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A 10-Year Systematic Review (1 January 2014 to 1 January 2024) on the Potential Health Benefits of Quinoa

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Abstract

Quinoa has recently gain popularity since the declaration of International Year of Quinoa in 2013. However, there are still limited reviews on quinoa in terms of nutrition and health. Thus, the aim of this 10-year systematic review is to assess the nutritional profile and potential health benefits of quinoa. PubMed search was done on 10 January 2024 and 164 papers were identified within the past 10 years (1 January 2014 to 1 January 2024). After exclusions, a total of 35 papers were included in this systematic review. The 35 papers were categorised into three main themes: (a) effects of processing techniques, (b) potential health benefits, and (c) genotype and phenotype variation.

Introduction

According to the United Nations, the world population is expected to increase from 8.5 billion to 9.7 billion, and to 10.4 billion in 2030, 2050, and 2100 respectively [1]. This indicates the need to ensure sufficient food is available to prevent food hunger. The former director general of Food and Agriculture Organisation, Graziano da Silva, shared that quinoa is a cost-benefit solution to global hunger and improvement to the food industry [2] as 2013 is declared as the International Year of Quinoa (IYQ) to recognise the cultivation of quinoa.

Quinoa, originating from the Andean region more than 5000 years ago, is classified as a pseudocereal, belonging to the plant family whereby the plants produce starchy seeds for consumption. This differs from starchy grains; such as wheat, corn, or rice; that belongs to the grass family. Compared to other starches, quinoa is able to adapt and grow in various climatic differences and stresses such as soil with low moisture, high salinity, high acidity, and frost [3]. Moreover, quinoa is highly nutritious, with abundant amounts of protein, oil, amino acids, polyunsaturated fatty acids (PUFA), vitamins, and minerals [3]. Peru, Bolivia, and Ecuador are the major producers (70-80%) of quinoa [4]. Since the declaration of IYQ, many studies on quinoa has been carried out [4]. This is supported by Data Bridge Market Research [5], noting that government support such as the National Institute of Agricultural Research has led to promising development and production of quinoa around the world. Increase in research is in line with demand for quinoa, which is increasing and expected to increase from market value of USD61 billion in 2021 to USD161 billion in 2029 [5]. As a result of adopting a more health-conscious diet, more consumers choose quinoa due to its nutritional benefits and gluten-free properties. Quinoa's popularity and recognition may have also increased due to COVID-19, whereby quinoa, which are healthy and have extended shelf

life, are preferred [5].

While quinoa has existed more than 5000 years ago, extensive research only began in 2013, which is inadequate compared to other crops. Out of the five systematic reviews available on PubMed (from 2014 to 2023), one looks into potential in improving processed food nutritionally and improving processing of quinoa [6]. One reviewed only 7 randomized control trials in ability for quinoa to improve blood glucose, weight, and BMI [7] while another focused on neurosurgery [8]. One looks into how superfoods have impact on metabolic syndrome risk but only 1 out of 133 were quinoa intervention [9] and the last one looks into health-promoting aspects of plant proteins, but no quinoa studies were included [10]. None of the 2 systematic reviews examined the nutritional and potential health benefits of quinoa. Thus, we present a 10-year systematic review is to assess the nutritional profile and potential health benefits of quinoa.

Methods

A PubMed search was done using the search term "(quinoa AND benefit*)" from 01 January 2014 to 01 January 2024[1]. The exclusion criteria were; (a) articles not written in English language, (b) articles with no free full-text available, (c) secondary articles such as systematic reviews, meta-analysis, and literature reviews, (d) articles with no mention of 'quinoa' in abstract or title, (e) articles that were focused on grains other than quinoa, and (f) articles not related to health and nutrition.

Results

164 papers were identified. After screening, 35 papers were included in this systematic review (Figure 1), and themed into 3 themes (Table 1).

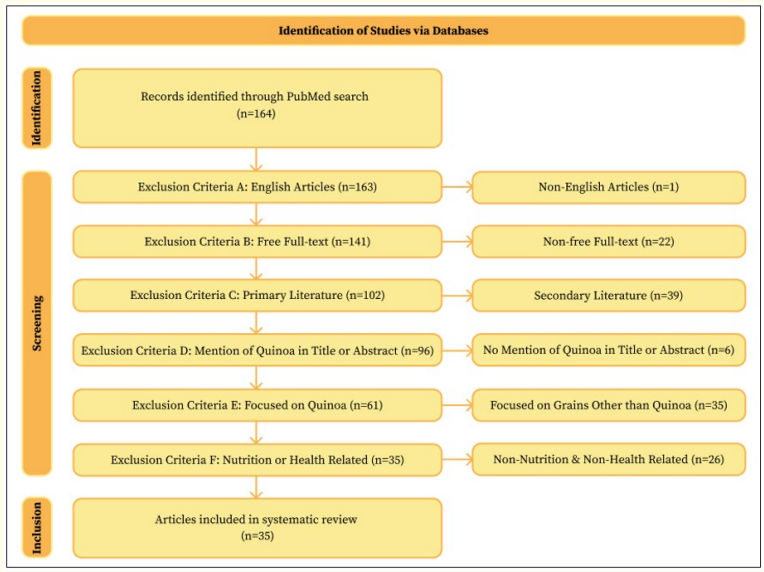

Figure 1: PRISMA diagram.

1. https://pubmed.ncbi.nlm.nih.gov/?term=quinoa+AND+benefi*&filter=dates.2014/1/1-2024/1/1

Theme		*Number of Articles*	*References*
1. Effects of processing techniques on:	Subtheme 1: Nutritional profile.	14	[11-24]
	Subtheme 2: Physical, mechanical, and functional properties of quinoa.	9	[15, 19, 21, 23-28]
	Subtheme 3: Gut microbiota.	3	[23, 29, 30]
2. Potential health benefits of quinoa.		10	[31-40]
3. Genotype and phenotype variation of quinoa affecting nutritional profile.		7	[22, 25, 41-45]

Table 1: Classification of studies based on themes.

Theme 1.1: Effects of processing techniques on nutritional profile

Processing techniques such as drying methods, polishing, milling, extrusion, cooking, fortification with silicon, iron, or vitamin B, and substitution of products with quinoa may have an impact on nutritional profile of quinoa.

Cellulose in quinoa decreased by 92.24% when milling lasted for 80 seconds, which was the most reduction compared to shorter milling time [18]. Milling time also significantly affects the starch content in quinoa ($p < 0.05$), with a longer milling time resulting in higher starch content [18]. Heat-moisture (HM) treatment does not directly affect total starch content but significantly affects its two forms. Amylose was significantly increased due to both HM (+9.25%) and with addition of pullulanase (+31.25%) [21]. In contrast, amylopectin was significantly decreased by 3.12% and 44.53% due to HM and pullulanase respectively [21]. HM also resulted in a significant increase by 4.18% in the amount of total dietary fibre in quinoa ($p < 0.05$) [21]. Overall, longer milling time and HM treatment helps to increase starch content in quinoa.

The protein content in quinoa was not affected by treatment involving heat; such as HM treatment, boiling, or steaming [17, 21]. Drying methods such as freeze, vacuum, or spray dry also does not change the protein content, remaining at an average of 85.2% [15]. Milling for 80 seconds decreased protein by 89.41%, compared to a shorter duration [18]. Thus, milling duration should be considered when looking into quinoa protein. However, fortifying quinoa with iron either by foliar or combination of by root and foliar had increased protein content (+93% and +88% respectively) [13]. Other than fortification, substituting products with quinoa seems to be a promising method to increase protein content as well. The higher the amount of product that is substituted with quinoa, the higher the increase in protein content [23, 24]. Overall, drying method and cooking does not affect protein but milling decreases while fortification with iron and quinoa substitution increases protein content.

Substitution, however, has a varying impact on fat content. Fat was significantly increased when 50% and 75% of cow's milk was substituted with quinoa milk [23]. In contrast, with higher substitution of pork back fat with quinoa, the fat content significantly decreased ($p < 0.05$) [24]. This may indicate that the effect of quinoa is dependent on the type of product, which may originally have higher or lower fats than quinoa.

Fortifying quinoa with iron via foliar application doubled the iron content from 85mg/kg to 190mg/kg [13]. Polishing quinoa resulted in decreased copper [17]. Copper contents remained similar when substituting cow's milk with quinoa milk [23]. Zinc was not affected by iron fortification [13] but polishing decreased the content [17], while quinoa substitution increased the content [23]. Iron fortification also increased the amount of manganese [13]. Polishing does not affect contents of molybdenum, nickel, sodium, or magnesium [17]. However, boiling led to significant loss in molybdenum by 43% ($p < 0.05$). In contrast, quinoa substitution increased sodium [23]. Calcium content decreased when quinoa was polished but when quinoa was steamed, the content increased [17]. Calcium also increased when cow's milk was substituted with quinoa. For phosphate, polishing increased its content [17] but fortifying quinoa with iron decreased phosphate [13]. As phosphate is formed from phytates which also forms iron, fortifying with iron may cause the

phytates to favour iron and not phosphate. Potassium was significantly lowered when boiled (-41%, $p < 0.05$) [17] and when cow's milk was substituted with quinoa milk [23]. Silicon had significantly increased when quinoa was fortified with silicon, with increasing fortification leading to increasing silicon [12]. This was more effective when applied via both root and foliar, compared to solely root or foliar [11]. Vitamin C increased when fortification of quinoa with either silicon or iron, both via the combination of foliar and root application [11, 13]. Boiling quinoa led to significant loss in vitamin B by 36% ($p < 0.05$) [17]. Overall, there is varying impact on the vitamins and minerals of quinoa.

Fortification of quinoa with iron via root and foliar decreased phenols [13]. Freeze-dried quinoa had higher phenols than air-dried quinoa [16]. Steaming quinoa is better than boiling in retaining phenols [17]. This could be related to the loss of phenols into the water when boiled. Longer milling time resulted in further reduction in polyphenols, with 80 seconds decreased by 95.46% [18]. Extrusion at higher temperatures of up to 160°C helps to release both free and bound phenolics, thus increasing its content in red quinoa [19]. Treating quinoa with enzyme increased free phenolics but does not affect bound phenolics [20]. Hydrolysis method also affects phenol content in quinoa. Acidic hydrolysis resulted in higher phenols than alkaline hydrolysis [22]. To obtain quinoa with a higher phenol content, freeze drying, steaming, shorter milling time, and extrusion of up to 160°C, and acidic hydrolysis could be considered when selecting processing techniques.

Fortifying quinoa with iron decreased flavonoids as well as anthocyanin [13]. Treating quinoa with enzyme had various effects on flavonoids. There were no changes in total flavonoids but increased free phenolics by 21.2% and significantly decreased bound phenolics by 23% [20]. Enzymatic treatment decreased rutin content [20] but extrusion significantly increased rutin, with higher temperatures of up to 160°C leading to higher rutin levels [19]. Freeze-dried had higher kaempferol 3-O-sophoroside than air-dried quinoa [16]. Processing techniques used in the studies does not seem to favour flavonoids except for freeze drying and extrusion methods.

Fortifying quinoa with vitamin B does not influence the superoxide dismutase (SOD) and glutathione reductase [14]. Drying methods does not affect the DPPH [16] but is affected by enzymatic treatment, increasing by 16.3% and 26.4% for free and bound DPPH respectively [20]. Enzymatic treatment also increased free ORAC levels by 48.7% but significantly decreased bound ORAC by 10.4% [20]. As for FRAP, freeze-dried resulted in higher FRAP than air-dried quinoa (211.4 and 35.2mTE/gDM respectively) [16]. Overall, only enzymatic treatment helped to increase DPPH and ORAC.

	Starch	***Protein***	***Fat***	***Vitamins & Minerals***	***Phenols***	***Flavonoids***
Drying		X [15]			Freeze > Air [16]	Freeze > Air [16]
Polishing				↓Cu, Ca [17] ↑P [17] X Na, Mg [17]		
Milling	↑ [18]	↓ [18]			↓[18]	
Extrusion					↑[19]	↑[19]
Cooking	↑ [21]	X [23, 24]		↑Ca [17] ↓K, vit. B [17]	↑[20] Steam > Boil [17]	↑[20]
Fortification		↑[13]		↑Si [11, 12] ↑Fe, Vit. C [13] ↓P [13] X Zn [13]	↓[13]	↓[13]
Substitution		↑[23, 24]	↑[23] ↓[24]			

Table 2: Summary of processing techniques affecting quinoa's nutritional profile. ↑increased, ↓decreased, X: no change.

Theme 1.2: Effects of processing techniques on physical, mechanical, and functional properties of quinoa

Processing techniques such as drying methods, treatment with sodium chloride (NaCl), heat, and cold, encapsulation, extrusion, and substitutions may have an impact on the physical, mechanical, and functional properties of quinoa.

Physical properties that can be affected include moisture, particle size, colour, pH, oil absorption capacity (OAC), and morphology of quinoa. Controlling the moisture content for quinoa is important in not just maintaining texture and consistency but also in preventing spoilage during its storage. Low moisture is needed to prevent the growth of microbes and mold. Drying methods does not have an impact on the moisture content of white quinoa flour [15]. Quinoa treated with NaCl significantly decreased moisture content [25]. Red quinoa that has been extruded significantly decreased moisture content, with a higher extrusion temperature leading to a higher decrease in moisture [19]. Pork back fat substituted with quinoa significantly increased moisture content, with a higher substitution leading to higher increase in moisture [24].

Particle size of quinoa is important in influencing the texture, appearance, and cooking time, which can be affected by drying methods. Compared to freeze and vacuum drying, spray drying seem to provide a smaller and more refined white quinoa, resulting in distribution that are more uniform [15]. This is probably due to a more dispersed drying using the spray method. Encapsulating quinoa with lotus root amylopectin (LRA) had an opposite effect, increasing the particle size of quinoa, which made it coarser [28]. Although a more refined quinoa would provide faster digestibility, quinoa with a coarse texture can be useful in making meat-based products or granola bars.

Colour of quinoa is crucial in appealing to consumers visually. Quinoa often comes in various colours such as white, red, and black. Thus, the more intense the colour of quinoa is, the brighter and appealing it appears. This can be measured using colorimetry, which can be described as L* (lightness), a* (redness/greenness), and b* (yellowness/blueness). Spray drying resulted in highest L* in white quinoa compared to freeze and vacuum drying [15]. In red quinoa, while extrusion had no significant impact on L* ($p > 0.05$), extrusion temperatures of 140°C and 160°C significantly decreased a* and b* ($p < 0.05$) [19]. However, temperatures of 120°C and 180°C does not result in much change to a* and b*. This shows that the red quinoa showed a more green and blue tone which deviates from the red and yellow tone of red quinoa. Manufacturers may want to evaluate the appearance of quinoa before selecting the appropriate extrusion temperature. Substitution of cow's milk with quinoa milk does not seem to have a significant impact in L* but 100% quinoa milk showed the lowest L*, indicating its darker appearance [23]. 50% substitution of pork back fat with quinoa significantly increased L* value ($p < 0.05$), which had shown a better appearance compared to other substitution % [24]. Thus, consideration should be given to the appearance when substituting quinoa in drinks and meat products.

pH of quinoa can affect the taste and nutritional impact on quinoa. If pH becomes too acidic, it can lead to a sourer taste, or if it becomes too alkaline, it can result in bland or chalky taste. If pH is not balanced, it can also affect the absorption and solubility of quinoa's nutrients, vitamins, and minerals. Cold treatment resulted in reduced pH, with colder treatment of -20°C being more acidic than 4°C [26]. Substitution of quinoa may have different effects in pH of different products. The higher the substitution of cow's milk with quinoa milk, the more acidic the product is [23] whereas the higher the substitution of pork back fat, the more alkaline the product is [24]. This shows that quinoa substitution can have various impact on the pH, depending on the product.

Oil absorption capacity (OAC) is the ability of quinoa to retain the oil that has been absorbed. Freeze drying significantly increased OAC of white quinoa flour ($p < 0.05$), compared to spray and vacuum drying [15]. As such, it allows high retainment of oil leading to smoother texture and higher aromatic compounds remained in quinoa, giving it its palatability. Thus, hoping for quinoa products to retain such properties, manufacturers may consider freeze drying method.

The morphology and microstructure of quinoa can influence the mechanical and functional properties of quinoa. Cold stress treatment caused quinoa seeds to become large, disintegrated, with increased membrane permeability, and holes [26]. Heat moisture treatment resulted in rough surface, formation of holes or pits, and seeds that are irregular and large [21]. This indicates that treatments

with harsh conditions can affect the morphology of quinoa. Both treatments resulted in weak structure, causing more disruption and thus significantly decreased the crystallinity of quinoa ($p < 0.05$) [21, 26]. However, encapsulation of quinoa did not affect the morphology as the seeds remained smooth without any pits formed [27].

Processing techniques can also affect mechanical properties such as texture. Texture of quinoa is important in the acceptability among consumers. A 100% substitution of cow's milk to quinoa milk resulted in the poorest texture but texture improved when substitution is at 25% and 50% [23]. The hardness and chewiness of pork back fat significantly decreased ($p < 0.05$) with quinoa substitution of more than 50% but remained similar with substitution of 25% and 50% quinoa [24]. Overall, it suggests that 50% and below of quinoa substitution can be beneficial in retaining texture of original products but higher than that can negatively affect the texture.

Functional properties of quinoa can also be affected by processing techniques. Freeze drying significantly increased emulsifying capacity and stability, whereas spray drying significantly increased capacity while vacuum significantly decreased capacity [15]. This could be due to the high temperature of vacuum drying resulting in structural damage, thus affecting its ability to emulsify. 100% substitution of quinoa with cow's milk or pork back fat resulted in poor flavour during the sensory evaluation but was acceptable when quinoa substitution was ≤50% [23, 24]. Surface hydrophobicity is the capacity of the quinoa to repel water, in which higher surface hydrophobicity indirectly results in smoother texture as it can interact well with oil and cause better emulsions. Freeze drying showed the highest surface hydrophobicity in white quinoa flour compared to spray and vacuum drying [15]. This could potentially be due to denaturation of quinoa when being freeze, exposing regions that are hydrophobic.

Physical properties			
Property	***Technique***	***Effect***	***Reference***
Moisture	Drying methods	No effect	[15]
	NaCl treatment	Significant decrease	[25]
	Extrusion	Higher temperature = higher decrease	[19]
	Pork back fat	Higher substitution = higher increase	[24]
Particle Size	Drying methods	Spray dry = smaller and refined	[15]
	Encapsulation	Increase size	[28]
Colour	Drying methods	Spray = highest L*	[15]
	Extrusion	No effect on L*	[19]
	Extrusion	140°C and 160°C significantly decrease a* and b*	[19]
	Cow's milk	Higher substitution = lower L*	[23]
	Pork back fat	50% substitution = significant increase in L%	[24]
pH	Cold treatment	Lower temperature = more acidic	[26]
	Cow's milk	Higher substitution = more acidic	[23]
	Pork back fat	Higher substitution = more alkaline	[24]
OAC	Drying method	Freeze dry significantly increase	[15]
Morphology	Cold treatment	Increase size and permeability	[26]
	Heat moisture	Increase size and irregular shape	[21]
Mechanical properties			
Property	***Technique***	***Effect***	***Reference***
Texture	Cow's milk	100% substitution = poor, 25% and 50% = acceptable	[23]
	Pork back fat	>50% substitution = decrease, 25% and 50% = acceptable	[24]

Functional properties			
Property	***Technique***	***Effect***	***Reference***
Emulsifying capacity	Drying method	Vacuum dry significantly decrease, freeze and spray dry significantly increase	[15]
Emulsifying stability	Drying method	Freeze dry significantly increase	[15]
Flavour	Cow's milk	>50% substitution = poor, ≤50% = acceptable	[23]
	Pork back fat	>50% substitution = poor, ≤50% = acceptable	[24]
Surface hydrophobicity	Drying method	Freeze dry = highest	[15]

Table 3: Summary of processing techniques on physical, mechanical, and functional properties of quinoa.

Theme 1.3: Effects of processing techniques on gut microbiota

Processing techniques such as cooking, fermentation, and substitution of products with quinoa can have an impact on the gut microbiota. The gut microbiota comprises of bacteria and viruses that plays a major role in metabolism of indigestible components and supporting the integrity of the mucosal barrier in the gut, which defends against pathogens. Beneficial bacteria; such as *Bacteroidetes*, *Firmicutes*, and *Proteobacteria*; were significantly increased in cooked, compared to uncooked seeds, but showed no difference in *Actinobacteria* [29]. This could be due to weakening of the seed structure when heated during cooking process, and thus result in the release of fermentation metabolites, which promotes bacterial growth. *Enterobacteriaceae* is a type of Gram-negative bacteria that is family to common pathogens such as *Salmonella*, *Escherichia coli*, *Klebsiella*, and *Enterobacter*. Fermenting has a potential to prevent the growth of *Enterobacteriaceae* which can be seen in fermented white quinoa with decreased *Enterobacteriaceae* from 8 CFU/mL to below the detection of limit of <1 CFU/mL [30].

Probiotics are microorganisms that promote the health of the gut, ensuring the diversity and balance of gut microbiota is maintained. Fermentation of white quinoa significantly increased beneficial bacteria, *Lactobacilli*, within 2 days but after 28 days, it significantly decreased ($p = 0.002$) [30]. This could be due to the changes if fermentation metabolites that are available, whereby, fermentation provides high fermentation metabolites at the start, promoting high *Lactobacilli*. Over time, fermentation metabolites decrease, which also result in decreased *Lactobacilli*. Substituting cow's milk with quinoa milk resulted in significantly higher *Streptococcus thermophilus*, *Lactobacillus acidophilus*, and *Bifidobacterium bifidum*, which was more prominent in 100% and 75% substitution [23]. This suggests that quinoa milk has a potential to provide high probiotics than cow's milk.

Overall, quinoa shows promising results in maintaining healthy gut microbiota. However, these studies only showed notable changes in some bacteria. Further studies need to be done to identify the effect of quinoa on wider variety of gut bacteria, probiotics, and other common pathogens.

Type of Bacteria	***Processing Technique***	***Effect***	***Reference***
Bacteroidetes	Cooking	Increased	[29]
Firmicutes	Cooking	Increased	[29]
Proteobacteria	Cooking	Increased	[29]
Actinobacteria	Cooking	No change	[29]
Enterobacteriaceae	Fermentation	Decreased	[30]
Lactobacilli	Fermentation	2 days: increased, 28 days: decreased	[30]
Lactobacillus acidophilus	Substitution	75% and 100% increased	[23]

Streptococcus thermophilus	Substitution	75% and 100% increased	[23]
Bifidobacterium bifidum	Substitution	75% and 100% increased	[23]

Table 4: Summary of effect of processing techniques on gut microbiota.

Theme 2: Potential health benefits of quinoa

Quinoa has resulted in the significant decreased of food consumption in animals [33, 36] as well as humans [38]. Both low and high consumption of quinoa polysaccharides (300 and 600mg/kg/d respectively) significantly lowered consumption of food among four-weeks-old rats with high fat diet (HFD) [33]. While older obese mice (9-10weeks/old) had lower food consumption, it remains insignificant [36]. This could suggest the satiety impact of quinoa on growing overweight or obese rats and mice. For obese humans, consuming 25g of quinoa resulted in reduction of calories after six weeks but have increased after twelve weeks while consuming higher amount of 50g has resulted in overall decreased after twelve weeks [38]. While these are insignificant, it can imply that small quantity of quinoa may not be sufficient to change calorie intake, but a higher quantity may have a better effect at decreasing calorie intake.

Quinoa may influence intake of the 3 macronutrients: carbohydrates, proteins, and fats. Obese humans consuming 25g white quinoa increased carbohydrate after twelve weeks while 50g increased carbohydrate only after six weeks and remained stagnant after twelve weeks [38]. Substituting carbohydrate with quinoa-based products significantly lowered carbohydrate intake in obese humans ($p = 0.004$) [40]. Thus, having personalised substitution of quinoa might be better at targeted satiety improvement and lowering carbohydrate intake.

Changes in protein intake were similar to carbohydrate intake. White quinoa increased protein intake with twelve weeks of 25g of white quinoa and only six weeks of 50g among obese humans [38]. Personalised quinoa substitution significantly reduced the level of amino acids: cystine ($p = 0.008$), arginine ($p = 0.008$), glutamic acid ($p = 0.008$), and proline ($p = 0.039$) [40]. This could be because these obese humans consumed lower amounts of carbohydrate, thus less quinoa consumption led to less amino acids that can be obtained.

Quinoa has various effects on fat intake. In healthy overweight males consuming quinoa-based bread for four weeks, there were no significant change in fat intake ($p > 0.05$) [39]. Whereas in obese humans, four weeks of white quinoa decreased fat intake, although insignificant [38], while quinoa-based products significantly increased fat intake ($p = 0.004$) [40]. Effects of red quinoa on total cholesterol were significantly lowered for obese mice (-26%, $p < 0.05$) [36] and stress-induced rats (-51.67%) [37], although it has a lower impact compared to HFD rats. HFD rats consuming 9% and 27% of quinoa significantly decreased total cholesterol by 59.37% and 61.52% respectively ($p < 0.005$) [33]. However, this was not seen in HFD rats consuming quinoa polysaccharide [32] and quinoa flour [35]. This may suggest that quinoa polysaccharide may not be as useful compared to the whole quinoa seed in reducing cholesterol, but this was not evident in obese humans [38]. Quinoa has a significant effect in lowering triglyceride in both animals and humans. For HFD rats, triglycerides were significantly reduced after consuming 300 and 600mg/kg/day of quinoa polysaccharides ($p < 0.05$) [32] or 20uL/g of quinoa ($p < 0.01$) [35]. Similarly, stress-induced rats consuming 30mgGAE/kg significantly reduced triglyceride [37]. Obese rats consuming red quinoa also had reduced triglyceride but were insignificant [36]. It is however, significantly reduced by 36.8% ($p = 0.001$) for obese humans consuming 50g of white quinoa [38]. Low-density lipoprotein (LDL) were significantly decreased for HFD rats consuming 300 and 600mg/kg/day of quinoa polysaccharides ($p<0.05$) [32] and 20uL/g of quinoa ($p < 0.01$) [35]. This was the also evident in obese mice consuming red quinoa (-57%, $p < 0.008$) [36] and stress-induced rats consuming red and yellow quinoa [37]. However, no effects were seen in obese humans [38]. There were also no differences seen in high-density lipoprotein (HDL) for HFD rats, mice, and obese humans [32, 35, 38] but were significantly increased in stress-induced rats [37]. Overall, quinoa might have a positive effect in reducing triglyceride and potential in improving cholesterol and LDL but may not be as useful for HDL.

Quinoa may have varying effects on body weight for HFD rats and mice. Consuming 1000mg/kg/d of quinoa led to significantly higher body weight for HFD rats [34] but was significantly decreased in HFD male mice consuming 20uL/g quinoa ($p = 0.0008$) [35]. For obese diabetic mice, body weight gain was delayed but eventually led to same weight as control [36]. Positive results were also seen in lowering body weight for obese humans [38, 40]. After twelve weeks of consuming white quinoa, 25g led to 1.5% decrease while 50g led to 1.7% decrease in body weight [38]. Similar results were seen when consuming foods made with quinoa flour, which significantly reduced after eight weeks ($p = 0.008$) [40]. Hence, there is promising evidence that quinoa can delay body weight gain, potentially due to satiety of quinoa as seen in decreased calorie intake. Quinoa does not seem to have an impact on BMI of obese rats [36] but were useful in significantly reducing BMI in obese humans ($p = 0.004$) [40]. Overweight and obese humans lowered their waist circumference by 1cm after consuming 25g of white quinoa in twelve weeks [38]. Twice the amount (50g) showed an earlier reduction of 0.2cm after six weeks and higher reduction of 1.3cm after twelve weeks [38]. A significant reduction of 1.5cm after four weeks consumption of quinoa flour by obese humans further supports the effects of quinoa on reducing waist circumference ($p = 0.015$) [40].

Quinoa consumption reduced the weight of kidney among stress-induced [37] and obese diabetic [36] rats after four and eight weeks respectively. This may suggest that quinoa have positive effects on reversing hypertrophy of kidney caused by stress or obesity. However, this has only been shown in rats and more trials are needed to see the effect in humans. Consuming 1000mg/kg/day of red quinoa for eight weeks significantly reduced weight of liver in HFD rats ($p < 0.05$) [34]. For the same duration, red quinoa also lowered liver weight among obese rats [36]. Reduction was also seen in stress-induced rats consuming quinoa [37]. With quinoa's ability to reduce liver weight, it may suggest that quinoa may potentially restore liver structure, thus improving liver function. This can be seen as consumption of 300mg/kg/day & 600mg/kg/day of quinoa polysaccharides decreased the damage to liver cells of HFD rats, with an increasing amount of quinoa polysaccharides leading to decreasing white lesions on liver [32]. Twelve weeks of 20uL/g of quinoa also significantly decreased fat depositions on liver of hypertensive rats ($p < 0.01$) [35]. Fat depositions on liver can result in scarring overtime, which can be seen as white lesions. Thus, it suggests that quinoa may reverse scarring of liver. Impact of quinoa on liver index further supports this. Liver index predicts the amount of fats accumulated in liver and thus, the lower the index, the better the liver status. In HFD rats, both 9% and 27% of quinoa consumption significantly decreased liver index ($p < 0.005$), with higher decrease for 27% after twelve weeks [33]. Aspartate aminotransferase (AST) and alanine aminotransferase (ALT), which are released by damaged liver cells can also be indicative of liver damage. Quinoa significantly lowered ALT in HFD and stress-induced rats ($p < 0.05$) [32, 33, 37]. AST were also significantly decreased in stress-induced rats consuming red or yellow quinoa [37] but were insignificant among hypertensive rats consuming quinoa polysaccharides [32].

Blood glucose decreased significantly in HFD rats consuming 20uL/g of quinoa flour for eight weeks ($p = 0.011$) [35]. For obese rats, 500mg/kg of red quinoa significantly decreased blood glucose by 36.2% after four hours of consumption ($p<0.001$) [31]. 30mgGAE/kg of red quinoa for four weeks reduced blood glucose in stress-induced rats [37]. While quinoa had shown effects in reducing blood glucose levels in rats, it does not seem to have an impact on humans. There were no significant differences in obese humans consuming white quinoa for twelve weeks [38] or quinoa flour for eight weeks [40]. However, quinoa flour seems to have an impact on HbA1c in obese humans as it reduced significantly from 6.1% to 5.5% after eight weeks ($p = 0.007$) [40]. Thus, while quinoa may not directly impact the immediate blood glucose, quinoa may improve long-term control of blood glucose in obese humans. Obese mice consuming red quinoa had higher insulin levels than obese rats that consumed a control diet for eight weeks [36]. Whereas for obese humans, twelve weeks of 50g of white quinoa decreased insulin by 14%, although it was insignificant [38].

Phenols, carotenoids, flavonoids, flavonols, and anthocyanin are commonly known to have antioxidant properties. Total phenols, carotenoids, flavonoids, and flavonols were significantly increased in stress-induced rats consuming 30mgGAE/kg of yellow or red quinoa ($p < 0.05$) [37]. However, total anthocyanin was significantly decreased ($p < 0.05$) [37]. Antioxidant effects can also be estimated with malondialdehyde (MDA), interleukins (IL), superoxide dismutase (SOD), and glutathione (GSH). In all the animal studies in this review, quinoa have been shown to significantly decrease MDA in HFD, obese, and stress-induced rats or mice [32-35, 37]. This shows quinoa's potential to reduce lipid peroxidation caused by oxidative stress, and thus prevent damage to cells. ILs are released

during an immune response to injury, which will then induce inflammation, resulting in oxidative stress. In HFD rats and mice, quinoa significantly decreased IL-10 [33], IL-6, and IL-1B [35] whereas in obese mice, quinoa lowered IL-6 although it was insignificant [36]. Quinoa has a potential to reduce the oxidative stress caused by ILs. SOD and GSH are antioxidants. Quinoa had significantly increased SOD in hypertensive, obese, and stress-induced rats or mice [33, 35, 37]. Consuming quinoa polysaccharide also increased SOD but was insignificant [32]. It was also found to significantly increased GSH in hypertensive and stress-induced rats [33, 37] and GSH-PX in hypertensive rats [33, 35]. Overall, quinoa may serve as a strong antioxidant.

Health Benefit	*Component*	*Change*	*References*
Anti-obesity	Calorie Intake	Decrease	[33, 36, 38]
	Carbohydrate Intake	Increase, then stagnant	[38]
		Decrease	[40]
	Protein Intake	Increase, then decrease	[38]
		Decrease	[40]
	Fat Intake	No change	[39]
		Decrease	[38]
		Increase	[40]
	Total Cholesterol	No change	[32, 35, 38]
		Decrease	[33]
	Triglyceride	Decrease	[32, 35-38]
	LDL	No change	[38]
		Decrease	[32, 35-37]
	HDL	No change	[32, 35, 38]
		Increase	[37]
	Weight	Decrease	[35, 36, 38, 40]
		Increase	[34]
	BMI	No change	[36]
		Decrease	[40]
	Waist Circumference	Decrease	[38, 40]
Kidney	Weight	Decrease	[36, 37]
Liver	Weight	Decrease	[34, 36, 37]
	Damage and White Lesions	Decrease	[32, 35]
	Liver Index	Decrease	[33]
	ALT	Decrease	[32, 33, 37]
	AST	Decrease	[32, 37]
Anti-diabetic	Blood Glucose	No change	[38, 40]
		Decrease	[31, 35, 37]
	HbA1c	Decrease	[40]
	Insulin	Increase	[36]
		Decrease	[38]

Antioxidant	Phenols, Carotenoids, Flavonoids, Flavonols	Increase	[37]
	Anthocyanin	Decrease	[37]
	MDA	Decrease	[32-35, 37]
	IL	Decrease	[33, 35, 36]

Table 5: Summary of health benefits of quinoa.

Theme 3: Genotype and phenotype variation of quinoa affecting nutritional profile

Various genotype and phenotype of quinoa have been studied (Table 6). Fat content was highest in Z-10-Y (4.58%) and lowest in H-1 (2.72%) [41]. Protein content was highest in YNB and QL-2 seeds (13.4g/100gDW), followed by LL-1 and QL-1 seeds (12.17g/100g-DW) and the least in GZ-4 seeds (10.69g/100gDW) [42]. As seeds are grown into 6-day-old sprouts, the highest and lowest protein contents remained the same (YNB=25.21, QL-2=20.74, QL-1=18.94, LL-1=18.73, GZ-4=17.01g/100gDW) [42]. This indicates that black quinoa has the highest amount of protein compared to red quinoa. White quinoa sprouts, H-1 and LL-1 was the highest for essential amino acids (AAs), isoleucine and methionine, respectively (Table 7). However, this was not the same for white quinoa seeds, as the highest seeds in essential AAs was seen in YNB and QL-2 seeds [42]. This suggests that black seeds may be high in essential AAs but as it grows, the amount may not increase as much compared to white quinoa sprouts. For genotypes, BL shows more promise than TH as BL was highest in aspartic and glutamic acids while TH was lowest in methionine and aspartic acid, compared to other varieties of quinoa (Table 7). For phenotypes, white varieties of quinoa seem to display both the highest and lowest in AAs. H-1 was the highest in half of AAs studied while LL-3 was the lowest in two-third of AAs studied. Overall, the amount of AAs was not favoured by a specific phenotype and may also differ depending on its growth stage.

Genotype	***Phenotype***		
	White	***Red***	***Black***
Z-10-Y TH BL TMH UDEC-5 Kcoito	Heili-1 (H-1), H-2, Long Li-1 (LL-1), LL-3 Qing-Li-1 (QL-1)	Gong Zha-4 (GZ-4), red-1 (R-1), R-3 Yunnan Red Cultivar (YNR)	Yunnan Black Cultivar (YNB) QL-2

Table 6: Genotype and phenotype of quinoa used.

Amino Acid	***Highest (g/100g)***	***Lowest (g/100g)***	***Reference***
Isoleucine	H-1 (1.052)	LL-3 (0.866)	[41]
Methionine	LL-1 (0.205)	TH (0.128)	
Arginine	H-1 (1.195)	LL-3 (0.958)	
Aspartic Acid	BL (2.014)	TH (1.650)	
Glutamic Acid	BL (2.516)	LL-03 (2.118)	
Glycine	H-1 (1.190)	LL-03 (0.970)	

Table 7: Summary of phenotype and genotype affecting AAs.

Vitamin and Minerals	*Highest (mg/100g)*	*Lowest (mg/100g)*	*Reference*
Vitamin C	TMH (69.48)	H-2 (36.63)	[41]
	GZ-4 (46.92)	LL-1 (22.82)	[42]
Vitamin B2	LL-1 (0.444)	GZ-4 (0.217)	
Calcium	R-3 (21.67)	TH (2.12)	[41]
Potassium	R-1 (525.21)	TH (467.22)	
Magnesium	LL-03 (219.34)	TH (68.94)	

Table 8: Summary of phenotype and genotype affecting vitamins and minerals.

The red colour seen in red quinoa is due to pigments such as anthocyanins, betalains, or carotenoids which could contribute to higher amounts of vitamin C seen in GZ-4, compared to white variety, H-2 and LL-1 (Table 8). In contrast, vitamin B2 is higher in white LL-1 than red GZ-4 (Table 8). The TH genotype was the lowest for all three minerals studied: calcium, potassium, and magnesium while the red phenotypes, R-3 and R-1, were dominant in calcium and potassium respectively (Table 8). Overall, the red variety of quinoa shows the most promise in higher amounts of vitamins and minerals.

The antioxidant activity of quinoa can be determined by its total phenolic content (TPC) and total flavonoids (TF) which includes kaempferol and quercetin, and carotenoids. These helps to scavenge free radicals; thus, acting as an antioxidant. Antioxidant activity was found to be highest in black compared to white quinoa [22]. This was in line with TPC which was higher in darker coloured quinoa seeds [22, 43]. It remains the same after 25 days of sowing, with highest TPC in red R-1 (71.01mg/g) and lowest in white H-1 (58.91mg/g) [41]. However, another study found that highest TPC in 6-day-old sprouts was in white QL-1 (10.92mgGAE/gDW) and lowest in red YNR (8.44mgGAE/gDW) [42]. TF was found to be highest in TMH genotype (9.05mg/g) and lowest in white H-1 (3.29mg/g) [41]. White quinoa had lower TF compared to red and black quinoa seeds [43]. However, similar to TPC, 6-day-old quinoa sprouts had highest TF in white QL-1 (5.91mgCE/gDW) and lowest TF in red GZ-4 (4.45mgCE/gDW) [42]. This may suggest that TPC and TF content in sprouts may differ from seeds and plant. Kaempferol and quercetin are a type of flavonoids which can have derivatives. Looking into kaempferol derivatives, K-3-galactoside was found to be higher in black rather than white and red quinoa [43]. However, three other kaempferol derivatives, K-B-glucoside, K-a-L-rhamnopyranosyl, and K-rutinoside was the highest in white quinoa [44]. Quercetin derivatives are also found to vary among the quinoa phenotypes. Black quinoa had the highest Q-B-d-galactoside and Q-B-galactoside while red quinoa had the highest Q-rutinoside, Q-B-D-galactopyranoside, Q-glucuronide [44]. This shows that kaempferol is mainly present in white quinoa while quercetin is mainly present in coloured quinoa. Overall, colour of quinoa can help determine the TPC, with darker colour resulting in higher TPC, but it is not as straightforward for TF.

Carotenoids are pigments, which mainly gives the yellow, orange, and red colours of a plant. Common types include beta-carotene, lycopene, and lutein, which also have antioxidant properties. TMH genotype had the highest beta-carotene (32.71mg/100g) while BL genotype had the lowest (12.42mg/100g) [41]. In terms of phenotype, the highest and lowest beta-carotene was found in black QL-2 (13.17mg/100gDW) and white QL-1 (8.04mg/100gDW) respectively [42]. The highest and lowest lycopene levels was both found in white quinoa varieties, LL-1 (51.52mg/100g) and H-2 (27.75mg/100g) respectively [41]. Lutein was found to be higher in darker coloured quinoa, with highest in black (0.98mg/100gDW), followed by red (0.72mg/100gDW) and white (0.53mg/100gDW) [42].

The UDEC-5 genotype, which is salt-resistant, had a higher ascorbate peroxidase (APX), glutathione reductase (GR), glutathione peroxidase (GPx), and malate dehydrogenase than Kcoito genotype, which is salt-sensitive [25]. These are enzymes which has an important role in the antioxidant activity, thus the higher these enzymes are, the better the antioxidant property. Overall, TMH genotype and coloured quinoa provides a higher antioxidant property, which are especially high in phenols and quercetin (Table 9).

Antioxidant	*Highest Content*	*Lowest Content*	*References*
Total Phenols (TP)	Coloured	White	[22, 41, 43]
	White	Red	[42]
Total Flavonoids (TF)	TMH	White	[41]
	Coloured	White	[43]
	White	Red	[42]
TF: kaempferol			
K-3-galactoside	Coloured	White	[43]
K-B-glucoside	White	Coloured	[44]
K-a-L-rhamnopyranosyl	White	Coloured	
K-rutinoside	White	Coloured	
TF: quercetin			
Q-B-d-galactoside	Coloured	White	[44]
Q-B-galactoside	Coloured	White	
Q-rutinoside	Coloured	White	
Q-B-D-galactopyranoside	Coloured	White	
Q-glucuronide	Coloured	White	
Beta-carotene	TMH	BL	[41]
	Coloured	White	
Lycopene	White (LL-1)	White (H-2)	
Lutein	Coloured	White	
Enzymes	UDEC-5	Kcoito	[25]

Table 9: Summary of phenotype and genotype affecting antioxidants.

Discussion

Key findings. This systematic review shows that quinoa is nutritious and has potential health benefits, which can be affected by processing techniques and variations in genotype and phenotype. Various nutrients are affected by various processing techniques (Table 2). Fortification of quinoa with iron increases the protein content [13]. This may indicate that bioavailability of iron in quinoa could promote the protein synthesis. While majority of the processing techniques improves level of phenols and flavonoids (Table 2), fortifying quinoa with iron resulted in decreased levels [13]. This could be due to how flavonoids may form a chelate iron [46]. Thus, higher iron available may lead to higher chelation, decreasing the availability of free flavonoids.

Various techniques affect the physical, mechanical, and functional properties of quinoa (Table 3.). Moisture property of quinoa mainly decreases with processing but substituting pork back fat with quinoa increases the moisture [24]. This is most likely due to how fats are dense and have lesser space to trap water, compared to quinoa which is not as dense. Extrusion temperatures do not impact the lightness but at higher temperatures, it decreases the redness and yellowness, making quinoa pale [19]. This could potentially be due to the destruction of carotenoids thus reducing the colour of quinoa. Overall, the selection of processing techniques of quinoa is dependent on the final properties that manufacturers are aiming for.

Cooking, fermentation, and substitution promotes gut microbiota by increasing good bacteria, decreasing bad bacteria, and increasing probiotics respectively (Table 4). However, fermentation of quinoa with Lactobacillus plantarum DSM 9843 resulted in increased Lactobacilli for the first 2 days but decreased after 28 days [30]. This could be due to initial nutrient-rich medium available for Lac-

tobacilli to grow but over time, viability is unstable leading to the drop in Lactobacilli. Future culture should consider the stability of viable cells to retain its good bacteria.

From this review, quinoa is seen to display anti-obesity properties. In a study done in obese humans, quinoa resulted in an initial increase in carbohydrate intake but no change after 6 weeks [38]. This may suggest that while quinoa consumption increases carbohydrate initially, it also promotes satiety. Similar findings can also be seen in calorie intake in rats and obese humans [33, 36, 38]. The difference in fat intake in two studies on obese humans could be due to the different interventions. The study showing decreased fats used a standard quinoa quantity [38] while the other study showing increased fats personalised the quinoa quantity, with a one-to-one replacement of normal to quinoa-based product [40]. Thus, a specified amount of quinoa may be beneficial for weight loss but a total conversion to quinoa would increase fats. This shows that quinoa is high in fats, which may be healthy fats as seen in the decreased triglyceride and LDL after quinoa consumption (Table 5). Quinoa was also seen to help with kidney and liver health as well as having anti-diabetic and antioxidant properties (Table 5). Although quinoa consumption increases the insulin levels in obese rats [36], the same was not seen in obese humans [38]. The increase in insulin could be due to the insulin growth factor-1 (IGF-1) production in growing rats which may not be as effective in already obese humans. It seems that quinoa may not influence insulin, but future works may investigate its effects with higher quantity of quinoa and a longer study period, especially since HbA1c in obese humans can be improved [40].

A specific quinoa phenotype does not seem to determine the amount of amino acids. For instance, white varieties of quinoa were the both the highest and lowest in amino acids [41]. However, it is unexpected that the total protein was highest in black quinoa [42]. This trend was the same for seeds and 6-day-old sprouts. However, although both white and black quinoa increase in amino acids from seeds to sprouts, it was significant in white quinoa and not in black quinoa. This may suggest that while colour does not necessarily determine the content, the growth of quinoa may have an effect. These differences in results can be due to the difference method used to measure amino acids. One study used the method which requires ninhydrin post-column derivatisation while the other used high performance liquid chromatography (HPLC), which is more sensitive and precise [47].

Coloured quinoa, either red or black, has an overall higher antioxidant activity compared to white quinoa due to its higher phenols, quercetin, beta-carotene, and lutein (Table 9). However, flavonoids may be favourable in both white and coloured quinoa. In the same study, two flavonoids, which includes three kaempferol and five quercetin derivatives, is found to be highest in white and coloured quinoa respectively [44]. Only one kaempferol derivative deviated from this [43] which could be due to the determination method. This study only used HPLC which is not as sensitive and selective compared to the other study using ultra performance liquid chromatography (UPLC) [48]. There are still many other derivatives which have yet to be studied and these derivatives may also have varying antioxidant abilities.

Despite the benefits of quinoa, it remains to be seen if it will be accepted by consumers as a staple alternative. Acceptance of quinoa was positive among Malawi, south African villagers, only if it was used a secondary component such as quinoa flour while consuming quinoa as an alternative to rice was not as welcomed [49]. In a 2023 study, 75% of quinoa-based chapattis and bars had acceptance closest to 100% wheat version [50]. This was an improvement to acceptance of only up to 50% substitution as seen in this review [23, 24]. Furthermore, key companies in India are highly invested in the production of various quinoa-based products, which can also be seen in other developed countries [51]. Thus, quinoa may not be favoured as a staple food replacement but slowly incorporating quinoa into common foods may promote its acceptance.

Limitations and future work

This systematic review has its own limitations. Articles used were only limited to one database, PubMed, and to articles with free access. This would have excluded articles from other journals that could provide further scientific evidence for evaluation in this review. More long-term randomised clinical trials on humans, both healthy and with a health condition, are needed to further prove

the potential health benefits of quinoa. The limitations specific to each theme are listed in Table 10 below and its potential solutions should be considered for future research.

Theme	*Limitations*	*Potential Solution(s)*
1.1	Lack of generalisability as only a specific type of quinoa was used [11-14, 19, 20].	Include a variety of quinoa types.
	Small sample size [12, 19, 20].	Larger sample size to increase statistical power, robustness, and reliability of results.
	Lack of control sample when comparing treatment of quinoa [21].	Include control sample of untreated quinoa for a more objective comparison.
	Overlooking novel components of quinoa when analysing using liquid chromatography-mass spectrometry (LC-MS) [16].	Utilising characterisation techniques such as nuclear magnetic resonance (NMR) or tandem mass spectrometry to identify specific components.
1.2	Lack of salt-resistant quinoa genotypes [25].	Include different varieties of salt-resistant genotypes for a more comprehensive finding.
	Short experiment duration of <3 weeks [25].	Longer duration to understand the long-term effects of salt treatment on quinoa development.
	Indirect measurement of GABA production using GAD activity [26].	Performing HPLC or enzyme-linked immunosorbent assay (ELISA) to directly measure GABA.
1.3	Limited to identifying microbes with 16s rRNA gene code [29, 30].	Performing shotgun metagenomic or whole genome sequencing to identify wider profile of microbes.
2	Small sample size [31, 37, 40].	Larger sample size for increase statistical power, robustness, and reliability of results.
	Short interventional period [38-40].	Longer interventional period to observe the long-term impacts.
	Non-compliance to intervention [38-40].	Incorporating compliance monitoring strategies.
	Recall bias when analysing diet via 3-day food diary [38].	Perform more robust dietary intake methods such as food frequency questionnaire (FFQ), dietary records, or multiple 24-hour dietary recall.
3	Lack of control sample when comparing treatment of quinoa [43, 45].	Include control sample to provide validation to observed results.

Table 10: Limitations and its potential solutions based on themes.

Strengths

The strength of this systematic review includes the use of PRISMA diagram which ensures the clarity, transparency, and accountability of article filtration, especially the exclusion of specific articles (Figure 1). This review also clearly shows the various themes which are discussed (Table 1). Moreover, the novelty of compiling health benefits and nutritional profile of quinoa in this systematic review will be useful for key industry leaders managing quinoa production. This review also included reliable and robust studies with randomised block design [11-13] and randomised controlled and cross-over trials [32, 38-40]. Literature gaps are also identified in this review, helping researchers to understand the limitations of studies and its potential solutions (Table 10).

Conclusion

With the increasing demand and popularity for quinoa worldwide, it is important to understand its nutrition and health benefits. Nutritional profile and properties of quinoa can be affected by various processing techniques, which should be selected based on the quality of end-product manufacturers or companies are looking for. It also depends on whether the processed quinoa would be consumed directly or used to make food products. Overall, quinoa has anti-obesity and antioxidant properties and while there is high potential for its anti-diabetic and liver health-promoting properties, it needs further human long-term clinical trials. Positive impact on the gut microbiota can also be seen although quinoa's effect on wider variety of microbes needs to be tested.

Supplementary Materials

Supplementary materials can be downloaded from https://bit.ly/Quinoa_SR.

Conflict of Interest

The authors declare no conflict of interest.

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