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Closing the loop: exploring apple pomace as a source of bioactive compounds in the framework of circular economy

Liege Aguiar Pascoalino,^{ID abc} Lillian Barros,^{ID ab} João C. M. Barreira,^{ID ab}
M. Beatriz P. P. Oliveira^{ID c} and Filipa S. Reis^{ID *ab}

Apple pomace (AP), the common designation of bio-residues generated during apple processing, holds a vast potential for alternative added-value solutions, particularly by applying new sustainable technologies in the food sector. This review provides an overview of the scientific validation of AP as a suitable source of starting materials for different competitive applications, compatible with circular economy guidelines and contributing to raising awareness about the impact and advantages of reincorporating bio-residues into the supply chain. The losses of the apple production chain, strategies to recover bio-residues, main nutritional and bioactive components, and innovative and eco-friendly technologies used for their extraction and subsequent use are thoroughly characterized. Additionally, a general perspective on the AP's bioavailability compounds will be presented, focusing on the association among nutrients in food and their physiological use.

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Sustainability spotlight

This review highlights the potential of apple pomace (AP), a bio-residue from apple processing, emphasizing its transformation into valuable materials through innovative and eco-friendly technologies. It aims to underscore the importance of reusing AP to reduce the economic and ecological impact its generation entails. Therefore, a solution is presented for companies, allowing the implementation of circular economy measures. The advance lies in validating AP as a source of nutritional and bioactive compounds, contributing to waste reduction and resource efficiency. Reintegrating AP into the supply chain, this work aligns with UN SDGs 2 (Zero Hunger), 3 (Good Health and Well-being), 12 (Responsible Consumption and Production), and 13 (Climate Action), promoting sustainable practices and reducing the biological footprint of food processing industries.

Introduction

Roughly a third of the global food production is wasted or lost annually; fruit and vegetable residues concentrate 22% of that volume, resulting in losses of about \$490 billion annually.^{1,2} Unexpectedly, if food leftover constituted a nation, it would rank as the third-largest producer of carbon dioxide, trailing behind the United States and China.³ According to the European Commission, food-related challenges, such as safety concerns and waste management, are among the most critical issues of the era, and food waste and loss were highlighted as one goal of the European Circular Economic Strategy.⁴ Due to this concern, the United Nations Sustainable Development Goal 12.3 was implemented,⁵ in which member states are committed to reducing worldwide food

waste per person by 2030, diminishing food waste across production and supply chains at both retail and consumer stages.

Diminishing food waste is a pathway to lower production costs, enhance food nutrition and security, and assist in environmental sustainability. It remarkably eases the strain on natural resources and decreases gas emissions.²

Due to expected impacts on the environment, economic losses, and ineffective use of resources, reducing food waste and losses has garnered the attention of manifold latest studies. In this context, the priority is identifying bio-residue production dynamics and developing tools to prevent this generation. In this way, managing inevitable losses by employing strategies such as reuse is possible. Furthermore, a considerable diversity of bio-residues has been demonstrated to be valuable for recovering compounds with high added value, mainly bioactive ones.^{6–9} It is crucial to discover sustainable solutions so they only end up being considered waste after being entirely utilized.

This review will explore the potential of using bio-residues from the apple production chain through a circular economy idea to extract high-added-value compounds with bioactive potential. It will also consider the issues of applying green and

^aCentro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus Santa Apolónia, 5300-253 Bragança, Portugal. E-mail: freis@ipb.pt

^bLaboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, Campus Santa Apolónia, 5300-253 Bragança, Portugal

^cREQUIMTE/LAQV, Science Chemical Department, Faculty of Pharmacy of University of Porto, Rua Jorge Viterbo Ferreira, 228, 4050-313 Porto, Portugal



eco-friendly extraction methods and the compound's potential in diverse food applications and health benefits.

Losses and reuses along the apple value chain

Apple (*Malus domestica* Borkh.) is one of the preferred fruits globally not just for its flavor, but also its nutritional value. Besides being consumed as fresh fruit, apple is an essential raw material in the fruit industry, especially for producing apple juice concentrate and cider.^{10,11} According to an FAO report, the global apple production in 2022 was estimated to be 113.8 million tons.¹² Moreover, the annual apple production in the European Union (EU-27) over the last ten years reached its highest point in 2018/19 at around 14.8 million tons and currently is approximately 12.2 million tons.¹³

With the development of the apple processing industry, the disposal of residues generated during fruit processing, known as apple pomace (AP), is a fundamental issue of high priority. The demand for green apple production and, simultaneously, the

destination of its bio-residues aiming to contribute to the circular economy (CE), and maintaining quality and safety are current challenging responsibilities.^{14–16} Indeed, the flaws begin in apple orchards, where the lack of sustainable practices generates many bio-residues that are discarded and, therefore, gives rise to several losses, including bioactive compounds that could be found in high concentrations and could be valued.^{10,14} Consequently, it is fundamental to develop better production management, including the CE system guidelines in apple cultivars, combining economic, environmental, and social issues with fabrication, thus promoting profit for companies and stakeholders.^{14,16}

The typical makeup of apple pomace (AP) consists of 93% to 97% skin/flesh, 2% to 4% seeds, and 1% of stems, and its nutritional composition encompasses 80% to 85% moisture, 3% to 8% fat, 0.6% to 4% ash, 2% to 7% proteins, and 15% to 19% of total fibers (Fig. 1).^{15,17,18} Mostly, apple peels are an



Liege Aguiar Pascoalino

Portugal). Her research focuses on recovering and valorising bio-residues from the cider industry, specifically apple pomace.

She has a Master degree in Chemical Engineering, integrated with the Dual Diploma project between the Federal Technological University of Paraná, Brazil (UTFPR) and the Polytechnic Institute of Bragança (IPB), Portugal. Currently, she is a PhD student in Pharmaceutical Sciences at the Faculty of Pharmacy of the University of Porto (FFUP) and IPB, with a research grant from the Foundation for Science and Technology (FCT,



Lillian Barros

and international patents, and is the principal researcher of several national/international projects. She has received awards from different organizations and is a Highly Cited Researcher in Clarivate since 2016. Research targets: identification, separation, and recovery of functional molecules from natural products.

She is a Principal Researcher at Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, vice-coordinator of CIMO, and vice-director of the Associate Laboratory SusTEC. She obtained a PhD "Doctor Europeus" in Pharmacy from the University of Salamanca (2008). She has published over 780 indexed papers in the Food Science and Technology area and has an 84 h-index. She has edited several books and book chapters, has registered national



João C. M. Barreira

Editor of 4 special issues and 2 topical collections in ISI-indexed peer-reviewed journals, Editorial Board Member in 8 ISI-indexed peer-reviewed journals, and Member of Scientific and Technical Support EFSA panel on Novel Foods & Nutrient Sources. SCOPUS: <http://www.scopus.com/authid/detail.uri?authorId=54895546900>.

He has a PhD in Pharmaceutical Sciences, and is a Researcher at Mountain Research Center (CIMO – group: Sustainable Processes and Products), and is author of 139 papers (8734 citations, 219 co-authors, h-index 53), 1 scientific book and 11 scientific book chapters (7 as first author), and 19 pedagogic manuals (first degree and MSc levels). He is a Senior Editor of Food Chemistry X journal, Editor of 5 scientific books, Lead Guest



M. Beatriz P. P. Oliveira

1450 communications in meetings, and has 2 granted patents by Europe and USA and 7 patents in evaluation. The developed work includes food science, security, environmental sustainability and plant extracts and agro-industrial by-products to add value.

Beatriz Oliveira is Full Professor from FFUP, Director of Master in Quality Control, a member of the EFSA Scientific Network for Risk Assessment of GMOs, and a member of a specialized committee from ASAE. She is the Head of GRESA/REQUIMTE/LAQV research group. She has large experience in supervision (45 PhD; 108 MSc), has co-authored more than 520 papers in international journals, 56 book chapters, 70 proceedings, and





Fig. 1 Graphical representation of (a) the morphological constitution and (b) the nutritional profile of apple pomace.

abundant font of dietary fiber, while seeds are generally high in bioactive lipids and polyphenols.¹⁹ Therefore, AP encompasses a diverse array of healthy compounds including phenolics, glycosides, alkaloids, volatile compounds, carbohydrates – particularly hemicellulose (4–24%), cellulose (7–44%), and pectin-dietary fibers, lipids, and proteins.^{8,15} Dietary fiber in AP generally consists of a balanced content of insoluble and soluble fibers and represents high-grade components related to cereals.²⁰ Studies highlight the potential of AP to fortify and enhance the nutritional value of foods, particularly due to its rich fiber composition. The total dietary fiber content in AP ranges from 45% to 51%, with both soluble and insoluble fractions, as previously described.^{8,18} AP has been successfully incorporated into cookies,²¹ muffins,²² and even beef burgers²³ to boost their fiber content, showcasing its versatility as a fiber-rich ingredient. With the well-documented health benefits of dietary fibers, utilizing AP in food products offers a sustainable and efficient approach to enhancing human health.⁸ In addition to indigestible fiber, AP also holds a substantial quantity of sugar and starch, rendering it an ideal substrate for fermentation products.²⁴ Queji *et al.* (2010) assessed the sugar profile in AP from 26 apple varieties with 18–31% fructose, 2.5–12.4% glucose, and 3.4–24% sucrose per dry weight.²⁵ Other studies

determined that almost 90% of the total fat in AP consists of unsaturated fatty acids, predominantly oleic and linoleic acids.^{26,27}

The leading end of AP is being employed in the manufacturing of animal feed. However, due to its small protein content, it does not constitute premium-quality feed, and there is a need to use the various compounds with the high added value present in pomace.^{28,29} Therefore, extracting nutrients and bioactive compounds from AP is crucial due to their health-related, environmental, and commercial benefits.

The circular economy and bio-residue recycling strategies

The concept of CE suggests a method contrasting to the conventional linear economy, where resources are removed, transformed into products, and then discarded after utilization. The closed systems have been considered the foremost foundation for eco-innovation, targeting at a “zero waste” economy and society where residues are employed as input for novel applications and products, a basis of industrial symbiosis.^{30,31}

Clean and circular production is considered a tactical component in manufacturing technology for current and upcoming products across various industrial sectors. Demand is concentrated on the advancement of alternative methodologies for the reduction of waste, the optimization of processes, and improvement in production effectiveness.^{28,32} Based on these concerns, the comprehensive idea of food production, exhibited in Fig. 2a, has been formulated. This approach aims to align synergistic objectives, such as the utmost product safety and quality, maximizing production efficiency, and incorporating environmental considerations into both food production and product development. In the concept, all factors and aspects should be considered coherently.³²

In terms of CE, valorization and recycling of residues allow materials to be returned to the supply chain, thus permitting economic development by reducing food losses.^{33,34} Implementing a CE model for the apple production chain can lead to greater sustainability since apple juice or cider manufacturing culminates in relatively low nutrient removal, resulting in apple pomace rich in nutrients of interest. Fig. 2b schematically shows an example of applying a CE approach in the apple production chain.

Wani & Mishra (2022b) studied a comprehensive CE model that manages controllable carbon emissions and degradation in an apple orchard, considering principles of a CE³⁵ focused on minimizing the quantity of waste produced, reusing edible fruits, applying its by-products, and mixing closed loops to achieve maximum outputs with minimal inputs, and promoting a more sustainable environment.³⁶

Establishing a closed-loop supply chain could be an arduous and essential portion of a CE aimed at waste reduction since apple orchards are increasing their popularity worldwide, and there has been a scarcity of mathematical modeling of these supply chains.³⁶

Overall, the trends, growths, and impacts of implementing the circular economy vary worldwide. According to Mak *et al.* (2020), in growing nations, it is noticed that there is a notable



Filipa S. Reis

She has a PhD in Pharmacy, with European mention and the highest honours, from the Complutense University of Madrid (UCM; 2017). Currently, she is a Researcher at Centro de Investigação de Montanha (CIMO group: Sustainable Processes and Products), FSR participates(d) in different R&D projects. She has published over 44 documents, including 4 international book chapters, 1 editorial, and 9 publications in proceedings of

scientific meetings (h-index of 23). She is an Editorial Board Member of BioMed Research International (section Biochemistry, Hindawi) and Frontiers in Nutrition (section Food Chemistry), and Guest Editor of some Special Issues (Applied Sciences, Processes, and Separations, MDPI).



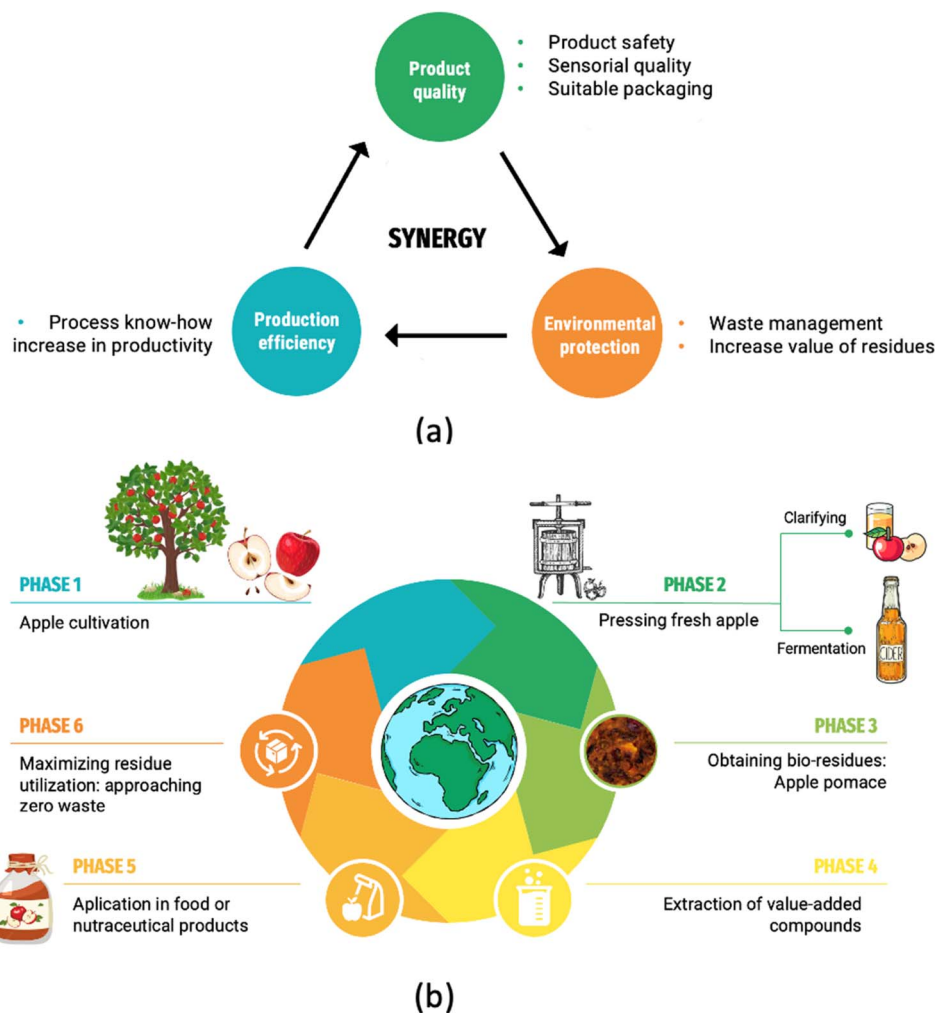


Fig. 2 (a) The comprehensive concept of food production; (b) schematic representation of the apple production chain following the circular economy guidelines.

increase in food loss during the stages immediately following harvest. On the other hand, developed economies experience a higher overall loss in the form of post-consumer food waste, affected by variables like aesthetics and inaccurate sell-by dates.³⁷ The composition of wastage is affected by specific characteristics of individual countries, such as market access, culture, legislation, and climate. Hence, all these diverse factors must be considered when analyzing different scales, market sizes, and the likelihood of resource reallocations and product replacements connected with the application of circular economy concepts.³¹

Developing concepts to valorize bio-residues from agribusiness thus contributes to a circular economy by creating economic value from by-products. Apple bio-residues, rich in interesting phytochemical compounds, have the prospective to be applied in food products for the upscale market, making them healthier and adding value to the end product, in addition to increasing the income of the companies that generate these products through their valorization and reduction of the costs associated with their disposal. More than that, products and

raw materials are kept in the economic cycle until they reach capacity, as the apple residues themselves are used as a bioactive source, increasing their usefulness. This strategy answers consumers' demands and the industry's search for new, cheaper, and natural ingredients for product improvement, besides promoting industrial competitiveness through the constant search for new ingredients and compounds of interest.

Recovery of compounds of interest from apple bio-residues

Studies have indicated that apple pomace (AP) contains phytonutrients that are valuable to one's health, particularly by decreasing the probability of illnesses including diabetes, cancer, and cardiovascular disease. The protective properties are believed to stem from the presence of nutrients and biologically effective compounds, such as fiber, vitamins, and phytochemicals.³⁸

Nutrients. Most of the dry weight of AP contains components not digestible by the human enzyme system, namely dietary fibers, which are classified into soluble and insoluble fibers. In AP, two-thirds of fibers are classified as insoluble, which



include cellulose, hemicelluloses (galactomannan, xyloglucan, and glucuronarabinoxylan), and lignin (*p*-coumaryl alcohols, sinapyl, and polymerized coniferyl). It also contains a considerable amount of starch and sugars (fructose, glucose, sucrose), creating an ideal substrate for fermentation products; the remainder is soluble fiber, mainly pectin.^{15,39} Incorporating dietary fiber into food products is an excellent food improvement technique since it could help to avoid several health conditions, including coronary heart disease, obesity, colon cancer, and diabetes. Dietary fiber is also a valuable ingredient in healthy foods as it lowers calorie and cholesterol levels, besides having a prebiotic influence.^{40,41} This bio-residue is also abundant in antioxidants, triterpenoids, polyphenolic compounds, malic acid, vitamins C and E, proteins, amino acids, and essential minerals.³⁹

Dry AP also comprises phosphorus, calcium, magnesium, and iron minerals. Additionally, about 90% of the total oil in AP is made up of unsaturated fatty acids, primarily oleic and linoleic acids. Phytochemicals such as chlorogenic acid, protocatechuic, and caffeic acid, as well as antioxidants and other polyphenols like quercetin, or phloridzin, have been extracted from AP.^{15,42} Thereby, the existence of value-added nutrients and phytochemicals in AP makes it a promising functional ingredient for various foods.

Bioactive compounds. Thorough research indicated that AP serves as a beneficial origin of phenolic constituents. Likewise, it contains higher bioactive compound concentrations than apple flesh itself.⁴³ The phenolic compounds within AP are predominantly phenolic acids (caffeic acid, hydroxycinnamic acids, and chlorogenic acid), flavonoids (catechins, quercetin,

flavonol, epicatechin, dihydrochalcones, and phloridzin) and anthocyanins (cyanidin glycosides).⁴⁴ Grigoras *et al.* (2013) assessed the bioactive molecules in AP and the primary phenols recognized were benzoic acids (gallic acid), flavonols (rutin), flavanols (catechin), hydroxycinnamic acids (chlorogenic acid), and chalcones (phloridzin). Of the triterpenes present, oleanolic and ursolic acids were the most prevalent. The authors concluded that for four cultivars (Pink Lady, Granny Smith, Gala, and Golden), crude extracts indicated potential antioxidant activity, validating that AP may be an esteemed font of bioactive molecules comprising not only triterpenes but also polyphenolic compounds.⁴⁵

Waldbauer *et al.* (2016) also verified that ursolic acid was the primary triterpene in AP, with lower amounts of oleanolic, maslinic, and betulinic acids. They proposed that the health-promoting properties of bioactive compounds in AP could be attributed to increased vascular nitric oxide bioavailability, mediated by improved endothelial nitric oxide synthase (eNOS) activity. To identify the components of AP responsible for enhancing nitric oxide bioavailability through eNOS activation, the researchers found triterpenoid acids as the predominant constituents in the most active fractions, affirming the capability of AP to serve as a reservoir of bioactive compounds.⁴⁶

Carpes *et al.* (2021) investigated the volatile compounds in AP and identified 56 volatiles belonging to different chemical classes: esters, terpenoids, alcohols/phenols, and ketones. α -Farnesene was the greatest common volatile compound, followed by sulcatone, ethyl phenyl propanoate, nonanal, and phenyl ethyl alcohol.⁴⁷ The Italian AP was studied by Ricci *et al.* (2019), and they also described α -farnesene as the prevalent

Table 1 Comprehensive overview of primary bioactive compounds found in apple pomace

Main classification	Examples	Amount	Ref.
Insoluble fibers	Cellulose, hemicelluloses (galactomannan, xyloglucan, and glucuronarabinoxylan), and lignin (<i>p</i> -coumaryl alcohols, sinapyl, and polymerized coniferyl)	36.5–57.9% of TDF (total dietary fibers)	15 and 39
Soluble fibers	Pectin	14.6–19.0% of TDF	15 and 39
Sugars	Fructose, glucose, and sucrose	18–31%; 2.5–12.4%; 3.4–24%, respectively	15 and 39
Minerals	Phosphorus, magnesium, calcium, and iron	0.07–0.076%; 0.02–0.036%; 0.06–0.1%; 31.8–38.8%, respectively	15 and 42
Unsaturated fatty acids	Linoleic and oleic acids	90% of total oil in apple pomace	15 and 42
Phenolic acids	Caffeic acid, hydroxycinnamic acids, and chlorogenic acid	In total: 523–1542 mg per kg per dry weight	44 and 50
Flavonoids	Quercetin, phloridzin, catechins, epicatechin, dihydrochalcones, and flavonol	In total: 2153–3734 mg per kg per dry weight	44 and 50
Anthocyanins	Cyanidin glycosides	In total: 50–130 mg per kg per dry weight	44 and 50
Triterpenes	Oleanolic acid, maslinic acid, and ursolic acid	9.6–20.4; 14.6–17.4; 7.9–17.1 mg g ⁻¹ respectively	45 and 46
Volatile compounds	α -Farnesene, sulcatone, ethylphenyl propanoate, and nonanal	26.6%; 8.3%; 5.7%; 5.5%; 5.4%, respectively	47 and 48
Organic acids	Malic and ascorbic acids	4.9–13.2; 0.3–0.5 mg g ⁻¹ , respectively	39 and 51
Tocopherols	α -Tocopherol	4.4–13.9 mg mL ⁻¹	39 and 52



sesquiterpene, while sulcatone was the most plentiful ketone. Additionally, phenylethyl alcohol and nonanal were identified at great concentrations in AP of the Italian variety after fermentation with *Lactobacillus rhamnosus*.⁴⁸

Madrera & Valles (2011) conducted a study to determine the presence of volatile compounds in AP. They identified various chemical groups, including 48 esters, 30 ketones and aldehydes, 19 norisoprenoids and terpenes, 9 acids, 8 alcohols, 4 lactones, and 6 compounds of further chemical structures. Their analysis of five different cultivars showed that these compounds' total number and proportion varied. However, the leading component within each chemical group remained consistent across all cultivars. For example, benzaldehyde was the dominant compound in the group of ketones and aldehydes, decanoic acid in the acids, a farnesol isomer in the group of terpenes, and ethyldecanoate in the group of lactones and esters. The only exception was the chemical group of alcohols, where the main compound differed among the five cultivars, with four of them having 1-octen-3-ol as the dominant compound, while one cultivar had 1-hexanol as the main compound.⁴⁹ Table 1 condenses the main bioactive compounds identified in apple pomace and discussed above.

Health effect: bioavailability of apple bioactive compounds

Bioactivity is the action of the absorbed compounds or their metabolites in metabolic pathways, thus exerting biological effects on the body. Nevertheless, bioactive compounds (such as polyphenols) need to be bioavailable to exert their biological effects. Their bioavailability corresponds to normal metabolism's digested, absorbed, and utilized portion. It can change based on their bioaccessibility, which measures the percentage of a consumed compound that is liberated from the solid food matrix and its subsequent availability for uptake within the small intestine or biotransformation *via* the gut microbiota. Hence, the health effects of apple pomace consumption may be influenced by bioactive compounds' absorption, metabolism, and distribution.⁴¹

Bondonno *et al.* (2017) concluded that alterations in the health advantages of apples as a whole food compared with isolated main polyphenols might be due to variances in their bioavailability. Several elements impact how well a person can absorb and metabolize polyphenols, including the amount consumed, microbial composition, and the occurrence of additional polyphenols and macronutrients in the food matrix. For instance, simultaneous intake of polyphenols and dietary fiber can decrease their absorption in the small intestine but increase the amount that reaches the large intestine. Then, polyphenols could be degraded to phenolic acids, and both dietary fiber and polyphenols may enhance the microbial composition of the colon.⁴¹

Pollini *et al.* (2022) assessed the bioavailability and bioaccessibility *in vitro* of phenolic compounds extracted from freeze-dried apple pomace (phloridzin, chlorogenic and gallic acids). Their outcome demonstrated that chlorogenic acid had a more significant bioaccessibility (44%) than gallic acid (7%), and phloridzin (17%), with comparable values observed for

both freeze-dried and fresh samples. More than that, solely chlorogenic acid showed upper bioavailability in basal compartments after 4 h, *i.e.*, 56% of chlorogenic acid passed the transepithelial barrier.⁵³

Researchers have investigated the bioavailability of epicatechin by utilizing both an apple extract (apple drink) and an apple puree holding varying concentrations of epicatechin. The authors concluded that both extracts are effective sources of bioavailable epicatechin. Nevertheless, epicatechin obtained from whole apples exhibits lower bioavailability compared to when it is consumed in the form of an epicatechin-rich apple extract incorporated into a beverage made with water. This finding supports the idea that the apple matrix diminishes epicatechin bioavailability.⁵⁴

Innovative processes used to recover bioactive from bio-residues

Numerous extraction procedures have been suggested in the bibliography for the useful recovery of bio-residues, from conventional solid-liquid extraction to non-conventional techniques, to improve the extraction yield of targeted compounds, evading deterioration and reduction in functionality during processing.⁵⁵ These non-conventional techniques comprise ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid-assisted extraction (SFE), pressurized liquid extraction (PLE), or enzyme-assisted extraction techniques.^{7,56-58} Fig. 3 illustrates a schematic representation of these types of extraction, while Table 2 condenses the various extraction methods applied to recover different compounds of interest from apple bio-residues.

Among the leading green extraction methodologies that replace conventional methods, supercritical fluid extraction with CO₂ (SFE) and high-pressure solvent extraction (HPSE) currently stand out because of their high output and the production of high-quality goods in less processing time and waste.⁸¹ These two techniques will be detailed below.

Supercritical fluid extraction with CO₂ (SFE)

Supercritical fluid extraction is mostly used in the food domain because it is safe and operated under easily achievable critical

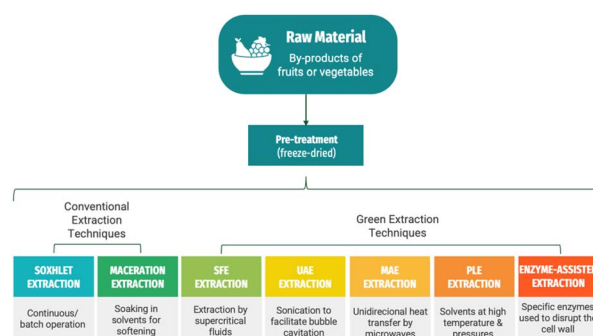


Fig. 3 Conventional and modern extraction procedures for plant-derived bio-residue recovery.



Table 2 Functional compounds recovered from bio-residues of the apple supply chain

Source	Compounds of interest	Recovery method	Potential applications	Recovery efficiency	Ref.
Apple pomace	Protein enrichment	Solid-state fermentation (<i>Rhizopus oligosporus</i>)	Improving the nutritional value in food applications	30.8% of soluble protein	59
	Lactic acid	Enzymatic digestibility	Fermentation of food and feed products	High susceptibility to enzymatic hydrolysis: 80% of the total glucan was converted into glucose	60
	Polyphenols	Supercritical (carbon dioxide + ethanol) extraction	Natural antioxidants and functional foods	Total phenolic content (TPC) equal to 0.47 gallic acid equiv. (GAE) per g	61
	Antioxidants and polyphenols	Pressurized liquid extraction (PLE)	Preservative of food products	Antioxidant activity 2.4 times higher	62
	Flavonoids	Microwave-assisted extraction (MAE)	Food fortification	62.7 mg GAE/100 g dry apple pomace	63
	Antioxidants	Ultrasound-assisted extraction (UAE)	Substitute of synthetic preservatives	TPC 30% higher	64
	Flavonols	Pressurized hot water extraction (PHWE)	Cosmetic, pharmaceutical, and food industries	Total yield of flavonols of 1.3 $\mu\text{mol g}^{-1}$ dry AP	65
	Fermentable sugars, ethanol, and acetic acid	Enzymatic hydrolysis and fermentation	Cosmetic, pharmaceutical, and food industries	Production of acetic acid at a concentration of 61.4 g/100 g	66
	Phenolic and terpenic compounds	MAE	Minimizing damage caused by oxidative stress due to radical species	AP extracts obtained by successive liquid-liquid extraction were able to inhibit the DPPH free radical	45
	Pectin	Subcritical water	Gelatinization, thickening and stabilization	Apple pomace pectin equal to 16.7%	67
	Phenolic compounds	MAE	Substitute to synthetic antioxidants, and dietary supplements	TPC of 15.8 mg GAE per g	68
	Propionic acid	Fermentation (<i>Propionibacterium freudenreichii</i>)	Preservative of food products	Propionic acid biosynthesis equal to 1.771 g L ⁻¹	69
	Bound phenolics	Pulsed electric field	Enhancing the healthy properties of food products and antioxidant agent	37.4% of TPC and 86% of antioxidant activity	70
	Antioxidants, phenolics and carotenoids	Supercritical fluid extraction (SFE)	Bakery, oil-based and cosmetic products	Antioxidant activity equal to 5.6 mg TEA per g of extract	71
Antioxidants, phenolics and carotenoids	Warm solvent extraction (WSE) and ultrasound-assisted extraction (UAE) techniques	Pharmaceutical, cosmetic, and food applications	TPC equal to 25 mg GAE per g (WSE) and 29 mg GAE per g (UAE)	72	
Fermentable sugars and pectin	Enzymatic hydrolysis	Conversion in value-added biochemicals	95.5 g pectin and 110.2 g fermentable sugars were produced from 500 g of AP	73	
Xylitol and 2G ethanol	Acid hydrolysis and fermentation (<i>Candida guilliermondii</i> and <i>Kluyveromyces marxianus</i>)	Elaboration of a biotechnological platform for the combined use of both the hemicellulosic and cellulosic fraction	10.47 g L ⁻¹ of ethanol and 9.10 g L ⁻¹ of xylitol	74	
Phenolic compounds	Pressurized liquids coupled on-line with solid phase extraction	Food and pharmaceutical industry	The solvent gradient, static time, and extraction temperature allowed higher mass transfer of the target analytes (furfurals, chlorogenic acids, flavonoids, and phloridzin)	75	





Table 2 (Contd.)

Source	Compounds of interest	Recovery method	Potential applications	Recovery efficiency	Ref.
Apple pomace ultrafiltration sludge	Citric acid	Fermentation (<i>Aspergillus niger</i>)	Preservative and flavoring in food and beverages	Citric acid concentration of 44.9 g/100 g	76
Apple industry waste biomass	Biobutanol	Fermentation (<i>Clostridium beijerinckii</i>)	Potential source of renewable energy	1.4 g L ⁻¹ of biobutanol	77
Apple peel and pulp	Fumaric acid	Fermentation (<i>Rhizopus oryzae</i>)	Chemical building block for coating compounds, synthetic resins, and plasticizers	25.2 g L ⁻¹ of fumaric acid	78
Apple peel and pulp	Catechins, flavonols (quercetin) and anthocyanins	PLE	Improving nutritional and organoleptic properties of foodstuffs	Confirms the efficiency of PLE to extract polyphenols from AP	79
Apple peels	Phenolic compounds	SFE	Natural antioxidant	Extractions from 15 g provided the highest phenolics yield of 800 mg/100 g dry peels	80

circumstances (31.1 °C and 73.8 bar). Furthermore, the lack of air and light through extraction minimizes the likelihood of degradation reactions occurring.⁶¹ This technique uses solvents above the critical point, which could be defined as “the specific pressure or temperature point above which gas and liquid do not exist as separate phases”. These fluids present the properties of both liquids in terms of diffusion, viscosity, and surface tension, as well as those of gases, allowing higher yields in a shorter time.⁸² Besides its lack of acute toxicity, CO₂ is also colorless, highly pure, non-flammable, odorless, and easily removed from the extract after decompression stage.⁷¹

Nevertheless, the major limitation lies in its small polarity, as CO₂ is non-polar and not appropriate as a solvent for polar compounds. The addition of organic co-solvents such as acetone, methanol, ethanol, or dichloromethane improves the solvating power of CO₂ and the yield of compound extraction by minimizing the matrix-analyte interactions.^{61,83}

Adil *et al.* (2007) studied the supercritical (ethanol and carbon dioxide) extraction of polyphenols from peach and apple pomaces and determined the antioxidant activities. The best pressure and temperature ranged between 55–57 MPa and 56–58 °C, respectively, with an ethanol concentration of 20% and an extraction time of 40 minutes for apple pomace. The anti-radical efficiencies and the total phenolic contents of the apple pomace extracts obtained were higher than those processed by conventional ethanol extraction, demonstrating that more active polyphenols were selectively extracted.⁶¹

Ferrentino *et al.* (2018) compared the extraction of antioxidants from apple pomace, applying conventional extraction techniques and SFE. Lesser yields were achieved by SFE apple pomace processing. On the other hand, the antioxidant capacity and total phenol recovery were higher than the extracts obtained by conventional extraction techniques. Generally, the outcomes indicate that fewer, but more active polyphenols are selectively extracted, reinforcing the SFE potential as a green technology for recovering high-value compounds from apple pomace.⁷¹

Massias *et al.* (2015) assessed the recuperation of phenolics from apple peels utilizing ethanol and CO₂ extraction. They concluded that this technology could recover the phenolics, yielding 120 mg from 15 g of peels using only 1.1 kg of extracting fluid.⁸⁰

High-pressure solvent extraction (HPSE)

High-pressure solvent extraction is an appealing choice compared to conventional solid-liquid extraction methods, proposing several benefits in what concerns separation conditions, selectivity, and the use of environmentally friendly solvents and technology for food and pharmaceutical applications. This method, also recognized as pressurized solvent extraction (PSE) or pressurized liquid extraction (PLE), comprises the use of H₂O or organic solvents at considerably raised pressures (3.3–20.3 MPa), and temperatures (313–473 K), enhancing the ability to conduct beneficial extractions due to its improved attributes related to solvation properties and mass transfer. Elevated temperatures lead to a decrease in liquid

solvent viscosity, an enhancement in solvent diffusivity through the matrix, and therefore, an acceleration in extraction kinetics. Furthermore, high pressure can reduce the surface tension of the solvent, forcing it into the matrix pores and hence simplifying the extraction of target compounds.^{57,84,85} Thereby, this type of extraction exploits the useful mixture of liquids' solvation properties and the beneficial transport characteristics of supercritical fluids.⁸⁶ The flexibility of pressurized solvents is fundamental due to the physicochemical properties of the solvent (viscosity, diffusivity, dielectric constant, and density), which could be measured by fluctuating the pressure and temperature of the system.⁸⁷

Nonetheless, a liquid separation step is also mandatory in the post-extraction steps, which is a relative inconvenience to SFE methodology.⁸⁴

Wijngaard & Brunton (2009) optimized the extraction of antioxidants (polyphenols) from apple pomace by pressurized liquids and concluded that when using this technique, the antioxidant capacity was improved 2.4 times in contrast to conventional extraction.⁶²

da Silva L. C. *et al.* (2023) studied the simultaneous extraction of apple pomace by gradient PLE coupled in line with solid-phase extraction and online with HPLC. The authors concluded that utilizing an extraction solvent gradient could be an esteemed instrument to enhance the variety of compounds extracted in a single process rather than employing consecutive extractions with diverse solvents, enhancing the extraction yield and achieving quantitative extractions.⁷⁵

Alonso-Salces *et al.* (2001) optimized the PLE extraction using diverse process variables (solvent, static time, temperature, and pressure) to increase a substantial recuperation of polyphenols from apple pulp and peel. Optimized conditions for the highest polyphenol recovery were defined: methanol at a temperature of 313 K and 7 MPa pressure for 5 min. Finally, the effectiveness of PLE as an eco-friendly technique for the extraction of polyphenols was similar to conventional solvent extraction, resulting in less solvent volume and shorter sample preparation times.⁷⁹

Application of bio-residues from the apple supply chain in food and nutraceutical industries

Several efforts have been made to recover bioactive compounds embedded in apples' bio-residues, since they are a prospective source for multiple bioactive compounds, including antioxidants, coloring pigments, phytochemicals, and nutrients, with functional and nutritional values.⁸⁸ Along these lines, the effective incorporation of these compounds into food and nutraceutical products and proper management of these organic bio-residues could supply economic and environmental advantages by decreasing food loss beyond the elaboration of new products, contributing to the competitiveness of the industries.

Accordingly, a brief overview will be presented on the major applications of apple bio-residues both in the food area and in nutraceuticals. According to different research reports, AP could have an extensive range of applications. Ayar *et al.* (2018), for instance, investigated the consequences of supplementing with

dietary fiber-rich apple pomace to probiotic ice creams. They concluded that it can be implemented in ice cream with enhanced viability of probiotic strains without contrary consequences on the microbiological, physicochemical, and sensory properties. The enriched ice creams presented physicochemical and sensory properties similar to the control, besides having highly satisfactory sensory properties.⁴⁰

The impact of apple pomace on the quality attributes of crackers was also researched by Mir *et al.* (2017). It was possible to assume the increased quantity of apple pomace in the flour preparation resulted in superior antioxidant capacities, total dietary fiber, and minerals in the end-product, considering that pomace-based rice crackers have beneficial effects for consumers, especially for coeliac disease patients.⁸⁹

Rupasinghe *et al.* (2008) examined the impact of baking on the dietary fiber and phenolics of muffins combined with apple skin powder. They noticed that these muffins were higher in dietary fiber, total phenolic content, and total antioxidant activity than the control. Their results indicate that apple skin powder might serve as an unconventional font of dietary fiber or as a specialty ingredient for bakery items or specific nutraceuticals and functional foods.²² Following this line of reasoning, Wolfe & Liu (2003), in their review paper, stated that valuable food ingredients could be produced from apple peels by drying and grinding without much loss of phytochemicals. Based on fresh weight, these samples' flavonoids and total phenolic contents were comparable to those of fresh apple peels. Thus, the developed ingredient apple peel powder could be a rich and appealing supplement to healthy foods, as a slight amount can significantly enhance the content of phytochemicals and antioxidant capacity of foods.⁹⁰

de Toledo N. M. V. *et al.* (2017) explored the sensory and physicochemical effects concerning the partial replacement of wheat flour in cookies with flours derived from apple bio-residues. The use of these bio-residues positively induced the nutritional attributes of the cookies, particularly their fiber content, deducing that they could be a possible alternative to be investigated for technological, nutritional, and sensory aims by the food industry.⁹¹ Usman *et al.* (2020) also investigated enriched cookies quality with apple pomace and based on the sensory and compositional characteristics, it was established that cookies with better-quality organoleptic properties could be made using wheat flour supplemented with 10% of apple pomace powder.²¹

Bortolini *et al.* (2020) tested a new approach using apple pomace in cider-making to recover phenolic compounds. The cider enriched with apple pomace was richer in phenolic compounds and, consequently, had higher antioxidant capacity. Also, the sensory analysis revealed lower intensities of sourness and higher intensities of bitterness, whereas the odor and astringency attributes were related to the control cider. The authors hypothesized that apple pomace demonstrated great potential as a source of phenolic compounds to be reintegrated into cider.⁹²

Huber & Rupasinghe (2009) studied apple peel's attributes as natural antioxidants to solve the question of lipid oxidation, particularly the degradation of polyunsaturated fatty acids,



a noteworthy problem in the industry affecting both consumers' health and food quality. The authors studied 21 apple genotypes and their profile of phenolic compounds and antioxidant capacities. The extracts were revealed to be potent inhibitors of the oxidation of polyunsaturated fatty acids. They thus could be pondered to develop new natural food antioxidants.⁹³

Henriquez *et al.* (2010) created an ingredient from Granny Smith apple peel, utilizing a pilot-scale drying method. Every effort to optimize the conservation of dietary fiber and phenolic compounds was determined. Moreover, they scanned the chemical and physical characteristics, sugar and mineral

content, and technological functional properties such as solubility index, water retention capacity, and dispersibility. The developed powder ingredient, a font of phenolic compounds and dietary fiber, was considered suitable for food formulations.⁹⁴

Regarding the pharmaceutical industry, it has been proven that phenolic compounds found in apples hinder fat synthesis in sebaceous cells and also modulate sebum production, thereby diminishing the appearance of acne. In that regard, natural products have a tendency to treat acne, decreasing the inflammation systems.^{95,96} Moreover, phenolic compounds

Table 3 Outline of versatile applications of apple pomace in food and pharmaceutical industries

Area	Application	Amount applied	Results	Ref.
Food industry	Ice cream	0.5% and 3% of apple pomace	Improved viability of probiotic strains without any negative consequences	40
	Brown rice-based crackers	3%, 6% and 9% of apple pomace	Higher antioxidant properties, fibers and minerals	89
	Muffins	4%, 8%, 16%, 24% and 32% of apple skin	Higher in dietary fiber, total phenolic content, and total antioxidant capacity	22
	Apple peel powder as an ingredient to supplement healthy foods	A small amount could greatly increase the phytochemical content and antioxidant activity of foods	Increasing the antioxidant activity and content of phytochemicals	90
	Cookies	5%, 10% and 15% of apple by-products; 5%, 10%, 15%, 20% and 25% of dried pomace	Positively influencing the fiber content and improved organoleptic properties	21 and 91
	Cider	47.3 g L ⁻¹ of dried apple pomace	Higher content of phenolic compounds and antioxidant activity	92
	Natural food antioxidants	Lipid stabilizing ability of 73.8% to 97.2%	Potential inhibitors of the oxidation of polyunsaturated fatty acids	93
	Powder ingredient for food formulations	Can be used in different concentrations as an ingredient in food formulations	Source of dietary fibers and phenolic compounds	94
	Mayonnaise	2 to 6% of apple pomace	Improved antioxidant properties, stability after 30 days, and higher overall acceptability	101
	Beef burger fortification	4% and 8%	Improved fiber and phenol content, and neutral flavor	23
Pharmaceutical industry	Treating acne	50 µg mL ⁻¹ of apple polyphenols	Inhibiting fat production in sebaceous cells and regulating sebum production	95 and 96
	Source of stabilizing agent	The reference particle load was set at 100 mg of powder per g of oil, corresponding to 4.8% wt/wt	Emulsifying potential due to the stabilizing pectins and proteins in the soluble portion	99
	Synthesis of silver nanoparticles	40 mL of apple pomace extract	The nanoparticles demonstrated high antibacterial activity, and they exhibited a spherical shape, uniform dispersion, small size, and a high degree of crystallization	100



demonstrated results on different skin syndromes such as rosacea, psoriasis, wounds, atopic dermatitis, and burns.⁹⁶

Apple pomace has gelling and emulsifying characteristics in the cosmetic, pharmaceutical, and food industries.^{97,98} Huc-Mathis *et al.* (2019) studied these apple pomace and oat bran properties. Their insoluble and soluble components stabilized oil-in-water emulsions, but the apple powder showed improved emulsifying potential due to the stabilizing pectins and proteins in the soluble portion. Both raw materials were regarded as renewable sources of stabilizers. Additionally, apple pomace can also serve as a reducing and stabilizing agent in the fabrication of metallic nanoparticles.⁹⁹

Ren *et al.* (2019) used apple pomace to synthesize silver nanoparticles. The green production method avoided the use of toxic reducing and dispersing agents. The Ag nanoparticles had great antibacterial activity. Moreover, they exhibited a uniform dispersion, small size, spherical shape, and a high degree of crystallization.¹⁰⁰

In that way, the use of apple pomace as a natural additive in the food industry is becoming gradually accepted as it seems to have several effective attributes, such as antioxidant, antimicrobial, and anti-inflammatory properties. Also, apple pomace presents a high potential to be exploited as a competitive and original source of cosmeceuticals, with possible application in developing numerous natural-based preparations while adding value to that industrial bio-residue.¹¹ Table 3 recapitulates all the applications cited in this topic.

Concluding remarks and future trends

Apple pomace is an inexpensive, easy to-obtain, and bioactive bio-residue. It has considerably high concentrations of bioactive molecules including dietary fibers, polyphenols, and pentacyclic triterpenes. The practical and sustainable use of apple pomace is an auspicious tendency in apple processing industries to decrease economic loss and environmental contamination. Apple pomace has the potential to diversify industry revenue streams through its conversion into high-value products that do not compromise human food security, besides significantly contributing to the circular economy. To enhance extraction yields, minimize processing time, and diminish the ecological impact of toxic solvents, replacing conventional methods with eco-friendly technologies has been demonstrated to be a promising solution. Despite this, the need to develop industrial processes aligned with a circular economy remains. Considering this, integrating the valorization concept permits the transformation of apple pomace into high-value products with pertinent prospective applications for human ingestion and pharmaceutical industries, such as extracting specific molecules and producing novel functional foods. Such transformation requires the food, pharmaceutical, and nutraceutical industries to promote the development of novel products. Lastly, bioavailability and bioaccessibility should be further studied and understood for applying these compounds of interest more efficiently in human health.

Data availability

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

Conflicts of interest

There are no conflicts to declare.

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