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# Road to valorisation of melon seeds (*Cucumis melo* L.): a comprehensive review of nutritional profiles, biological activities, and food applications

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Melon (*Cucumis melo* L.) is a commercial fruit planted worldwide in large quantities; meanwhile, substantial amounts of melon seeds as a by-product are generated within the food chain supply but are scarcely utilised. Currently, there is extensive attention on valorisation strategies of melon seeds, driven by circular economy strategies and the UN's sustainable development goals agenda. This by-product has high potential value and could be re-utilised and re-introduced into the supply chain as a promising ingredient in food development. The aim of this review is to highlight melon seed nutritional composition, biological activities of individual components, and current advances in food product development. Besides that, this review also highlights some promising green extraction technologies for maximising recovery value from melon seeds by reducing environmental burden. Ultimately, this review intends to promote a better understanding of melon seed properties that could enable the efficient utilisation of melon seeds and promote viable valorisation routes.

**Sustainability spotlight**

Melon seeds (*Cucumis melo* L.), a major by-product from the melon supply chain, are scarcely utilised and end up as food waste in landfills. However, this waste disposal strategy represents inefficient utilisation of natural resources, leading to economic losses and negative impacts on sustainable food system development. To this end, recycling and adding value to melon seeds as a novel ingredient and re-introducing them into the food chain align well with the sustainable food development and help to enhance the resilience of the food system. This review is expected to contribute to developing valorisation strategies of melon seeds, reducing food waste, and promoting their further development as a sustainable ingredient in food application, which is in line with SDG 2 and SDG 12.

## 1. Introduction

The Food and Agriculture Organisation (FAO) of the United Nations reported in 2015 that around 1.3 billion tons per year of food produced globally are lost or wasted across the food supply chain.[1] Food waste is currently a significant issue worldwide and has resulted in negative environmental, economic, and social impacts.[1] For this reason, most countries and organisations have been focusing on the development of circular food systems that are based on capturing value and minimizing waste, aiming to reduce food waste by 50% by 2030.[1–3] To this end, a variety of food waste management practices have been proposed: (i) recovery and reuse can contribute to food waste reduction and promote an efficient use of natural resources; (ii) development and design of green technologies and circular economy systems towards more sustainable patterns of production, to minimize the adverse effect of chemicals and waste on human health and the environment; (iii) raise public awareness for sustainable development and promote lifestyles in harmony with nature.[2–5] Based on this background, the food biorefinery concept has been put forward to advance circular economy across the food supply chain.[6–8] The food biorefinery concept considers the recovery of components from food supply chains, including waste or by-products and develops novel valorisation strategies as an extension or addition to established strategies (*e.g.* animal feed and composting), leading to the production of medium/high value products, such as functional ingredients, chemicals and biomaterials.[9]

Melon (*Cucumis melon* L.) is an important commercial horticultural crop in the world. It belongs to the Cucurbitaceae family and is cultivated in several warm parts of the world, including Europe, Asia, America, and Africa.[10] Due to its sweet and juicy flesh as well as attractive aroma, melon appeals to

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a large consumer base and is also processed by the food industry into a variety of food products (*e.g.* juices, fruit salads, desserts, canned fruit, and ice cream). Data from FAOSTAT (Food and Agriculture Organization of the United Nations Statistical Analysis) in 2021 showed that the annual worldwide production of melon was approximately 29 million tons, with the largest production in Asia (77%), followed by America (11.5%) and Europe (6.9%). As a seasonal fruit, roughly 70% of melon is directly consumed as fresh fruit by households and the rest is processed into food products; in addition, melon seeds, about 5–10% of the total melon weight (about 1.5 to 2.9 million tons), are generally considered as a non-edible part, and therefore classified as a by-product and usually end up in landfills.[11–15] This disposal method reflects the inefficient use of natural resources, leading to economic value loss, and has a negative impact on the environment [generating greenhouse gas (GHG) emissions when decomposed in landfills, and soil/water contamination].[16,17] In line with the content of the United Nations Sustainable Development Goals (SDG), such as SDG 2 (zero hunger) and SDG 12 (sustainable consumption and production), melon seeds have recently attracted attention as a potential food ingredient, aiming to improve the sustainability of the food system and stimulate the circular economy.

In this context, this review aims to comprehensively summarise the nutritional value of melon seeds and biological activities of individual components, and provide state-of-the-art applications as valuable ingredients in food product development. Besides, this review also highlights the promising green extraction methods to maximise the potential value of melon seeds with a sustainable and eco-friendly approach.

## 2. Botany, origin and cultivation of *Cucumis melo*

Melon (*Cucumis melo*) is one of the most ancient and important crops in the world and has been cultivated for several thousand years. The origin of melon is under debate, but several areas have been proposed such as Asia, Africa and Australia.[18] According to the geographical distribution and the most comprehensive phylogenetic analysis, it seems that the initially domesticated melon (*Cucumis melo*) originated in Asia.[19,20] In addition, the highly diversified melon varieties in India and China further support this view.[21]

Melon (*Cucumis melo* L.) belongs to the Cucurbitaceae family which includes watermelon, squash, cucumber and pumpkin.[22,23] As a result of variety, and morphological and physiological diversity, two subspecies were put forward to distinguish melon, *C. melo* subsp. *melo* and *C. melo* subsp. *agrestis*.[24] In addition, melon is divided further into 16 botanical species, with 11 botanical group classifications in *C. melo* subsp. *melo* and 5 botanical group classifications in *C. melo* subsp. *agresits*.[25,26] Some of these groups are major commercial melon varieties due to their great taste and high productivity; the most commercially important groups and their representing varieties are listed in Table 1 and Fig. 1. In the UK, the most consumed melon varieties are Galia, Honeydew, Cantaloupe, Piel de Sapo, and Matice, mainly from Spain, Brazil, Honduras, and Costa Rica.[11]

## 3. Chemical composition of melon seeds

Melon seeds have an oval shape, a smooth hard surface with yellow colour, and a white-yellow inner kernel (Fig. 2). It has been reported that melon seeds are a rich source of oil, protein, and minerals.[10,30] Their composition is summarised in Table 2 and is affected by multiple factors, including variety, region, climate, and growing conditions among others.[12,31–34]

### 3.1. Protein

The protein content of melon seeds ranges from 14.91% to 39.8% (w/w) (Table 2) and is comparable to other high oil seeds

Table 1 The most commercially important cultivar groups of melon and their characteristics[a]

| Number | Group name | Representing variety | Description |
|---|---|---|---|
| (a) | *Reticulatus* (subsp. *melo*) | Netted muskmelon | Round, netted, having a green or orange flesh |
| (b) | *Cantalupensis* (subsp. *melo*) | Cantaloupe melon | Round, smooth or warted, flesh green or orange, non-netted |
| (c) | *Inodorus* (subsp. *melo*) | Honeydew melon | Smooth-skinned, having a sweet, juicy, and light green to white flesh |
| (d) | *Flexuosus* (subsp. *melo*) | Serpent melon | Long to very long (cucumber-like), wrinkled or smooth, flesh white and not sweet or slightly acidic |
| (e) | *Conomon* (subsp. *agrestis*) | Oriental pickling melon | Smooth, green or white peel, with white flesh, sweet or bland not aromatic |
| (f) | *Chito* (subsp. *melo*) | Garden melon | Round, smooth, small lemon or orange-size, with bland white flesh |
| (g) | *Dudaim* (subsp. *melo*) | Queen Anne's pocket melon | Small, striped orange or brown, white and bland flesh, highly aromatic |
| (h) | *Chinensis* (subsp. *agrestis*) | Songwhan Charmi melon | Pyriform, green with spots, medium sweet with green or orange flesh, not aromatic |
| (i) | *Makuwa* (subsp. *agrestis*) | Oriental melon | Oblate, smooth, light or yellow peel, sweet white flesh and quite aromatic |

[a] Compiled from ref. 25 and 27–29.


Fig. 1 Images of representative melon cultivar varieties.[27,28]

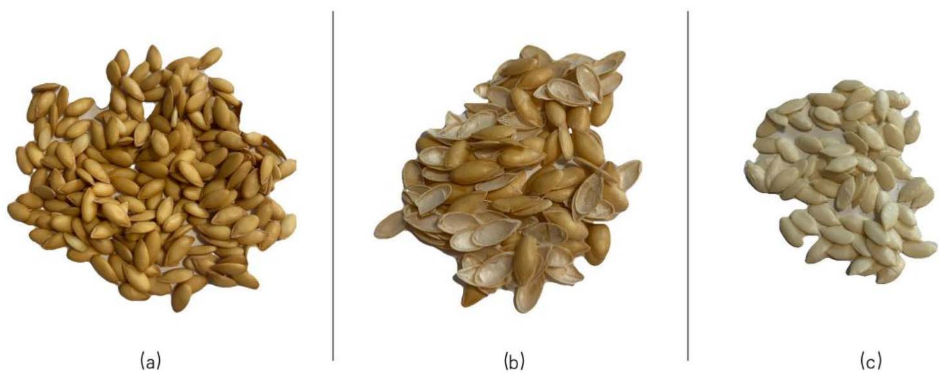


Fig. 2 The morphology of the different parts of melon seeds (*Cucumis melo* L.): (a) the whole melon seeds; (b) the shell of melon seeds; (c) the kernel of melon seeds.

in protein content, including flaxseeds (20.3%, w/w), rapeseed (19%, w/w), sesame seeds (15.7%, w/w), and sunflower seeds (24.2%, w/w);[35] in addition, compared with other by-products in protein content, such as Japanese quince (*Chaenomeles japonica*) seeds (24.6–33.2%, w/w),[36] chayote (*Sechium edule* (Jacq.) Swartz) seeds (5.5% w/w),[37] mango seed kernels (6.7% w/w);[38] the above results indicate that melon seeds could be a potential source of protein. Glutelin (38.7%, w/w of protein), albumin (34.5%, w/w of protein), and globulin (24.1%, w/w of protein) are the predominant protein fractions, whereas prolamin is usually present in low levels (2.8%, w/w of protein). In terms of protein solubility, it is a typical U curve and the minimum solubility is at pH 4.[39,40] With regard to the amino acid profile, the major amino acids of melon seed protein are

 

Table 2 Proximate composition of melon seeds

| Component (%, w/w) | Melon seed (*Cucumis melo*) | "Maazoun" variety | "*Ananas*" variety | *C. melo* var. *reticulates* Naud hybrid "Chunli" | Three varieties | *Cucumis melo* var. *inodorus* | *Cucumis melo* hybrid AF-522 |
|---|---|---|---|---|---|---|---|
| Protein | — | 27.41 | 26.15 | 29.90 | 34.6–39.8 | 25.0 | 14.91 |
| Ash | 4.08 | 4.83 | 2.78 | 4.05 | 4.6–5.1 | 2.4 | 4.20 |
| Oil | 30.7 | 30.65 | 28.44 | 35.36 | 41.6–44.5 | 25.0 | 30.83 |
| Fibre | — | 25.32 | 34.08 | 19.52 | 4.5–8.5 | 23.3 | 19.00 |
| **Minerals (mg per 100 g)** | | | | | | | |
| Potassium | 509.804 | 1148.75 | 994.04 | — | — | — | — |
| Magnesium | 101.715 | 1062.25 | 745.94 | — | — | — | — |
| Calcium | 55.392 | 506.13 | 691.9 | — | — | — | — |
| Sodium | 41.176 | 336.5 | 400.00 | — | — | — | — |
| Iron | 4.901 | 2.69 | 23.13 | — | — | — | — |
| Zinc | 4.656 | 2.34 | 9.40 | — | — | — | — |
| Copper | 0.833 | 0.53 | 64.86 | — | — | — | — |
| References | 61 | 30 | 60 | 34 | 33 | 31 | 62 |

glutamic acid (17.5–20% of protein), arginine (13.4–17% of protein), leucine (7.4–7.5% of protein), and aspartic (9.0–10% of protein), whereas lysine (2.8–3.5% of protein) and methionine (0.8–2.2% of protein) are present in low levels.[32,34,41] Several studies have shown that melon seed protein contains all 10 essential amino acids but has only a small amount of cysteine (non-essential amino acid).[32,34,42]

### 3.2. Fibre

Dietary fibre is important to human gut health and can increase satiety to reduce food intake.[43] Many studies in the literature have demonstrated the biological activity of dietary fibre through *in vitro* (*e.g.* antioxidant capacity assays and α-amylase activity inhibition) and *in vivo* (*e.g.* animal models and human trials), including maintenance of a health gut microbiome, hypoglycaemic properties, and antioxidant activity.[44–47] The dietary fibre in melon seeds ranges from 19.52% to 34.08% w/w (Table 2). In addition, dietary fibre can be divided into soluble dietary fibre (SDF) (*e.g.* pectin, oligosaccharides, and soluble hemicelluloses) and insoluble dietary fibre (IDF) (*e.g.* cellulose, insoluble hemicelluloses, and lignin).[43] Studies conducted by Mallek-Ayadi *et al.*[30] reported that SDF and IDF in melon seeds of Maazoun variety were 3.14% and 22.18% w/w, respectively, indicating that IDF is the major dietary fibre in melon seeds. In addition, Zhang *et al.*[48] investigated the carbohydrate composition of melon seeds and the results showed that melon seeds contained 4.8–5.4% (w/w) of cellulose, 3.3–3.7% (w/w) of hemicellulose, and 6.0–6.8% (w/w) of lignin. However, further detailed information on the carbohydrate composition of melon seeds is still scarce; further research is needed to provide more comprehensive understanding of melon seed carbohydrates, their nutritional profile and any potential benefits for human health.

### 3.3. Minerals

The mineral content of melon seeds is detailed in Table 2, with the most prominent ones being potassium, magnesium, calcium, and sodium. It is important to note that the potassium content can reach 1148.75 mg per 100 g in melon seeds (Table 2). According to the new guidance on dietary potassium from the WHO, potassium-rich foods include bean and peas (∼1300 mg/100 g), nuts (∼600 mg/100 g), spinach (∼550 mg/100 g), and banana (∼350 mg/100 g).[49] Compared with these potassium-rich foods, it can be concluded that melon seeds have a high content of potassium and could be considered as a new source of potassium. The high sodium dietary intake is a major public health issue in both developed and developing countries and is linked with increased risk of hypertension and cardiovascular diseases. The WHO suggests increased potassium intake and decreased sodium intake to reduce the risk of heart disease.[50,51] In potassium fortified food applications, Srivastava[52] used virgin coconut meal (1700 mg/100 g of potassium) as wheat flour substitution in biscuit production and found that biscuits containing 25% virgin coconut meal (442.06 mg/100 g) had a seven-fold increase in potassium content compared to control biscuit (100% wheat flour, 59.24 mg/100 g). Additionally, Sanz-

Table 3 Fatty acid composition of melon seed oil[a]

| Fatty acid compositions (%) | Nine varieties of melon seed oil | "Maazoun" variety | Cantaloupe melon seed oil (*Cucumis melo* L. var. *reticulatus*) | Three varieties of melon seed oil | Honeydew melon seed oil (*C. melo* var. *inodorus*) | *C. melo* var. *reticulates* Naud hybrid 'ChunLi' | Culinary melon seed oil (*Cucumis melo* var.*acidulus*) | *Cucumis melo* hybrid AF-522 |
|---|---|---|---|---|---|---|---|---|
| C12:0 | — | — | — | — | 0.2 | 0.023 | — | — |
| C13:0 | — | — | — | — | — | 0.006 | — | 0.36 |
| C14:0 | 0.04–0.06 | 0.04 | — | — | 0.2 | 0.251 | 0.056 | 0.04 |
| C15:0 | 0.02–0.03 | 0.03 | — | — | — | 0.132 | — | 0.03 |
| C16:0 | 7.19–9.74 | 8.71 | 9.1 | 9.88–15.65 | 8.4 | 23.878 | 11.65 | 9.52 |
| C17:0 | 0.06–0.08 | 0.07 | 0.1 | — | — | 0.191 | — | 0.07 |
| C18:0 | 4.57–5.86 | 5.54 | 4.6 | 5.81–7.80 | 4.6 | 5.671 | 7.40 | 4.89 |
| C20:0 | 0.17–0.28 | 0.16 | 0.1 | 0.24–0.56 | 0.5 | 0.272 | 0.248 | 0.18 |
| C21:0 | 0.00–0.01 | — | — | — | — | 0.035 | — | — |
| C22:0 | 0.03–0.07 | — | — | — | — | 0.425 | 0.077 | — |
| C23:0 | — | — | — | — | — | 0.221 | — | — |
| C24:0 | 0.04–0.05 | 0.06 | 0.1 | — | — | 1.456 | — | 0.12 |
| SFA | 12.12–16.18 | 14.61 | 14.0 | 15.93–24.01 | 13.9 | 32.561 | 19.431 | 15.21 |
| C15:1 | — | — | — | — | — | 0.309 | — | — |
| C16:1 | 0.08–0.12 | 0.08 | 0.1 | — | 0.3 | 0.096 | 0.076 | 0.17 |
| C17:1 | 0.01–0.03 | 0.03 | — | — | — | 0.019 | | 0.03 |
| C18:1 | 15.23–33.96 | 15.84 | 15.9 | 14.25–29.30 | 16.8 | 12.101 | 13.70 | 19.42 |
| C20:1 | 0.11–0.16 | 0.13 | 0.1 | — | — | 0.078 | — | 0.11 |
| C22:1 | — | 0.02 | — | — | — | — | — | 0.40 |
| C24:1 | — | — | — | — | — | 0.071 | — | — |
| MUFA | 15.43–34.27 | 16.1 | 16.1 | 15.25–29.30 | 17.1 | 12.674 | 13.776 | 20.1 |
| C18:2 | 50.69–69.22 | 68.98 | 63.5 | 45.90–68.07 | 69.0 | 53.872 | 66.55 | 64.13 |
| C18:3 | 0.15–0.26 | 0.2 | 0.2 | 0–0.22 | — | 0.871 | 0.22 | 0.20 |
| C20:2 | 0.01–0.01 | — | — | — | — | 0.028 | — | — |
| PUFA | 50.85–69.49 | 70.08 | 63.70 | 45.90–68.27 | 69.0 | 54.771 | 66.77 | 64.33 |
| References | 12 | 30 | 115 | 60 | 31 | 34 | 73 | 62 |

[a] SFA – saturated fatty acid; MUFA – monounsaturated fatty acid; PUFA – polyunsaturated fatty acid.

Penella *et al.*[53] added whole amaranth flour (470 mg/100 g of potassium) in bread production and 40% addition level increased potassium content of bread from 188 mg/100 g to 321 mg/100 g. Based on the above studies, the potential of melon seeds as a promising ingredient to fortify potassium content in food production is revealed. Besides, melon seeds can also be regarded as a source of calcium (506 mg/100 g) when compared with plain low-fat yogurt (189 mg/100 g), tofu (183 mg/100 g), and whole milk (116 mg/100 g).[54]

### 3.4. Oil

The oil content of melon seeds ranges from 25.0% to 44.5% w/w (Table 2). Compared with other conventional oilseeds such as sunflower seeds (approximately 40% w/w),[55] peanut (approximately 50% w/w),[56] and soybean (approximately 15% w/w),[57] the oil content in melon seeds is generally similar to that in sunflower seeds and peanut and higher than that of soybean. Due to the expansion of markets and the increased requirement for food and non-food applications of vegetable oils (*e.g.* biodiesel), the development of new oil sources has been important for many oilseed-importing countries.[58] Compared with other novel sources, melon seeds have higher quantities of oil than mango seeds (7.0% w/w), strawberry seeds (7.6% w/w), grape seeds (9.7% w/w) and kumquat (33.5% w/w),[59] indicating that melon seeds could be used as a novel source of oil.

**3.4.1. Fatty acid composition of melon seed oil.** The fatty acid composition of melon seed oil is shown in Table 3. It is mainly constituted of linoleic acid (C18:2, 55.90–68.98%), followed by oleic acid (C18:1, 12.101–33.96%), palmitic acid (C16:1, 7.19–23.878%), and stearic acid (C18:0, 4.57–7.80%).[30,31,33,34,60–62] The linoleic acid content of melon seed oil is similar to that of apple seed oil (58.9%), sunflower oil (62.2%), soybean oil (53.2%), and grape seed oil (74.7%).[42,59,63] According to Marangoni *et al.*[64] linoleic acid is inversely correlated with cardiovascular disease risk. Additionally, Wang *et al.*[14] detected conjugated linolenic acid (CLnA) in melon seeds (1.97–2.16 mg CLnA per g seed), which was lower than that in cherry seeds (12.79 CLnA per g seed), but higher than that in apple seeds (0.38 mg CLnA per g seed) and pear seeds (0.05 mg CLnA per g seed). CLnA is a positional and geometric isomer of linolenic acid (C18:3), and has been suggested to have potentially positive effects on cardiovascular health.[65,66]

**3.4.2. Physicochemical characteristics of melon seed oil.** The physicochemical characteristics of the oil indicate its quality. Table 4 lists the various chemical and physical parameters of melon seed oil which highlight its potential as edible oil. The acid value is normally positively correlated with the free fatty acid content, whereas the peroxide value is related to the degree of lipid oxidation.[67,68] These two parameters indicate oil stability during storage because high acid and peroxide values characterise oil that are more susceptible to oxidation.[69] Melon seed oil has a relatively good oxidative stability, as shown by its low peroxide and acid values (Table 4).[12,70–72] The iodine value reflects the level of unsaturated content in oil.[69] The high iodine value of melon seed oil indicates a high level of unsaturated fatty acid composition as also confirmed by its high content of oleic acid (18 : 1) and linoleic acid (18 : 2).[30,60,72,73] The saponification value indicates the content of high molecular weight triacylglycerols.[71] The saponification value of melon seed oil is slightly higher than that of other crop oils (*e.g.* sunflower oil, pumpkin oil, and kenaf seed oil) and this indicates a high content of high molecular weight triacylglycerols.[69,71,74] Generally, the iodine and saponification values can be used as indicators of the potential nutritional value of the oil.[68,75] Therefore, and considering the above, it can be suggested that melon seed oil could be considered a novel edible oil with commercial potential.

**3.4.3. Sterols and tocopherols in melon seed oil.** Sterols have similar chemical structures and biological properties to cholesterol and are associated with LDL-cholesterol reduction in humans.[76,77] The sterol content in melon seed oil is shown in Table 5. Total sterol content is reported to be higher than that of some conventional oils, such as sunflower (192 mg/100 g of oil), pumpkin (91.3 mg/100 g of oil), and soybean (164.9 mg/100 g of oil), but lower than that of grape seed (300.5 mg/100 g of oil), tomato seed (169.8 mg/100 g of oil) and passion fruit seed oil (244.4 mg/100 g of oil).[30,78,79] Petkova & Antova[33] analysed the sterol composition from three melon seed varieties and reported that β-sitosterol was the main component (50–64%), followed by Δ5-avenasterol (19.7–42.7%) and stigmasterol (2.7–4.8%).

Tocopherols, major forms of vitamin E, are natural lipid-soluble antioxidants, which include homologues of α, β, γ, and δ (Fig. 3). γ-Tocopherol is predominant in melon seed oil[80] and is considered a highly effective antioxidant that can inhibit oil oxidation and increase the oxidative stability by scavenging the peroxy radicals[81] Hashemi *et al.*[82] investigated the oxidative stability of several seed oils under microwave heating conditions; melon seed oil was more stable than watermelon oil, due to the tocopherol content of the former (125 mg kg$^{-1}$) compared to watermelon oil (111 mg kg$^{-1}$).

Table 4 Physicochemical parameters of melon seed oil

| Parameters | "*Ananas*" variety | *C. melo* var. *reticulates* Naud hybrid "Chunli" | Three varieties | *Cucumis melo* hybrid AF-522 | Three varieties |
|---|---|---|---|---|---|
| Acid value (mg KOH per g) | 9.60 | 1.51 | 1.5–2.1 | 2.06 | 07–1.8 |
| Peroxide value (meq $O_2$ per kg) | 1.04 | 3.95 | 1.1–3.4 | 4.96 | 6.7–8.9 |
| Iodine value (g $I_2$ per 100 g) | 128.44 | 89.5 | 115–128 | 112 | 117.0–147.2 |
| Saponification value (mg KOH per g) | 178.30 | 226.73 | — | 210.62 | 108.9–205.4 |
| References | 60 | 34 | 33 | 62 | 105 |

Table 5 Sterols and tocopherol content in melon seed oil

| Sterols (mg per 100 g of oil) | Yellow melon seed oil (*Cucumis melo* var. *inodorus* Naudin) | Canary melon seed oil (*Cucumis melo* L.) | "Maazoun" variety | "*Ananas*" variety | Nine varieties |
|---|---|---|---|---|---|
| Campesterol | — | — | 0.92 | 1.13 | — |
| Campestanol | — | | 0.59 | 0.20 | — |
| Stigmasterol | — | — | 1.29 | 2.11 | — |
| β-Sitosterol | 21.02 | — | 206.42 | 324.84 | — |
| Sitostanol | — | — | 4.84 | 10.78 | |
| Δ5-Avenasterol | — | — | 2.18 | 153.31 | — |
| Cholesterol | — | — | 0.88 | 0.36 | — |
| Stimastanol | 11.71 | — | — | — | — |
| Brassicasterol | | — | — | 3.20 | — |
| Total phytosterol | 32.73 | — | 217.12 | 495.93 | — |
| **Tocopherols (mg per 100 g of oil)** | | | | | |
| α-Tocopherol | 2.05 | 6.88 | 2.85 | — | 3.74–7.47 |
| β-Tocopherol | — | — | — | — | — |
| γ-Tocopherol | 24.96 | 63.08 | 18.13 | — | 9.98–45.67 |
| δ-Tocopherol | ND | 0.77 | 6.09 | — | 0.93–2.72 |
| Total tocopherols | 27.01 | 70.73 | 27.07 | — | 14.65–55.86 |
| References | 78 | 80 | 30 | 60 | 12 |

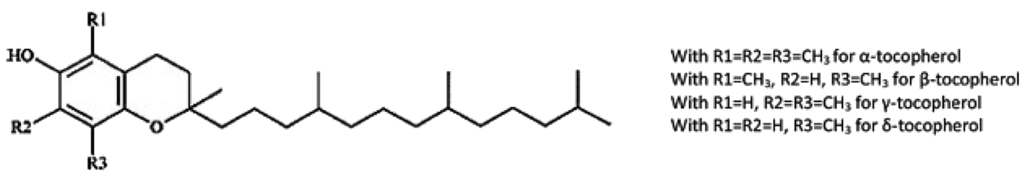


Fig. 3 Chemical structure of tocopherol (Fine *et al.*[79]).

## 4. Extraction technology

Based on their composition, melon seeds hold potential as a source of value-added compounds, such as lipids, protein, fibre, minerals, and polyphenols, and can have a variety of applications in many sectors, such as food, pharmaceutical, and cosmetics. Recovery of these value-added compounds can maximise the value of melon seeds. Therefore, appropriate extraction technologies are key for scale-up studies and commercial applications[83] In the following sections, extraction technologies are discussed in detail, including conventional and novel green technologies, targeting the recovery of value-added compounds from melon seeds. Additionally, the advantages and disadvantages of conventional and novel green technologies (supercritical fluid extraction, enzyme assisted extraction, and ultrasonic assisted extraction) are listed in Table 6.

### 4.1. Conventional solvent extraction (CSE)

Solvent extraction is a conventional method for the recovery of high value-added compounds, such as protein, oil, polysaccharides, and polyphenols. Solvent extraction usually includes solid–liquid and liquid–liquid extraction. The process involves mixing the material with a suitable non-polar solvent (*e.g.* hexane and petroleum ether for oil extraction) or polar solvent (*e.g.* ethanol and methanol for polyphenol extraction) to make the compound move into the extraction solvent where it can be separated or concentrated.[83,91,92] However, some of the organic solvents used, such as *n*-hexane and tetrahydrofuran, could be potentially harmful and toxic for humans, animals and/or the environment.[93] Besides, conventional solvent extraction has many drawbacks, including long operation times, poor extraction efficiency, solvent residue in final products and flammable risks.[84,85] Therefore, novel, environmentally friendly extraction methods are needed to overcome these drawbacks.

### 4.2. Supercritical fluid extraction (SFE)

Supercritical fluid extraction (SFE) is an environmentally friendly extraction method that mainly uses carbon dioxide ($CO_2$; typical non-polar solvent; non-toxic and green) as a supercritical fluid. $CO_2$ at its supercritical fluid state has high solvation power and can diffuse like a gas in solid matrices.[94–96] In addition, ethanol or methanol, as a polar co-solvent, can be added into supercritical $CO_2$ to target the extraction of polar compounds (*e.g.* phenolics) (Fig. 4).[93] Supercritical fluid extraction has many advantages compared with conventional solvent extraction including a faster, cleaner, and easier separation of the solute from the solvent. SFE has demonstrated it potential for extraction of many compounds, such as oils,

Table 6 Summary of advantages and disadvantages of conventional and novel green technologies[a]

| Method | Advantages | Disadvantages |
|---|---|---|
| Conventional solvent extraction (CSE) | Simplicity of process<br>Cost effectiveness<br>Modulation of selectivity by solvent choice | Solvent residue in final products<br>Use of large amount of toxic solvents<br>Energy intensive<br>Flammable risks |
| Supercritical fluid extraction (SFE) | Low temperature<br>Less or no solvent usage<br>Fast extraction rate<br>Easy solvent recovery avoiding expensive post-processing | Expensive and complex equipment<br>High operation cost<br>Low polarity of supercritical $CO_2$ |
| Enzyme assisted extraction (EAE) | Enzyme reusability<br>Mild reaction conditions<br>Low energy consumption and operational costs<br>High selectivity<br>Ease of operation | Long incubation time<br>Complicated drying process after enzymatic treatment<br>Lack of long-term stability of enzymes<br>Enzyme cost |
| Ultrasonic assisted extraction (UAE) | Simplicity of process<br>High yield<br>Fast extraction rate<br>Less solvent usage | Non-uniform distribution of ultrasound energy<br>Degradation of active compounds from plant matrices due to oxidative pyrolysis caused by hydroxyl (OH–) radicals during cavitation |

[a] Data compiled from ref. 84–90.

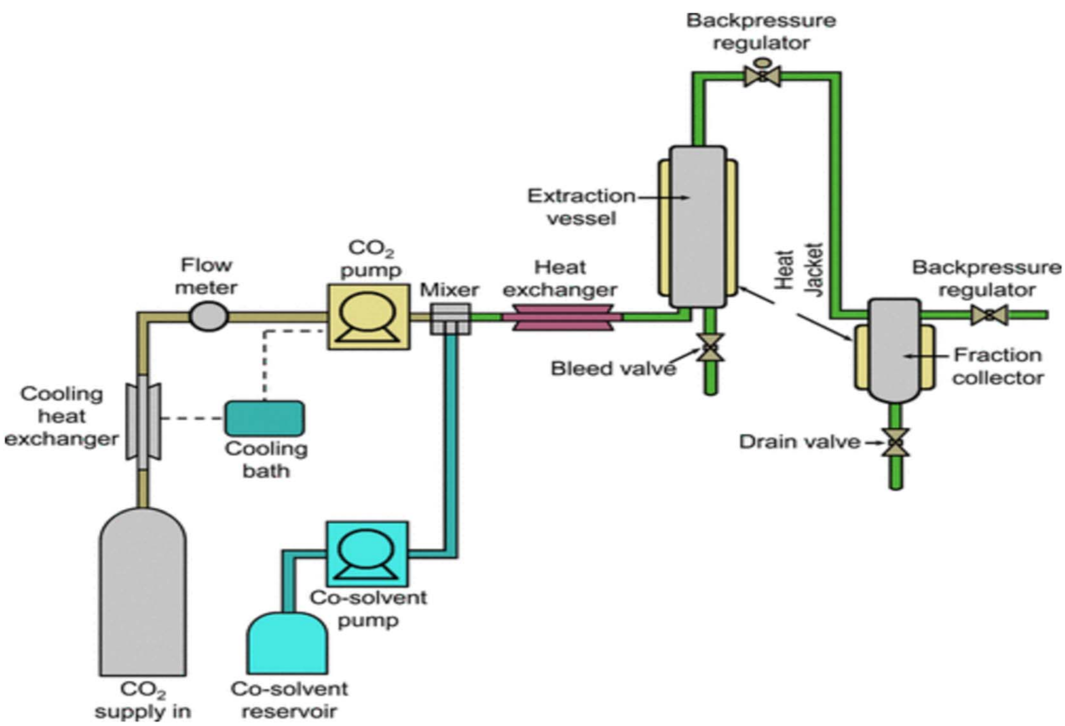


Fig. 4 Schematic representation of the supercritical $CO_2$ system coupled with co-solvent (Koubaa *et al.*[97]).

phenolics, and pigments. For example, Lima *et al.*[98] used the SFE technique to extract phenolics from potato (*Solanum tuberosum*) peels and found that 37% of the total phenolic acid content and 82% of the caffeic acid in this matrix were successfully extracted under the optimized process conditions (80 °C, 350 bar, MeOH 20%, and $CO_2$ flow rate of 18.0 g min$^{-1}$). Additionally, Maran *et al.*[99] used SFE to extract oil from melon seeds. They reported that the fatty acid composition of melon seed oil was not different between SFE and hexane Soxhlet extraction, but the total yield of oil (48.11%) using SFE (extraction at 44 MPa, 49 °C, 0.64 g min$^{-1}$ of flow rate, and 81 min of extraction time) was slightly higher than that of hexane Soxhlet extraction (46.83%). Ekinci & Gürü[100] reported that the highest yields of extracted oil, β-sitosterol, and stigmasterol by

 

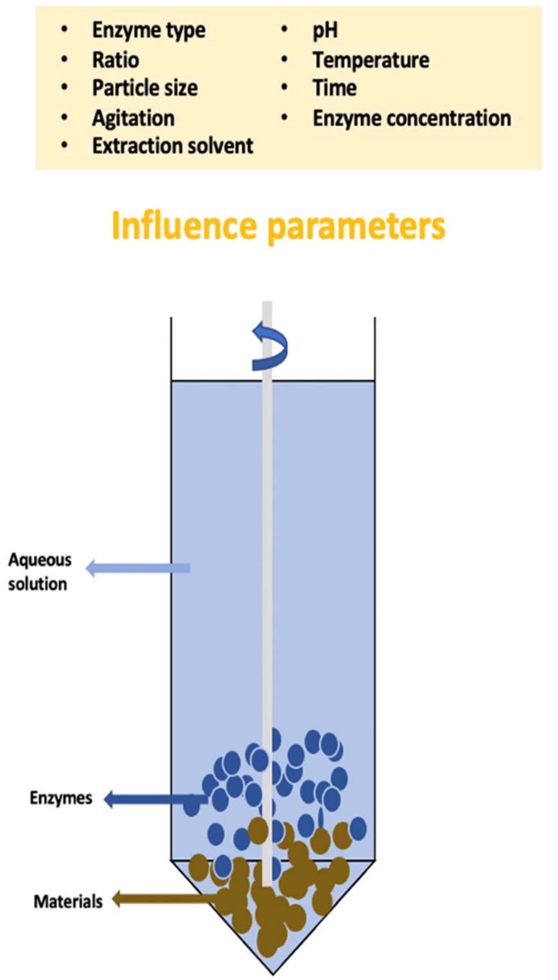


Fig. 5 Schematic representation of extraction assisted by enzymes.

SFE were 36.8 g/100 g, 304 mg $kg^{-1}$, and 121 mg $kg^{-1}$, respectively, whereas the optimal conditions were 33 °C, 200 bar, and 11 g $CO_2$/min, extraction time of 3 h, and the mean particle size of 0.4 mm.

### 4.3. Enzyme assisted extraction (EAE)

Enzyme assisted extraction (EAE) is an environmentally friendly extraction method because enzymes can be combined with green solvents (water) or aqueous-alcoholic solvents (*e.g.* aqueous methanol solvent and aqueous ethanol solvent) to eliminate or reduce the amount of organic solvent usage.[101] The principle of enzyme assisted extraction is that specific enzymes (such as cellulases, pectinases, and hemicellulases) are selected to disrupt or hydrolyse the cell wall structure, enhance cell permeability and thus increase the extraction yield of target components (*e.g.* oil and polyphenols) (Fig. 5).[91,102,103] It is important to note that many parameters should be considered to achieve optimal extraction conditions in the enzyme assisted processing, including pH, temperature, time, particle size of samples, nature of the extraction solvent, enzyme concentration, agitation rate and the ratio between the enzyme and substrate.[84,91,101] EAE has demonstrated its potential for oil extraction. For example, Ribeiro *et al.*[104] compared oil extraction from sesame oil by EAE (using pectinase and alcalase) and conventional solvent extraction; it showed that the quantity of the oil extracted by EAE (36.65%) was lower than that from solvent extraction (59.97%), while the quality of the EAE extracted sesame oil was better than that conventionally extracted in terms of antioxidant capacity, total phytosterol content, and total polyunsaturated fatty acid content. In addition, Zhang *et al.*[105] extracted melon seed oil in three varieties and compared the oil quality between EAE (using protease and cellulase) and conventional extraction methods (cold-pressed and Soxhlet extraction); the results showed that

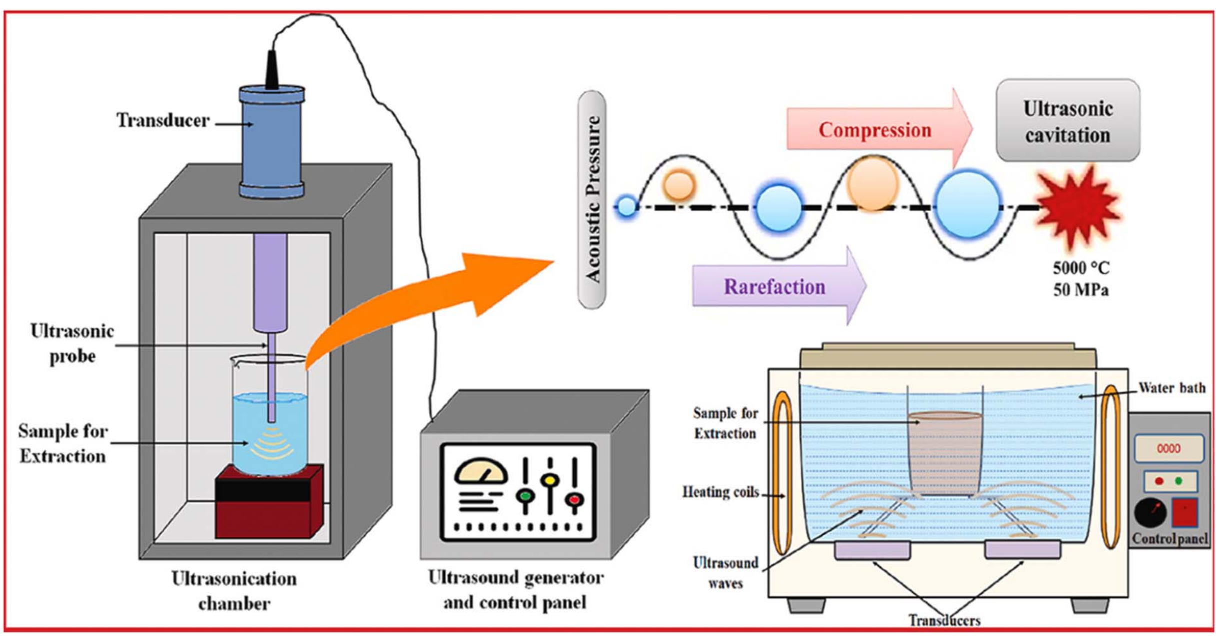


Fig. 6 Schematic representation of ultrasonic-assisted extraction (More *et al.*[106]).

melon seed oil obtained by EAE (15.0–67.3 mg/100 g of oil) had higher tocopherol content than that of oil extracted by conventional extraction methods (6.8–52.4 mg/100 g of oil). In addition, during the storage test, the EAE derived oil exhibited better oxidative stability compared to the oil extracted by other two conventional methods. However, in practical oil extraction, EAE could lead to the formation of an emulsion, which in turn needs de-emulsification processing to further improve the oil extraction yield.

### 4.4. Ultrasonic assisted extraction (UAE)

The principle of ultrasonic assisted extraction (UAE) is based on the energy change of the expansion of sound waves in a liquid (Fig. 6).[92] In UAE processing, the transmission of ultrasound through the medium generates cavitation bubbles which grow further and collapse, resulting in vibration, mixing, and pulverization; these in turn, enhance the molecular vibration frequency, disrupt the cell wall, and accelerate the rate of heat or mass transfer.[91,93,107] Therefore, the extraction yield is increased and extraction time is decreased.[107] Process parameters such as type of solvent, extraction time and temperature, as well as frequency of ultrasound waves, have been mentioned as key variables for the effectiveness and efficiency of the UAE process.[108] UAE has been successfully applied in oil, protein, phenolics, and other bioactivity compounds. Rivas *et al.*[109] and Piasecka *et al.*[110] successfully used the UAE method to extract dietary fibre and oil from broccoli by-products (leaves, stems and inflorescence remains) and cranberry seeds, respectively. Besides, UAE can be combined with other extraction methods to facilitate cell wall disruption and overcome some limitations of other extraction methods (*e.g.* considerable long extraction time and low extraction efficiency).[101] For example, it can be combined with the enzymes, leading to an ultrasonic-assisted enzymatic extraction (UAEE) method.[91] Tang *et al.*[103] and Kumar T. *et al.*[111] used the UAEE method to extract dietary fibre and oil in bamboo shoot by-products (the head and foot of *Chimonobambusa quadrangularis* shoots) and sea buckthorn berry, respectively. The potential advantage that UAEE could offer is the acceleration of extraction and enzymatic hydrolysis processes through cavitation, thereby improving the enzymatic extraction efficiency.[112]

## 5. Utilisation of melon seeds in food product development

The conversion of food by-products as ingredients in food formulations is one of the most attractive strategies to reduce food loss and capture value. Recently, the utilisation of melon seeds and their subsequent components in food formulation has been explored and has demonstrated their potential as ingredients. The following section presents current advances in the application of melon seeds and their components in various food matrices.

Karakaya *et al.*[113] developed a melon seed beverage that was made of melon seeds, sugar, and water through blending, and demonstrated that the beverage was a good source of minerals (iron and magnesium) and protein, and gave very good results in the hedonic test as 'liked very much' (4.9 on a 5-point hedonic scale). In addition, Zungur Bastıoğlu *et al.*[114] produced a plant-based milk from melon seed spray dried powder as alternatives to vegans, vegetarians, and lactose-intolerant. Melon seed spray-dried powder showed good solubility (92.0–99.2%) and storage stability (moisture content and water activity are 2.1–2.4% and 0.260–0.310, respectively) but exhibited poor flowability (50.44–53.23 Carr index value) and tended to form lumps. In terms of sensory evaluation, melon seed milk showed very good visual attributes, particularly a creamy, white colour appearance.

da Cunha *et al.*[115] used melon seeds in baker's confectionary products. Specifically, melon seed flour was used as raw material to partly replace wheat flour in three inclusions: 10% melon seed flour, 30% melon seed flour, and 50% melon seed flour; the control was 100% wheat flour. The results demonstrated that all cakes containing melon seed flour were well accepted by the panel, as did the control group (100% wheat flour); in terms of their flavour (sweetness) attribute, the score was slightly reduced with increasing the ratio of melon seed flour. In the analysis of global acceptance (nine-point scale), the 10% melon seed flour cake had the highest acceptance (7.08) compared to the control (6.56).

Tarjuelo *et al.*[116] reformulated dried sausage (fuet) using melon seed oil (extracted using a hydraulic press) as a pork fat substitute, at 50%, 75%, and 100% (w/w). Reformulated fuet sausages had higher linoleic acid content as compared to control fuet sausages (100% pork fat). However, in the sensory evaluation, the sensory score for fuet sausages made with melon seed oil was lower than that of the control in terms of appearance, texture, odour, and taste. In terms of texture, fuet sausage made with melon seed oil had a significantly lower ($p < 0.05$) hardness value than the control. Overall, from a nutritional point of view, the evidence in this study suggests the possibility of melon seed oil in sausage application, which could lead to nutritionally more balanced meat products.

Zhang *et al.*[117] used defatted melon seed as a wheat flour substitute in bread production at 5% and 10% replacing levels. The results showed that adding defatted melon seeds can improve the bread nutritional value, especially fibre content; bread made with 10% defatted melon seeds (3.41 g/100 g) showed more than five-fold fibre content compared to 100% wheat flour bread (0.56 g/100 g). However, in terms of bread physical characteristics, defatted melon seed addition decreased the bread volume and cell number and increased the bread hardness value; in addition, as addition of defatted melon seed increased, bread crust became more darker. Subsequently, Zhang & Li[118] used different particle sizes of melon seed oil cake (MSOC, obtained from cold-pressed) as wheat flour substitution in bread production at 3% and 6% replacing levels. The results demonstrated that bread containing 3% MSOC exhibited satisfactory quality compared to control bread (100% wheat flour) in terms of bread volume and texture; in addition, reduction of the MSOC particle size could result in a lower bread volume and harder texture but with an improved crumb structure.

The above studies highlight some promising progress with regard to melon seed utilisation in food formulations. However, challenges in product quality and organoleptic aspects still exist and further work is required to optimise processing parameters and develop products acceptable by consumers. Additionally, the food matrix can influence the bioactivity and bioavailability of nutrients during the digestion process, and currently, there is still no sufficient information regarding the potentially nutritional properties of incorporated melon seed in food. Based on this point, further research is needed to identify and evaluate the bioavailability, absorption, and bioactivity of melon seed nutrients *in vivo*. Moreover, considering the safety and quality of by-products is also an important part of valorisation strategies to ensure food safety for customer consumption. In general, allergens, microbiological safety, and contamination assessment (*e.g.* pesticide residues and toxins) are the most common considerations in food safety evaluation.[17,119] Although there is no available information about melon seed safety and quality at present, it merits an important aspect of research in the future.

# 6. Biological activity of melon seed compounds

Melon seeds could be a potential source of natural bioactive compounds. Research studies have indicated the biological activity of melon seeds including their antioxidant and antiproliferative activities, as well as their health benefits in preventing or reducing the risk of chronic diseases, such as diabetes, obesity, and cardiovascular conditions.[120–124] Studies by Chen & Kang[120] demonstrated *in vitro* that hexane extracts of the melon (*Cucumis melo* L. var. *makuwa* Makino) seed have potential ability as an anti-diabetic by inhibiting the activity of α-glucosidase and α-amylase, by 35% and 62% respectively; this is because the inhibition of these enzymes can delay carbohydrate digestion and glucose absorption thereby controlling the increase in postprandial plasma glucose, which has potential benefits for type 2 diabetics. According to the study, this could be attributed to presence of unsaturated fatty acids in the hexane extracts of melon seeds. Additionally, Chen *et al.*[121] further demonstrated that the three key fatty acids in the melon extracts, palmitic, linoleic and oleic acid, had high enzyme inhibitory effects *in vitro*, especially linoleic acid which demonstrated the strongest inhibition towards α-glucosidase and α-amylase.

Rolim *et al.*[122] studied the anti-proliferative effects of melon seed extracts on cancer cells (SiHa, HeLa, HT-29, and 786-0) and attributed this to their phenolic content. The results showed that melon seed extracts, obtained using distilled water, aqueous ethanol (30 : 70, v/v), and aqueous methanol (30 : 70, v/v) as solvents, exhibited inhibition activity for all four types of cancer cells. Zhang *et al.*[125] demonstrated that melon seed extracts obtained using methanol, distilled water, and chloroform showed highly effective anticancer activity in HeLa cell lines and were more cytotoxic to HCT116 cell lines.

Rasouli *et al.*[124] purified protein from melon seeds as a trypsin inhibitor and explored its potential anti-angiogenesis and anti-proliferation activities. The results showed that the molecular mass of purified protein was 3 kDa and the trypsin inhibition activity was 765 CIU $mg^{-1}$ (chymotrypsin inhibitory unit per mg of protein). When the concentration of purified protein reached 40 μg $mL^{-1}$, the angiogenesis in the Human Umbilical Vein Endothelial Cells (HUVEC) capillary tube formation model was completely inhibited. Moreover, even at very high concentrations, *i.e.* 120 μg $mL^{-1}$, there was no cytotoxic effect as assessed by LDH cytotoxicity assays. Thus, this study indicated that purified melon seed protein could be used as a botanical derivative promoting anti-angiogenesis and anti-proliferation effects.

Although melon seed extracts seem to exhibit promising bioactive properties in *in vitro* studies, there is lack of information derived from *in vivo* studies that could further support these findings. Therefore, there is a need for *in vivo* studies to produce more comparable and reliable data, to validate the bioactive effects of melon seed extracts on health and assist in the design of melon seed valorisation strategies.

# 7. Environmental and economic impact

Food and agriculture process waste is becoming an acute issue in the world. According to the estimates, global food waste is around 30% (around 1.3 billion tons), which increases greenhouse gas (GHG) emissions by 6% indirectly and causes economic value losses about 1 trillion US dollar value.[126,127] As mentioned earlier, melon seed waste is around 1.5–2.9 million tons. To this end, developing comprehensive valorisation strategies for melon seed waste is of great significance to reduce food waste, which can reduce economic losses and is beneficial for the environment.

From an environmental impact point of view, GHG emissions per ton of food waste/by-products could be up to 706–896 kg $CO_2$ eq.[128] Therefore, reducing and re-utilisation of melon seed waste could reduce GHG emissions to a large extent, which can reduce the environmental burden. In addition, high efficiency utilisation of food waste for food production can reduce food losses, and help to reduce food waste in landfills, contributing to a win–win situation across the dimensions of food security and environmental protection.

Apart from the environmental protection, evidence supports the economic viability of upcycled food by-products. For example, Wang *et al.*[14] reported that in the USA, melon seed waste can generate 37.5 tons of CLnA (conjugated linolenic acids), which can create over 6 million US dollar value. As mentioned earlier, melon seeds also contain other high potential phytochemicals available, such as fibre, protein, minerals, and linoleic acid, which can be extracted and then re-utilised in various sectors (*e.g.* food, chemical, personal care, and pharmaceutical). Taking into account the above potential value of melon seed waste, upcycling of melon seed waste could provide financial benefits.

# 8. Future perspectives

Given the current advances in melon seed valorisation and applications, various perspectives are needed to be focused on future studies. As discussed in above sections, future studies could focus on the following aspects:

(i) Quality, microbiological, and contaminants assessment of melon seeds. Although current study has demonstrated the potential value of melon seeds, the quality and safety of melon seeds are still gaps. Therefore, to guarantee melon seeds' edibility and consumers' safety, more studies on the quality and safety of melon seeds are necessary, such as allergens, content of anti-nutritional compounds (*e.g.* phytic acid, tannins, and oxalate), microbiological and contaminant assessment. Apart from that, the application of processing technologies to improve the quality and safety of melon seeds and its related products is also must in this area of research in future.

(ii) Technological improvement; the validation and assessment of bioactive effects of extracted compounds. The comparable data between green extraction technologies and conventional extraction technologies on recovering value-added compounds of melon seeds are still lacking. Additionally, the data on bioactive effects of melon seed extracts by an *in vivo* study are still lacking. An appropriate extraction method is important, since it can determine the quality, safety, and yield of final products;[101,103,105] in addition, novel green technologies can overcome the limitation of conventional technologies (*e.g.* extraction efficiency, sustainability, and safety) and are in line with sustainable development and green economy.[83,106] Therefore, enormous studies are needed to identify the effect of these technologies on the biological properties (*in vitro* and *in vivo*) and quality of the target compounds, aiming to produce high-quality end products that can be used in various sectors.

(iii) Consumer acceptance and affordability; improvement of melon seed food quality. Consumer acceptance is an important determinant of the successful commercialization of either newly developed or reformulated products.[129] Melon seeds are an uncommon ingredient in most of the countries, thus, melon seed food products could cause food neophobia for consumers.[130] To this end, how to increase consumers' acceptance and affordability for melon seed food products is necessary in future studies, including designing and marketing new products, and improvement of melon seed food quality (*e.g.* flavour, texture, appearance, nutritional value, and nutrient bioavailability).

## 9. Conclusions

Melon seeds hold potential as a source of oil as well as other functional food ingredients (protein/peptides, polyphenols, minerals, and dietary fibre). Research on the valorisation of melon seeds should aim at maximising their utilisation, converting into value-added products, applicable in food or other sectors (*e.g.* pharmaceuticals and cosmetics), to reduce waste and promote sustainability. Moreover, one of the important concepts for the circular economy is valorisation of food waste to achieve economic growth by lowering the environmental burden approach. From this point of view, in order to better transform towards a circular economy, extraction methods should be further developed and evaluated to create a more eco-friendly and sustainable recycling process to produce diverse value-added products. Regarding melon seed applications in food, the main limitation is related to their quality and organoleptic aspects. Therefore, optimising intrinsic quality parameters influencing the incorporation of melon seeds or their components in foods is an important area of research which should be further pursued.

## Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

## Conflicts of interest

The authors report there are no competing interests to declare.

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