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Review

Bioactive Compounds, Composition and Potential Applications of Avocado Agro-Industrial Residues: A Review

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Abstract: In recent years, the global production and industrialization of avocados has led to the generation of large numbers of peel, seeds, and leaf by-products with significant environmental implications. Current efforts, including the Sustainable Development Goals, aim towards the development of sustainable operations through the valorization of waste. Previous research has focused on studying the rich chemical composition of these avocado by-products. Current studies are working on the isolation of polyphenols, flavonoids, phenolic acids and other bioactive compounds found in avocado peel, seeds and leaves for applications in nutraceutical products in the food, pharmaceuticals and cosmetics industries. The inclusion of these extracts in industrial matrices often requires stabilization technologies such as encapsulation emulsions to ensure the delivery and bioactivity of these target compounds. This review will discuss the global production volumes of avocado and its by-products as well as the potential inclusion in various industries based on their chemical compositions. Additionally, this work addresses the various applications that have been previously proposed for the wastes and their extracts. This review also covers the stabilization techniques previously employed in avocado extract treatment, their applications, and the current challenges and opportunities associated with avocado by-products.

Keywords: avocado extract; bioactive compounds; agri-food byproducts; encapsulation; stabilization; agri-food waste

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Citation: Féliz-Jiménez, A.; Sanchez-Rosario, R. Bioactive Compounds, Composition and Potential Applications of Avocado Agro-Industrial Residues: A Review. *Appl. Sci.* **2024**, *14*, 10070. https://doi.org/10.3390/app142110070

Academic Editors: Katarzyna Marciniak-Lukasiak, Anna Zbikowska and Piotr Lukasiak

Received: 22 September 2024
Revised: 6 October 2024
Accepted: 11 October 2024
Published: 4 November 2024

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1. Introduction

Avocado (*Persea americana*) is one of the most widely consumed tropical fruits with demand exponentially growing over the last decade [1]. In 2022, global avocado production was approximately 8.98 million metric tons, which represents an increment of 1.05 compared to the 8.57 million metric tons totaled in 2021 [2]. The largest production of avocado comes from Central America and the Caribbean region. In 2021, Mexico reported a grand total of 2,442,945 tons of avocados, almost a third of the world's production [3]. More than 500 varieties of avocado have been identified; nevertheless, among the numerous species of avocado previously identified, only a handful are widely cultivated and commercialized, including Bacon, Ettinger, Pinkerton, Reed, Fuerte and Hass [4]. The latter are extensively consumed internationally.

Avocado is mostly consumed as fresh produce. Recent industrialization of avocado includes oil extraction and guacamole commercialization which only require the pulp of the fruit, generating significant amounts of waste causing environmental issues, such as gas emissions, and water pollution, among others, that require urgent attention [5].

The byproducts typically represent about 40% of the total avocado industrialization. These numbers can increase depending on various factors such as the size of the industry, the extent of processing, and so on. The seeds and peel represent an average of 18–31% of the mass of the fruit, depending on the variety of avocado [6], reaching an annual grand total of more than 1.2 million tons of avocado seeds and peels [7]. Additionally, tree pruning

during the winter and summer seasons lead to an accumulation of residual biomass from the leaves of the avocado trees [8,9].

Current industrial processes point towards more sustainable practices, particularly in the agro-industrial realm. Several by-products are generated by the avocado sector which could be exploited by industries in beneficial ways to contribute to the zero-waste target as well as the circular economy idea proposed in the Sustainable Development Goals (SDGs). SDGs are a collaborative effort between all countries of the United Nations that seek the reduction of poverty, elimination of hunger, and protection of the planet among other objectives. In the current 2030 agenda, the second goal focuses on food security, high nutrition and sustainable agriculture. The 9th and 12th goals aim to reach sustainable industrialization, consumption, and production [10]. To contribute to these collective efforts of sustainability, the appropriate management of agro-industrial residues is required.

Previous studies focused on avocado byproducts have found a large variety of compounds of added value in these by-products including protein, lipids, fiber, and carbohydrates [5,11]. Moreover, the presence of bioactive molecules such hydroxycinnamic acids, flavonoids, and proanthocyanins make avocado seeds, peel and leaves a possible source of antioxidants for industrial applications [12]. These compounds can be recovered from the avocado residues using hydroalcoholic solvents along with various extraction methods including maceration, ultrasound-assisted extraction, and microwave-assisted extraction (MAE), among others [13–16]. The overall antioxidant capacity and phenolic content of the extracts depend on the extraction parameters. Previous studies have shown potential applications of the extract and by-products in the food, pharmaceutical, pigment and nutraceutical sectors [5]. The inclusion of the extract into pharmaceutical or food preparations usually requires stabilization processes that help maintain the antioxidant capacity of these compounds. Some techniques previously employed include emulsification and microencapsulation through various methods such as spray-drying, coacervation, and freeze-drying [17,18].

This article reviews the bioactive profile of avocado extracts from their seeds, peels, and leaf waste and their potential application and stabilization methods. First, we discuss the residues associated with avocado industrialization and their possible application in various sectors. Second, we cover the chemical composition of the avocado by-products, including minerals, phytochemicals, lipids, protein and carbohydrate content. Third, we discuss the treatment technologies that have been tested to extend the antioxidant capacity of the avocado extracts. We then conclude with the challenges to overcome in the waste recycling of the avocado industry.

2. Uses of Avocado Agro-Industrial Residues: Seed, Peel, and Leaves

Driven by the environmental concern of the large amount of residue generated by the avocado industry, numerous studies have been dedicated to finding valuable chemical compounds in avocado seeds (ASs), peel (AP), and leaves (ALs) and their potential application in other industrial sectors (See Figure 1). The high content of flavonoids and phenolic acids in these residues have been studied as potential antioxidants, particularly for the food and pharmaceutical industry [19].

Dabas et al. observed that ground ASs produce a bright orange color ($\lambda_{max\ visible}$ = 480 nm) in water. Furthermore, the authors obtained a phenolic content of approximately 219.4 mg/g gallic acid equivalent (GAE) for the AS extract, which shows potential applications in the food industry as a source of natural pigments [20]. Later on, Hatzakis et al. identified the main-colored compound in the AS extract using HPLC-UV/Vis and named it perseorangin, a yellow-orange solid compound that contains glycosylated benzotropone and absorbs at λ_{max} = 445 [21].

Other studies delved into the potential of avocado peel extracts as an antioxidant and functional food ingredient. Rotta et al. used dried avocado peel in tea formulations, resulting in a beverage with notable antioxidant activity of 1954.24 μM Trollox equivalent (TE), and a total phenolic and flavonoid content of 123.57 mg GAE/L and 14.09 mg

quercetin equivalent (QE)/L, respectively, showing no statistical difference after 45 days of storage, showcasing the stability of AP teas and potentially developing high antioxidant functional beverages [22]. Another approach by Merino et al. developed highly antioxidant bioplastic films from AP and AS for food packaging applications. The films were processed by three different methods, and it was shown that using hydrolysis and plasticization followed by blending with pectin polymers obtained the materials with the most competitive properties and notable antioxidant activity, ranging from 3.3 to 4.7 µmol TE/g dried sample, developing a sustainable alternative to traditional food packaging [7]. Vargas-Torrico et al. incorporated an AP extract into gelatin/carboxymethylcellulose active films, enhancing their mechanical properties without affecting their integrity. The incorporation of AP extract also significantly decreased the moisture and solubility in the films, from 12.48 to 11.02% and 40.13 to 35.39%, respectively. The DPPH scavenging activity increased significantly, from 24.16 to 63.47%. Fresh berries were stored in the films, and a perseveration study showed no fungal activity in over six days of storage [23].

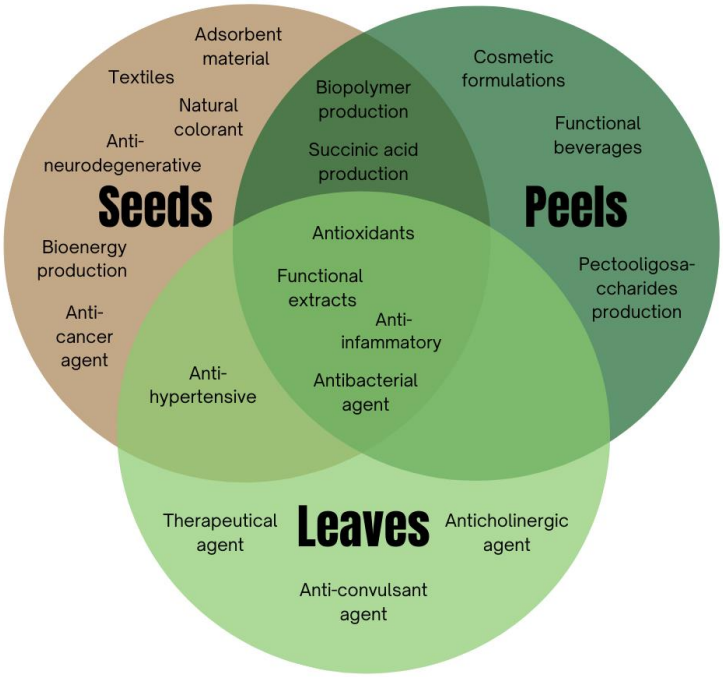


Figure 1. Avocado byproducts and their potential application in different industrial sectors.

In pharmaceutics, avocado leaves are widely used due to their therapeutical properties [24]. ALs have been studied as potential antihypertensives, demonstrating an inhibition of the angiotensin-converting enzyme of 73.3%, which causes a decrease in both systolic and diastolic blood pressure [25]. Similar work observed anticonvulsant properties, delaying the onset of pentylenetetrazole-, picrotoxin -, and bicuculline-seizures in mice [26]. Another pertinent study showed anticholinergic activity in AL. The hydroalcoholic extracts of the leaves demonstrated strong inhibition of acetylcholine and butyrylcholine enzymes, ranging from 0.0168 to 0.0171 and 0.0214 to 0.0226 IC_{50}, µg/mL, respectively, which could be potentially used to treat neurodegenerative diseases. AL extracts also showed strong antioxidant activity ranging from 240 to 601 IC_{50}, µg/mL [15]. Srianthie et al. studied the potential antioxidant, antibacterial and anti-inflammatory activity of aqueous AL extracts. The extract showed a lower antioxidant activity than the ascorbic acid reference, 11.3–52.3% and 28.0–90.7%, respectively. However, it still represents the potential to act as a free radical scavenger in the protection of biomolecules and the prevention of various diseases. Additionally, the anti-inflammatory activity of the extract during the lysis of human red blood cells was measured, resulting in membrane protection of 48.0–60.6% in contrast to the 39.7–49.0% observed with aspirin, showing that AL extract offered higher membrane

protection than aspirin [27]. Dabas et al. studied the antioxidant activity of a colored AS extract as well as the in vitro cancer inhibitory potential of this extract. The methanolic extract showed dose-dependent antioxidant activity, with an ORAC value of roughly 2012 TE/mg. Moreover, the AS extract reduced the lipid hydroperoxide formation in an oil-in-water emulsion by 33%. The extract also reduced the viability of human breast, lung, colon and prostate cancer cells in vitro, with half maximal inhibitory concentrations of 19–132 µg/mL after 48 h of treatment [28]. Additional antidiabetic and hypocholesterolemic properties have been observed in AS extracts [29] as well as anti-neurodegenerative properties [30].

In cosmetics, Ferreira et al. incorporated AP ethanolic extracts in both oil-in-water and water-in-oil cosmetic formulations [31]. The results showed strong DPPH inhibition of, approximately, 93.92% and a low IC_{50} value of roughly 37 (μg_{sample} $mL_{DPPH}{}^{-1}$), therefore showing a high antioxidant capacity, dependent on extraction time. In addition, inhibition in the growth of bacteria of the *Staphylococcus* family was evaluated. The AP extract showed a notable inhibition halo diameter against *S. aureus* and *S. epidermidis*, measuring at approximately 13 and 14 mm, respectively; however, for the *E. coli* strain, there was no considerable halo observed (<5.0 mm). These results were compared to formulations with BHT and phenoxyethanol, demonstrating the potential to replace synthetic preservatives in products. Recent environmental applications of ASs as low-cost adsorbent material to eliminate heavy metals from wastewater demonstrated a removal efficiency of up to 98.86% in reducing the concentration of hexavalent chromium ions from wastewater, sea water and tap water [32]. Other studies were able to prepare Cu^{+2} nanoparticles using AS extract with antibacterial properties; moreover, these nanoparticles were used as adsorbent in the removal of Cd^{+2} from contaminated water at a low cost with a removal percentage of 97%. [33]. Avocado seeds can also be a source of biogas and biodiesel, as well as a source of natural dye and starch for production [34]. Moreover, Rodríguez-Martínez et al. proposed a novel biorefinery strategy that employs avocado seed and peels to obtain compounds with an active market demand such as phenolic extracts, succinic acid, and pectooligosaccharides [5].

3. Chemical Composition of Seeds, Peel, and Leaves

The chemical composition of avocado byproducts can vary depending on the part of the fruit, processing method and variety [35]. Table 1 shows the chemical composition of the residues from different varieties of avocado. The key components typically studied are protein, moisture, lipids, and ash, and the main ones are fiber and carbohydrates [11].

Table 1. Chemical composition of byproducts from different varieties of avocado. Different letters indicate dry or fresh sample; a = fresh sample, b = dry sample. NR = not reported.

Avocado Residue	Variety	Component (g/100 g Sample)						
		Moisture	Protein	Fats	Carbohydrates	Ash	Fiber	Reference
Seed	Negra de la Cruz	58.70 ± 0.20 a	0.60 ± 0.20 a	1.32 ± 0.61 a	33.51 ± 1.51 a	1.10 ± 0.01 a	4.92 ± 2.71 a	[36]
	Hass	57.61 ± 3.61 a	1.91 ± 0.0 a	2.02 ± 0.31 a	32.04 ± 1.72 a	1.52 ± 0.02 a	5.01 ± 0.21 a	
	Hass	13.27 ± 0.01 b	19.94 ± 1.40 b	15.73 ± 1.19 b	48.21 ± 4.12 b	0.84 ± 0.02 b	4.10 ± 0.16 b	[37]
	Hass	NR	3.4 ± 0.01 b	3.2 ± 0.01 b	67.5 ± 0.01 b	1.6 ± 0.01 b	21.6 ± 0.01 b	[38]
	NR	13.09 ± 0.14 b	2.64 ± 0.0 b	0.33 ± 0.00 b	80.12 ± 0.15 b	3.82 ± 0.00 b	2.87 ± 0.00 b	[39]
	NR	8.6 ± 0.14 b	23.0 ± 2.80 b	14.1 ± 0.18 b	44.7 ± 4.80 b	2.4 ± 0.70 b	7.1 ± 1.23 b	[40]
	Thompson red	60.51 ± 0.80 b	0.20 ± 0.09 b	2.09 ± 0.07 b	35.27 b	1.93 ± 0.12 b	3.08 ± 0.13 b	[41]
	Hass	54.45 ± 2.33 a	2.19 ± 0.16 a	14.7 ± 0.32 a	NR	1.29 ± 0.03 a	NR	[42]
	NR	9.92 ± 0.01 b	17.94 ± 1.40 b	16.54 ± 2.10 b	48.11 ± 4.13 b	2.40 ± 0.19 b	3.10 ± 0.18 b	[43]
	NR	67.2 ± 0.6 b	9.6 ± 1.6 b	3.9 ± 0.3 b	NR	2.3 ± 0.4 b	10.7 ± 2.8 b	[44]

Table 1. *Cont.*

Avocado Residue	Variety	Component (g/100 g Sample)						
		Moisture	Protein	Fats	Carbohydrates	Ash	Fiber	Reference
Peel	Thompson red	68.44 ± 1.91 b	0.52 ± 0.15 b	8.62 ± 0.20 b	19.53 b	2.89 ± 0.17 b	12.74 ± 0.67 b	[41]
	Hass	69.13 ± 2.58 a	1.91 ± 0.08 a	2.20 ± 1.65 a	NR	1.50 ± 0.08 a	NR	[42]
	NR	4.0 ± 0.1 b	6.4 ± 0.2 b	4.7 ± 0.4 b	NR	2.0 ± 0.3 b	43.9 ± 2.1 b	[44]
Leaf	NR	5.3 3 ± 0.62 b	25.54 ± 2.52 b	4.01 ± 0.16 b	7.34 ± 0.41 b	19.38 ± 4.34 b	38.40 ± 5.12 b	[43]
	NR	8.01 ± 1.13 b	NR	NR	NR	6.24 ± 1.30 b	NR	[45]

There are several factors including climate, precipitation, and region that may impact the development of the fruit and therefore, the chemical content of the avocadoes [4]. Therefore, significant differences can be found between authors, even when it is the same variety of avocados. Similarly, different fractions of proximate components can vary depending on the byproduct referenced. For the AS, the main components are carbohydrates which can be found ranging from 32.04 to 80.12%, followed by fiber contents ranging from 2.87 to 21.6%, fats extending from 0.33 to 16.54%, and proteins that can fluctuate from 0.20 to 23.0%, along with other valuable proximate components found in AS such as ash and moisture, ranging from 0.84 to 3.82% and 8.6 to 67.2%, respectively. As for the AP, it was found to be mostly composed of fiber and fats, which can range from 12.74 to 43.9% and 2.20 to 8.62%, respectively, along with a significant fraction of moisture that can vary from 4.0 to 69.13%; other components can be found, such as carbohydrates (19.53%), protein (0.52–6.4%) and ash (1.50–2.89%). Lastly, ALs are mostly composed of fiber (38.40 ± 5.12%) and proteins (25.54 ± 2.52%), and different authors have also found fractions of moisture ranging from 5.33 to 8.01%, fats and carbohydrates at approximately 4.01% and 7.34%, respectively, and ash in the range of 6.24 to 19.38%.

Because of the high content of carbohydrates in these byproducts, specifically ASs, which can contain paraffins such as methane and fermentable sugars, avocado byproducts represent a very promising source for bioenergy production, such as biogas and ethanol. In addition, because of the oil content of both AP and ASs, these extracted oils can be used for the production of biodiesel [5,34,46]. ASs can also be a good source of dietary fiber, generally consisting of 21.6 g of fiber/100 g, depending on the cultivar. Siol and Sadowska designed a cereal product with AS powder that showed significantly higher content of total phenolics and antioxidant activity compared to control, and also was able to increase the dietary fiber content by 4% percent, even in the lowest level of addition of AS powder. These results allowed the AS powder to be claimed as a "source of fiber" according to regulations [38]. Because AS has a high content of carbohydrates, it also contains high levels of starch, over 90%, which can be applied to create biopolymers, textile production as a sizing, stiffening and thickening agent, as well as other food applications [34,47,48]. Both ASs and AP, because of their lipid content, are promising potential sources of saturated, monosaturated and polysaturated fatty acids. Morais et al. studied the composition of different parts and dried peels of tropical fruits cultivated in Brazil, and, when compared with the other samples, ASs showed the highest content of fatty acids. The main fatty acids that can be found in AP and ASs are oleic acid, linoleic acid, alpha-linoleic acid, and docosahexaenoic acid, which are very important for human health [44]. These fatty acids are key in preventing heart diseases, which highlights the potential of these residues as functional food ingredients.

As shown in Table 2, several minerals are also found in the by-products. Elements such as sodium, calcium, magnesium, phosphorus, zinc, iron, copper, potassium and manganese can be found in the leaves, peels and seeds of the avocado [5]. A few studies have also identified the presence of several vitamins in the by-products. For instance, in the AP and ASs of the Hass variety, Vinha et al. identified Vitamin C, at approximately 4.1 and 2.6 mg per 100 g of fresh weight, and Vitamin E, at approximately 2.13 and 4.82 mg per 100 g of fresh weight, respectively [42]. Other studies have identified vitamins A, B_1, B_2, B_3, C,

and E in concentrations of 10.11, 0.33, 0.29, 0.06, 97.8, and 0.12 mg per 100 g of ASs [49]. The chemical content of AP, ASs, and ALs offer a huge potential as a source of high-value compounds that can be applied in different areas of industry.

Table 2. Mineral composition of byproducts of different varieties of avocado. NR = not reported.

Avocado Residue	Component (mg/100 g Dry Sample)									
	Na	Ca	Mg	P	Zn	Fe	Cu	K	Mn	References
Seed	0.30–39.4	0.820–434.9	0.100–55.8	0.097–57.35	0. 09–1.6	0.31–3.7	0.98–16.7	4.160–1202.6	1.5 ± 0.1	[40,43,44]
Peel	21.1 ± 2.2	679.3 ± 53.6	46.9 ± 2.3	NR	1.6 ± 0.2	2.3 ± 0.3	14.5 ± 2.1	899.0 ± 71.2	1.4 ± 0.1	[44]
Leaf	80.42 ± 9.12	56.13 ± 3.31	75.60 ± 13.31	48.9 ± 5.50	7.21 ± 2.62	14.61 ± 4.18	5.71 ± 1.26	148.92 ± 0.12	NR	[43]

The mineral composition of avocado by-products is of great importance for both the health and industry sectors. For instance, mining metals such as Mn, Mg, Ca, Na, and K could benefit steel making, alloys, cement fabrication, salts, and fertilizer production, respectively, at the industrial level [50]. Over the last decade, there has been a rapid increase in the manganese demand for various applications including agricultural production, battery manufacturing, and steel production which depends heavily on this element [51]. Another widely used metal that could be isolated from avocado residues is copper, which conventional mining protocols carry significant environmental consequences such as air, soil, and water contamination [52]. The availability of these elements in the waste as well as the feasibility of the recovery processes must be considered. Health benefits associated with these minerals include the participation in biological redox reactions of copper, the prevention of anemia by iron, energy processing of phosphorous and magnesium, regulation of ATP by sodium and potassium, and enzyme binding of zinc [53]. On the other hand, high intake of Na and K has been associated with hypertension, and excess zinc may lead to copper and iron deficiencies [54].

4. Bioactive Profile of Avocado By-Product Extracts

Various extraction methods can be considered for the recovery of the high-value bioactive constituents from AP, ASs and ALs. These procedures include conventional solid–liquid extractions such as maceration, hot extraction, and Soxhlet, as well as novel green technologies like microwave and ultrasound-assisted extractions. Hue et al. assessed the efficiency of maceration, percolation, hot, and Soxhlet extraction in recovering polyphenolic compounds from avocado seeds using 70% ethanol in a 1:3 avocado/solvent ratio. The extraction yields ranged from 14 to 21%, with maceration being second to last at 16%. As for TPC, Soxhlet extraction and maceration showed the highest efficiency for polyphenol compound extraction, with 189.67 and 179.04 mg GAE/g dry weight, respectively. Overall, Soxhlet extraction and maceration proved to be the most effective [55].

Novel green technologies have been previously employed in the extraction of bioactive compounds [8]. For instance, ultrasound-assisted extraction (UAE) can be used with a large variety of solvents due to its yields, cost efficiency, and simplicity. Husen et al. evaluated the effects of UAE on the phenolic content of avocado extracts, and the results showed higher TPC values than those extracted conventionally, 219–235 mg GAE/100 g and 130–163 mg GAE/100 g, respectively [56]. Other green technologies found in the literature are Ohmic heating-assisted extraction (OHAE) and microwave-assisted extraction (MAE). OHAE allows a more efficient extraction of bioactive compounds by producing electroporation in cellular tissues [57], while MAE is based on the direct impact on polar compounds by polarization of polar water molecules in food, and offers advantages such as quicker heating for the extraction of bioactive compounds, therefore lowering the extraction time, and producing higher yields [8,58]. Gumustepe et al. compared both OHAE and MAE for the valorization of avocado leaves obtaining 37.35 and 23.32 mg of TPC per 100 g extract, respectively. The authors believe that the high temperatures required in MAE impact the integrity of the polyphenolic compounds [8].

Another important variable that affects bioactive compound recovery is the solvent. Most studies have focused on hydroalcoholic solvents due to their potential applications in the food and pharmaceutical industries. Folasade et al. studied the influence of four different solvents on the antioxidant properties of avocado seeds. The solvents selected were acetone, ethanol, ethyl acetate and water. The highest antioxidant value reported was from 100% acetone, while the lowest was from 70% ethanol, 265.75 and 150.6 mg AAE/100 g, respectively. This variation in antioxidant activity indicates that the solubility of antioxidant compounds on the selected solvent directly impacts these results. Authors also found that antioxidant activity was higher when solvents were used at 100% concentration, with 100% ethyl acetate, ethanol and water extracts showing results of 229.65, 214.2 and 175.95 mg AAE/100 g, respectively. TPC values ranged from 5.03 to 10.99 mg GAE/100 g, with 100% acetone being the highest, and 70% ethanol the lowest; these results also showed no significant difference between water and ethyl acetate values, 6.25 and 6.65 mg GAE/100 g, respectively [59]. New and sustainable deep eutectic solvents (DESs), which are based on natural compounds, like amino acids, sugars and carboxylic acids, and are found in most organisms, have been studied for the extraction of bioactive phenolic compounds from avocado peels. Rodríguez-Martínez et al. selected five different DESs and evaluated their efficiency by measuring their phenolic and flavonoid content, and all tested DESs showed better results when compared to ethanol. The highest TPC results for DESs were 92.03 and 92.09 mg GAE/g dried AP, while ethanol showed 25.27 mg GAE/g dried AP [60]. Extraction time can also highly impact the yield of extraction; nevertheless, most authors have found it to be highly experimental, depending on the extraction method and solvent used.

Several authors have further studied the chemical composition of these avocado extracts with analytical techniques such as high and ultra-performance liquid chromatography (HPLC and UPLC), mass spectrometry (MS) and other variations of these techniques. Although the concentration of phenolics, flavonoids and other compounds can be measured with UV/Vis spectrophotometry, chromatographic techniques are necessary to assess the structure and activity of these compounds. Velderrain-Rodríguez et al. identified the phenolic compounds in avocado seed, peel and seed coat extracts using AcQuity Ultra Performance™ liquid chromatography with a triple quadrupole detector mass spectrometer (UPLC-ESI-MS/MS) to identify phenolic compounds such as phenolic acids, flavonoids and terpenes, achieving the detection of 72 different compounds [13]. In another study, Trujillo-Mayol et al. used high-performance liquid chromatography paired with a quadrupole time-of-flight mass/mass spectrometry (HPLC-ESI-qTOF-MS/MS) to identify the phenolic compounds in AP extracts, detecting 48 compounds between phenolic acids and flavonoids. [61].

As shown in Table 3, depending on the byproduct (seed, peel or leaves), these bioactive compounds can be found in different concentrations. AP has been reported to contain high concentrations of phenolic acids, such as 4-hydroxybenzoicacid, chlorogenic acid, benzoic acid, and p-coumaric acid and flavonoids such as type B procyanidin dimers, catechins and quercetin derivates. ASs can contain high concentrations of phenolic acids such as tyrosol-derived phenolic molecules and flavonoids among catechin derivates, sakuranetin and luteolin. Penstemide is a terpene that has been found in AP and AS extracts. As for AL extracts, these have been proven to have a higher content of total phenols than ASs and AP, and are rich in phenolic acids like p-coumaric acid and chlorogenic acid, and flavonoids among catechin and quercetin derivatives [6,9,13,16].

Table 3. Bioactive profile of avocado byproducts. GA (Gallic Acid); GAE (Gallic Acid Equivalent); RE (Rutin Equivalent); QE (Quercetin Equivalent); TE (Trolox Equivalent). * Most relevant, is not limited to. Different letters indicate a different expression of concentration in TPC, TFC and DPPH analysis; a = (mMol GA/100 g of extract); b = (mg GAE/g dried extract); c = (mg GAE/g extract); d = (μg GAE/mg extract); e = (mg GAE/100 g extract); f = (mMol Cat. eq./100 g of extract); g = (mg RE/g dried extract); h = (μg QE/mg dried extract); i = (EC_{50} μg/mL); j = (μg TE/g dried extract); k = (mgTE/g dried extract); l = (IC_{50} g Antioxidant/kg DPPH); m = (μMol TE/g dried extract); n = (mg TE/g extract); o = (IC_{50} μg/mL); p = (IC_{50} mg/mL).

Avocado Residue	Extraction Method	Observation	Bioactive Compounds *	Total Phenolic Content (TPC)	Total Flavonoid Content (TFC)	DPPH	References
Peel	Maceration	Peel residues were freeze-dried before the extraction process. Solvent used 80% ethanol, incubated for 20 h at 40 °C.	Flavonoids (epicatechin; type B procyanidin dimer, type B procyanidin trimer, Procyanidin tetramer, quercetin arabinoside glucoside, kaempferol arabinoside glucoside) Phenolic acids (Protocatechuic acid glucoside; tyrosol glucoside arabinoside; 5-O-caffeoylquinic acid) Terpenes (Penstemide)	309.95 ± 25.33 a	12.54 ± 0.52 f	72.64 ± 10.70 i	[13]
	Solid–Liquid Extraction (SLE)	50–70 °C, hydroalcoholic mixture (60/70%)	Flavonoids (glycosylated quercetins (arabinosyl, diglucoside, rhamnoside, xylosyl rhamnoside, rutinoside, etc.), procyanidins, (epi)catechin, luteolin, kaempferol) Phenolic acids (derivatives of quinic acid or shikimic acid)	190 ± 10 b	Not Reported	1500 j	[62]
	Ultrasound-Assisted Extraction (UAE)	50 °C; 37 kHz	Flavonoids (catechin, epigallocatechin 3-coumarate, quercetin-dihexose, quercetin O-arabinosyl-glucoside, rutin, quercetin, quercetin 3-glucoside, luteolin 7-O-(2″-O pentosyl) hexoside), naringenin, taxifolin) Phenolic acids (4-hydroxybenzoic acid; chlorogenic acid; benzoic acid; p-coumaric acid)	45.34 ± 1.7 b	87.56 ± 1.2 g	73.23 ± 3.4 k	[16]
	Maceration	Solvent used 80%methanol for 24 h at 15 °C. The filtered samples were lyophilized.	Flavonoids (catechin, epicatechin, apigenin, kaempferol, quercetin, quercetin diglucoside, quercetin 3-O-arabinosyl-glucoside) Phenolic acids (quinic acid, citric acid, 5-O-caffeoylquinic acid, caffeic acid, syringic acid, p-coumaric acid, ferulic acid, sinapic acid)	1058.0 ± 59.7 b	Not Reported	82.5 ± 4.1 l	[63]
	Ultrasound-microwave combined method	The solvent used was 80% ethanol and distilled water.	Flavonoids (quercetin diglucoside, quercetin3-O-arabinoglucoside, quercetin3-O-galactoside, kaempferol, procyanidin dimer B, (epi)catechin, procyanidin trimer B, quinic acid derivatives) Phenolic acids (5-O-caffeoylquinic acid, chlorogenic acid dimer, protocatechuic acid, ethyl chlorogenate)	297.42 ± 10.7 b	Not Reported	900.4 ± 8.8 m	[61]

Table 3. *Cont.*

Avocado Residue	Extraction Method	Observation	Bioactive Compounds *	Total Phenolic Content (TPC)	Total Flavonoid Content (TFC)	DPPH	References
Seed	Microwave-assisted extraction (MAE)	The experiment used two designs, one with one with acetone (99.5% (*v*/*v*) purity) at 70% and one with ethanol (99.5% (*v*/*v*) purity). We will reference the extracts with acetone at 70%, since it was shown to extract bioactive compounds with higher antioxidant activity.	Flavonoids (catechin, epicatechin, (epi)catchin gallate) Phenolic acids (3-O-caffeoylquinic acid, 3-p-coumaroylquinic acid, caffeoylquinic acid)	307.09 ± 14.16 c	Not reported	266.56 ± 2.76 n	[14]
	Solid–Liquid Extraction (SLE)	50–70 °C, hydroalcoholic mixture (60/70%)	Flavonoids (trimer procyanidins, (epi)catechin, luteolin, kaempferol) Phenolic acids (derivatives of chlorogenic acid)	60 ± 10 b	Not Reported	500 ± 10 j	[62]
	Maceration	Seed residues were freeze-dried before extraction process. Solvent used 80% ethanol, incubated for 20 h at 40 °C.	Flavonoids (catechin, epicatechin, procyanidin dimer (type B), procyanidin trimer (type A), sakuranetin, luteolin) Phenolic acids (salidroside, caffeoylshikimic acid, 3-O-caffeoylquinic acid) Terpenes (Penstemide)	232.36 ± 12.25 a	2.13 ± 0.22 f	90.91 ± 3.59 i	[13]
	Maceration	Solvent used 80%methanol for 24 h at 15 °C. The filtered samples were lyophilized	Flavonoids (catechin, epicatechin, apigenin, kaempferol, quercetin, quercetin diglucoside, quercetin 3-O-arabinosyl-glucoside) Phenolic acids (quinic acid, citric acid, 5-O-caffeoylquinic acid, caffeic acid, syringic acid, p-coumaric acid, ferulic acid, sinapic acid)	1303.0 ± 67.7 b	Not Reported	90.1 ± 4.5 l	[63]
Seed Coat	Maceration	Seed Coat residues were freeze-dried before extraction process. Solvent used 80% ethanol, incubated for 20 h at 40 °C.	Flavonoids (type B procyanidin dimers, type B procyanidin trimers, catechin, epicatechin, type A procyanidin dimers, type A procyanidin trimers) Phenolic acids (3-O-caffeoylquinic acid, 4-O-caffeoylquinic acid, 5-O-caffeoylquinic acid, tyrosol glucoside, salidroside) Terpenes (Penstemide)	208.87 ± 11.67 a	3.41 ± 0.36 f	36.80 ± 11.03 i	[13]
Leaves	Ultrasonic Extraction	The extracts were fermented with lactic acid bacteria. Dried fermented powder was dissolved in an 80/20 ethanol/water solution to the place in the ultrasonic bath.	Flavonoids (procyanidin dimer, procyanidin trimer, catechin diglucopyranoside, cinchonain, quercetin and quercetin derivatives, luteolin derivatives, cinchonain) Phenolic acids (protocatechuic acid-4-glucoside, p-coumaric acid, chlorogenic acid, sinapic acid-C-hexoside)	17.34–30.72 b	Not Reported	25.56–53.88 k	[9]

Table 3. *Cont.*

Avocado Residue	Extraction Method	Observation	Bioactive Compounds *	Total Phenolic Content (TPC)	Total Flavonoid Content (TFC)	DPPH	References
Leaves	Cooking (Water)	This study prepared water and ethanol extracts of avocado (Folium perseae) leaves. Both were referenced. For the ethanolic extract: extracted for 1 h. The extract was filtered and evaporated at 40 °C. The ethanolic residue of the first extraction was re-extracted under similar and stored at −20 °C until use.	Flavonoids (kaempferol, quercitrin, pyrogallol, luteolin-7-glucoside, rutin, isorhamnetin, kaempferon-3-O-rutinoside)	0.092 d	0.328 h	601.001 o	[15]
			Phenolic acids (fumaric acid, caffeic acid, chlorogenic acid)				
	Maceration (Ethanol)		Flavonoids (herniarin, kaempferol, quercitrin, quercetin-3-O-arabinoside, quercetin, luteolin-7-glucoside, luteolin-5-glucoside, kaempferon-3-O-rutinoside, rutin, isorhamnetin)	0.218 d	1.480 h	240.400 o	
			Phenolic acids (gallic acid, fumaric acid, caffeic acid, ellagic acid, chlorogenic acid, rosmarinic acid)				
	Microwave-assisted extraction	This study compared two different extraction methods; both were referenced.	Flavonoids (epicatechin, rutin, quercetin)	9005.5–13,459.0 e	Not reported	3.41 ± 0.24 p	[8]
			Phenolic acids (gallic acid, protocatechuic acid, p-hydroxybenzoic acid, chlorogenic acid, p-coumaric acid, rosmarinic acid, cinnamic acid)				
	Ohmic heating-assisted extraction		Flavonoids (epicatechin, rutin)	24,223.7–31,737.8 e	Not reported	2.96 ± 0.15 p	
			Phenolic acids (protocatechuic acid, p-hydroxybenzoic acid, chlorogenic acid, cinnamic acid)				

The presence of these phytochemicals in AP, ASs and ALs contributes to the different high-value properties previously reported such as antioxidant, anti-inflammatory, antidiabetic, antimicrobial, among others. Both phenolic acids and flavonoids have the capacity to act as antioxidants and antimicrobials, allowing the extracts rich in these compounds to be used as food and pharmaceutical additives. Gallic acid, which is a phenolic acid, has been reported to exhibit antioxidant, antidiabetic, anti-inflammatory and antimicrobial activities [64,65]. Another phenolic acid with antioxidant, anticancer, antidiabetic and anti-inflammatory pharmaceutical properties is protocatechuic acid [66–68]. The p-Coumaric acid is a polyphenol that also exhibits antioxidant and anti-inflammatory potential [69]. Caffeic acid is a potential natural antioxidant, as well as an anticancer and anti-inflammatory agent also found in avocado byproducts [70–74]. Sinapic and Ferulic acid also exhibit antioxidant and anti-inflammatory activity [75–79]. Coumarin has shown antibacterial, anticancer, antioxidant, anti-inflammatory, antiproliferative and anticholinergic activities [80–83]. Procyanidins exhibit anticancer, anti-inflammatory and antidiabetic activities [84,85]. Lastly, condensed tannins (proanthocyanidins) that include catechin and epicatechin, have shown antioxidant, anti-inflammatory, antidiabetic and anticancer activities [86,87]. Different flavonoids, like catechin derivates and trans-5-O-caffeoyl-D-quinic acid, have shown potential anti-inflammatory activity, while other polyphenols like quercetin, epicatechin, rutin and chlorogenic acid have been reported as potential antidiabetics, because of their capacity to inhibit glucosidase enzymes [8,16]. Several studies have considered these characteristics of AP, AS and AL extracts for several applications. In the food industry, for example, Ferreira et al. studied the possibility of replacing synthetic preservatives in mayonnaise with AP extracts. They observed no changes in the physical and chemical properties of the mayonnaise and the samples with AP extracts showed a more effective inhibition than the controls with ascorbic acid. These results show the potential of AP extracts to replace synthetic antioxidants and antibacterial chemicals in food matrices [88]. Trujillo-Mayol et al. studied the inhibitory effects of AP extracts in reducing oxidation of proteins and lipids as well as the formation of harmful products in beef and soy-based burgers. The results demonstrated a greater protective effect in beef burgers with AP extract compared

to the controls. Moreover, the inhibition of heterocyclic aromatic amines and acrylamide was also observed in both beef and soy burgers with AP extract [89]. Further studies by Trujillo-Mayol et al. observed a reduction in the oxidation of protein and lipids during gastric digestion in vitro. The authors concluded that the risk factors associated with *H. pylori* infection were reduced by the inclusion of AP extract in the burgers [90]. Leontopoulos et al. studied the potential of pomegranate peel, AP and AS waste extracts as a tool for the biocontrol of pathogenic fungi in plants. The in vitro results showed a 10.21% reduction in the mycelium growth of *Aspergillus niger* compared to the control in medium agar containing 100% AP [91]. In previous studies, the antioxidant activity and cancer inhibition potential of AS extract were demonstrated with results showing a reduction in the viability of human breast, lung, colon and prostate cancer cells in vitro [28].

5. Stabilization of Bioactive Compounds Extracts

5.1. Encapsulation Technologies

Encapsulation is a technology for coating solids, liquids, or gaseous materials into miniature sealed capsules. The capsules can range from nano (10–1000 nm) and micro (1–1000 μm) to millicapsules (larger than 1 mm) [92]. The use of microencapsulation technologies aids in the control and release of organoleptic properties as well as ingredients in foods as well as other matrices [93]. Moreover, the composition and activity of bioactive phenolic compounds are stabilized through microencapsulation [94]. There are various techniques employed to create the bioactive-containing capsules. Among these, spray drying is well-known for its simplicity; a solution containing the core and wall material is fed, and then atomized into a mist inside a chamber, to which hot air is then applied to produce a powder. Moreover, scale-up is relatively easy and affordable [95]. Another widely employed encapsulation technology for bioactive-rich extracts is freeze-drying. This is a dehydration process in which sensitive substances are not exposed to high temperatures [96]. The retention of volatile compounds will depend on the chemical nature of the system [97]. Phytochemicals from avocado seeds and peels have been previously microencapsulated through spray-drying, lyophilization, and several chemical coacervation methods [17].

The encapsulation of avocado skin oil has been previously achieved through spray-drying techniques using maltodextrin and Hi-Cap as coating materials, obtaining an encapsulation efficiency in the range of 60 to 80%. In addition, the moisture content, bulk density and mean diameter of the particles were measured, with results ranging from 1.10 to 1.34%, 0.35 to 037 g/cm^3 and 15.10 to 18.22 μm, respectively [98]. Additionally, Kautsar et al. achieved single-core, smooth microcapsules that maintained both antioxidant and antimicrobial activity of the avocado by-product extracts over time through gum Arabic spray-drying. The microcapsule's antioxidant activity only decreased by 2.36% after 4 weeks of storage and maintained antimicrobial activity against *E. coli* and *S. aureus* after 7 days, while the unencapsulated extract's antioxidant activity decreased by 7.53% and lost the antimicrobial activity after seven days. The highest yield was found at a 5:10 ratio of extract:gum Arabic, at 49.78% [99]. In the case of freeze-drying, avocado seed extract microcapsules were able to retain the bioactivity after 30 days of storage using cassava and corn starch as wall materials. Cassava starch was found to be more efficient in microencapsulating the extract, and in DPPH and hydroxyl free radical scavenging activity, there was a significant decrease over time; nevertheless, TPC values significantly increased over time. The microcapsules were shelf stable, with the moisture content increasing from 3.0 to 5.4% after 30 days of storage [18]. This demonstrates the potential development of supplements and functional foods.

The stabilization of avocado seed and peel extract is of great importance to the food industry where various products could benefit from the antioxidant properties of these compounds. Moreover, the valorization of these agro-industrial residues represents a significant advantage for the avocado oil industry as well as cosmetics and pharmaceutics. For instance, avocado peel extract microcapsules prepared through complex coacervation were effective at reducing oxidation in proteins and reducing the growth of microorganisms

in ground beef when incorporated as a preservative. Two wall material matrices were studied, alginate–collagen and pectin–collagen, both emulsified and non-emulsified. These microcapsules showed great results on encapsulation yield, moisture and water activity: 58.72–73.60%, 2.46–6.30% and 0.210–0.342, respectively. Phenolic compounds, such as chlorogenic acid and catechin, were present in the extract, and were not degraded by the acidic pH required for the coacervation process [100].

Chitosan nanocapsules of avocado peel extract demonstrated greater efficacy against human cancer cells in vitro in comparison to direct use of the peel extract. These results are promising for the development of non-invasive lung cancer treatment [101]. Similarly, avocado seed extract nanoparticles showed higher antioxidant capacity compared to control and induced death in leukemia cells in vitro. The particles had an average size ranging from 166.9 to 305.2 nm, and a polydispersity index of 0.19 to 0.26. In addition, an entrapment efficiency of up to 82% was accomplished. The nanoparticles exhibited a DPPH result of 2661.63 µmol TE/g sample, significantly higher than the control, and also showed that the survival rates of different leukemia cell lines, when treated with the nanoparticles, decreased to 8.15–63.9%. This again demonstrates the possibility of medicine applications as well as food incorporation [102].

5.2. Emulsions

Emulsions are biphasic preparations of immiscible liquids with small-sized droplets of one liquid solution of a drug dispersed in a continuous medium. This technology has also been explored in avocado residues extracts. For instance, Procyanidin-rich extract from avocado seeds was emulsified into nanoparticles and tested demonstrating stability in various pH conditions, temperatures and salt concentrations for up to 90 days. Moreover, the nanoparticles were efficient in preventing the migration of cancer cells in in vitro assays [103]. On the other hand, phenolic extracts from avocado peel and seeds were emulsified and their bioactivity tested, demonstrating a reduction in the formation of secondary oxidation products as well as an overall retardation in oxidation [104]. In a recent study, the stability of avocado seed extract emulsions was tested for up to 20 days of storage and the antioxidant capacity was maintained even during oral–gastric digestion in vitro. This increases the by-product value and potentially tackles environmental waste problems [105].

6. Challenges and Future Perspectives

As industries try to find ways to become more environmentally friendly, the reutilization of the waste generated from different processes is pivotal. Avocado waste extracts have been widely studied, showing potential as natural food additives as well as interesting pharmaceutical properties. To the extent of our knowledge, there are no studies or clinical trials that describe the effects of bioactive compounds extracted from avocado byproducts on human health, therefore emphasizing the need for more thorough research on the safety of utilizing these extracts for human consumption. However, there have been some clinical trials that evaluated the effects of phenolic compounds from other medicinal plants on human health [106]. Zhao et al. carried out a phase I study of the topical application of epigallocatechin-3-gallate (EGCG) in patients with breast cancer to treat radiation dermatitis. A total of 24 patients were enrolled, and no acute toxicity was related to the treatment, and the reported symptoms of radiation dermatitis decreased after 2 weeks of treatment, proving that the treatment was well tolerated and effective [107]. Zhao et al. also had previously carried out a phase I study of the oral administration of EGCG in patients with advanced stage III lung cancer and observed significant regression of seophagitis to grade 0/1 in most patients, concluding that the oral administration of EGCG is feasible, safe and effective [108]. McLarty et al. studied the effects of tea polyphenols on prostate cancer. Twenty-six men with positive prostate biopsies were given daily doses of polyphenon E, which contained EGCG, epicatechin, epigallocatechin, epicatechin-3-gallate, and led to a significant decrease in serum levels of PSA, HGF, and VEGF, supporting the potential

role of polyphenon E in the treatment of prostate cancer [109]. Other polyphenols, such as anthocyanins and resveratrol, have also exhibited antidiabetic properties by reducing blood glucose and improving glycemic control, respectively [110]. There are still several breaches in research that need to be further studied when it comes to the effects of polyphenols on human health, such as the different factors that can affect the bioavailability and bioactivity of polyphenols [111].

Few authors have studied the techno-economic feasibility of scaling up these extraction technologies at an industrial level. Tesfaye et al. studied the techno-economic evaluation of the extraction process of starch from avocado seeds, and concluded that it is an economically feasible process, and estimated a rate of return of 75%, a break-even analysis of 82% and a 2-year payback period, demonstrating that these sustainable technologies can be profitable at an industrial level [112]. Sousa et al. modeled and studied techno-economic feasibility of a biorefinery based on avocado waste. Using Aspen Plus v12.1 software, the authors modeled, simulated and optimized an avocado waste biorefinery, which could potentially achieve a gross profit of 3.7×10^7USD/year for capital costs of USD 30.7×10^6 operating in optimal conditions. These results prove that it is possible for industries to take advantage of these agro-industrial residues in a sustainable and profitable way [113]. Nevertheless, there should be more focus on modeling and studying the economic feasibility of these technologies at an industrial level, especially for food and pharmaceutical applications. There are many limitations that can be associated with these technologies for utilizing these agro-industrial residues, starting with the fact the waste requires delicate handling to ensure its quality, which can be a challenge for small-scale producers. In addition, waste can vary in composition and quantity, making it difficult for industries to standardize procedures, and the regulations around the utilization of avocado waste to produce functional products are still not clear and are continuously evolving. Another obstacle is that the utilization of these byproducts can elevate the energy consumption and waste stream, causing a negative environmental impact [35,114].

On the other hand, for the effective application of avocado extracts in pharmaceuticals, food, and cosmetic products, the stabilization and delivery must be studied and tested. The most complex aspect of microencapsulation is choosing the wall material, which will directly influence the performance of the capsules. The coating material must be biodegradable, resistant to the intestinal tract, provide protection of the bioactive molecules against extreme conditions, non-reactive, tasteless and cost-effective to be suitable for use in the food industry [115]. The added stabilization protocol of the extract involves extra investments that must be carefully considered. The economic analysis of a particular microencapsulation process should reflect on the encapsulation or stabilization technology chosen, the coating material chosen, and the complexity of the procedure [116]. For example, a food-safe gelatin coacervation process requires the drying of the wet capsules for easy handling. Considering a weight of 550 kg of core material to be processed, the cost of raw wall materials, including processing aids, is approximately USD 2391.00, and labor cost, including processing, formulation and sieving and drying cost, is USD 3330.00, amounting to a total cost of USD 5721.00. This would place the cost per kg of processed core and the cost per liter of processed product at 10.40 and 9.27 USD, respectively [116] (Veršič, 2014). Although the implementation of these technologies presents an added cost, the technique has widespread effects across the health, food and beauty industry, with a market value of nearly USD 12.15 billion in 2023, and an expected growth of USD 36.34 billion by 2032 [117]. As for regulations, the U. S. Food and Drug Administration in their Code of Federal Regulations, Title 21, Part 172, Sec. 172.230 outlines the safe use of microcapsules in food, specifying the allowed components, usage restrictions and labeling requirements [118].

Another residue that should be further studied is the large volumes of wastewater generated with the production of avocado oil. Permal et al. produced powder rich in phenolic compounds and antioxidants from avocado wastewater through spray drying methods [119]. The results demonstrated the possible applications of the powder in the food industry as they were effective in preventing lipid oxidation in pork sausages. Another

niche to be exploited is avocado leaves. ALs have higher contents of total phenols and flavonoids, as well as a higher radical scavenging ability than peel, seed, and pulp [120].

7. Conclusions

As industries steer towards more environmentally friendly practices, the recycling of the waste generated from different processes is vital. Both avocado seed and peel extracts have been proven to function as natural food additives and preservatives in the hopes of replacing synthetic ones currently used, therefore making the food industry more sustainable. Nevertheless, there is not much knowledge of the metabolic paths and molecular mechanisms in humans. Bioplastic films derived from avocado seed and peel have also demonstrated the potential to replace traditional food packaging; nevertheless, further studies must be carried out to gather information on their stability and applicability in various industries. The innumerable pharmaceutical applications of these residues as antihypertensive, anti-inflammatory, anti-diabetic, anti-convulsant, and anti-cancer, among many others, along with the growing numbers of potential food applications, highlight the need for more thorough research on safety and the possible effects of human consumption. Future research should focus on the uncovered potential of avocado leaves as a functional food and pharmaceutical ingredient.

Author Contributions: Conceptualization, R.S.-R.; methodology, A.F.-J.; software, A.F.-J.; validation, A.F.-J. and R.S.-R.; formal analysis, A.F.-J.; investigation, A.F.-J. and R.S.-R.; resources, A.F.-J.; data curation, A.F.-J.; writing—original draft preparation, A.F.-J. and R.S.-R.; writing—review and editing, R.S.-R.; visualization, A.F.-J.; supervision, R.S.-R.; project administration, R.S.-R.; funding acquisition, R.S.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fondo Nacional de Innovación y Desarrollo Científico y Tecnológico, Dominican Republic. Grant number 2022-2D3-075.

Acknowledgments: We would like to thank Sergio Sánchez for his time and effort in reviewing the manuscript.

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

References

1. Tamayo-Ramos, D.I.; Salazar-González, J.A.; Casson, S.A.; Urrea-López, R. Old and new horizons on Persea americana transformation techniques and applications. *Plant Cell Tissue Organ Cult.* **2022**, *150*, 253–266. [CrossRef]
2. Avocado Production Worldwide 2022. (n.d.). Statista. Available online: https://www.statista.com/statistics/577455/world-avocado-production/ (accessed on 9 September 2024).
3. Avocado Production by Country 2024. (n.d.). Available online: https://worldpopulationreview.com/country-rankings/avocado-production-by-country (accessed on 9 September 2024).
4. Araújo, R.G.; Rodriguez-Jasso, R.M.; Ruiz, H.A.; Pintado, M.M.E.; Aguilar, C.N. Avocado by-products: Nutritional and functional properties. *Trends Food Sci. Technol.* **2018**, *80*, 51–60. [CrossRef]
5. Rodríguez-Martínez, B.; Romaní, A.; Eibes, G.; Garrote, G.; Gullón, B.; del Río, P.G. Potential and prospects for utilization of avocado by-products in integrated biorefineries. *Bioresour. Technol.* **2022**, *364*, 128034. [CrossRef] [PubMed]
6. López-Anguiano, L.-A.; Guajardo-Flores, C.-G.; Martín-del-Campo, S.-N.; Pineda-Lozano, C.-S. Avocado Byprod-ucts as a Source of Functional and Nutraceutical Compounds. In *Food Byproducts: Valorization through Nutraceutical Production*; Nova Science Publishers: Hauppauge, NY, USA, 2023; pp. 3–30. Available online: https://novapublishers.com/shop/food-byproducts-valorization-through-nutraceutical-production/ (accessed on 12 September 2024).
7. Merino, D.; Bertolacci, L.; Paul, U.C.; Simonutti, R.; Athanassiou, A. Avocado Peels and Seeds: Processing Strategies for the Development of Highly Antioxidant Bioplastic Films. *ACS Appl. Mater. Interfaces* **2021**, *13*, 38688–38699. [CrossRef] [PubMed]
8. Gumustepe, L.; Kurt, N.; Aydın, E.; Ozkan, G. Comparison of ohmic heating- and microwave-assisted extraction techniques for avocado leaves valorization: Optimization and impact on the phenolic compounds and bioactivities. *Food Sci. Nutr.* **2023**, *11*, 5609–5620. [CrossRef] [PubMed]
9. De Montijo-Prieto, S.; Razola-Díaz, M.d.C.; Barbieri, F.; Tabanelli, G.; Gardini, F.; Jiménez-Valera, M.; Ruiz-Bravo, A.; Verardo, V.; Gómez-Caravaca, A.M. Impact of Lactic Acid Bacteria Fermentation on Phenolic Compounds and Antioxidant Activity of Avocado Leaf Extracts. *Antioxidants* **2023**, *12*, 298. [CrossRef]
10. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development (A/RES/70/1)*; UN General Assembly: New York, NY, USA, 2015. Available online: https://sdgs.un.org/2030agenda (accessed on 3 October 2024).

11. Cárdenas-Castro, A.P.; Fernández-Ochoa, Á.; Cádiz-Gurrea, M.d.l.L.; Segura Carretero, A.; Sáyago-Ayerdi, S.G. Bioactive Phytochemicals from Avocado Oil Processing By-Products. In *Bioactive Phytochemicals from Vegetable Oil and Oilseed Processing By-Products*; Ramadan Hassanien, M.F., Ed.; Springer International Publishing: New York, NY, USA, 2023; pp. 403–430. [CrossRef]
12. Salazar-López, N.J.; Domínguez-Avila, J.A.; Yahia, E.M.; Belmonte-Herrera, B.H.; Wall-Medrano, A.; Montalvo-González, E.; González-Aguilar, G.A. Avocado fruit and by-products as potential sources of bioactive compounds. *Food Res. Int.* **2020**, *138*, 109774. [CrossRef]
13. Velderrain-Rodríguez, G.R.; Quero, J.; Osada, J.; Martín-Belloso, O.; Rodríguez-Yoldi, M.J. Phenolic-Rich Extracts from Avocado Fruit Residues as Functional Food Ingredients with Antioxidant and Antiproliferative Properties. *Biomolecules* **2021**, *11*, 977. [CrossRef]
14. Araújo, R.G.; Rodriguez-Jasso, R.M.; Ruiz, H.A.; Govea-Salas, M.; Pintado, M.E.; Aguilar, C.N. Process optimization of microwave-assisted extraction of bioactive molecules from avocado seeds. *Ind. Crops Prod.* **2020**, *154*, 112623. [CrossRef]
15. Polat Kose, L.; Bingol, Z.; Kaya, R.; Goren, A.C.; Akincioglu, H.; Durmaz, L.; Koksal, E.; Alwasel, S.H.; Gülçin, İ. Anticholinergic and antioxidant activities of avocado (Folium perseae) leaves–phytochemical content by LC-MS/MS analysis. *Int. J. Food Prop.* **2020**, *23*, 878–893. [CrossRef]
16. Rodríguez-Martínez, B.; Ferreira-Santos, P.; Gullón, B.; Teixeira, J.A.; Botelho, C.M.; Yáñez, R. Exploiting the potential of bioactive molecules extracted by ultrasounds from avocado peels—Food and nutraceutical applications. *Antioxidants* **2021**, *10*, 1475. [CrossRef] [PubMed]
17. Ozkan, G.; Franco, P.; De Marco, I.; Xiao, J.; Capanoglu, E. A review of microencapsulation methods for food antioxidants: Principles, advantages, drawbacks and applications. *Food Chem.* **2019**, *272*, 494–506. [CrossRef] [PubMed]
18. Awolu, O.O.; Fole, E.T.; Oladeji, O.A.; Ayo-Omogie, H.N.; Olagunju, A.I. Microencapsulation of avocado pear seed (Persea Americana mill) bioactive-rich extracts and evaluation of its antioxidants, in vitro starch digestibility and storage stability. *Bull. Natl. Res. Cent.* **2022**, *46*, 34. [CrossRef]
19. Gómez, F.S.; Sánchez, S.P.; Iradi, M.G.G.; Azman, N.A.M.; Almajano, M.P. Avocado Seeds: Extraction Optimization and Possible Use as Antioxidant in Food. *Antioxidants* **2014**, *3*, 439. [CrossRef] [PubMed]
20. Dabas, D.; Elias, R.J.; Lambert, J.D.; Ziegler, G.R. A colored avocado seed extract as a potential natural colorant. *J. Food Sci.* **2011**, *76*, C1335–C1341. [CrossRef]
21. Hatzakis, E.; Mazzola, E.P.; Shegog, R.M.; Ziegler, G.R.; Lambert, J.D. Perseorangin: A natural pigment from avocado (Persea americana) seed. *Food Chem.* **2019**, *293*, 15–22. [CrossRef]
22. Rotta, E.M.; de Morais, D.R.; Biondo, P.B.F.; dos Santos, V.J.; Matsushita, M.; Visentainer, J.V. Use of avocado peel (Persea americana) in tea formulation: A functional product containing phenolic compounds with antioxidant activity. *Acta Scientiarum. Technol.* **2016**, *38*, 23–29. [CrossRef]
23. Vargas-Torrico, M.F.; von Borries-Medrano, E.; Aguilar-Méndez, M.A. Development of gelatin/carboxymethylcellulose active films containing Hass avocado peel extract and their application as a packaging for the preservation of berries. *Int. J. Biol. Macromol.* **2022**, *206*, 1012–1025. [CrossRef]
24. Duarte, P.F.; Chaves, M.A.; Borges, C.D.; Mendonça, C.R.B. Avocado: Characteristics, health benefits and uses. *Ciência Rural* **2016**, *46*, 747–754. [CrossRef]
25. Sutiningsih, D.; Sari, D.P.; Adi, M.S.; Hadi, M.; Azzahra, N.A. Effectiveness of avocado leaf extract (Persea americana Mill.) as antihypertensive (11:1100). *F1000Research* **2022**, *11*, 1100. [CrossRef]
26. Ojewole, J.A.O.; Amabeoku, G.J. Anticonvulsant effect of Persea americana Mill (Lauraceae) (Avocado) leaf aqueous extract in mice. *Phytother. Res.* **2006**, *20*, 696–700. [CrossRef] [PubMed]
27. Srianthie, D.; Udayangani, D.N.; Chamari, H. Antioxidant, antibacterial and anti-inflammatory potential of the aqueous extract of the raw leaves of sri lankan variety of persea americana miller (avocado). *Int. J. Ayurveda Pharma Res.* **2020**, *8*, 1–11.
28. Dabas, D.; Elias, R.J.; Ziegler, G.R.; Lambert, J.D. In Vitro Antioxidant and Cancer Inhibitory Activity of a Colored Avocado Seed Extract. *Int. J. Food Sci.* **2019**, *2019*, 6509421. [CrossRef] [PubMed]
29. Dabas, D.; Shegog, R.M.; Ziegler, G.R.; Lambert, J.D. Avocado (*Persea americana*) seed as a source of bioactive phytochemicals. *Curr. Pharm. Des.* **2013**, *19*, 6133–6140. [CrossRef] [PubMed]
30. Bangar, S.P.; Dunno, K.; Dhull, S.B.; Kumar Siroha, A.; Changan, S.; Maqsood, S.; Rusu, A.V. Avocado seed discoveries: Chemical composition, biological properties, and industrial food applications. *Food Chem. X* **2022**, *16*, 100507. [CrossRef]
31. Ferreira, S.M.; Falé, Z.; Santos, L. Sustainability in Skin Care: Incorporation of Avocado Peel Extracts in Topical Formulations. *Molecules* **2022**, *27*, 1782. [CrossRef]
32. Mahmoud, M.E.; El-Said, G.F.; Ibrahim, G.A.A.; Elnashar, A.A.S. Effective removal of hexavalent chromium from water by sustainable nano-scaled waste avocado seeds: Adsorption isotherm, thermodynamics, kinetics, and error function. *Biomass Convers. Biorefinery* **2024**, *14*, 14725–14743. [CrossRef]
33. Ibrahim, F.M.; Najeeb, D.A.; ThamerSadeq, H. Green preparation of Cu nanoparticles of the avocado seed extract as an adsorbent surface. *Mater. Sci. Energy Technol.* **2023**, *6*, 130–136. [CrossRef]
34. Tesfaye, T.; Ayele, M.; Gibril, M.; Ferede, E.; Limeneh, D.Y.; Kong, F. Beneficiation of avocado processing industry by-product: A review on future prospect. *Curr. Res. Green Sustain. Chem.* **2022**, *5*, 100253. [CrossRef]
35. Sandoval-Contreras, T.; González Chávez, F.; Poonia, A.; Iñiguez-Moreno, M.; Aguirre-Güitrón, L. Avocado Waste Biorefinery: Towards Sustainable Development. *Recycling* **2023**, *8*, 81. [CrossRef]

36. Flores, M.; Ortiz-Viedma, J.; Curaqueo, A.; Rodriguez, A.; Dovale-Rosabal, G.; Magaña, F.; Vega, C.; Toro, M.; López, L.; Ferreyra, R.; et al. Preliminary Studies of Chemical and Physical Properties of Two Varieties of Avocado Seeds Grown in Chile. *J. Food Qual.* **2019**, *2019*, 3563750. [CrossRef]
37. Nwaokobia, K.; Oguntokun, M.O.; Okolie, P.L.; Ogboru, R.O.; Idugboe, O.D. Evaluation of the chemical composition of Persea americana (Mill) pulp and seed. *J. Biosci. Biotechnol. Discov.* **2018**, *3*, 83–89. [CrossRef]
38. Siol, M.; Sadowska, A. Chemical Composition, Physicochemical and Bioactive Properties of Avocado (Persea americana) Seed and Its Potential Use in Functional Food Design. *Agriculture* **2023**, *13*, 316. [CrossRef]
39. Egbuonu, A.C.C.; Opara, I.C.; Onyeabo, C.; Uchenna, N.O. Proximate, functional, antinutrient and antimicrobial properties of avocado pear (Persea americana) Seeds. *J. Nutr. Health Food Eng.* **2018**, *8*, 00260. [CrossRef]
40. Ifesan, B.O.T.; Olorunsola, B.O.; Ifesan, B.T. Nutritional Composition and Acceptability of Candy from Avocado Seed (Persea americana). *Int. J. Agric. Innov. Res.* **2015**, *3*, 1631–1634.
41. Tan, C.X.; Tan, S.S.; Ghazali, H.M.; Tan, S.T. Physical properties and proximate composition of Thompson red avocado fruit. *Br. Food J.* **2021**, *124*, 1421–1429. [CrossRef]
42. Vinha, A.; Moreira, J.; Barreira, S. Physicochemical Parameters, Phytochemical Composition and Antioxidant Activity of the Algarvian Avocado (*Persea americana* Mill.). *J. Agric. Sci.* **2013**, *5*, 12. [CrossRef]
43. Arukwe, U.; Amadi, B.A.; Duru, M.K.C.; Agomuo, E.N.; Adindu, E.A.; Odika, P.C.; Lele, K.C.; Egejuru, L.; Anudike, J. Chemical composition of Persea americana leaf, fruit and seed. *Int. J. Res. Rev. Appl. Sci.* **2012**, *11*, 346–349.
44. Morais, D.R.; Rotta, E.M.; Sargi, S.C.; Bonafe, E.G.; Suzuki, R.M.; Souza, N.E.; Matsushita, M.; Visentainer, J.V. Proximate Composition, Mineral Contents and Fatty Acid Composition of the Different Parts and Dried Peels of Tropical Fruits Cultivated in Brazil. *J. Braz. Chem. Soc.* **2017**, *28*, 308–318. [CrossRef]
45. Guevara, D.I.; Payrol, J.A.; Santana, D.P.; Quintero, R.C. Estudio fitoquímico preliminar y actividad antioxidante de un extracto acuoso de hoja de aguacate (*Persea americana* Mill.). *QhaliKay Rev. De Cienc. De La Salud* **2021**, *5*, 3. [CrossRef]
46. Chimezie, E.C.; Wang, Z.; Yu, Y.; Nonso, U.C.; Duan, P.-G.; Kapusta, K. Yield optimization and fuel properties evaluation of the biodiesel derived from avocado pear waste. *Ind. Crops Prod.* **2023**, *191*, 115884. [CrossRef]
47. Tesfaye, T.; Gibril, M.; Sithole, B.; Ramjugernath, D.; Chavan, R.; Chunilall, V.; Gounden, N. Valorisation of avocado seeds: Extraction and characterisation of starch for textile applications. *Clean Technol. Environ. Policy* **2018**, *20*, 2135–2154. [CrossRef]
48. Mora-Sandí, A.; Ramírez-González, A.; Castillo-Henríquez, L.; Lopretti-Correa, M.; Vega-Baudrit, J.R. Persea Americana Agro-Industrial Waste Biorefinery for Sustainable High-Value-Added Products. *Polymers* **2021**, *13*, 1727. [CrossRef]
49. Egbuonu, A.C.C.; Egbuonu, C.; Opara, C.; Atasie, O.; Mbah, U. Vitamins Composition and Antioxidant Properties in Normal and Monosodium Glutamate-Compromised Rats' Serum of Persea Americana (Avocado Pear) Seed. *Open Access J. Chem. OAJC* **2017**, *1*, 19–24. [CrossRef]
50. Sanchez-Rosario, R.; Hildenbrand, Z.L. Produced water treatment and valorization: A techno-economical review. *Energies* **2022**, *15*, 4619. [CrossRef]
51. Clarke, C.; Upson, S. A global portrait of the manganese industry—A socioeconomic perspective. *NeuroToxicology* **2017**, *58*, 173–179. [CrossRef]
52. Izydorczyk, G.; Mikula, K.; Skrzypczak, D.; Moustakas, K.; Witek-Krowiak, A.; Chojnacka, K. Potential environmental pollution from copper metallurgy and methods of management. *Environ. Res.* **2021**, *197*, 111050. [CrossRef]
53. Godswill, A.G.; Somtochukwu, I.V.; Ikechukwu, A.O.; Kate, E.C. Health Benefits of Micronutrients (Vitamins and Minerals) and their Associated Deficiency Diseases: A Systematic Review. *Int. J. Food Sci.* **2020**, *3*, 1–32. [CrossRef]
54. Lozano Muñoz, I.; Díaz, N.F. Minerals in edible seaweed: Health benefits and food safety issues. *Crit. Rev. Food Sci. Nutr.* **2020**, *62*, 1592–1607. [CrossRef]
55. Hue, H.T.; Thai, N.M.; Dao, P.T.A. Survey on different polyphenol extraction methods from avocado seed (Persea americana Mill) and assay on their antioxidant and acute toxicity activities. *Vietnam J. Chem.* **2021**, *59*, 870–876. [CrossRef]
56. Husen, R.; Ando, Y.; Ismail, A.; Shirai, Y. Effect of ultrasonic-assisted extraction on phenolic content of avocado. *Malays. J. Anal. Sci.* **2014**, *18*, 690–694.
57. Pereira, S.G.; Teixeira-Guedes, C.; Souza-Matos, G.; Maricato, É.; Nunes, C.; Coimbra, M.A.; Teixeira, J.A.; Pereira, R.N.; Rocha, C.M.R. Influence of ohmic heating in the composition of extracts from *Gracilaria vermiculophylla*. *Algal Res.* **2021**, *58*, 102360. [CrossRef]
58. Barba, F.J.; Zhu, Z.; Koubaa, M.; Sant'Ana, A.S.; Orlien, V. Green alternative methods for the extraction of antiox-idant bioactive compounds from winery wastes and by-products: A review. *Trends Food Sci. Technol.* **2016**, *49*, 96–109. [CrossRef]
59. Folasade, O.A.; Olaide, R.A.; Olufemi, T.A. Antioxidant Properties of Persea Americana M. Seed as Affected by Different Extraction Solvent. *J. Adv. Food Sci. Technol.* **2016**, *3*, 101–106. [CrossRef]
60. Rodríguez-Martínez, B.; Ferreira-Santos, P.; Alfonso, I.M.; Martínez, S.; Genisheva, Z.; Gullón, B. Deep Eutectic Solvents as a Green Tool for the Extraction of Bioactive Phenolic Compounds from Avocado Peels. *Molecules* **2022**, *27*, 6646. [CrossRef] [PubMed]
61. Trujillo-Mayol, I.; Casas-Forero, N.; Pastene-Navarrete, E.; Lima Silva, F.; Alarcón-Enos, J. Fractionation and Hydrolyzation of Avocado Peel Extract: Improvement of Antibacterial Activity. *Antibiotics* **2021**, *10*, 23. [CrossRef]

62. Rojas-García, A.; Villegas-Aguilar, M.d.C.; García-Villegas, A.; Cádiz-Gurrea, M.d.l.L.; Fernández-Ochoa, Á.; Fernández-Moreno, P.; Arráez-Román, D.; Segura-Carretero, A. Characterization and Biological Analysis of Avocado Seed and Peel Extracts for the Development of New Therapeutical Strategies. *Biol. Life Sci. Forum* **2022**, *18*, 9. [CrossRef]
63. Rosero, J.C.; Cruz, S.; Osorio, C.; Hurtado, N. Analysis of Phenolic Composition of Byproducts (Seeds and Peels) of Avocado (*Persea americana* Mill.) Cultivated in Colombia. *Molecules* **2019**, *24*, 3209. [CrossRef]
64. Gong, W.; Wang, R.; Huang, H.; Hou, Y.; Wang, X.; He, W.; Gong, X.; Hu, J. Construction of double network hydrogels using agarose and gallic acid with antibacterial and anti-inflammatory properties for wound healing. *Int. J. Biol. Macromol.* **2023**, *227*, 698–710. [CrossRef]
65. Variya, B.C.; Bakrania, A.K.; Patel, S.S. Antidiabetic potential of gallic acid from Emblica officinalis: Improved glucose transporters and insulin sensitivity through PPAR-γ and Akt signaling. *Phytomed. Int. J. Phytother. Phytopharm.* **2020**, *73*, 152906. [CrossRef]
66. Chen, J.; Dai, X.; Jiang, C.; Fu, Y.; Jiang, T.; Tang, L.; Wang, L.; Wang, Q.; Huang, G.; Cao, J. One new protocatechuic acid methyl ester and one enantiomeric pair of dihydroflavones isolated from Phymatopteris hastata. *Phytochem. Lett.* **2021**, *43*, 130–134. [CrossRef]
67. Olayan, A.; Aloufi, A.S.; AlAmri, O.D.; Ola, H.; Abdel, A.E. Protocatechuic acid mitigates cadmium-induced neurotoxicity in rats: Role of oxidative stress, inflammation and apoptosis. *Sci. Total Environ.* **2020**, *723*, 137969. [CrossRef]
68. Yamabe, N.; Park, J.Y.; Lee, S.; Cho, E.-J.; Lee, S.; Kang, K.S.; Hwang, G.S.; Kim, S.-N.; Kim, H.Y.; Shibamoto, T. Protective effects of protocatechuic acid against cisplatin-induced renal damage in rats. *J. Funct. Foods* **2015**, *19*, 20–27. [CrossRef]
69. Bal, S.S.; Leishangthem, G.D.; Sethi, R.S.; Singh, A. P-coumaric acid ameliorates fipronil induced liver injury in mice through attenuation of structural changes, oxidative stress and inflammation. *Pestic. Biochem. Physiol.* **2022**, *180*, 104997. [CrossRef] [PubMed]
70. Grodzicka, M.; Pena-Gonzalez, C.E.; Ortega, P.; Michlewska, S.; Lozano, R.; Bryszewska, M.; de la Mata, F.J.; Ionov, M. Heterofunctionalized polyphenolic dendrimers decorated with caffeic acid: Synthesis, characterization and antioxidant activity. *Sustain. Mater. Technol.* **2022**, *33*, e00497. [CrossRef]
71. Kar, A.; Panda, S.; Singh, M.; Biswas, S. Regulation of PTU-induced hypothyroidism in rats by caffeic acid primarily by activating thyrotropin receptors and by inhibiting oxidative stress. *Phytomed. Plus* **2022**, *2*, 100298. [CrossRef]
72. Kfoury, M.; Geagea, C.; Ruellan, S.; Greige-Gerges, H.; Fourmentin, S. Effect of cyclodextrin and cosolvent on the solubility and antioxidant activity of caffeic acid. *Food Chem.* **2019**, *278*, 163–169. [CrossRef]
73. Mirzaei, S.; Gholami, M.H.; Zabolian, A.; Saleki, H.; Farahani, M.V.; Hamzehlou, S.; Far, F.B.; Sharifzadeh, S.O.; Samarghandian, S.; Khan, H.; et al. Caffeic acid and its derivatives as potential modulators of oncogenic molecular pathways: New hope in the fight against cancer. *Pharmacol. Res.* **2021**, *171*, 105759. [CrossRef]
74. Raviadaran, R.; Ng, M.H.; Chandran, D.; Ooi, K.K.; Manickam, S. Stable W/O/W multiple nanoemulsion encapsulating natural tocotrienols and caffeic acid with cisplatin synergistically treated cancer cell lines (A549 and HEP G2) and reduced toxicity on normal cell line (HEK 293). *Mater. Sci. Eng. C Mater. Biol. Appl.* **2021**, *121*, 111808. [CrossRef]
75. Altındağ, F.; Rağbetli, M.Ç.; Özdek, U.; Koyun, N.; Ismael Alhalboosi, J.K.; Elasan, S. Combined treatment of sinapic acid and ellagic acid attenuates hyperglycemia in streptozotocin-induced diabetic rats. *Food Chem. Toxicol.* **2021**, *156*, 112443. [CrossRef]
76. Kaur, J.; Mehta, V.; Kaur, G. Preparation, development and characterization of Leucaena leucocephala galactomannan (LLG) conjugated sinapic acid: A potential colon targeted prodrug. *Int. J. Biol. Macromol.* **2021**, *178*, 29–40. [CrossRef] [PubMed]
77. Saeedavi, M.; Goudarzi, M.; Mehrzadi, S.; Basir, Z.; Hasanvand, A.; Hosseinzadeh, A. Sinapic acid ameliorates airway inflammation in murine ovalbumin-induced allergic asthma by reducing Th2 cytokine production. *Life Sci.* **2022**, *307*, 120858. [CrossRef] [PubMed]
78. Bao, Y.; Chen, Q.; Xie, Y.; Tao, Z.; Jin, K.; Chen, S.; Bai, Y.; Yang, J.; Shan, S. Ferulic acid attenuates oxidative DNA damage and inflammatory responses in microglia induced by benzo(a)pyrene. *Int. Immunopharmacol.* **2019**, *77*, 105980. [CrossRef] [PubMed]
79. Yang, J.; Chen, J.; Hao, Y.; Liu, Y. Identification of the DPPH radical scavenging reaction adducts of ferulic acid and sinapic acid and their structure-antioxidant activity relationship. *LWT* **2021**, *146*, 111411. [CrossRef]
80. Alagesan, V.; Ramalingam, S.; Kim, M.; Venugopal, S. Antioxidant activity guided isolation of a coumarin compound from Ipomoea pes-caprea (Convolvulaceae) leaves acetone extract and its biological and molecular docking studies. *Eur. J. Integr. Med.* **2019**, *32*, 100984. [CrossRef]
81. Çakmakçı, E.; Özdemir, M.; Şen, F.; Bulut, M.; Yalçın, B. Vegetable oil-based, coumarin-containing antibacterial thermosets with improved thermal stability via copper-free thermal azide-alkyne click polymerization. *Ind. Crops Prod.* **2022**, *182*, 114870. [CrossRef]
82. Dandriyal, J.; Singla, R.; Kumar, M.; Jaitak, V. Recent developments of C-4 substituted coumarin derivatives as anticancer agents. *Eur. J. Med. Chem.* **2016**, *119*, 141–168. [CrossRef]
83. Seo, W.D.; Kim, J.Y.; Ryu, H.W.; Kim, J.H.; Han, S.-I.; Ra, J.-E.; Seo, K.H.; Jang, K.C.; Lee, J.H. Identification and characterisation of coumarins from the roots of Angelica dahurica and their inhibitory effects against cholinesterase. *J. Funct. Foods* **2013**, *5*, 1421–1431. [CrossRef]
84. Liu, Y.; Sun, R.; Lin, X.; Wu, L.; Chen, H.; Shen, S.; Li, Y.; Wei, Y.; Deng, G. Procyanidins and its metabolites by gut microbiome improves insulin resistance in gestational diabetes mellitus mice model via regulating NF-κB and NLRP3 inflammasome pathway. *Biomed. Pharmacother.* **2022**, *151*, 113078. [CrossRef]

85. Na, W.; Ma, B.; Shi, S.; Chen, Y.; Zhang, H.; Zhan, Y.; An, H. Procyanidin B1, a novel and specific inhibitor of Kv10.1 channel, suppresses the evolution of hepatoma. *Biochem. Pharmacol.* **2020**, *178*, 114089. [CrossRef]
86. Sharma, A.K.; Beniwal, V. Biosynthesis and medicinal applications of proanthocyanidins: A recent update. *Biocatal. Agric. Biotechnol.* **2022**, *45*, 102500. [CrossRef]
87. Shen, W.; Li, W.; Shao, Y.; Zeng, J. Proanthocyanidin delays litchi peel browning by inhibiting ethylene biosynthesis, respiratory metabolism, and phenol oxidase activities. *Sci. Hortic.* **2023**, *309*, 111677. [CrossRef]
88. Ferreira, S.M.; Santos, L. From by-product to functional ingredient: Incorporation of avocado peel extract as an antioxidant and antibacterial agent. *Innov. Food Sci. Emerg. Technol.* **2022**, *80*, 103116. [CrossRef]
89. Trujillo-Mayol, I.; Sobral, M.M.C.; Viegas, O.; Cunha, S.C.; Alarcón-Enos, J.; Pinho, O.; Ferreira, I.M. Incorporation of avocado peel extract to reduce cooking-induced hazards in beef and soy burgers: A clean label ingredient. *Food Res. Int.* **2021**, *147*, 110434. [CrossRef]
90. Trujillo-Mayol, I.; Viegas, O.; Sobral, M.M.C.; Casas-Forero, N.; Fiallos, N.; Pastene-Navarrete, E.; Faria, M.A.; Alarcón-Enos, J.; Pinho, O.; Ferreira, I.M. In vitro gastric bioaccessibility of avocado peel extract in beef and soy-based burgers and its impact on Helicobacter pylori risk factors. *Food Chem.* **2022**, *373*, 131505. [CrossRef]
91. Leontopoulos, S.; Skenderidis, P.; Petrotos, K.; Mitsagga, C.; Giavasis, I. Preliminary studies on suppression of important plant pathogens by using pomegranate and avocado residual peel and seed extracts. *Horticulturae* **2022**, *8*, 283. [CrossRef]
92. Mishra, M. (Ed.) *Handbook of Encapsulation and Controlled Release*; CRC Press: Boca Raton, FL, USA, 2015. [CrossRef]
93. Calderón-Oliver, M.; Pedroza-Islas, R.; Escalona-Buendía, H.B.; Pedraza-Chaverri, J.; Ponce-Alquicira, E. Comparative study of the microencapsulation by complex coacervation of nisin in combination with an avocado antioxidant extract. *Food Hydrocoll.* **2017**, *62*, 49–57. [CrossRef]
94. Tirado-Kulieva, V.; Atoche-Dioses, S.; Hernández-Martínez, E.; Tirado-Kulieva, V.; Atoche-Dioses, S.; Hernández-Martínez, E. Phenolic compounds of mango (Mangifera indica) by-products: Antioxidant and antimicrobial potential, use in disease prevention and food industry, methods of extraction and microencapsulation. *Sci. Agropecu.* **2021**, *12*, 283–293. [CrossRef]
95. Choudhury, N.; Meghwal, M.; Das, K. Microencapsulation: An overview on concepts, methods, properties and applications in foods. *Food Front.* **2021**, *2*, 426–442. [CrossRef]
96. Pudziuvelyte, L.; Marksa, M.; Sosnowska, K.; Winnicka, K.; Morkuniene, R.; Bernatoniene, J. Freeze-drying technique for microencapsulation of Elsholtzia ciliata ethanolic extract using different coating materials. *Molecules* **2020**, *25*, 2237. [CrossRef]
97. Poshadri, A.; Aparna, K. Microencapsulation technology: A review. *J. Res. ANGRAU* **2010**, *38*, 86–102.
98. Chimsook, T. Microwave assisted extraction of avocado oil from avocado skin and encapsulation using spray drying. *Key Eng. Mater.* **2017**, *737*, 341–346. [CrossRef]
99. Kautsar, D.B.; Rois, M.F.; Faizah, N.; Widiyastuti, W.; Nurtono, T.; Setyawan, H. Antioxidant and Antimicrobial Agents from Avocado (Persea americana) Seed Extract Encapsulated in Gum Arabic through Spray Drying Method. *Period. Polytech. Chem. Eng.* **2023**, *67*, 1. [CrossRef]
100. Calderón-Oliver, M.; Escalona-Buendía, H.B.; Ponce-Alquicira, E. Effect of the addition of microcapsules with avocado peel extract and nisin on the quality of ground beef. *Food Sci. Nutr.* **2020**, *8*, 1325–1334. [CrossRef]
101. Sahyon, H.A.; El-Shafai, N.M.; Elnajjar, N.; Althobaiti, F.; Aldhahrani, A.; Alharbi, N.S.; Shoair, A.G.F.; El-Mehasseb, I.M. Avocado peel extract loaded on chitosan nanoparticles alleviates urethane toxicity that causes lung cancer in a mouse model. *Int. J. Biol. Macromol.* **2023**, *234*, 123633. [CrossRef] [PubMed]
102. Chuacharoen, T.; Polprasert, C.; Sabliov, C.M. Avocado seed extract encapsulated in zein nanoparticles as a functional ingredient. *J. Agric. Food Res.* **2024**, *18*, 101332. [CrossRef]
103. Cerda-Opazo, P.; Gotteland, M.; Oyarzun-Ampuero, F.A.; Garcia, L. Design, development and evaluation of nanoemulsion containing avocado peel extract with anticancer potential: A novel biological active ingredient to enrich food. *Food Hydrocoll.* **2021**, *111*, 106370. [CrossRef]
104. Velderrain-Rodríguez, G.R.; Salvia-Trujillo, L.; González-Aguilar, G.A.; Martín-Belloso, O. Interfacial activity of phenolic-rich extracts from avocado fruit waste: Influence on the colloidal and oxidative stability of emulsions and nanoemulsions. *Innov. Food Sci. Emerg. Technol.* **2021**, *69*, 102665. [CrossRef]
105. Sánchez-Quezada, V.; Gaytán-Martínez, M.; Recio, I.; Loarca-Piña, G. Avocado seed by-product uses in emulsion-type ingredients with nutraceutical value: Stability, cytotoxicity, nutraceutical properties, and assessment of in vitro oral-gastric digestion. *Food Chem.* **2023**, *421*, 136118. [CrossRef]
106. Bakrim, S.; El Omari, N.; El Hachlafi, N.; Bakri, Y.; Lee, L.-H.; Bouyahya, A. Dietary Phenolic Compounds as Anticancer Natural Drugs: Recent Update on Molecular Mechanisms and Clinical Trials. *Foods* **2022**, *11*, 3323. [CrossRef]
107. Zhao, H.; Zhu, W.; Jia, L.; Sun, X.; Chen, G.; Zhao, X.; Li, X.; Meng, X.; Kong, L.; Xing, L.; et al. Phase I study of topical epigallocatechin-3-gallate (EGCG) in patients with breast cancer receiving adjuvant radiotherapy. *Br. J. Radiol.* **2016**, *89*, 20150665. [CrossRef] [PubMed]
108. Zhao, H.; Zhu, W.; Xie, P.; Li, H.; Zhang, X.; Sun, X.; Yu, J.; Xing, L. A phase I study of concurrent chemotherapy and thoracic radiotherapy with oral epigallocatechin-3-gallate protection in patients with locally advanced stage III non-small-cell lung cancer. *Radiother. Oncol.* **2014**, *110*, 132–136. [CrossRef] [PubMed]

109. McLarty, J.; Bigelow, R.L.H.; Smith, M.; Elmajian, D.; Ankem, M.; Cardelli, J.A. Tea polyphenols decrease serum levels of prostate-specific antigen, hepatocyte growth factor, and vascular endothelial growth factor in prostate cancer patients and inhibit production of hepatocyte growth factor and vascular endothelial growth factor in vitro. *Cancer Prev. Res.* **2009**, *2*, 673–682. [CrossRef]
110. Cao, H.; Ou, J.; Chen, L.; Zhang, Y.; Szkudelski, T.; Delmas, D.; Daglia, M.; Xiao, J. Dietary polyphenols and type 2 diabetes: Human Study and Clinical Trial. *Crit. Rev. Food Sci. Nutr.* **2018**, *59*, 3371–3379. [CrossRef] [PubMed]
111. Marino, M.; Del Bo', C.; Martini, D.; Porrini, M.; Riso, P. A Review of Registered Clinical Trials on Dietary (Poly)Phenols: Past Efforts and Possible Future Directions. *Foods* **2020**, *9*, 1606. [CrossRef] [PubMed]
112. Tesfaye, T.; Ayele, M.; Ferede, E.; Gibril, M.; Kong, F.; Sithole, B. A techno-economic feasibility of a process for extraction of starch from waste avocado seeds. *Clean Technol. Environ. Policy* **2021**, *23*, 581–595. [CrossRef]
113. Sousa, D.; Rodrigues, D.; Castro, P.M.; Matos, H.A. Equation-Oriented Modeling and Optimization of a Biorefinery Based on Avocado Waste. *Processes* **2024**, *12*, 91. [CrossRef]
114. Puglia, D.; Pezzolla, D.; Gigliotti, G.; Torre, L.; Bartucca, M.L.; Del Buono, D. The Opportunity of Valorizing Agricultural Waste, Through Its Conversion into Biostimulants, Biofertilizers, and Biopolymers. *Sustainability* **2021**, *13*, 2710. [CrossRef]
115. Lim, K.J.A.; Cabajar, A.A.; Migallos, M.K.V.; Lobarbio, C.F.Y.; Taboada, E.B. Microencapsulation of Phenolic Compounds from Waste Mango Seed Kernel Extract by Spray Drying Technology. *Nat. Environ. Pollut. Technol.* **2019**, *18*, 765–775.
116. Veršič, R.J. Chapter 32—The Economics of Microencapsulation in the Food Industry. In *Microencapsulation in the Food Industry*; Gaonkar, A.G., Vasisht, N., Khare, A.R., Sobel, R., Eds.; Academic Press: Cambridge, MA, USA, 2014; pp. 409–417. [CrossRef]
117. Microencapsulation Market Size, Share, Trend, Growth | 2032. (n.d.). Available online: https://www.expertmarketresearch.com/reports/microencapsulation-market (accessed on 5 October 2024).
118. CFR—Code of Federal Regulations Title 21. (n.d.). Available online: https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=172.230 (accessed on 5 October 2024).
119. Permal, R.; Chang, W.L.; Seale, B.; Hamid, N.; Kam, R. Converting industrial organic waste from the cold-pressed avocado oil production line into a potential food preservative. *Food Chem.* **2020**, *306*, 125635. [CrossRef]
120. Oboh, G.; Adelusi, T.; Akinyemi, A. Inhibitory effect of phenolic extract from leaf and fruit of avocado pear (*Persea americana*) on Fe^{2+} induced lipid peroxidation in rats' pancreas In Vitro. *FUTA J. Res. Sci.* **2013**, *9*, 276–286.

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