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Review

Unlocking Potential Perspectives of *Cucumis melo* L. Fruit: Development of Bio-Functional Food Ingredients for Sustainability and Health Benefits

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Abstract

Cantaloupe melon (*Cucumis melo* L.) processing generates significant amounts of underutilized by-products that represent a promising source of bioactive compounds. Renowned for its abundance of β-carotene and phenolic antioxidants, it has garnered increased attention in recent years due to its nutritional profile. Melon side-streams, such as peels, seeds, and residual pulp, have emerged as valuable sources for sustainable functional ingredient development. This work provides updated insights into the phytochemical composition and bioactive properties of cantaloupe melon, with emphasis on the recovery and valorization of its by-products through conventional and emerging eco-friendly extraction technologies. These strategies are also discussed within a biorefinery perspective aimed at improving biomass utilization and promoting the development of value-added functional ingredients. Additionally, this review addresses how such approaches contribute to circular economy principles, supporting more sustainable and resource-efficient food production models.

Keywords: melon by-products; compound recovery; biorefinery approach; eco-friendly extraction techniques; circular economy

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Academic Editor: Yonghui Li

Received: 24 November 2025
Revised: 26 February 2026
Accepted: 21 March 2026
Published: 29 March 2026

1. Introduction

Global food systems generate large volumes of waste and underutilized biomass, representing a critical sustainability challenge and untapped source of high-value bioactive compounds. Across sectors such as food, health, cosmetics, and agriculture, food waste has gained attention as a strategic reservoir of functional molecules with technological and biological relevance. These compounds include gums, resins, or colorants, which can be used as food additives to improve organoleptic characteristics or facilitate food processing. In addition, food waste streams are increasingly recognized as sources of compounds with antioxidant, anti-inflammatory, and health-promoting properties, which can be incorporated into functional foods, food supplements, cosmetics, or agricultural applications [1–3].

Within this context, fruit waste plays a particularly relevant role due to its high moisture content, rapid perishability, and concentration of bioactive metabolites. In this sense, the cantaloupe melon (*Cucumis melo* L.) stands out as a highly promising raw material for food waste recovery and bio-functional ingredient development, due to the large volume of waste generated during its consumption and industrial processing. Melon processing and fresh consumption produce substantial amounts of by-products, including peels, seeds, and residual pulp, which are commonly discarded despite their considerable nutritional and functional potential, thereby contributing to food loss. Traditionally, cantaloupe melon consumption has been associated with the prevention of chronic diseases such as aging-related disorders, inflammation, and certain types of cancer, an effect largely attributed to its diverse profile of bioactive compounds [2].

This fruit is an annual plant that grows as a vine [4], and it is currently considered one of the most popular fruit crops worldwide, with increasing production driven by consumer demand and agro-industrial expansion. It is of great economic importance and is generally cultivated in hot and dry climatic zones such as China, Turkey, and Iran, which are the main producers of this fruit [5]. Its industrial processing has brought different products from the fruit mesocarp, such as juices, jams, dehydrated pulp, and salads or snacks [6]. Nevertheless, during its processing, some by-products such as pulp fractions, seeds, and hulls are generated, being a great source of bio-functional products.

Depending on both the plant matrix and the possible application, different extraction strategies can be applied, including conventional and emerging green technologies, as well as a wide range of solvents. This article focuses on cantaloupe melon (*C. melo* L.) as a model fruit for food waste assessment and valorization, highlighting the bioactive richness of both edible and non-edible fractions. The biomolecules present in whole fruit include pectin, soluble and insoluble fibers, vitamins, carotenoids, polyphenols, and lipids [6]. Together, these compounds make melon waste a strategic resource for the development of bio-functional food ingredients, enriched flours for bakery applications, clean-label food additives, and innovative matrices for advanced technologies such as 3D food printing [7–10]. Accordingly, the valorization of melon waste aligns sustainability goals with innovation in food design and human health. This review examines the recovery and valorization of cantaloupe melon by-products through conventional and emerging strategies within a biorefinery framework, highlighting their potential as sustainable sources of bio-functional ingredients.

2. Production and Uses of Cantaloupe Melon

In 2021, cantaloupe melon cultivation was carried out by 95 nations, with China being the largest producer with a contribution of 12.9 million tons. Worldwide, total production is estimated at more than 23 million tons of melon fruit, of which around 500–700 thousand tons were produced in Mexico [11]. According to the latest data reported worldwide by the FAO [12], cantaloupe melon production in recent years has varied (Table 1); however, production trends have been maintained in the main producing countries (Figure 1), increasing every year over the last 5 years, with Asia being the major producer with 81.26% of the world's melons, followed by America 11.32%, Europe 5.31%, and Africa 2.1%.

This crop, belonging to the Cucurbitaceae family, is a thermophilic plant and requires low humidity and a temperature range between 18 and 26 °C to favor fruit ripening [13]. It is native to Africa and India [14], its production is influenced by various abiotic and biotic stress factors, such as soil salinization, which is detrimental to the yield and quality of the crop due to toxicity issues, in addition to the presence of heavy metals such as copper and manganese, representing a threat to public health. On the other hand, biotic stress caused by microorganisms and insect pests also impact crop loss and decreased fruit quality [15,16]. As a defense to these conditions, plants have developed acclimation mechanisms at physiological, molecular, and cellular levels, having the ability to detoxify toxic compounds. The presence of several MATE genes called CmMATE1-CmMATE39 has been identified, which showed a positive response to salt, copper, and manganese stress conditions [16].

Table 1. Estimative numbers and continent representativity of cantaloupe melon (*Cucumis melo* L.) production (tons) worldwide.

	Year					
Country	**2020**	**2021**	**2022**	**2023**	**2024**	**Representative (%)**
1. China	13,065,467	13,294,873	13,315,963	13,220,656	13,267,988	81.26
2. Turkey	1,724,856	1,638,638	1,587,230	1,403,214	1,479,000	
3. India	1,368,000	1,478,000	1,498,000	1,498,000	1,540,738	
4. Kazakhstan	1,165,397	1,395,171	1,214,413	1,371,382	1,498,584	
5. Iran	892,448	752,897	676,318	641,099	569,759	
6. Afghanistan	793,496	796,827	758,068	702,765	701,220	
7. United States of America	608,472	613,416	662,586	582,345	600,602	11.32
8. Guatemala	713,339	721,020	656,293	756,306	767,019	
9. Brazil	634,404	607,057	699,853	867,544	816,939	
10. Mexico	612,940	550,282	579,901	648,541	579,006	
11. Spain	610,980	652,600	524,040	516,520	594,010	5.31
12. Italy	593,410	607,380	590,230	762,580	771,640	
13. Niger	33,477	37,408	43,122	58,186	82,529	2.11
14. Morocco	504,864	540,561	479,917	449,541	245,517	
Total	23,321,550	23,686,130	23,285,934	23,478,679	22,993,446	

Source: FAO [12].

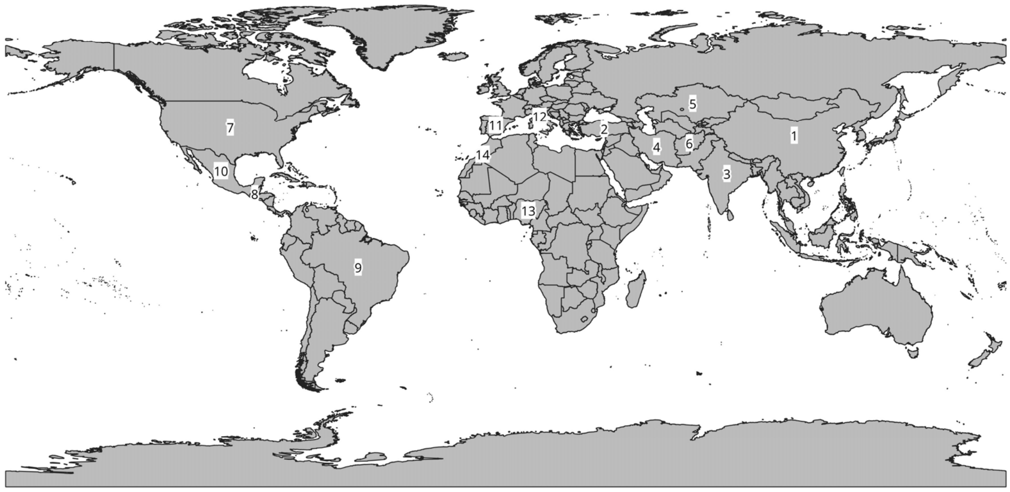

Figure 1. Global distribution of the main cantaloupe melon (*Cucumis melo* L.) producing countries. Countries are identified as follows: (1) China; (2) Türkiye; (3) India; (4) Kazakhstan; (5) Iran; (6) Afghanistan; (7) United States of America; (8) Guatemala; (9) Brazil; (10) Mexico; (11) Spain; (12) Italy; (13) Niger; (14) Morocco. Map based on Natural Earth data (NACIS-supported dataset). The boundaries shown do not imply official endorsement or acceptance by the authors.

Cantaloupe melon is grown under diverse management practices across large production areas, making the plants susceptible to a wide range of soil and climate conditions. This variability influences genotype–environment interactions, which are reflected in the expression of total soluble solids in the fruit, i.e., in the sugar content [17]. Temperature is another key factor affecting sugar accumulation; high temperatures during the final week before harvest are associated with lower soluble solids, whereas cooler conditions favor higher fruit quality [18]. Additionally, cantaloupe melon exhibits considerable variation in size, weight, shape, color, texture, flavor, and chemical composition. Consequently, its genetic diversity has attracted attention for improving fruit quality and crop yield [19,20].

The fruit has a short shelf life of less than a week when stored at 5–10 °C [21], which has led to increasing interest in product development through technologies that offer a value-added product with a longer time of availability for consumption, such as spray drying. This method has allowed the transformation of cantaloupe melon pulp into a powder of soft consistency, non-sticky, and pale yellow in color [22]. Another method used is encapsulation to retain bioactive compounds and bioavailable phytochemicals longer. Recent studies have shown that carotenoids nanoencapsulated in porcine gelatin exhibit low toxicity and have anti-inflammatory potential [23]. A similar study showed that nanoencapsulation promotes the preservation and improves the antioxidant potential of carotenoids exposed to different storage conditions [24], so this method allows obtaining a functional ingredient with longer shelf life.

Because of industrialization and consumption focused on fruit pulp, a significant amount of waste is generated. The hulls are rich in carbohydrates, proteins, ash, total dietary fiber, and antioxidants such as polyphenols and flavonoids [1,25]. Their bioactive and nutritional composition suggests that they could be useful for the development of new functional products [26], while the seeds contain many nutrients such as proteins, fibers, and minerals [27]. In Arab countries, the seeds are intended for human consumption as snacks after salting and roasting, while in India they are used in the preparation of dishes and desserts [28]. From this residue, an oil is obtained which is frequently used in African countries, which is rich in bioactive compounds such as unsaturated fatty acids, flavonoids, phenolic acids, phytosterols, and tocopherols, so melon seed oil contains significant nutritional value [27].

It has been reported that cantaloupe melon by-products are rich in value-added bioactive compounds with potential health-promoting properties, including antimicrobial, antioxidant, anti-inflammatory, antidiabetic, anti-ulcer, anti-angiogenic, and prebiotic effects [10,26,28–30]. As illustrated in Figure 2, these bioresources can be redirected from conventional processing streams toward the production of bioactive ingredients, seed oil, and functional foods, thereby contributing to the reduction of food loss and supporting circular economy strategies.

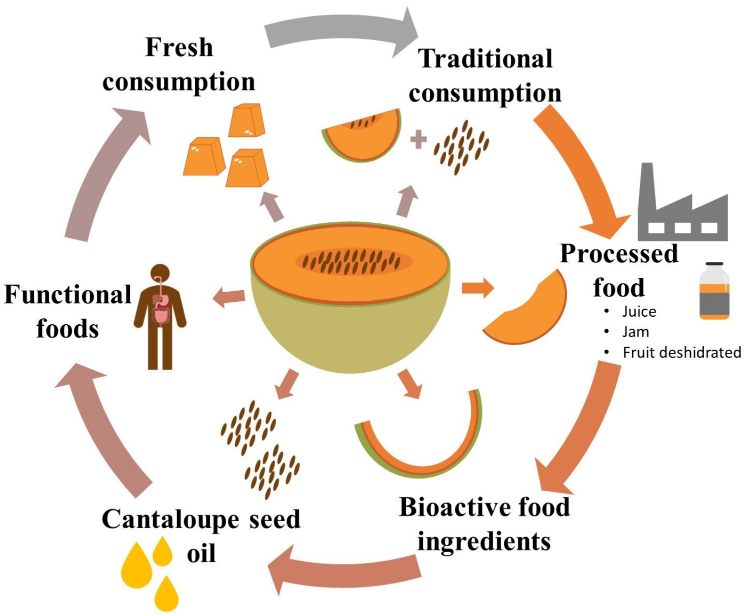

Figure 2. Schematic overview of the integral use of cantaloupe melon (*Cucumis melo* L.), including edible fractions and by-products for bioproduct development.

3. Extraction of Bioactive Molecules by Traditional and Eco-Friendly Methods

3.1. Traditional Methods—A Brief Overview

Whole melon fruit consists principally of pulp (60–65%), peel (20–25%), and seeds (5–10%), although these values can differ depending on the cultivar [6]. All these fruit tissues, including peel and seeds, can be considered as a great source of bioactive compounds with great potential for application in food, cosmetic, or pharmaceutical activities [28,31]. The nutritional and bioactive composition of cantaloupe melon includes complex (cellulose, hemicellulose, pectin, and lignin) and simple (glucose, fructose, and sucrose) carbohydrates, proteins/enzymes, minerals, chlorophylls, oils, fatty acids (PUFAs), and phenolic and volatile compounds, as well as vitamins (vitamin C and β-carotene) [2,3,32]. These natural compounds have been already obtained by the application of several traditional and novel technologies. Table 2 summarizes a chronological comparison of extraction methods, processing conditions, target compounds, and corresponding yields obtained from different melon tissues. For instance, traditional methods applied for cantaloupe melon tissue processing for the extraction of several compounds, such as carotenoids and phenolics, involve mechanical disruption, solid–liquid extractions, macerations, and thermo-chemical hydrolysis [33–35]. In this regard, milling processes, for example using disks, balls, hammers, rolls, and colloid disruption, are traditional mechanical techniques with the aim to reduce the particle size from macro- (metro and/or centimeters) to micro-scale (micrometer) and increase the surface contact area with the biomass and solvent, enhancing particle control and surface contact during the solid–liquid extraction or hydrolysis steps [36]. This is exemplified by the process of extracting oil from the seeds. Initially, the sample is ground, followed by the application of the most common extraction method, the Soxhlet technique. This involves continuous refluxing of the organic solvent (e.g., hexane or ether) over an extended period (6 to 12 h), after which the organic phase is separated using a rotary evaporator [27,37]. Acidic and alkaline thermos-hydrolysis by H_2SO_4, HCl, or H_3PO_4, and NaOH, KOH, or NH_4OH, respectively, have been the most common chemical methods used to obtain several natural polymers (structural carbohydrates) due to their ability to depolymerize the biomass to small monomers and help with the solubilization/hydrolysis of lignin, improving the cellulose availability as well as pectin solubilization for recovery, mostly from the peels where higher concentrations are reported [38,39]. Acidic processes can be developed at concentrated or diluted levels using high temperatures (100–200 °C) although mild temperatures (25–60 °C) are nowadays preferable, and alkali also can work at low temperatures (30–60 °C). However, both methods have some serious issues, including toxicity in the final product, equipment damage, mechanical wear, and the production of hazardous compounds (furfural derivatives, among others), as well as negative aspects related with long reaction times (hours to days) and water pollution stream generation [40].

Table 2. Chronological utilization of cantaloupe melon fruit and its parts as sources for the obtention of bio-functional compounds using traditional vs novel methods.

			Traditional			
Extractive Method	**Source**	**Processing Sequence and Conditions**	**Bio-Functional Compound**	**Yield**	**Highlights/Remarks**	**Reference**
Solid–liquid extraction	Pulp Peel Leaf	Solid–liquid ratio (1:10 *w*/*v*), homogenization for 15 min plus 60 min in a sonicator. Filtration and total methanol evaporation.	Phenolics	89.6% 50.33% 16.29%	Leaf extract showed the highest total phenolic content (26.4 mg GAE/g extract) and total flavonoid content (69.7 RE/g extract)	[41]
Soxhlet extraction and transesterification	Seeds	Refluxed n-hexane for 6 h; methanol-to-oil ratio (9.7:1), catalyst concentration (0.50%) reaction temperature (55 °C) and reaction time (73 min)	Oil-to-biodiesel	86%	The extracted oil is used for biodiesel production. High methyl esters of four fatty acids. Linoleic (C18:2; 50.34%), oleic (C18:1; 21.12%), palmitic (C16:0; 17.68%), and stearic (C18:0; 10.84%) acids.	[37]
Hot acidic extraction	Pulp	Solid–liquid ratio (1:25 *w*/*v*), pH 2.4, alcohol:water ratio of 1.5 and a temperature of 74 °C for 30 min	Pectin	4.53%	Soft processes using citric acid and hydrogen peroxide at low temperature.	[42]
Mechanical milling and concentration	Pulp	Juice concentration (8 °Brix) in a rotary evaporator at 40, 50, and 60 °C at 80 rpm to 40, 52.5, and 65 °Brix.	Cucumisin		Enzymatic activity improvement: milk clotting (511 U/mL) and gelatin digestion activities (162 GDU/g) was obtained at 40 °C and 65 °Brix.	[43]
Cold extraction	Seeds	Chloroform, methanol, and water (2:1:0.8 *v*/*v*/*v*) at room temperature	Oil (PUFAs)		Rich in fatty acids: linoleic (C18:2; 59.0%), oleic (C18:1; 26.4%), palmitic (C16:0; 8.7%), stearic (C18:0; 5.3%), eicosanoic (C20:0; 0.2%) acids.	[44]
Hot acidic extraction	Peels	Optimal conditions of pH 1, temperature of 95 °C, and ratio of 10 *v*/*w* after 200 min	Pectin	29.48%	Use of citric acid; galacturonic acid content of 48%, rheological weak gel behavior at 1% *w*/*v*. High emulsifying capacity 35%.	[45]
Ethanolic maceration	Peels	Ethanol (95%) in an orbital shaker regulated at 30 °C for 24 h. The sample extract filtration and evaporated under vacuum to total dryness	Phenolics and flavonoids	332 and 95.46 mg/100 g extract, respectively	High antioxidant activity due to the presence of 3-hydroxybenzoic acid (33.45 mg/100 g) and apigenin-7-glycoside (29.34 mg/100 g).	[1]
Maceration	Seeds	Solid–liquid ratio with hexane (1:5, *w*/*v*) and shaken for 4 h, centrifuged for 15 min at 1000× *g*. Rotatory evaporation at 40 °C	Oil and phenolics	30.65% and 304.10 mg/100 g oil, respectively	High fatty acid content: C18:2 (68.98%), C18:1 (15.84%), and C16:0 (8.71%). Linoleic and oleic acids represent 93% of total fatty acids. Presence of β-sitosterol (206.42 mg/100 g oil) and amentoflavone (32.80 µg/g oil)	[46]

https://doi.org/10.3390/pr14071105

Table 2. *Cont.*

Extractive Method	Source	Processing Sequence and Conditions	Bio-Functional Compound	Yield	Highlights/Remarks	Reference
Traditional						
Maceration	Pulp	Pulp dehydration (55 °C for 24 h). Maceration using 95% ethanol (1:4 *w*/*v*). Partition using ethanol:hexane (1:1 *v*/*v*) and 10% NaCl (1:10 *v*/*v*). Evaporation under low pressure at 28 °C.	Carotenoids	2.6%	Carotenoid content (4.62 mg/100 g). β-carotene the main compound (2.82 mg/100 g)	[33]
Novel						
Three-phase partitioning	Pulp	Ammonium sulfate saturation (60%), crude extract to t-butanol ratio (1.0:1.25) at pH (8.0) and temperature 20 °C	Cucumisin		Useful strategy to concentrate and purify cucumisin with 4.61 purification folds and 156% activity recovery. Stable proteolytic activity at 20–70 °C and a pH 2.0–12.0. *Km* (2.24 mg/mL) and *Vmax* constants (1048 mM/min).	[47]
Microwave-assisted extraction	Rinds	Power 700 W, irradiation time 112 s, pH 1.50, and solid–liquid ratio (1:30)	Pectin	18.15 g/100 g	Low time consumption, high-methylated galacturonic acid-rich (70%), molecular weight of 390.47 kDa, and antioxidant capacity (DPPH and ABTS).	[48]
Polyelectrolyte precipitation	Peels	Low concentrations of polyelectrolyte 0.0033% and 0.006% (*w*/*v*) at acid pH 3 to 5	Cucumisin	0.17 g/100 g	High stable proteolytic and milk-clotting activities in a wide range of $CaCl_2$ (20–60 mM), pH (5–7), and temperatures (30–85 °C).	[49]
Microwave-assisted extraction	Peels	Power (414.4 W), irradiation time (12.75 min), and liquid to solids ratio (20.94 mL/g)	Pectin	32.81%	Low methoxy pectin, (19.3%), D-galacturonic acid content (40.75%), molecular weight 57 kDa, high foaming capacity (38.6–110.3%) and foaming stability (5.2–65.2%), and high emulsifying capacity index (44.1 m^2/g) and stability (69.3%).	[50]
Deep eutectic solvent	Peels	NaOAc:urea:water with molar ratio 1:3:1.6 (10% (*w*/*w*) at 90 °C for 10 min	Oligosaccharides, protein, and phenolics	Oligogalacturonides (90%), proteins, and phenolics were 2.87 g/100 g and 435 mg/100 g, respectively	A multi-products development approach. Pectin low degree of methyl esterification (7.95 g/100 g) and a galacturonic acid content of 49.44%.	[51]
Autohydrolysis and alkaline deep eutectic solvent	Peels	Ethanol (85%) precipitation and sodium acetate/urea/water extraction (1:3:1.6)	Pectin Phenolics	16.11 and 18.05 g/100 g, respectively 79.55 and 4.08 mg GAE/g, respectively	Sequential extraction of both bioactive compounds. Moreover, protocatechuic, ferulic acids, orientin, vitexin, and naringenin were quantified, improving antioxidant capacity.	[52]
Enzyme-assisted extraction	Seeds	Protease enzymes (21 g enzyme/Kg of seed), pH 6, temperature at 50 °C, and incubation time of 36 h	Oil	71.55%	Low concentration of enzyme and mild conditions of pH and temperature.	[53]
Enzyme-assisted extraction	Pulp	Combination of cellulase (20 U/g) and cellulase (10 FPU/g) in 0.1 M citric buffer pH 5.5 at 50 °C for 2 h	Pectin	81.0 mg/g dry weight	Pectin with high galacturonic acid content (72.2%) and antioxidant activity (1729.81 μM TE/100 g DW), containing phenolic acids (1184 μg FA/g DW).	[54]
Solid-state fermentation by *Bacillus amyloliquefaciens*	Peel	Incubation at 37 °C for 2 days	Lipase	10 U/mL	Extracellular enzyme production.	[55]

GAE: gallic acid equivalents; RE: rutin equivalent; GDU: gelatin digestion unit; NaOAc: sodium acetate; FPU: filter paper units; TE: Trolox equivalents; DW: dry weight; FA: ferulic acid equivalents.

3.2. Novel Methods—A Current Outlook

On the other hand, physical disruption by microwave is an emerging process that uses radiation frequencies between infrared and radio waves (300 MHz–300 GHz). In this process the biomass absorbs the radiation, and the molecules are excited to a higher energy level allowing the disruption of the chemical linkages between polysaccharides (cellulose–

hemicellulose–lignin) [56]. Kazemi et al. [48] combined microwaves and a thermo-chemical process to extract pectin from cantaloupe melon peels, obtaining a higher yield (18%) when compared to a traditional process from the pulp (4.5%) [42]. The advantages of the microwave process are (i) low power consumption, (ii) high uniformity and selectivity, and (iii) short reaction times. Therefore, microwave processing can emerge as a cleaner, faster, and more productive process with low energy consumption and high pectin quality and yield. Another example of a novel extractive process is liquid–liquid extraction using deep eutectic solvents (DES). These solvents comprise hydrogen bond acceptors and donors at specific molar ratios. Typically, DES systems are prepared at defined molar ratios (e.g., 1:2 or 1:3 hydrogen bond acceptor to donor), which influences solvent viscosity, polarity, and extraction efficiency [57]. Currently, they are being investigated as superior green extractive agents compared to both ionic liquids and organic solvents [58,59]. These solvents are utilized for their non-toxic nature, lack of reactivity with water, and, principally, their biodegradability [51]. However, there are limited reports on their applications in cantaloupe melon processing. One such instance is the use of a sodium acetate/urea/water extraction solvent (1:3:1.6) for extracting pectin from peel, resulting in an 18.05 g/100 g yield [52]. Despite these advantages, the recovery and removal of DES from the extracted bioactive compounds remains a key challenge due to their low volatility and strong solvation capacity. Recent advances suggest that membrane-based separation strategies, such as bipolar membrane electrodialysis coupled with ultrafiltration, may enable selective recovery of DES components while preserving non-ionizable target molecules [60]. This approach supports solvent recycling and reduces downstream purification constraints, improving the feasibility of DES-assisted extraction processes.

Regarding proteins with biological activity (enzymes) extraction, ammonium sulfate ($(NH_4)_2SO_4$) and alcoholic (nR-OH) precipitation are the most typical processes for their obtention, however, their use is limited due to the principally toxic processes and bioactivity loss [61]. Therefore, protein precipitation by polyelectrolytes has emerged as a tool to address these limitations. This method involves the formation of insoluble complexes between a non-toxic polyelectrolyte and proteins in aqueous solutions, driven by attraction and repulsion interactions between oppositely charged ions at specific pH and mild temperatures (20–30 °C). Importantly, this process does not require sophisticated or expensive equipment, making it easy to scale up, environmentally friendly, and cost-effective [62]. Cucumisin enzyme from cantaloupe melon peel industrial residues, carrying a positive electric charge, was precipitated by carrageenan, a negatively charged polysaccharide, at pH 3, yielding 0.17 g/100 g and showing high specific proteolytic (4.24 U/mg protein) and milk-clotting activity (191.50 MCU/mg) [49]. This method showed favorable outcomes when compared with the three-phase partitioning method using saturated ammonium sulfate (60%) mixed with the sample and t-butanol (1.0:1.25) at pH 8.0 for cucumsin recovery from pulp juice, obtaining a maximum specific proteolytic and milk-clotting activities of 3.26 U/mg protein and 26.86 MCU/mg [47].

The enzyme-assisted extraction method stands out as a leading biological disruption technique for converting lignocellulosic residues and releasing bioactive compounds. This method utilizes biocatalysts, such as enzymes, to facilitate mild reactions at temperatures below 90 °C and within a wide pH range (4 to 9) [63]. Cellulase (exoglucanases and endoglucanases), hemicellulase, pectinase, cellobiase, α-amylase, alcalase, xylanase, lacase, and lignin oxidase are among the most commonly applied enzyme cocktails used to hydrolyze the principal components of lignocellulosic residues, including β-1,4 glycosidic bonds in cellulose and β-1,4-D glycosidic linkages in xylans present in hemicellulose, as well as to promote lignin oxidation. Others enzymes, such as proteases, β-glucanase, and lipases are also used to enhance residue hydrolysis [64,65]. One of the key features of this method is the cell wall disruption, which leads to the release of certain types of bioactive compounds (phenolics, pigments, oligosaccharides, and oils) linked to carbohydrate, lipid, and protein chains. Additionally, this process has several benefits, such as good conversion rates, quality of extract, green extraction (non-organic solvent usage), reduced purification process, and scalability [66]. Although this method has been widely reported for its application on several plant-based residues and by-products, for example, grape pomace for phenolics [67], tomato waste for lycopene [68], passion fruit peel for pectin [66], seaweed for proteins [69], mango peels for phenolics [70], among others, there are still few literature reports on its application to cantaloupe melon fruit. Such is the case of Nyam et al. [53], who utilized protease enzymes to extract oil from Kalahari melon seeds, achieving a high recovery yield of 71.55%. Additionally, Milošević and Antov [54] employed a combination of cellulase and xylanase enzymes to extract pectin from *Cucurbita moschata*, resulting in a yield of 81 mg pectin/g of dry weight, notable for its high galacturonic acid content (72.2%) and antioxidant properties (1729.81 μM Trolox equivalents/100 g dry weight).

Solid-state-fermentation-assisted extraction is another biological alternative method that is showing important insights on bioactive compound recovery and production, employing different carbon sources by applying different microorganisms [71]. Key advantages of this fermentative process include higher production yields, reduced water consumption, and the absence of toxic reagents. This method represents a nature-like and multi-purpose process, which can be developed by filamentous fungi, bacteria, and yeast at very soft conditions of temperature (20 to 40 °C) and moisture (60 to 75%), allowing the conversion of the lignocellulosic constitutes of biomasses into a smaller molecules [72]. For instance, cellulose and hemicellulose can be broken down into small sugars (mostly glucose, galactose, mannose, xylose, arabinose), and lignin into small alcohols, phenols, and aromatic compounds (among others), while simultaneously producing other important compounds, such as phenolics, carotenoids, single-cell protein, enzymes, organic acids, and bioremediation agents [73–75]. Further examples include the utilization of pomegranate peel as a substrate for *Aspergillus niger* to obtain polyphenols (234.85 mg GAE/g dry matter) [76], Rambutan peel as substrate for *Saccharomyces cerevisiae* to recover ellagic acid (458 mg/g dry matter), and faba bean as a substrate for *Bacillus pumilus* to release flavonoids (20 mg/g dry matter) [77]. While there is a wealth of literature on the application of solid-state fermentation for obtaining value-added compounds from various lignocellulosic samples, research on its application to melon tissues remains limited. One example is the study by Baltaci et al. [78], who conducted liquid fermentation using cantaloupe melon peels to produce the endoglucanase enzyme (12.6 U/mL) from *Exiguobacterium mexicanum* after 60 h of incubation at pH 6.0 and 40 °C. Rodríguez-Luna et al. [79] used melon agricultural waste for the production of endoglucanase (1.21 U/mL), xylanase (11.00 U/mL), and laccase (18.23 U/mL) enzymes by *A. niger* at 30 °C for 240 h. Similarly, Mazhar et al. [55] used melon peels for the production of lipases (10 U/mL) by *B. amyloliquefaciens* at pH 7 and 40 °C for 72 h. Importantly, beyond its role in biotransformation, fermentation can act as a complementary pre-treatment step that enhances matrix disruption and improves the accessibility of intracellular bioactive compounds for subsequent extraction processes.

In this context, the integration of biological approaches, such as fermentation, with emerging green solvents and physical extraction technologies represents a promising strategy to maximize compound recovery while minimizing environmental impact. It is important to highlight that the use of green solvents enhances the extraction of certain bioactive compounds, resulting in lower environmental impact and allowing for easy solvent removal [80–82].

Overall, novel extraction methods, including physical, chemical, and biologically assisted strategies, offer significant advantages such as higher extraction yields, reduced

https://doi.org/10.3390/pr14071105

processing times, decreased use of hazardous solvents, and lower energy consumption. However, their successful implementation requires a deeper understanding of process parameters, matrix interactions, and compound stability to ensure extract quality and scalability. Therefore, within the framework of sustainable melon waste valorization, these emerging technologies represent key tools for improving the efficient recovery of bioactive compounds and enabling their subsequent application in food, nutraceutical, and health-related systems.

4. Prospective Biorefinery Processing Approach for Integrative Bioactive Compounds Obtention

At present, there is an urgent demand for more sustainable and natural options in foods, materials, chemicals, and fuels, with a focus on promoting health and well-being, biodegradability, and renewability. In this regard, cantaloupe melon fruit and its by-products offer a promising solution. Due to their inherent nature, bioactive composition, widespread availability, and low cost resulting from large-scale production from agriculture to retail, they serve as valuable raw materials for extracting and recovering bioactive compounds. These compounds are in high demand in both the market and industrial sectors for the development of innovative ingredients or additives for the food (e.g., texturizers, softeners, milk coagulants, and colorants), cosmetic (natural pigments), and pharmaceutical sectors (fortified, functional, nutraceutical, and prebiotic ingredients). For example, carotenoids and polyphenols from cantaloupe melon fruit and its parts have been reported to have antioxidant, anti-inflammatory, and antimicrobial capacities, among other beneficial properties for health and well-being, with cantaloupe melon dietary fiber recently highlighted for its gastrointestinal enhancement and prebiotic effects [83].

On the other hand, although many of those traditional methods previously described are currently consolidated processes already exploited for many years for scientific and industrial purposes for the obtention of numerous bioactive compounds, most of them are currently catalogued as neither sustainable nor cost-effective processes, with significant impacts on the environment, and, therefore, are far from fulfilling the new policies for sustainable development [84–86]. In this respect, diverse novel/green methods have gained special attention as cheaper, more suitable, and environmentally friendly processes to proficiently take advantage of the natural resources through less extensive unit operations and reductions in time and cost, while increasing yields and purity, as well as obtaining more diversified and functionally valuable end-products, namely natural fibers (cellulose and pectin), proteins, vitamins, and antioxidant carotenoids/polyphenols [87,88]. In addition to their nutritional and bioactive roles, some of these recovered compounds, particularly pectin and dietary fibers, exhibit techno-functional properties that make them suitable for advanced structuring applications. Among emerging food design technologies, 3D food printing has gained increasing attention as a platform for incorporating bio-based materials derived from agri-food residues. Melon-derived pectin, due to its gel-forming ability, viscosity modulation, and water retention capacity, can function as a structural component in printable food matrices ("food inks"), enabling layer-by-layer deposition and shape stability [7,89–91]. This opens new possibilities for designing customized functional foods with controlled texture, nutrient delivery, and bioactive release profiles. Therefore, the development of an integrative biorefinery process that combines compound recovery with emerging structuring technologies could further expand the application spectrum of melon-derived ingredients beyond conventional uses. By unifying several specific unit operations and technologies approaches, this strategy could boost the total exploitation of these biomasses without compromising environmental or economic sustainability in industrial settings, while also enabling more sustainable management processes and the generation of diverse value-added bioproducts in alignment with current polices and directives [92,93]. Hence, the integrative processing strategy consists of obtaining individual compound through a biorefinery and zero-waste approach, which can generate additional economic streams and environmental benefits, turning agricultural losses and industrial fruit waste derived from the processing of cantaloupe melon fruit into more sustainable and eco-friendly production systems, promoting a circular economy (Figure 3).

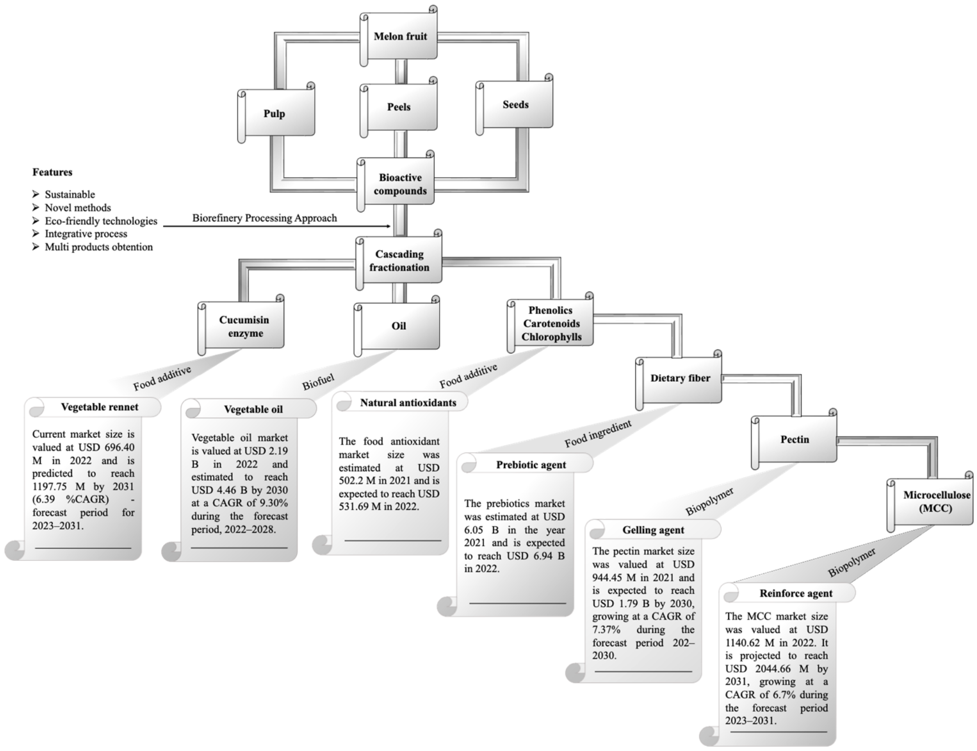

Figure 3. Conceptual spectrum of high-value compounds produced from cantaloupe melon (*Cucumis melo* L.) fruit and by-products via an integrated biorefinery approach.

5. Limitations, Challenges, and Research Directions

Although notable advances and innovation on processing technologies and extractive methods are gaining strength in the research field, multiple factors, such as technological, operational, and supportive regulatory frameworks, limit their application, obstructing the comprehensive implementation of a sustainable food supply chain, not only for all types of fruit and vegetables but also within the production of their side-streams and by-products for their valorization [94,95]. These impediments encompass biomass stability, techno-economic constraints, and regulatory deficiencies, requiring resolution to exploit the potential benefits of the bio-functional ingredients produced by the upcycling of melon by-products under a circular bioeconomy approach to reach the final consumers. In this regard, the lack of standardization and management of by-products is one of the initial limitations from the beginning of the food supply chain due to significant inconsistencies in fruit quality, heterogeneity, and seasonal variability, but also microbial stability. Standardization, classification, and practical preprocessing protocols complicate unit operation design, process optimization, and raw material integration. Therefore, future actions should emphasize the establishment of global residual certification protocols and preprocessing standards and be adapted to each specific country that generates melon fruit and its by-products [96]. Technology transfer and scalability are both major issues due to the costs and investment needed. Developing and maintaining intellectual property and/or patents is, in most cases, very expensive for researchers from universities, and in some cases the technology and methods are not yet proven in a real pilot or industrial environment, making the scalability the major challenge attributed to capital intensity, process complexity, and low yield and reproducibility [97]. On the other hand, the limited awareness and poor support from stakeholders also affect mostly the decision-making among society, investors, and policy makers. Nowadays, many companies are still agnostic and unsure if products coming from residues or undervalued biomasses can be a real business and still consider this as a major risk for them. Nevertheless, their engagement in sustainable food and waste valorization systems is vital to boost innovation and business cases, improving the bioeconomy by using these bioresources as raw materials to obtain value-added functional ingredients with health-promoting effects [98]. Overall, research must prioritize and increase efforts to overcome these limitations and challenges, guaranteeing ingredient stability, safety, and compounds bioaccessibility and availability when consumed, as well as process optimization and validation to improve the biomass conversion efficiency and system resilience. Moreover, it is necessary to raise awareness among governments and policy makers to open actions and calls, thus expanding financial access and ensuring their participation in sustainable and circular agri-food systems.

6. Final Remarks

The utilization of cantaloupe melon as a source of bioactive compounds represents a promising opportunity to promote sustainable innovation in the food industry. Its rich composition in carotenoids, polyphenols, pectins, and dietary fibers provides a solid foundation for developing high-value functional ingredients that contribute to human health and align with circular bioeconomy principles.

Integrating advanced and eco-efficient extraction technologies within a biorefinery framework enables the full valorization of this fruit and its by-products. This approach maximizes compound recovery, minimizes waste, and supports the transition toward more resource-efficient and environmentally responsible food systems.

Looking ahead, the biorefinery-derived compounds from cantaloupe melon offer potential applications in the development of next-generation functional foods. Beyond their nutritional value, these ingredients may also serve structural roles within emerging food design systems, reinforcing the link between sustainable resource recovery and innovative food manufacturing approaches.

In this sense, the convergence of biorefinery strategies with advanced structuring technologies represents a key pathway for transforming agricultural by-products into high-value functional materials. Such integration may facilitate the development of tailor-made foods with enhanced nutritional and sensory attributes, while simultaneously contributing to waste reduction and circular production models.

Future research should focus on linking biorefinery-based extraction strategies with emerging design technologies, driving the evolution of sustainable, health-oriented, and customized foods derived from agricultural by-products like cantaloupe melon.

Author Contributions: Writing—original draft preparation and methodology, A.L.-T.; conceptualization, writing—original draft preparation, and supervision, R.G.-G., I.E.D.-R. and R.E.B.-C.; investigation and visualization, J.L.G.-G. and D.A.C.; writing—review and editing, project administration and supervision, M.L.F.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Acknowledgments: Ricardo Gómez-García would like to acknowledge the Fundação para a Ciência e a Tecnologia (FCT) for his individual grant as a Junior Researcher contract (reference https://doi.org/

10.54499/2023.08203.CEECIND/CP2855/CT0004). Jorge L. Guía-García and María L. Flores-López acknowledge the support from DIP-UADEC-C01-2025-55. Irma E. Dávila-Rangel thanks Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECIHTI, Mexico) for postdoctoral fellowship support (SECIHTI grant number 3054517).

Conflicts of Interest: The authors declare no conflicts of interest.

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