin converting enzyme (Mudgil et al., 2020). Further, effective bioactive peptides have been obtained by synergistic treatment of quinoa protein with pepsin and trypsin; peptides with molecular weight < 5 kDa showed antioxidant activity, and peptides with molecular weight > 5 kDa showed the strongest anticancer activity (Vilcacundo, Miralles, Carrillo, & Hernandez-Ledesma, 2018). The main protein precursors of quinoa peptides are 13S globulin seed storage protein 2-like, legumin A-like, and 11S globulin seed storage protein 2-like, accounting for 32.15 %, 21.01 % and 20.25 % of the total peptides, respectively (Guo, Hao, Fan, Richel, & Ren, 2021).

2.2. *Bioactive polysaccharides*

Polysaccharides are high molecular weight carbohydrates bound by glycosidic bonds, which have a variety of biological activities. Quinoa polysaccharides mainly include starch polysaccharides and non-starch polysaccharides. Starch is the most important carbohydrate in quinoa seeds. The crude starch content is about 60 %, and among the starches, the amylopectin content is higher than the amylose content (Barreto, Miano, Alvarez, & Pérez, 2021). Jiang et al. (2020) found that the starch in quinoa showed better resistance to retrogradation than corn or wheat starch, and the amylose content of four varieties of quinoa ranged from 9.43 % to 10.90 %. A preliminary study indicated that germination significantly impacted on the structural and physicochemical properties of quinoa starch, such as decreases in the relative crystallinity (Xing, Teng, Sun, Zhang, & Qin, 2021).

A low molecular weight (8852 Da) quinoa polysaccharide component, composed of galacturonic acid and glucose monosaccharide, has demonstrated antioxidant, anti-inflammatory and anticancer activities (Hu, Zhang, & Zou, 2017). An active polysaccharide with a glycosidic bond of Glc-(1→, →4)-Glcp-(1→, →4, 6)-Glcp-(1 → was isolated and purified from quinoa by alkali-extraction and was identified to have strong antioxidant activity (Teng, Qin, Shi, Zhang, & Ren, 2020). In addition, another bioactive polysaccharide (SQWP-2) was isolated and purified from quinoa, and it arrested the differentiation of 3 T3-L1 cells by inhibiting PPARγ and C/EBPα and showed anti-obesity activity (Teng, Shi, Yao, & Ren, 2020). Ultrasonic assisted extraction technology has been used to extract another quinoa polysaccharide, which was composed of glucose and arabinose at a molar ratio of 1.17:1 (Cao et al., 2020).

Dietary fiber is a type of carbohydrate that has nutritional functional activity and cannot be digested by the human small intestine, but can be partially digested and metabolized by microorganisms in the large intestine. The total dietary fiber content in quinoa ranges from 7 to 9.7 %, mainly in the embryo, and the soluble dietary fiber content ranges from 1.3 to 6.1 % (Abugoch, 2009). Replacing refined grains with fiber-rich, gluten-free whole grains such as quinoa is an effective way to address gluten-free fiber deficiencies in the diet of people with celiac disease symptoms.

2.3. *Saponins*

Quinoa saponins represent glycated secondary metabolites that exist in bran and seeds, and these chemicals are formed by carbohydrate chains connected to hydrophobic aglycone through glycoside chains (Fiallos-Jurado et al., 2016). In addition, saponins are considered to be the main factors causing the bitter and astringent taste in quinoa. Saponin content decreases during processing such as pearling, which reduces quinoa's bitterness.

Because saponin is a characteristic substance in quinoa, there are many studies on methods for its determination. Yousif, Snowball, D'Antuono, Dhammu, and Sharma (2020) developed an innovative method based on water droplet surface tension to quantify saponin content more accurately, with concentrations measured in the range of 0.05 to 0.15 mg/mL. The total saponin content of quinoa was 3.33 %, and after atmospheric pressure, under pressure and toasting treatments the saponin content percentages decreased slightly to 2.48 %, 2.54 % and 2.69 %, respectively (Nickel, Spanier, Botelho, Gularte, & Helbig, 2016). Mass spectrometer analysis showed that the saponin content decreased during quinoa germination, from about 0.4 % after 12 h sprouting, to 0.05 % in seeds sprouted for 72 h (Estrella, Borgonovo, Buratti, Ferranti, & Marti, 2021). In total, twenty triterpene saponins have been isolated from different parts of quinoa (Tiwatt et al., 2008).

Although quinoa saponins are considered anti-nutritional factors, there are still many studies indicating that quinoa saponins have beneficial biological activities, such as anti-inflammatory, antibacterial, antioxidant, anti-obesity and neuroprotective effects (Dong, Yang, Hou, & Xue, 2020; Han et al., 2019). Dong et al. (2020) isolated six components of saponins from quinoa and following treatment of Staphylococcus aureus, Staphylococcus epidermidis and Bacillus cereus, these led to degradation of the cell walls and destruction of the plasma membrane and membrane proteins, resulting in the leakage of cell contents. In another biochemical study, quinoa saponin hydrolysate inhibited pancreatic lipase activity and reduced cholesterol in a dose-dependent manner (Hierro, Casado-Hidalgo, Reglero, & Martin, 2021). Compared with quinoa extract containing saponin, quinoa extract without saponin has lower total polyphenols, total flavonoids, tocopherols and antioxidant activity. Pandya, Thiele, Zurita-Silva, Usadel, and Fiorani (2021) evaluated the saponin content in 114 different quinoa germplasms and their corresponding saponins. The relative saponin content ranged from 0.22 to 15.04 mg/g seed dry weight and the difference between the genotypes lay in their aglycone and glycoside unit quantities and types (Pandya et al., 2021). Interestingly, crude saponins extracted from quinoa have demonstrated stronger antifungal activity than purified saponins (Woldemichael & Wink, 2001). With crude saponins inhibiting the growth of Candida albicans at a concentration of 50 μg/mL. In contrast, the minimum inhibitory concentration of purified saponins and distreptomycin were 100 μg/mL and 500 μg/mL, respectively. The difference between crude and purified saponins may be attributed to synergistic interactions between multiple components of the extract, and these may affect several molecular targets simultaneously (Woldemichael & Wink, 2001).

2.4. Polyphenols and flavonoids

Polyphenols are important products of biologically active plant secondary metabolism, with one or more aromatic rings and hydroxyl groups in the structure, and are widely found in quinoa. The content of such phenolic compounds affects the taste of quinoa as well as its functional properties.

Tang et al. (2015) detected 23 polyphenols in quinoa, mainly vanillic acid, ferulic acid and their derivatives, quercetin, kaempferol and their glycosides.Darker quinoa seeds have higher phenolic concentrations and antioxidant activity. The polyphenol content of quinoa is also affected by the environmental factors at the planting site. Antognoni, Potente, Biondi, Mandrioli, and Ruiz (2021) determined the polyphenol content in the two quinoa varieties, Regalona and Titicaca, which were grown in Denmark and Italy. The main difference between the Regalona varieties grown in the two places was the free vanillic acid and daidzein contents, whereas for Titicaca there were variations in the content of quercetin derivatives between the two locations.

Work conducted by Liu, Zhu, Yao, Chen, and Li (2020) reported that the total phenol content (TPC) in red quinoa, white quinoa and black quinoa ranged from 514.03 to 1409.54 mg gallic acid equivalent / 100 g. Eight separate phenolic acids were detected, and the total acid content ranged from 86.21 to 188.76 μg / g. Protocatechuic acid is the main phenolic acid in red quinoa and black quinoa. Polyphenols in red and black quinoa are mainly in a combined form, while they exists in a free form in white quinoa. García-Parra et al. (2021) reported pinocembrin and apigenin for the first time among quinoa compounds, and these polyphenols are known to be triggered by plant pathogens in other species.

The main flavonoids identified in quinoa are flavonols, including quercetin and kaempferol glycosides. In addition, a small amount of myricetin and isorhamnetin exist in some quinoa varieties (Balakrishnan & Schneider, 2020). After gastric and intestinal enzyme treatment, it was found that most flavonoids in quinoa were intact and the concentrations increased significantly. Besides, in experiments on a simulated gastric phase comprising hydrolysis under acidic conditions to release phenolic compounds bound to other nutrients, the phenolic content of the gastric extract from quinoa seeds, sprouts and flakes was approximately twice that of the undigested extract. Further, Hirose, Fujita, Ishii, and Ueno (2010) isolated and identified four flavonol glycosides from Japanese quinoa seeds - quercetin, kaempferol 3-O-(2′’,6-di-O-α-rhamnopyranosyl)-β-galactopyranosides, quercetin 3-O-(2′’,6′’-di-O-α-rhamnopyranosyl)-β-glucopyranoside and quercetin 3-O-(2″-O-β-apiofuranosyl-6″-O-α-rhamnopyranosyl)-β-galactopyranoside. According to Liu et al. (2020), the total flavonoid content ranged from 177.49 to 407.75 mg rutin equivalent (RE)/100 g in white, red and black quinoa.

2.5. Other compounds

In addition to the above active substances, quinoa also contains some low-content ingredients such as anthocyanins, fatty acids, minerals, etc., which also play an important role in promoting human health.

Previous studies have shown that the color of quinoa is related to the anthocyanin content, and it has been identified that the antioxidant activity of dark quinoa is higher than other colors (Eam & Ch, 2020).

There is a high proportion of unsaturated fatty acids in quinoa oil, which are more beneficial to health than saturated fatty acids. Quinoa lipids are relatively stable and are not easily oxidized after heating or following contact with oxygen. Palmitic acid is the main saturated fatty acid in quinoa, accounting for 10 % of the total fatty acid content. Unsaturated fatty acids include oleic acid, linoleic acid and linolenic acid (Valcárcel-Yamani & Lannes, 2012). The fatty acid content in the embryo of quinoa grain is higher than the content in the ectoderm, pericarp and seed coat. It is worth noting that the fatty acid content varies between different quinoa varieties. Duarte, Goessling, Fonseca, Jacobsen, and Matos (2022) analyzed the fatty acid profiles of 10 quinoa varieties grown in the same geographic location using different chemometric multivariate approaches. Palmitic acid ranged from approximately 15 % in Pandela Rosada to about 8.6 % in the seed of Titicaca. The relative content of myristic acid in the seeds of different quinoa varieties was similar. In addition, the fatty acid content of quinoa also varies with processing. Electron beam irradiation is a new and effective food sterilization processing method, which has been widely used in the storage and sterilization industry. The content of polyunsaturated fatty acids in quinoa increased by 3 % at 1 kGy and the value of ω3/ω6 increased by 5 % after electron beam irradiation (Luo et al., 2021). The phytic acid content in quinoa is significantly higher than in lentils, whole wheat and broad beans. After irradiation treatment, the phytic acid content of quinoa decreased significantly, mainly due to the influence of free radicals and the breakage of the phytate ring. Tannins are an antinutritional factor, and their adverse effects are due to their ability to compound macromolecules, thereby reducing the nutritional value of food. The average total amount of tannins observed in quinoa seeds grown in Peru is 0.88 mg CE g-1 (Ruales & Nair, 1993) and the tannin content in quinoa is closely related to the color. Black quinoa has a high content, but the tannins in white quinoa are almost undetectable (Melini & Melini, 2021). In addition, the tannin content is reduced during food processing. Quinoa has significantly higher levels of riboflavin and folic acid than wheat and rice. The contents of potassium, magnesium, phosphorus, iron and copper in quinoa whole grains are relatively high, and are higher than in wheat. Phosphorus, potassium and magnesium are located in the embryo. Calcium is mainly present in the seed coat, which can become compounded with pectin (Tan et al., 2020). In addition, quinoa also contains active ingredients such as betaine, phytic acid, squalene, and phytosterols, which have antibacterial, antiviral, and antiallergic properties that help reduce the risk of cardiovascular disease and diabetes. Quinoa contained higher amounts of betaine than other pseudocereals, approximately 3930 μg/g (Ross, Zangger, & Guiraud, 2014).

The content of quinoa active ingredient is generally well defined, and attention should be paid to the varietal differences and their variations in processing to meet specific nutritional needs. In addition, the metabolites produced by these components during digestion should also deserve in-depth study.

3. Biological activities

Quinoa is a functional nutritious crop due to its many health-promoting substances. Therefore, we should also pay attention to its health effects. Due to its high nutritional value and gluten-free properties, quinoa is beneficial for sensitive groups such as children, the elderly and patients with diabetes, dyslipidemia, obesity and celiac disease. Most of these properties are reported to be due to dietary fiber, peptide minerals, fatty acids, antioxidants, and especially phytochemicals. Many studies have shown that quinoa and its bioactive compounds have a variety of health promoting effects. They can be used as antioxidants as well as antidiabetic, anticancer, anti-inflammatory, antihypolipidemic, and antihypertensive agents. The different biologically active ingredients in quinoa and their respective active mechanisms in vivo and in vitro are shown in Fig. 2 and Fig. 3. Functional activity types, processing methods, compounds, research objects were shoewd in Table2.

3.1. *Antioxidant activity*

Oxidative stress caused by the imbalance between ROS production and antioxidant defense may lead to body damage. Many biologically active ingredients in quinoa have been proven to have antioxidant activity in vitro and in vivo. Antioxidant activity is an important index to evaluate the ability of compounds to reduce reactive oxygen species, and many chemical detection methods have been developed to evaluate the antioxidant activity of foods.

Different processing methods have an important influence on the antioxidant activity of quinoa. Germination treatment has been shown to increase the content of phenols and antioxidant capacity in quinoa. However, processes such as steaming destroy the tissue structure of quinoa, resulting in a large loss of phenolics and a decline in antioxidant capacity (Gu, Chang, Bai, Li, & Wang, 2021). During grinding, the contents of total phenols and flavonoids decreased by 31.5 % and 41.4 % respectively, and total antioxidant activities according to the ORAC and FRAP assays also decreased by 39.6 % and 40.7 %, respectively (Han et al., 2019). In a broader study of the antioxidant activity of various parts of the quinoa plant, roots and sprouts were observed to have higher antioxidant capacity than other parts, which may be due to their different phenolic compounds (Lim, Park, & Yoon, 2020). Quinoa ethanol extract had effective antioxidant capacity according to the ferric reducing/antioxidant power and 1,1-diphenyl-2-picrylhydazyl assays, thus indicating excellent antioxidant capacity, which is related to the extract's high flavone content (Lee & Yoon, 2017). Finally, aqueous alcohol extracts of quinoa seed coat may contain mercaptan compounds, which inhibit microsomal lipid peroxidation and reduce microsomal mercaptan content (Letelier, Rodríguez-Rojas, Sánchez-Jofré, & Aracena-Parks, 2011).

In addition, quinoa peptides and polysaccharides also have obvious antioxidant activity. For example, quinoa peptides produced by trypsin digestion have DPPH free radical scavenging ability, which is mainly due to the expansion of protein molecules after hydrolysis and the greater availability of electron donor amino acids (Daliri et al., 2021). The peptide lunasin from quinoa has shown weak DPPH radical scavenging activity, but had strong ABTS (+) radical scavenging activity and oxygen radical scavenging activity (Ren et al., 2017). A purified quinoa alkali-extracted polysaccharide has also been reported to have the ability to reduce DPPH, ABTS, hydroxy radicals, superoxide radicals and ferric ions (Teng et al., 2020 a). A betaine-loaded nanocarrier based on the 11S globulin from quinoa showed a stronger antioxidant effect than unloaded ones (Jimena et al., 2019). The vitamin E present in quinoa also has the effect of preventing lipid oxidation (Schumacher et al., 2010).

As shown in Fig. 2, a diet supplemented with quinoa seeds reduced the oxidative stress in plasma, kidney, liver and lung of rats fed with fructose. Plasma lipid peroxidation was also inhibited, which was reflected in a significant decrease in the plasma malondialdehyde (MDA) concentration (Pasko, Barton, Zagrodzki, & Izewska, 2010). In work conducted by researchers in Morocco, quinoa seeds possessed high phenol content and strong antioxidant activity according to the DPPH,

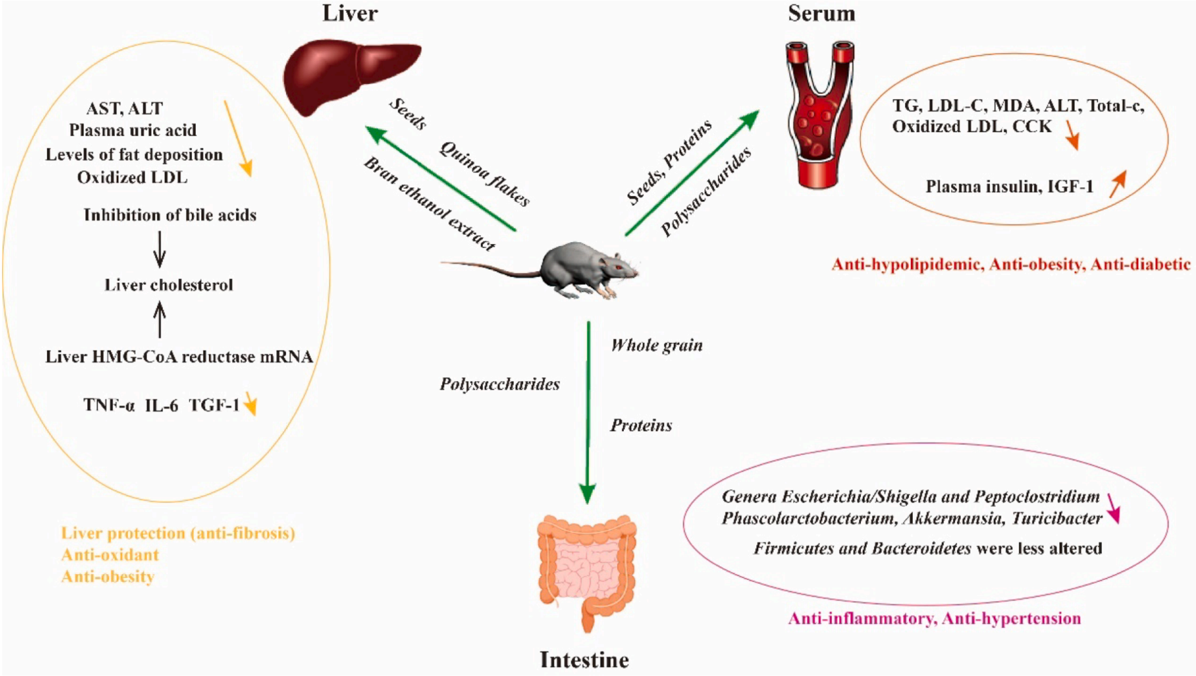

Fig. 2. Different biologically active ingredients in quinoa and their active mechanisms in vivo. Quinoa and its biologically active ingredients mainly act on the small intestine, muscle and liver. AST, aspartate transaminase; ALT, alanine aminotransferase; LDL, low-density lipoprotein; TNF-α, tumor necrosis factor-α; IL-6, interleukin-6; TGF-1, transforming growth factor-β1; TG, triglyceride; LDL-C, cholesterol LDL; MDA, malondialdehyde; CCK, cholecystokinin; IGF-1, insulin-like growth factor-1.

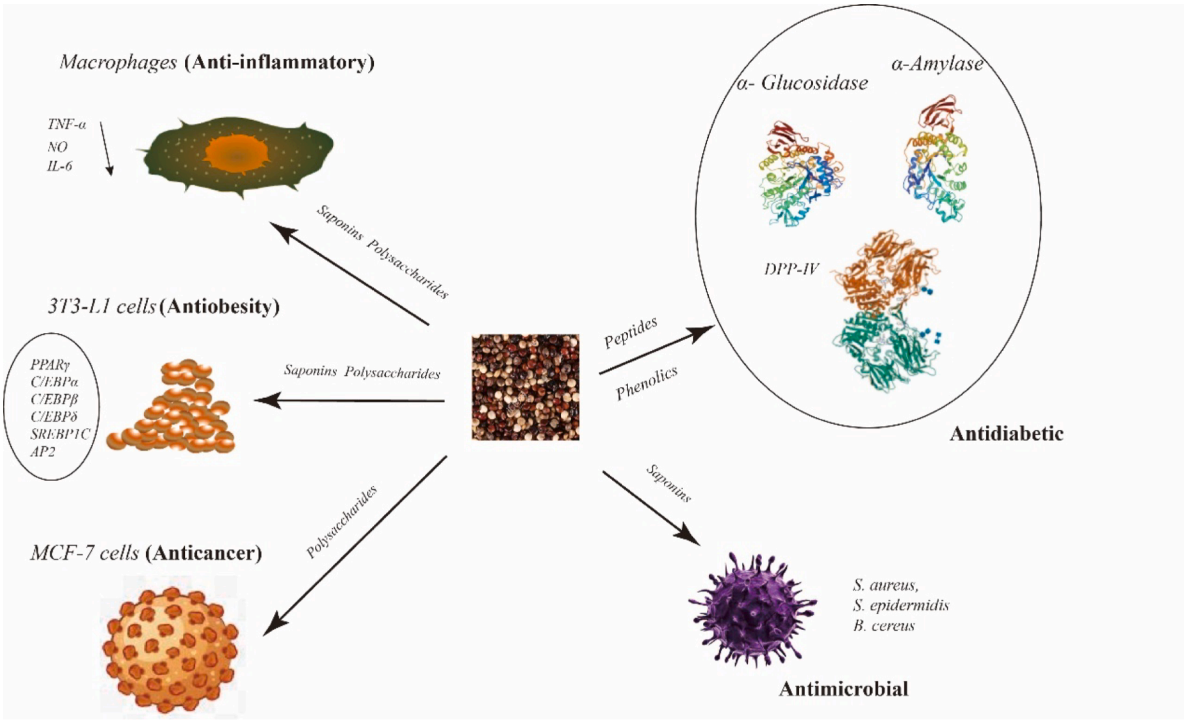

Fig. 3. Different biologically active ingredients in quinoa and their active mechanisms in vitro. TNF-α, tumor necrosis factor-α; NO, nitric oxide; IL-6, interleukin-6; PPAR γ, peroxisome proliferator-activated receptor γ; C/EBP α, CCAAT/enhancer binding protein α; C/EBP β, CCAAT enhancer binding protein β; C/EBP δ, CCAAT enhancer binding protein δ; SREBP1-c, sterol regulatory element binding protein-1c; Ap2, apetala2; DPP-IV, dipeptidyl peptidase-IV.

Table 2
Effect of functional components of quinoa on biological activity.

Functional activity types	Processing method	Compounds	Research object	References
Antioxidant activity	germination↓, grinding↓, steaming↓,	phenols, mercaptan, peptides, polysaccharides, vitamin E	ORAC, FRAP, iron and 1,1-diphenyl-2-picryl-hydrin, DPPH, ABTS, hydroxy radicals, superoxide radicals,	Gu et al., 2021; Han et al., 2019; Letelier et al., 2011; Daliri et al., 2021; Teng et al., 2020; Schumacher et al., 2010
Anticancer activity		polysaccharides, phenolic, amaranthin, apigenin II	MCF-7 cell, SMMC 7721 cell, human cervical cancer cell lines (C4-I, HTB-35, HTB-34), human colorectal cancer cell line HCT-116, prostate cancer cells	Hu et al., 2017; Paśko et al., 2019; Stiki et al., 2020; Gawlik-Dziki et al., 2013;
Antidiabetic activity	germination↑, fermentation↑, 20-hydroxyecdysone↑	oleanolic acid, ethyl acetate extract, protein hydrolysates, dietary fiber,	α-glucosidase, α-amylase, obese hyperglycemic mice, DPP-IV,	Ujiroghene et al., 2019 ; Ayyash et al., 2018; Graf et al., 2014; Nongonierma et al., 2015;
Anti-inflammatory activity		saponins, lunasin, polyphenols, phenols, peptides	macrophages, Caco-2 cells,	Ren et al., 2017; Noratto et al., 2015; Capraro et al., 2020; Shi et al., 2019; Liu et al., 2020
Hypolipidemic activity	ultrasonic↑	Polysaccharides, ethanol extract,	rats,	Cao et al., 2020; Hashem et al., 2021; De Carvalho et al., 2014
Anti-obesity activity		Saponins, Polysaccharides, 20-hydroxyecdysone,	3 T3-L1 cells, rats,	Yao et al., 2015; Teng et al., 2020; Foucault et al., 2012
Liver protection activity		phenols, polyunsaturated fatty acids, phytic acid, α, γ, δ-tocopherols, red quinoa bran ethanol extracts	HepG2 cancer cell line, obese mice, male rats	Mohamed et al., 2019; Gewehr et al., 2016; Lin et al., 2019; Abdel-Wahhab et al., 2021
Antihypertensive activity		protein, peptides	Hypertensive rats, ACE,	Ogawa et al., 2001; Guo et al., 2021; Zheng et al., 2019
Antimicrobial activity	alkali transformation↑	saponins, complex formed by starch and gold nanoparticles, phenolic	Escherichia coli, Staphylococcus aureus, Botrytis cinerea, halitosis-related bacteria	Sun et al., 2019; Pagno et al., 2015; Pereira et al., 2020

"↑" and "↓" indicated the positive or negative effects on biological activity after processing.

FRAP and β - carotene bleaching tests, and the quinoa ethyl acetate extract had the highest antioxidant activity (Marmouzi, ElMadani, Charrouf, Cherrah, & El, 2015). The above studies show that quinoa secondary metabolites may be used as potential therapeutic agents in many pathophysiological processes involving oxidative stress.

Quinoa extracts have also shown antioxidant activity in real food systems. Hsian-tsao can be added to quinoa protein to prepare edible films. The antioxidant activity of composite films increased from 44.59 % to 71.72 %, which was due to the fact that Hsian-tsao contains flavonoids, polyphenols, terpenes and other substances, which had a strong scavenging ability for DPPH (Zhao, Chen, Gao, Feng, & Tang, 2021). Pichia myanmarensis produces non-alcoholic beer through joint fermentation with quinoa, and the product has strong antioxidant activity, mainly due to the phenolics and flavonoids in quinoa (Prasad, Vidyalakshmi, Baskaran, & Anand, 2022). A study indicated a decrease in total polyphenols, total flavonoids, and γ tocopherol content and antioxidant activity in quinoa ethanol extract after removal of saponins (Miranda et al., 2017). However, the process of removing saponins by washing with water did not adversely affect the ability to inhibit lipid oxidation in a marine-oil heated model system. In another study, quinoa ethanol extract blocked Atlantic chub mackerel lipid oxidation and hydrolysis, which was effective in improving the quality of current commercial seafoods (Miranda et al., 2018). The above studies have shown that quinoa extract can exhibit antioxidant capacity in the actual food system, thereby improving food quality and shelf life.

3.2. *Anticancer activity*

At present, most studies on the anticancer activity of quinoa have focused on in vitro cell experiments. Hu et al. (2017) used quinoa extract on MCF-7 breast cancer and SMMC 7721 human hepatoma cancer cell lines and demonstrated that the polysaccharide component had inhibitory effects on the cancer cells, but not on normal cells. This result shows promise for the development of quinoa extracts as anticancer agents. There are a large number of phenolic compounds in quinoa leaves that play a role in chemoprevention and as anticancer agents through synergistic effects on oxidative stress and ROS-dependent intracellular signal transduction (Gawlik-Dziki et al., 2013). Paśko, Tyszka-Czochara, Namieśnik, Jastrzębski, and Leontowicz (2019) compared the anticancer activities of several pseudocereals and found that quinoa had cytotoxic activity against human cervical cancer cell lines (C4-I, HTB-35, HTB-34). The hypocotyls of quinoa are rich in amaranthin and apigenin II, which have been proven to slightly inhibit the activity of cancer cells. Stiki et al. (2020) identified 13 phenolic compounds in quinoa varieties Puno and Titicaca, and found an effective anticancer activity against human colorectal cancer cell line HCT-116 from quinoa seed extract. Quinoa leaves are also a substantial source of active components including a variety of phenolic acids that can inhibit the proliferation of prostate cancer cells in vitro, and that also play a chemopreventive role in oxidative stress and ROS dependent intracellular signal transduction (Gawlik-Dziki et al., 2013). With expansion of the quinoa industry, the clinical application of anticancer treatments derived from quinoa and its extracts may become more significant.

3.3. *Antidiabetic activity*

It is well known that α-glucosidase directly participates in the metabolic pathways of starch and glycogen, releasing glucose by hydrolyzing the glucosidic bond, and that α-amylase hydrolyzes α-1,4-glycosidic bonds in starch to produce dextrin, oligosaccharides and monosaccharides. Therefore, the inhibitory effect of α-glucosidase and α-amylase is considered to be an effective way to lower blood sugar levels. Many ingredients in quinoa show antidiabetic activity.

Probiotic fermentation can enhance the health characteristics of grains. For example, Bifidobacterium fermentation significantly increased the α-glucosidase inhibitory activity of quinoa (Ayyash, Johnson, Liu, Al-Mheiri, & Abushelaibi, 2018), and oleanolic acid from germinated quinoa incorporated into a yoghurt beverage had a strong inhibitory effect on α-glucosidase (Ujiroghene et al., 2019).

In small animal studies, a quinoa ethanol leachate containing 20-hydroxyecdysone, which is a common phytoecdysteroid, as well as flavone glycoside and protein, significantly reduced the fasting blood glucose of obese hyperglycemic mice (Graf et al., 2014). More recently, an ethyl acetate extract of quinoa has shown good antidiabetic activity according to an amylase activity assay (Hassan, Al-Salman, Redha, Salem, & Saeed, 2020). Further, feeding rats on a high fructose diet with quinoa seeds significantly reduced the levels of serum total cholesterol, low density lipoprotein and triglyceride plasma total protein, and achieved hypoglycemic effects (Pasko et al., 2010).

HPLC-DAD analysis has shown that the distribution of phenolic compounds in quinoa is not exclusive to the outer layer of the grain, as extracts from quinoa bran and hulls have demonstrated significant effects on α-amylase and α-glucosidase inhibitory activity (Hemalatha, Bomzan, Rao, & Sreerama, 2016). The mechanism of dipeptidyl peptidase 4 (DPP IV) inhibitors is to increase incretin levels, which inhibits glucagon release. An in vitro experiment indicated that the IC50 value of QPI for DPP-IV inhibition was 11.8 mg/mL, but after hydrolysis, the inhibitory effect of quinoa protein hydrolysates (QPH) on DPP-IV was significantly improved (Nongonierma, Maux, Dubrulle, Barre, & Fitzgerald, 2015). In another study, the inhibition of DPP-IV by different enzyme-treated quinoa protein hydrolyzates was compared. The inhibitory activity of alkaline protease and chymotrypsin hydrolysate is better than bromelain hydrolysate. The difference may be attributed to the specificity of the enzyme used for proteolysis and the hydrolysis conditions (Mudgil et al., 2020).

Chen et al. (2021) compared the structural, physicochemical and functional characteristics of dietary fiber in quinoa and wheat. Quinoa soluble dietary fiber showed higher α-amylase and α-glucosidase inhibition abilities than wheat soluble dietary fiber, which is related to the specific network structure, fiber composition and bound polyphenol content of dietary fiber.

The antidiabetic activity of functional components of quinoa in vivo and their physical, chemical and nutritional interactions with other components in the food system need to be further studied.

3.4. *Anti-inflammatory activity*

Macrophages are stimulated by lipopolysaccharides (LPSs) to produce inflammatory mediators, such as nitric oxide (NO), which are used as an index to evaluate the anti-inflammatory activity of active substances. Saponins and lunasin in quinoa seeds have also been associated with inhibiting the overproduction of inflammatory mediator, including NO, TNF-α, and IL-6, suggesting that quinoa saponins may be a good functional food ingredient for the prevention and treatment of inflammation (Ren et al., 2017).

Polyphenols extracted from quinoa can downregulate IL-1 β, IL-8 and TNF cytokines in cultured colonic epithelial Caco-2 cells and also prevent obesity-induced inflammation and promote gastrointestinal health in mice (Noratto, Carrion-Rabanal, Medina, & Mencia, 2015). Two purified chenopodins (low / high charge chenopodin) have demonstrated potential anti-inflammatory activity in an intestinal cell Caco-2 model by activating the NF- κ B signaling pathway and inhibiting IL-1 β expression (Capraro, Benedetti, Dio, Bona, & Scarafoni, 2020).

In vitro enzymatic hydrolysis technology has been widely used in food protein treatment to produce peptides with a variety of beneficial effects. Shi, Hao, Teng, Yao, and Ren (2019) found that the total protein and the protein hydrolysate of quinoa inhibited the release of NO and had anti-inflammatory activity.

Quinoa leaf extracts and quinoa phenols can inhibit LPS-stimulated NO production in a concentration-dependent manner, and the inhibitory activity of free phenols is higher than bound polyphenols. In addition, the phenolic substances of red quinoa have better anti-inflammatory activity than those of white quinoa (Liu et al., 2020).

3.5. *Hypolipidemic activity*

A quinoa polysaccharide extracted using ultrasonic technology was shown to be composed of glucose and arabinose with a molar ratio of 1.17:1, and it assisted in reducing the contents of TG, LDL-C, MDA, ALT and AST and significantly improved dyslipidemia in rats induced by a high fat diet (Cao et al., 2020). It also regulated the structure of the intestinal microbial community, reduced the ratio of Firmicutes and Bacteroides, and improved HFD-induced hyperlipidemia.

An ethanol extract of quinoa seeds led to normalization of the levels of leptin and adiponectin hormone, and improvement to growth performance in hyperlipidemic rats (Hashem, Mahmoud, & Abd-Allah, 2021). It also reduced lipid peroxidation, increased catalase and glutathione peroxidase activities and reduced malondialdhyde. A study on 35 overweight people showed that eating 25 g of quinoa flakes for breakfast for four consecutive weeks could regulate blood lipids, increase the serum level of the antioxidant factor glutathione, and increase the urinary excretion of intestinal lignans (De Carvalho et al., 2014).

3.6. Anti-obesity activity

Quinoa is a food crop with well-known anti-obesity activity. Nevertheless, the mechanism of its strong anti-obesity effect is not clear. After treatment with saponins and the polysaccharide SQWP-2 derived from quinoa, the differentiation of 3 T3-L1 cells was affected and the expression of PPAR γ, C/EBP α, C/EBP β, C/EBP δ, Srebp1c and Ap2 was significantly inhibited (Teng et al., 2020; Yao et al., 2015). Foucault et al. (2012) found that adipose tissue-specific effects were mainly related to a reduction in adipocyte size and the expression of several genes involved in lipid storage, including lipoprotein lipase and phosphoenolpyruvate carboxykinase. Subsequently, supplementation of quinoa extracts rich in 20-hydroxyecdysone (QE) or pure 20-hydroxyecdysone (20E) in a high-fat diet was able to prevent the development of obesity. The anti-obesity effect of QE is due to increased energy consumption, glucose metabolism and oxidation, which impair adipogenesis and cause a reduction in dietary lipid storage in adipose tissue. In addition to QE and polysaccharides, quinoa seeds contain a large number of other active substances, some of which may also have anti-obesity effects and are worthy of further exploration.

3.7. Liver protection activity

As mentioned above, quinoa is rich in phenols, polyunsaturated fatty acids and phytic acid, and has demonstrated anticancer activity in the HepG2 cancer cell line and protective effects on non-alcoholic fatty liver disease (Mohamed et al., 2019). Indeed, much work in animal models has demonstrated beneficial effects on liver function from quinoa in the diet and quinoa extracts. Liver lipid peroxidation in rats fed quinoa was reported as being significantly lower than in the control group, and suggested the grain's ability to reduce lipid peroxidation in the liver. In another study, dietary supplementation with quinoa significantly promoted the balance between α, γ, δ-tocopherol content, which led to improved lipid distribution in the liver (Gewehr et al., 2016). Further, the intake of quinoa can prevent hepatic steatosis in obese mice.

Red quinoa bran ethanol extracts can improve liver fibrosis in mice by activating the antioxidant enzyme system and blocking the TGF-1 pathway (Lin, Ke, Cheng, & Lee, 2019). Chenopodium quinoa ethanolic extract significantly increased the values of GSH, SOD, GPX and catalase in liver of male rats so as to relieve the hepatotoxicity induced by cyclophosphamide (Abdel-Wahhab, Mannaa, Ashry, Khaled, & Gomaa, 2021).

3.8. Antihypertensive activity

Many studies have investigated the effects of quinoa on systolic blood pressure. Hypertensive rats fed with quinoa had significant reductions in blood pressure at five weeks, suggesting that quinoa has an antihypertensive effect (Ogawa, Watanabe, Mitsunaga, & Meguro, 2001). During gastrointestinal digestion, quinoa protein releases many promising bioactive peptide precursors, which may reduce blood pressure by regulating intestinal flora (Guo et al., 2021). ACE inhibitory activity is an in vitro indicator for evaluating antihypertensive properties. Several components in quinoa have been shown to have ACE inhibitory activity, especially peptides. Non-fermented quinoa had low ACE-inhibition. However, the ACE-inhibition increased markedly after 24 h of fermentation by L. plantarum which suggests that proteolysis occurred in the fermented grains raised the antihypertensive activities (Ayyash et al., 2018). Zheng et al. (2019) used cellulase and hemicellulose to extract albumin from quinoa bran, and hydrolyzed it using alkaline protease and trypsin to produce bioactive peptides. RGQVIYVL is an enzyme that exhibits high ACE inhibitory activity (IC50 = 38.16 μM) and exhibits significant antihypertensive effects in spontaneously hypertensive rats at concentrations of 100–150 mg/kg body weight. Molecular docking simulations show that it can interact with the active ACE site through hydrogen bonding with high binding force.

3.9. Antimicrobial activity

Antibacterial properties of quinoa components have been demonstrated by several groups. It has been reported that the alkali transformed saponins of quinoa hulls, especially the ATS-80 low polar component, show stronger antibacterial activity against three kinds of halitosis-related bacteria than the original quinoa saponins, and thus the alkali derivatives can be used as an oral cleaning treatment (Sun, Yang, & Xue, 2019). In another example, complexs formed by quinoa starch and gold nanoparticles are stabilized by an ionic silesquioxane, which can effectively inhibit Escherichia coli and Staphylococcus aureus, and can be used in food packaging to prolong shelf life effectively via inhibition of Escherichia coli and Staphylococcus aureus (Pagno et al., 2015).

The chemical components of quinoa have also been found to have antifungal activity. When alkali treated quinoa saponin extract acts on Botrytis cinerea, mycelial growth and conidial germination are significantly inhibited, with the alkali treatment leading to stronger antifungal activity due to the increased affinity between saponin derivatives and sterols in the cell membrane (Stuardo & Martín, 2008). The addition of 30 % quinoa achieved antifungal activity through increases in the content of amino acids and phenylactic and hydrophenylactic acids during the semi-liquid phase of wheat fermentation for packaged bread production (Dallagnol, Pescuma, Rollán, Torino, & Valdez, 2015). Quinoa essential oil has also shown antifungal effects on Aspergillus niger, Aspergillus oryza, Mucor pusillus and Fusarium oxysporum at low concentrations (10 ug/mL) (Ferdes, Juhaimi, & Ghafoor, 2017). Pereira et al. (2020) reported that quinoa phenolic extracts had antibacterial and antifungal activities against microbial strains.

Many studies have focused on quinoa protein modification or exogenous addition of active small molecules to optimize the inherent antimicrobial activity. Quinoa extracts have also shown antimicrobial activity in real food systems. Many studies have focused on quinoa protein modification or exogenous addition of active small molecules to optimize the inherent antimicrobial activity. Quinoa protein infused with lysozyme and subsequently modified with ultrasound or heat can be used to make active packaging films, with films prepared at pH 7.5 possessing the highest antimicrobial properties according to the inhibitory zones of Staphylococcus spp., Streptococcus agalactiae and Enterococcus faecalis (Mir, Riar, & Singh, 2023). Robledo et al. (2018) prepared a nanoemulsion-thymol-quinoa protein/chitosan coating and investigated the effect on the growth of inoculated cherry tomato mold, with significant inhibition of growth reported. Quinoa peptide-loaded liposomes have also led to significant inhibition of total bacterial, Staphylococcus aureus, mold and yeast counts in 12-day refrigerated burgers (Yekta, Rezaei, Nouri, Azizi, & Khaneghah, 2019). These studies have shown that modified processed quinoa protein has bacteriostatic effects and has the potential to be used as a novel preservative in food systems.

4. Industrial applications of quinoa

In recent years, many researchers have conducted in-depth research on the nutritional value of quinoa and the development of quinoa products. After processing, the texture, nutritional properties, and digestive properties of quinoa may be changed. Therefore, different processing methods could have a great impact on the nutritional quality and health benefits of quinoa products.

Quinoa can be used in baked goods such as biscuits, cakes, muffins and pies. Indeed, flour from colored quinoa seeds is considered to have antioxidant activity and is used as a functional ingredient in bread making. Similar results appeared in another study, and compared with wheat biscuits, quinoa biscuits have higher lysine content and higher antioxidant activity (Jan, Panesar, & Singh, 2018). Quinoa products can be used as antioxidants and natural nitrates in bologna sausage with high microbial safety (Fernández-López, Lucas-González, Roldán-Verdú, Viuda-Martos, & Pérez-Lvarez, 2020). Moreover, quinoa paste can partially replace fat during the cooking of meat products, which increases the health of the product to a certain extent by reducing fat content and improving fiber content (Pellegrini et al., 2018). The most acceptable edible effect was achieved with the addition of 5 % red quinoa. The swelling index, cooking loss, water absorption and protein loss of pasta is improved after the addition of quinoa, whose protein is rich in high lysine and methionine content, thus enhancing the product's nutritional and functional properties. There are also many studies focusing on the development of fermented quinoa products. Matsuo (2003) fermented quinoa with low spore Rhizopus to prepare quinoa tempeh and found significantly lower values of thiobarbituric acid-reactive substances in the serum and liver in rats fed with quinoa tempeh compared to rats fed with quinoa. Further, the activity of liver glutathione peroxidase in quinoa tempeh-fed rats was higher than in the quinoa grain-fed rats. These results showed that quinoa tempeh had higher antioxidant activity than quinoa grain in vivo.

Previous studies have explored the role of quinoa in dairy drinks, and have demonstrated its application potentiality. The yogurt produced from germinated quinoa can be used as a functional food beneficial to human health because of its strong antioxidant activity (Ujiroghene et al., 2019). Adding quinoa extract to goat milk can shorten the fermentation time and improve the vitality of lactic acid bacteria and the viscosity of the yogurt. Camel milk and quinoa seeds have also been used to make a mixed fermented milk with high nutritional value, and due to low water activity, coliform, yeasts, and molds were not detected, which indicated its safety (Abd-Rabou, Shehata, Sohaimy, & Awad, 2020).

The processing of gluten-free beverages is a key direction of research into new quinoa products. Indeed, malted quinoa beverages have higher protein content (2.9 g /100 ml) and total phenol content (2.9 mg Gallic Acid Equivalents (GAE)/g) than unmalted quinoa beverages, and have the potential for antidiabetic and antihypertensive effects (Kaur & Tanwar, 2016). Hussein, Fouda, Mehaya, Mohamed, and Mohamed (2020) added quinoa seeds and carrot juice to almond milk to prepare a beverage, whose γ-tocopherol content reached 0.557 μg/g, and it is suitable as a functional beverage to protect liver and heart tissue through reductions in TC, TG, LDL-C, MDA and TNF-α. Furthermore, the inherent differences in quinoa varieties may influence processing and product characteristics. For example, two quinoa varieties were used as raw materials to make fermented beverages, and it was found that compared to the variety Rosada de Huancayo, Pasankalla had higher protein content and lower saponin content and viscosity loss, which were more suitable for beverage production (Urquizo et al., 2017).

Bioactive substances existing in quinoa have the potential to be used as cosmetic additives. Quinoa seed extract rich in saponins shows the ability to reduce surface tension and can be used in cosmetics to penetrate the skin and enhance elasticity.

In addition to seeds, the nutritional value of other parts of the quinoa plant, including stems, leaves and roots, can be explored to increase product variety. For example, previous studies have confirmed that quinoa has the potential to produce high-quality leafy vegetables. Zhang et al. (2020) found that gastrointestinal digestion greatly affects the absorption and antioxidant capacity of polyphenols and flavonoids in quinoa sprouts. The content of protein, amino acids and potassium in quinoa leaves is higher than in amaranth or spinach, and quinoa leaves are also rich in polyphenols and flavonoids. In fact, quinoa leafy vegetables have great potential for introduction into the human diet as a new type of green vegetable. However, there have been few studies undertaken on the anti-nutritional factors in quinoa leaves, such as the changes in the saponin content, that may affect the nutritional quality of leaves. Therefore, more research is needed to determine appropriate levels for the safe and palatable consumption of quinoa leaves in the human diet.

Finally, the application of quinoa as animal feed is worthy of attention. Shah et al. (2020) assessed forage yield and morphological and quality traits during flowering and grain filling of 15 quinoa accessions, and found that genotypes possessing more branches and moderate plant height produced more quinoa forage. Quinoa seed meal has been used as a protein source to feed chickens, which improved kidney function (ALT and AST) and liver function (urea and creatinine), indicating that quinoa can be added to poultry feed to improve health (Mustafa et al., 2019). Jacobsen, Skadhauge, and Jacobsen (1997) found that the nutritional value of quinoa in chicken feed is better than wheat and corn. However, adding whole quinoa seeds to the feed will reduce the growth of chickens, but shelled quinoa can improve their weight gain in the short term. Therefore, growth inhibition is mainly caused by bitter compounds in bran. After a short adjustment, poultry can adapt to the bitter taste of saponins and make effective use of the nutrients in quinoa (Jacobsen et al., 1997). Besides seeds, the nutritional value of quinoa hay and straw is also important. The crude protein contents of quinoa hay and straw reach 19.9 % and 10.6 % respectively, and the dry matter digestibility is 75.8 % and 54.2 % respectively (Asher, Galili, Whitney, & Rubinovich, 2020). Therefore, quinoa could be used as a dual-purpose crop for grain production and livestock feed.

Although the quinoa industry is currently in a period of rapid expansion, some problems remain that need to be solved urgently. There are potential safety risks associated with improper consumption of quinoa products (saponin content etc.), and so the detection methods for various nutrients should be clarified. Research into the functional activity of quinoa has not been extensive enough, with insufficient development of functional products, and the utilization rate of by-products requiring improvement. Therefore, the development of differentiated and precise nutritional products is also an important direction for the quinoa industry.

5. Conclusion

Quinoa is an edible and medicinal plant that contains a variety of functional components, such as proteins, polysaccharides, saponins, polyphenols, flavonoids and other compounds. In vitro and in vivo experiments have demonstrated that quinoa and its bioactive components have a variety of health-promoting effects. Although some studies have explored the benefits derived from quinoa and its bioactive compounds, additional studies are needed for a comprehensive understanding. In terms of health outcomes, human clinical trials are an authoritative method to determine the curative effect of foods commonly used in medicine and food. Therefore, further well-designed clinical trials should be conducted to confirm the health benefits of quinoa and related products. The nutritional content of quinoa will also change under environmental adversity, but research in this area has been scarce and is worthy of in-depth exploration.

While a variety of quinoa products, such as healthy beverages and functional fermented foods have been developed and are widely consumed, there are few studies on the changes in the important bioactive compounds under different food processing methods. Further testing and development are thus needed to improve the application of quinoa in the functional food industry. At the same time, the application of quinoa components in cosmetics and medicine requires greater attention. In order to ensure the effectiveness and safety of all of these products, it is necessary to apply reliable scientific tools to evaluate the quality of quinoa and its functional components.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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