Journal of
Food and Pharmaceutical Sciences

Review Article

Unlocking the Therapeutic Potential of Avocado Peel Waste: A Comprehensive Review of Phytochemicals and Pharmacological Activities

Kevin Awidarta[1,2], Abdul Rohman[3]* and Agung Endro Nugroho[4]

[1]Master in Pharmaceutical Sciences, Faculty of Pharmacy, Universitas Gadjah Mada, Yogyakarta, Indonesia
[2]Department of Pharmaceutical Chemistry, Faculty of Medicine, Universitas Brawijaya, Malang, Indonesia
[3]Department of Pharmaceutical Chemistry, Faculty of Pharmacy, Universitas Gadjah Mada, Yogyakarta, Indonesia
[4]Department of Pharmacology and Clinical Pharmacy, Faculty of Pharmacy, Universitas Gadjah Mada, Yogyakarta, Indonesia
*Corresponding author: Abdul Rohman | Email: abdulkimfar@gmail.com

Received: 16 June 2025; Revised: 31 August 2025; Accepted: 1 September 2025; Published: 30 September 2025

Abstract: Avocado peel waste, a significant byproduct of the global avocado industry, represents an underutilized resource rich in bioactive compounds, prompting growing interest in its potential pharmacological applications. This review addresses the need to explore these compounds within the context of sustainable waste management and natural therapeutic development, aiming to evaluate their chemical composition and biological activities. A comprehensive analysis was conducted by synthesizing data from peer-reviewed studies, focusing on phytochemical identification using advanced techniques such as UHPLC-QTOF-MS, HPLC-DAD, and LC-DAD-ESI-MS, alongside pharmacological assessments via methods like DPPH, TBARS, and in vitro assays. The findings reveal that avocado peels, particularly from the Hass cultivar, contain diverse phytochemicals including phenolics, flavonoids, and organic acids, exhibiting antioxidant, neuroprotective, antibacterial, antifungal, antiplatelet, antiaging, anti-inflammatory, and anticancer properties. These activities are attributed to mechanisms such as radical scavenging, enzyme inhibition, and apoptosis induction, with specific studies highlighting neuroprotective effects in Parkinson's disease models. The review concludes that avocado peel waste holds substantial promise as a sustainable source of bioactive compounds for food and pharmaceutical applications, though challenges like bioavailability and cultivar variability necessitate further research. Innovative extraction and formulation strategies could unlock its full therapeutic potential, contributing to a circular economy and health innovation.

Keywords: fruit by-products; neuroprotective; oxidative stress; phenolics; sustainability

1. INTRODUCTION

Avocado, a member of the Lauraceae family, is an evergreen dicotyledonous plant native to Mexico, now widely cultivated and consumed globally due to its nutritional value and culinary versatility [1], [2]. While the fruit's flesh is highly prized, its peel, which constitutes a significant portion of the fruit's weight, is often discarded as agricultural waste [3]. This overlooked byproduct, however, is rich in bioactive compounds such as phenolic compounds, flavonoids, and tannins, which have garnered attention for their potential pharmacological properties [4]. The increasing global production of avocados, coupled with environmental concerns over waste management, underscores the need to explore avocado peel as a sustainable source of natural compounds with therapeutic applications.

Avocado peel contains bioactive compounds with diverse pharmacological activities. These include antioxidant, anti-inflammatory, antimicrobial, and anticancer properties [5], [6]. These activities are primarily attributed to the presence of polyphenols, which neutralize free radicals, reduce oxidative stress, and modulate cellular pathways associated with chronic diseases [7], [8].

Additionally, compounds such as catechins, quercetin derivatives, and proanthocyanidins in avocado peel have shown promising effects in inhibiting microbial growth and suppressing tumor cell proliferation in preclinical studies [9], [10], [11]. The pharmacological potential of these compounds highlights the possibility of repurposing avocado peel waste into value-added products, such as nutraceuticals, functional foods, or pharmaceutical agents, thereby contributing to both health and economic benefits.

Despite the promising pharmacological properties of avocado peel, its utilization remains limited due to challenges in extraction techniques, compound stability, and large-scale processing. Current research focuses on optimizing green extraction methods, such as ultrasound-assisted or microwave-assisted extraction, to maximize the yield and bioactivity of these compounds [12], [13]. Furthermore, the growing interest in sustainable practices and circular economies has spurred investigations into transforming avocado peel waste into innovative products, aligning with global efforts to reduce agricultural waste [14]. This review aims to elucidate the potential of avocado peel as a source of bioactive compounds, explore their pharmacological activities, and discuss the prospects and challenges of their application in food and pharmaceuticals. Throughout this review, the term 'avocado peel' refers to the outer skin of the avocado fruit, which is often discarded as waste. Some studies may use 'avocado skin,' but for consistency, 'peel' will be used here.

2. MATERIALS AND METHODS

The literature search was performed using the Scopus database on June 12, 2025, using multiple keywords and Boolean operators of "Avocado peel*" OR "Avocado by-product" AND "bioactive compound*" OR "secondary metabolite," resulting in 47 articles. Inclusion criteria in this review included: publication years (2018-2024), document type (original article), language (English), source type (journal), and publication stage (final). Only full-text relevant articles were included after the screening of titles and abstracts, resulting in 19 articles contained in this review (Figure 1).

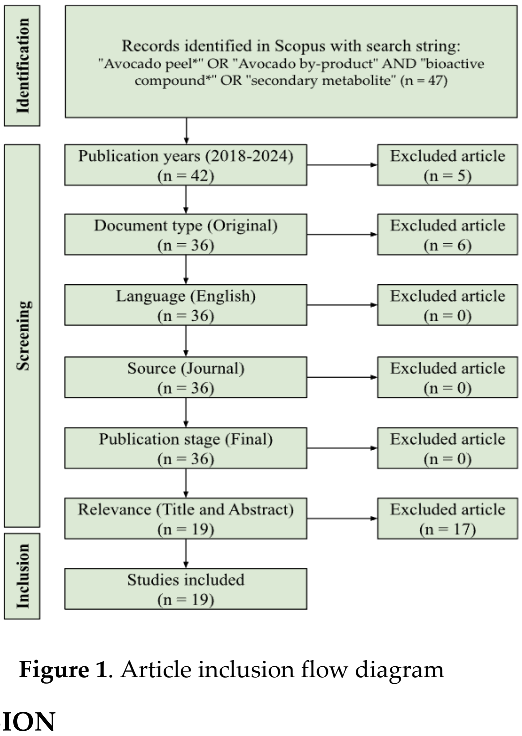

Figure 1. Article inclusion flow diagram

3. RESULTS AND DISCUSSION

3.1. Phytochemicals of Avocado Peel

Avocado peels, often discarded as agricultural waste, are a rich reservoir of phytochemicals with significant bioactive potential. The peel covers approximately 18% of the total fresh weight, comprising higher phenolic content and antioxidant activity than the reported values in the other parts (pulp and seed) [1], [15], [16]. The primary active pharmacological moieties of avocado peels include chlorogenic acid, quercetin derivatives, and procyanidins, which are responsible for their potent antioxidant, anti-inflammatory, antimicrobial, and anticancer properties [17], [18]. Chlorogenic acid (5-O-caffeoylquinic acid), an ester of quinic acid and cinnamic acid, is a hydroxycinnamic acid (phenolic compound) abundant in avocado peel, significantly contributing to its high antioxidant capacity [17], [19]. Among the identified flavonoids, quercetin and its derivatives, primarily found in fruit peels, were the dominant compounds. These flavonols are well-known for their potent antioxidant, anticancer, and anti-inflammatory properties [6], [10].

Previous studies have reported that avocado peel contains more than 30 phenolic compounds that were divided into three groups, including hydroxycinnamic acids, flavonols, and flavan-3-ols [6]. Advanced analytical techniques, such as high-performance liquid chromatography (HPLC) and mass spectrometry (MS), have enabled precise identification and quantification of these compounds, revealing their structural diversity [20]. These studies have identified a diverse array of compounds, including phenolics, flavonoids, organic acids, fatty acids, terpenoids, pigments, and alkaloids, within the peels of various avocado cultivars. These compounds are associated with several biological activities such as antioxidant, anti-inflammation, prevention of cancer, and some chronic diseases [6].

The composition and concentration of phytochemicals in avocado peels vary depending on factors such as cultivar, ripening stage, and environmental conditions [6], [21]. For instance, Hass avocados exhibit higher levels of procyanidin B2 (48.38 ± 0.04 mg/g) and epicatechin (40.21 ± 0.24 mg/g) compared to Fuerte (28.34 ± 0.23 mg/g and 30.40 ± 0.28 mg/g, respectively) [15]. This difference may contribute to the superior antioxidant capacity observed in Hass peels, as procyanidins are known for their strong radical-scavenging abilities [22]. The efficiency of extracting phytochemicals from avocado peels depends on the solvent and method used. Traditional techniques, such as maceration combined with wet grinding, provide better yields and preserve compounds like chlorogenic acid and epicatechin more effectively than other methods [13]. Other conventional methods, such as solid-liquid extraction, exhibit superior extraction capabilities for phenolic compounds, including p-hydroxybenzoic acid and vanillic acid, compared to modern techniques like ultrasonic-assisted extraction [23]. Factors such as the extraction method, temperature, solvent type, duration, and whether single or combined techniques are used all affect the outcome [13], [24].

Therefore, ongoing research is needed to test different conditions and technology combinations to optimize the recovery of these bioactive compounds. Understanding the phytochemical composition of avocado peels and improving their extraction is crucial for unlocking their potential as a sustainable source of bioactive molecules for pharmaceutical and nutraceutical applications. To ensure the quality and consistency of avocado peel extracts, chlorogenic acid and quercetin serve as key marker compounds due to their abundance, detectability, and significant bioactivity. These can be quantified using HPLC-DAD or UHPLC-QTOF-MS to monitor extract quality and standardize formulations [24], [25].

Table 1. Phytochemicals of Avocado Peels Based on Their Cultivars

Topic	Phytochemicals	Cultivars	Identification Method	References
Antioxidant and neuroprotective effects of Hass avocado peel extracts	Alkaloids, Organic acids, Pigments, Fatty acids, and Phenolic compounds	Hass	UHPLC-QTOF-MS	[25]
Effect of extraction process on phenolic compounds of the Hass avocado peel from industrial by-product	Phenolic compounds	Hass	HPLC-DAD	[24]
Phytochemical characterization of *Persea americana* Mill. by-products	Phenolics and Flavonoid compounds	Hass	LC-DAD-ESI-MS	[1]

continued Table 1..

Identification of bioactive compounds from avocado seed and peel	Organic acids, Phenolics, and Flavonoid compounds	Duke and Fuerte	HPLC	[26]
Avocado waste biological evaluation as a potential source of bioactive compounds	Organic acids, Fatty acids, Phenolics, and Flavonoid compounds	Hass	HPLC-ESI-QTOF-MS	[5]
Identification of phytochemicals in avocado peel	Organic acid, Hydroxycinnamic acids, Hydroxybenzoic acids, Phenolic alcohols, Flavonoids, and Fatty acids	Hass	HPLC-DAD-ESI-QTOF-MS	[27]
Green extraction of phenolic compounds from avocado peel	Phenolic compounds	Hass	UPLC-DAD	[9]
Effect of cultivars on avocado peel compounds	Fatty acids, Organic acids, Pigments, and Phenolic compounds	Hass	HPLC and GC-FID	[28]
Bioactive identification of avocado peel using ultrasonic extraction	Phenolics and Flavonoid compounds	Hass	HPLC-TOF-MS	[10]
Exploration of avocado waste products as a natural source of phytochemicals	Phenolic compounds	Hass and Fuerte	HPLC-MS/MS	[15]
Investigating the generation of antioxidants and biogas from avocado by-products	Organic acids, Phenolic and Flavonoid compounds	Creole	UHPLC-MS	[23]
Microwave-assisted extraction and characterization of compounds from avocado peel	Organic acids, Phenolic and Flavonoid compounds	Hass	HPLC-DAD-ESI-TOF-MS	[29]
Avocado byproducts as a source of neuroprotective compounds via pressurized liquid extraction	Organic acids, Fatty acids, Phenolics, and Flavonoid compounds	Hass	UHPLC-ESI-QTOF-MS	[30]
Metabolomic analysis of ripe Creole and Hass avocados	Organic acids, Fatty acids, Terpenoids, Pigments, Phenolics, and Flavonoid compounds	Hass, Creole	HPLC and GC-FID	[31]
Neuroprotective effects of Colinred avocado peel in transgenic knockdown Parkin *Drosophila melanogaster*	Phenolics and Flavonoid compounds	Colinred, Hass, Reed, Fuerte	HPLC-MS-DAD	[32]
Extraction optimization for the recovery of bioactive compounds of avocado peel	Phenolics and Flavonoid compounds	Hass	HPLC-DAD-ESI-TOF-MS	[33]
Phenolic extract from avocado by-products as a functional food	Phenolics and Flavonoid compounds	-	UPLC-ESI-MS/MS	[11]
Phytochemical recovery from avocado peel using microwave-assisted extraction	Phenolics and Flavonoid compounds	Hass	HPLC-ESI-MS	[12]
Extraction influence on the recovery of avocado peel compounds	Organic acids, Fatty acids, Amino acids, Phenolics, and Flavonoid compounds	Hass	UPLC-ESI-MS/MS and GC-MS	[13]

Table 1 highlights the rich phytochemical diversity in avocado peels, particularly from the Hass cultivar, which is frequently studied due to its global prevalence. Key compounds identified include alkaloids, organic acids, pigments, fatty acids, and phenolic compounds, as demonstrated by UHPLC-QTOF-MS in studies focusing on antioxidant and neuroprotective effects [25]. Other research using HPLC-DAD and LC-DAD-ESI-MS has confirmed the presence of phenolic and flavonoid compounds, underscoring the peel's potential as a source of bioactive molecules [1], [24]. The variety of extraction and identification methods, such as HPLC and advanced mass spectrometry, reflects the complexity of these phytochemicals, with Hass peels showing a broad spectrum of constituents that vary slightly across studies depending on the analytical approach.

The inclusion of other cultivars like Duke, Fuerte, Colinred, Creole, and Reed suggests that phytochemical profiles may differ across avocado varieties, with organic acids, phenolics, and flavonoids consistently identified in both seed and peel [34]. The use of sophisticated techniques like HPLC-ESI-QTOF-MS and HPLC-DAD-ESI-QTOF-MS indicates a trend toward precise characterization, revealing compounds such as hydroxycinnamic acids and hydroxybenzoic acids. This variability highlights the need for standardized extraction methods to ensure consistent yields, as factors like cultivar and processing conditions can influence the phytochemical composition of avocado peels [35], [36], [37].

3.2. Pharmacological Activities of Avocado Peel Phytochemicals

The diverse phytochemicals identified in avocado peels, such as phenolics and flavonoids, are not only structurally complex but also functionally significant. These compounds are known to interact with biological systems in ways that can lead to various pharmacological effects, including antioxidant, anti-inflammatory, and neuroprotective activities [38], [39]. Understanding these interactions is crucial for exploring the therapeutic potential of avocado peel waste. Table 2 reveals a wide array of pharmacological activities linked to avocado peel phytochemicals, with antioxidant effects being the most extensively studied. Mechanisms such as radical scavenging (assessed via DPPH, ABTS, ORAC) and metal chelation (FRAP) demonstrate the peel's ability to reduce oxidative stress, a key contributor to chronic diseases. The inhibition of β-carotene degradation and lipid peroxidation (TBARS) further supports this profile, aligning with the phenolic and flavonoid content identified earlier.

The neuroprotective potential of avocado peel phytochemicals is highlighted by the moderate inhibition of acetylcholinesterase (AChE) activity, assessed through in vitro methods, suggesting a role in managing neurodegenerative conditions [25], [30]. A specific study on avocado (*Persea americana* var. Colinred) peel extract demonstrated its ability to prevent locomotor impairment, reduce lifespan, and elevate lipid peroxidation (LPO) in transgenic KD parkin *Drosophila* exposed to paraquat (PQ), a model for Parkinson's disease (PD) [32]. These findings indicate that polyphenols, such as epicatechin in Colinred peel extract (CRE), may act as prophylactic agents in antioxidant therapy for PD prevention. Collectively, these results emphasize the therapeutic promise of avocado peel phytochemicals, warranting further research into their clinical applications.

Table 2. Pharmacological effects of avocado peel compounds

Activities	Mechanism	Methods	References
Antioxidant	Radical scavenging	DPPH, ABTS, ORAC, NO·, O_2·, ROO·, HOCl	[1], [5], [10], [11], [12], [13], [15], [23], [24], [25], [26], [29], [30], [32]
	Metal chelating	FRAP	[1], [5], [9], [10], [11], [15], [26], [29], [32]
	Inhibit degradation of β-carotene	β-carotene bleaching	[1]
	Lipid peroxidation	TBARS	[1], [32]
Neuroprotection	Inhibition of AChE	AChE in vitro	[1], [25], [32]
Antibacterial	Alteration of membrane fluidity	Agar well diffusion, microdilution	[1], [9]
Antifungal	-	Microdilution	[1]

continued Table 2..

Antiplatelet	Inactivate protein complexes involved in platelet aggregation	Turbidimetric	[5]
Antiaging	Inhibition of MMP1, MMP2, MMP3, MMP7	MMP inhibitor profiling kit	[29]
	Inhibition of tyrosinase	Tyrosinase inhibitor screening kit	[5]

continued Table 2..

	Inhibition of xanthine oxidase	Cayman's Xanthine Oxidase Fluorometric Assay Kit	
	Inhibition of elastase	Hydrolysis of substrate MeOSuc-Ala-Ala-Pro-Val-pNa	
	Inhibition of HYAlase	Turbidimetric	
	Inhibition of collagenase	Colorimetric	
Antiinflammation	Inhibition of TNF-α and NO production	LPS-stimulated RAW 264.7 macrophage	[15]
Anticancer	Induction of apoptosis and oxidative stress	Caco-2, HeLa in vitro	[10], [11]

2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), oxygen radical absorbance capacity (ORAC), nitric oxide radical (NO·), superoxide radical (O_2·), peroxyl radical (ROO· **),** hypochlorous acid (HOCl), ferric reducing antioxidant power (FRAP), thiobarbituric acid reactive substances (TBARS), acetylcholinesterase (AChE), matrix metalloproteinase (MMP), lipopolysaccharides (LPS), human colorectal adenocarcinoma (Caco-2), human cervix epithelioid carcinoma (HeLa).

Beyond their antioxidant and neuroprotective benefits, avocado peel phytochemicals exhibit a fascinating array of additional pharmacological activities that captivate scientific interest. These include antibacterial and antifungal effects, achieved by disrupting microbial cell membranes and halting growth, as well as antiplatelet action through the inactivation of protein complexes, which could support cardiovascular health [40], [41]. The peels also demonstrate remarkable anti-aging potential by inhibiting key enzymes, including tyrosinase, xanthine oxidase, elastase, hyaluronidase, and collagenase, offering possibilities for innovative skin care [42]. These diverse effects highlight the peel's versatility as a natural therapeutic resource.

Further expanding its therapeutic promise, avocado peel extracts demonstrate anti-inflammatory properties by reducing tumor necrosis factor-alpha (TNF-α) and nitric oxide (NO) production in lipopolysaccharide (LPS)-stimulated macrophages, as well as anticancer activity through inducing apoptosis and oxidative stress in Caco-2 and HeLa cancer cell lines. The wide range of experimental methods employed underscores the robustness of this research, yet questions remain regarding how efficacy varies across avocado cultivars and the need for clinical validation. Challenges such as poor bioavailability and instability under physiological conditions may limit their practical use. Still, ongoing studies are tackling these hurdles with innovative encapsulation techniques and advanced formulation strategies, paving the way for enhanced therapeutic applications. Antioxidant activity is the most promising for product translation, supported by extensive in vitro (DPPH, ABTS, FRAP, TBARS) and in vivo evidence (e.g., reduced lipid peroxidation in Parkinson's models) [23]. Its robust mechanistic data and applicability in food preservation and nutraceuticals make it closest to commercial application.

3.3. Potential Uses of Avocado Peels in Food and Pharmaceuticals

The valorization of avocado peel waste offers exciting prospects for the food and pharmaceutical industries, embodying the principles of a circular economy by transforming a common byproduct into valuable resources (Figure 2) [43], [44]. In the food sector, extracts from avocado peels act as natural antioxidants, effectively extending the shelf life of perishable goods while serving as eco-friendly alternatives to synthetic preservatives like butylated hydroxytoluene (BHT) [45]. Additionally, their robust antimicrobial properties enable the development of active packaging materials that combat microbial spoilage, as supported by studies [1], [9]. These properties have been tested against key foodborne pathogens, including Gram-positive bacteria such as *Staphylococcus aureus* and *Streptococcus dysgalactiae* subsp. equisimilis, as well as Gram-negative strains like *Escherichia coli* and *Pseudomonas putida*, which pose significant challenges in food safety.

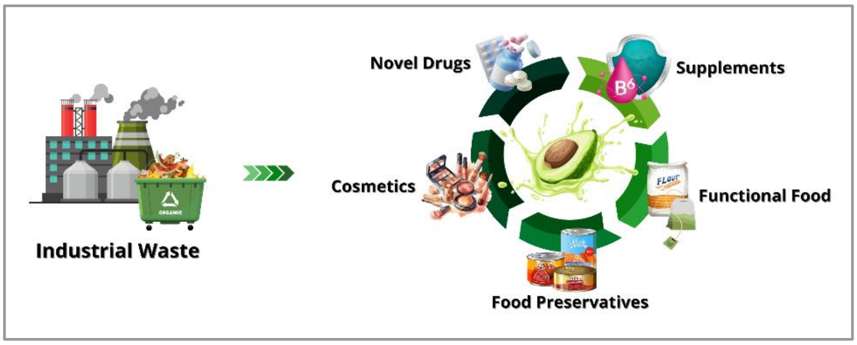

Figure 2. Utilization of Industrial Avocado Skin Waste in Food and Pharmaceutical Industries.

Testing has revealed strong antibacterial activity, particularly in avocado peels extracted using deep eutectic solvents (DES) or green extraction methods, highlighting the critical role of extraction techniques in enhancing bioactivity [9]. This suggests that the choice of extraction method significantly influences the peel's antimicrobial potential, with optimized protocols showing promise against a range of bacteria. Further refinement of these methods is essential to maximize antibacterial efficacy, paving the way for innovative, sustainable applications in food preservation and beyond, making avocado peel waste a compelling focus for future research and industry adoption.

Furthermore, integrating phytochemicals extracted from avocado peels into functional foods, such as flour or dietary supplements, presents an exciting opportunity to deliver health-enhancing compounds directly to consumers. The peels' modest oil content enhances their suitability for use in avocado peel flour, which positively influences the sensory qualities, such as texture and flavor, of bakery products. This flour emerges as a promising ingredient to fortify industrialized goods with bioactive compounds, potentially replacing a portion of wheat flour in baked items [28]. Such substitution could significantly boost the phytochemical content of these products, offering nutritional benefits and aligning with the growing demand for healthier food options. Avocado peel has also been formulated into a tea beverage containing phenolics and has been demonstrated to have superior antioxidant activity compared to apple tea, with good acceptability based on sensory analysis, making it a promising product [46].

In the pharmaceutical industry, bioactive compounds derived from avocado peels show promise for developing novel drugs or nutraceuticals that target oxidative stress-related diseases, infections, and cancers. Stability evaluations indicate that avocado peel extract can be effectively incorporated into both emulsion cosmetics, water-in-oil, and oil-in-water, where it functions as an antioxidant and antibacterial agent, offering a viable alternative to synthetic preservatives like BHT. Notably, the extract demonstrates greater efficacy and stability in oil-in-water emulsions, enhancing its potential for commercial applications [47]. However, challenges such as scalability, cost-effective extraction, and regulatory approval must be addressed to realize these applications fully. Emerging technologies, such as encapsulation techniques, can further improve the stability and bioavailability of these compounds, facilitating their integration into commercial products. By transforming avocado peel waste into value-added products, these applications not only mitigate environmental concerns associated with agricultural waste but also contribute to sustainable innovation in food and healthcare.

3.4. Future Outlook

Future research on avocado peel waste should prioritize advancements in analytical and product development strategies to maximize its therapeutic and commercial potential. Developing standardized UHPLC-QTOF-MS protocols will ensure consistent quantification of key marker compounds, such as chlorogenic acid and quercetin, facilitating quality control of extracts. Scaling up green extraction techniques, including the use of deep eutectic solvents, is essential to enhance yield and cost-effectiveness while maintaining sustainability [48]. Exploring nanoencapsulation and liposomal delivery systems will improve the bioavailability of bioactive compounds, particularly for antioxidant and anti-inflammatory applications, enabling their integration into functional foods and nutraceuticals [49], [50]. Conducting clinical trials to validate these pharmacological effects, especially the well-documented antioxidant and neuroprotective properties, will bridge the gap to commercial translation. Furthermore, integrating avocado peel valorization into circular economy models through scalable industrial processes will support environmental sustainability and economic growth, transforming this agricultural byproduct into a valuable resource for the food, pharmaceutical, and cosmetic industries [44].

4. CONCLUSION

This review highlights the significant potential of avocado peel waste as a sustainable source of bioactive phytochemicals, particularly phenolics and flavonoids, which exhibit diverse pharmacological activities. These include antioxidant, neuroprotective, antimicrobial, and anticancer effects, making the peels valuable for both food and pharmaceutical applications. However, challenges such as bioavailability, cultivar variability, and extraction scalability must be addressed through further research. Innovative approaches, including optimized extraction methods and advanced formulation techniques, are essential for unlocking the full therapeutic potential of avocado peels. Ultimately, valorizing this agricultural waste not only supports environmental sustainability but also contributes to health innovation and economic growth. Avocado peel emerges as a promising source of bioactive phytochemicals for pharmaceutical and food applications. However, further studies are needed to address cultivar variability and enhance compound bioavailability for industrial implementation.

Funding: This research received no external funding.

Acknowledgements: The author would like to acknowledge the funding support from the Indonesia Endowment Fund for Education (LPDP), Ministry of Finance, Republic of Indonesia (LOG-10697/LPDP/LPDP.3/2024).

Conflicts of interest: The authors declare no conflict of interest

References

[1] B. Melgar *et al.*, "Bioactive characterization of Persea americana Mill. by-products: A rich source of inherent antioxidants," *Industrial Crops and Products*, vol. 111, pp. 212–218, Jan. 2018, doi: 10.1016/j.indcrop.2017.10.024.

[2] E. Hurtado-Fernández, A. Fernández-Gutiérrez, and A. Carrasco-Pancorbo, "Avocado fruit— Persea americana," in *Exotic Fruits*, Elsevier, 2018, pp. 37–48. doi: 10.1016/B978-0-12-803138-4.00001-0.

[3] A. Castagna *et al.*, "Transforming Agricultural Waste from Mediterranean Fruits into Renewable Materials

and Products with a Circular and Digital Approach," *Materials*, vol. 18, no. 7, p. 1464, Mar. 2025, doi: 10.3390/ma18071464.

[4] B. Olas, "The Pulp, Peel, Seed, and Food Products of Persea americana as Sources of Bioactive Phytochemicals with Cardioprotective Properties: A Review," *IJMS*, vol. 25, no. 24, p. 13622, Dec. 2024, doi: 10.3390/ijms252413622.

[5] A. Rojas-García *et al.*, "Biological Evaluation of Avocado Residues as a Potential Source of Bioactive Compounds," *Antioxidants*, vol. 11, no. 6, p. 1049, May 2022, doi: 10.3390/antiox11061049.

[6] S. Akan, "Phytochemicals in avocado peel and their potential uses," *Food Health*, vol. 7, no. 2, pp. 138–149, 2021, doi: 10.3153/FH21015.

[7] J. Liu *et al.*, "Regulation of aging-related chronic diseases by dietary polyphenols: An updated overview," *Current Research in Food Science*, vol. 11, p. 101163, 2025, doi: 10.1016/j.crfs.2025.101163.

[8] C. Vidjeyamannane, A. Joy, K. Prakash, and R. Saravanakumar, "A comprehensive review on the role of plant-derived bioactive metabolites driving ROS-mediated apoptosis in cancer," *Med Oncol*, vol. 42, no. 9, p. 420, Aug. 2025, doi: 10.1007/s12032-025-02985-x.

[9] B. Rodríguez-Martínez, P. Ferreira-Santos, I. M. Alfonso, S. Martínez, Z. Genisheva, and B. Gullón, "Deep Eutectic Solvents as a Green Tool for the Extraction of Bioactive Phenolic Compounds from Avocado Peels," *Molecules*, vol. 27, no. 19, p. 6646, Oct. 2022, doi: 10.3390/molecules27196646.

[10] B. Rodríguez-Martínez, P. Ferreira-Santos, B. Gullón, J. A. Teixeira, C. M. Botelho, and R. Yáñez, "Exploiting the Potential of Bioactive Molecules Extracted by Ultrasounds from Avocado Peels—Food and Nutraceutical Applications," *Antioxidants*, vol. 10, no. 9, p. 1475, Sep. 2021, doi: 10.3390/antiox10091475.

[11] G. R. Velderrain-Rodríguez, J. Quero, J. Osada, O. Martín-Belloso, and M. J. Rodríguez-Yoldi, "Phenolic-Rich Extracts from Avocado Fruit Residues as Functional Food Ingredients with Antioxidant and Antiproliferative Properties," *Biomolecules*, vol. 11, no. 7, p. 977, Jul. 2021, doi: 10.3390/biom11070977.

[12] R. G. Araujo, R. M. Rodríguez-Jasso, H. A. Ruíz, M. Govea-Salas, M. Pintado, and C. N. Aguilar, "Recovery of bioactive components from avocado peels using microwave-assisted extraction," *Food and Bioproducts Processing*, vol. 127, pp. 152–161, May 2021, doi: 10.1016/j.fbp.2021.02.015.

[13] E. Martínez-Gutiérrez, "Study of Influence of Extraction Method on the Recovery Bioactive Compounds from Peel Avocado," *Molecules*, vol. 28, no. 6, p. 2557, Mar. 2023, doi: 10.3390/molecules28062557.

[14] B. K. Ndwandwe, S. P. Malinga, E. Kayitesi, and B. C. Dlamini, "Avocado seed-derived bioactive compounds for functional food packaging solutions: current developments and future prospects – a review," *Food Bioscience*, vol. 72, p. 107446, Oct. 2025, doi: 10.1016/j.fbio.2025.107446.

[15] M. A. Tremocoldi *et al.*, "Exploration of avocado by-products as natural sources of bioactive compounds," *PLoS ONE*, vol. 13, no. 2, p. e0192577, Feb. 2018, doi: 10.1371/journal.pone.0192577.

[16] P. Jimenez *et al.*, "Pulp, Leaf, Peel and Seed of Avocado Fruit: A Review of Bioactive Compounds and Healthy Benefits," *Food Reviews International*, vol. 37, no. 6, pp. 619–655, Aug. 2021, doi: 10.1080/87559129.2020.1717520.

[17] G. O. Izu *et al.*, "Unravelling the Influence of Chlorogenic Acid on the Antioxidant Phytochemistry of Avocado (Persea americana Mill.) Fruit Peel," *Antioxidants*, vol. 13, no. 4, p. 456, Apr. 2024, doi: 10.3390/antiox13040456.

[18] D. A. Waly, A. H. Abou Zeid, E.-S. A. El-Kashoury, S. F. Moustafa, A. M. El-Halawany, and R. S. Mohammed, "Avocado fruit peel and flesh as antioxidant and anti-inflammatory agents: A comparative phytochemical and in vitro study," *South African Journal of Botany*, vol. 179, pp. 334–344, Apr. 2025, doi: 10.1016/j.sajb.2025.02.012.

[19] A. Ahangarpour, M. Sayahi, and M. Sayahi, "The antidiabetic and antioxidant properties of some phenolic phytochemicals: A review study," *Diabetes & Metabolic Syndrome: Clinical Research & Reviews*, vol. 13, no. 1, pp. 854–857, Jan. 2019, doi: 10.1016/j.dsx.2018.11.051.

[20] M. Atanassova, W. Zahnit, M. Messaoudi, A. Rebiai, N. Benchikha, and B. Sawicka, "Analytical Techniques for Phytochemical Analysis and Functional Investigation," in *Biotechnology and Phytochemical Prospects in Drug Discovery*, B. Sawicka, M. Messaoudi, and A. Rebiai, Eds., in Interdisciplinary Biotechnological Advances. , Singapore: Springer Nature Singapore, 2025, pp. 151–187. doi: 10.1007/978-981-96-2790-5_6.

[21] A. Kosińska, M. Karamać, I. Estrella, T. Hernández, B. Bartolomé, and G. A. Dykes, "Phenolic Compound Profiles and Antioxidant Capacity of *Persea americana* Mill. Peels and Seeds of Two Varieties," *J. Agric. Food Chem.*, vol. 60, no. 18, pp. 4613–4619, May 2012, doi: 10.1021/jf300090p.

[22] J. Hao *et al.*, "Proanthocyanidin polymers (condensed tannins) from lychee seeds exhibit antioxidant, anticancer, anti-α-amylase, and anti-tyrosinase activities," *International Journal of Biological Macromolecules*, vol. 308, p. 142641, May 2025, doi: 10.1016/j.ijbiomac.2025.142641.

[23] M. C. Garcia-Vallejo *et al.*, "Exploring the production of antioxidants and biogas from avocado (Persea Americana var. Americana) residues as an alternative for developing rural bioeconomies," *Sustainable Chemistry and Pharmacy*, vol. 33, p. 101089, Jun. 2023, doi: 10.1016/j.scp.2023.101089.

[24] F. García-Ramón *et al.*, "Avocado Hass peel from industrial by-product: effect of extraction process variables on yield, phenolic compounds and antioxidant capacity," *Front. Sustain. Food Syst.*, vol. 7, p. 1255941, Nov. 2023, doi: 10.3389/fsufs.2023.1255941.

[25] J. F. Grisales-Mejía *et al.*, "Antioxidant and neuroprotective potential of extracts from Hass avocado peel obtained through a biorefinery process: A sustainable strategy for the valorization of agro-food waste," *LWT*, vol. 214, p. 117119, Dec. 2024, doi: 10.1016/j.lwt.2024.117119.

[26] S. A. E.-H. Zaki, F. A. E.-A. Ismail, S. H. Abdelatif, N. R. A. El-Mohsen, and S. A. Helmy, "Bioactive Compounds and Antioxidant Activities of Avocado Peels and Seeds," *Pakistan J. of Biological Sciences*, vol. 23, no. 3, pp. 345–350, Feb. 2020, doi: 10.3923/pjbs.2020.345.350.

[27] J. G. Figueroa, I. Borrás-Linares, J. Lozano-Sánchez, and A. Segura-Carretero, "Comprehensive identification of bioactive compounds of avocado peel by liquid chromatography coupled to ultra-high-definition accurate-mass Q-TOF," *Food Chemistry*, vol. 245, pp. 707–716, Apr. 2018, doi: 10.1016/j.foodchem.2017.12.011.

[28] A. L. Ramos-Aguilar *et al.*, "Effect of cultivar on the content of selected phytochemicals in avocado peels," *Food Research International*, vol. 140, p. 110024, Feb. 2021, doi: 10.1016/j.foodres.2020.110024.

[29] J. G. Figueroa, I. Borrás-Linares, R. Del Pino-García, J. A. Curiel, J. Lozano-Sánchez, and A. Segura-Carretero, "Functional ingredient from avocado peel: Microwave-assisted extraction, characterization and potential applications for the food industry," *Food Chemistry*, vol. 352, p. 129300, Aug. 2021, doi: 10.1016/j.foodchem.2021.129300.

[30] J. F. Grisales-Mejía *et al.*, "Hass Avocado (Persea americana Mill.) residues as a new potential source of neuroprotective compounds using pressurized liquid extraction," *The Journal of Supercritical Fluids*, vol. 204, p. 106117, Jan. 2024, doi: 10.1016/j.supflu.2023.106117.

[31] A. L. Ramos-Aguilar *et al.*, "Metabolomic analysis and physical attributes of ripe fruits from Mexican Creole (Persea americana var. Drymifolia) and 'Hass' avocados," *Food Chemistry*, vol. 354, p. 129571, Aug. 2021, doi: 10.1016/j.foodchem.2021.129571.

[32] H. F. Ortega-Arellano, M. Jimenez-Del-Rio, and C. Velez-Pardo, "Neuroprotective Effects of Methanolic Extract of Avocado Persea americana (var. Colinred) Peel on Paraquat-Induced Locomotor Impairment, Lipid Peroxidation and Shortage of Life Span in Transgenic knockdown Parkin Drosophila melanogaster," *Neurochem Res*, vol. 44, no. 8, pp. 1986–1998, Aug. 2019, doi: 10.1007/s11064-019-02835-z.

[33] J. G. Figueroa, I. Borrás-Linares, J. Lozano-Sánchez, R. Quirantes-Piné, and A. Segura-Carretero, "Optimization of drying process and pressurized liquid extraction for recovery of bioactive compounds from avocado peel by-product," *Electrophoresis*, vol. 39, no. 15, pp. 1908–1916, Aug. 2018, doi: 10.1002/elps.201700379.

[34] V. Di Stefano, G. Avellone, D. Bongiorno, S. Indelicato, R. Massenti, and R. Lo Bianco, "Quantitative evaluation of the phenolic profile in fruits of six avocado (*Persea americana*) cultivars by ultra-high-performance liquid chromatography-heated electrospray-mass spectrometry," *International Journal of Food Properties*, vol. 20, no. 6, pp. 1302–1312, Jun. 2017, doi: 10.1080/10942912.2016.1208225.

[35] T. P. Magangana, N. P. Makunga, O. A. Fawole, and U. L. Opara, "Processing Factors Affecting the Phytochemical and Nutritional Properties of Pomegranate (Punica granatum L.) Peel Waste: A Review," *Molecules*, vol. 25, no. 20, p. 4690, Oct. 2020, doi: 10.3390/molecules25204690.

[36] C. O. Nyakang'i, R. Ebere, E. Marete, and J. M. Arimi, "Avocado production in Kenya in relation to the world, Avocado by-products (seeds and peels) functionality and utilization in food products," *Applied Food Research*, vol. 3, no. 1, p. 100275, Jun. 2023, doi: 10.1016/j.afres.2023.100275.

[37] M. Vega-Alvarez *et al.*, "High drying temperatures preserve the phenolic compounds and antioxidant, antihyperglycemic and antibacterial activities in avocado peel (Persea americana)," *Food Measure*, vol. 19, no. 3, pp. 1651–1661, Mar. 2025, doi: 10.1007/s11694-024-03061-0.

[38] N. Rahman, S. M. Sabang, R. Abdullah, and B. Bohari, "Antioxidant properties of the methanolic extract of avocado fruit peel (Persea americana Mill.) from Indonesia," *Journal of Advanced Pharmaceutical Technology & Research*, vol. 13, no. 3, pp. 166–170, Jul. 2022, doi: 10.4103/japtr.japtr_22_22.

[39] A. Ovalle-Marin, C. Parra-Ruiz, F. Rivas, J. Orellana, D. Garcia-Diaz, and P. Jimenez, "Characterization of Persea americana Mill. peels and leaves extracts and analysis of its potential in vitro anti-inflammatory properties," *BLACPMA*, vol. 19, no. 4, pp. 395–407, Jun. 2020, doi: 10.37360/blacpma.20.19.4.27.

[40] M. Kamaraj, V. Dhana Rangesh Kumar, T. G. Nithya, and U. Danya, "Assessment of Antioxidant, Antibacterial Activity and Phytoactive Compounds of Aqueous Extracts of Avocado Fruit Peel from Ethiopia," *Int J Pept Res Ther*, vol. 26, no. 3, pp. 1549–1557, Sep. 2020, doi: 10.1007/s10989-019-09965-6.

[41] N. J. Salazar-López, M. L. Salmerón-Ruiz, J. A. Domínguez-Avila, M. A. Villegas-Ochoa, J. F. Ayala-Zavala, and G. A. González-Aguilar, "Phenolic compounds from 'Hass' avocado peel are retained in the indigestible fraction after an in vitro gastrointestinal digestion," *Food Measure*, vol. 15, no. 2, pp. 1982–1990, Apr. 2021, doi: 10.1007/s11694-020-00794-6.

[42] M. E. Orqueda, I. C. Zampini, K. Bravo, E. Osorio, and M. I. Isla, "Potential use of native fruits waste from Argentina as nonconventional sources of cosmetic ingredients," *J of Cosmetic Dermatology*, vol. 21, no. 10, pp. 5058–5065, Oct. 2022, doi: 10.1111/jocd.14959.

[43] B. Rodríguez-Martínez, A. Romaní, G. Eibes, G. Garrote, B. Gullón, and P. G. Del Río, "Potential and prospects for utilization of avocado by-products in integrated biorefineries," *Bioresource Technology*, vol. 364, p. 128034, Nov. 2022, doi: 10.1016/j.biortech.2022.128034.

[44] T. Sandoval-Contreras, F. González Chávez, A. Poonia, M. Iñiguez-Moreno, and L. Aguirre-Güitrón, "Avocado Waste Biorefinery: Towards Sustainable Development," *Recycling*, vol. 8, no. 5, p. 81, Oct. 2023, doi: 10.3390/recycling8050081.

[45] J.-G. Rodríguez-Carpena, D. Morcuende, M.-J. Andrade, P. Kylli, and M. Estévez, "Avocado (Persea americana Mill.) Phenolics, In Vitro Antioxidant and Antimicrobial Activities, and Inhibition of Lipid and Protein Oxidation in Porcine Patties," *J. Agric. Food Chem.*, vol. 59, no. 10, pp. 5625–5635, May 2011, doi: 10.1021/jf1048832.

[46] E. M. Rotta, D. R. D. Morais, P. B. F. Biondo, V. J. D. Santos, M. Matsushita, and J. V. Visentainer, "<b>Use of avocado peel (*Persea americana*) in tea formulation: a functional product containing phenolic compounds with antioxidant activity," *Acta Sci. Technol.*, vol. 38, no. 1, p. 23, Jan. 2015, doi: 10.4025/actascitechnol.v38i1.27397.

[47] S. M. Ferreira, Z. Falé, and L. Santos, "Sustainability in Skin Care: Incorporation of Avocado Peel Extracts in Topical Formulations," *Molecules*, vol. 27, no. 6, p. 1782, Mar. 2022, doi: 10.3390/molecules27061782.

[48] U. K. Panigrahi, "Green Extraction of Phenolic Compounds from Avocado (Persea Americana Mill.) Peel Using Deep Eutectic Solvents: Optimization, Characterization, And Sustainable Recovery Approach," *AJBR*, pp. 482–489, Sep. 2024, doi: 10.53555/AJBR.v27i1S.1520.

[49] A. Rezagholizade-shirvan, M. Soltani, S. Shokri, R. Radfar, M. Arab, and E. Shamloo, "Bioactive compound encapsulation: Characteristics, applications in food systems, and implications for human health," *Food Chemistry: X*, vol. 24, p. 101953, Dec. 2024, doi: 10.1016/j.fochx.2024.101953.

[50] C. Wen *et al.*, "Strategic Approaches for Co-Encapsulation of Bioactive Compounds: Technological Advances and Mechanistic Insight," *Foods*, vol. 14, no. 12, p. 2024, Jun. 2025, doi: 10.3390/foods14122024.