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Review

# Advances and future perspectives in agricultural waste valorization

Prisco Prete,[1] Martino Forino,[2] Daniele Cespi,[3,4,*] and Raffaele Cucciniello[1,*]
[1]Department of Chemistry and Biology "Adolfo Zambelli", Salerno University, Via Giovanni Paolo II 132, 84084 Fisciano, Italy
[2]Department of Agricultural Sciences, Grape and Wine Science Division, University of Napoli 'Federico II', Viale Italia, 83100 Avellino, Italy
[3]Dipartimento di Chimica Industriale "Toso Montanari", Alma Mater - Università di Bologna, Via Piero Gobetti, 85, 40136 Bologna, Italy
[4]Center for Chemical Catalysis - C3, University of Bologna, Via Piero Gobetti 85, 40136 Bologna, Italy
*Correspondence: daniele.cespi2@unibo.it (D.C.), rcucciniello@unisa.it (R.C.)
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## SUMMARY

Agricultural waste valorization has emerged as a promising strategy to support the circular bioeconomy by reducing waste streams and generating sustainable alternatives to fossil-derived chemicals. In this review, we discuss the valorization of agricultural waste to value-added chemicals, reporting on secondary metabolites extracted from different waste biomasses. Additionally, we focus on extraction techniques and their environmental impacts, as assessed by life cycle assessment (LCA) studies. Finally, we discuss emerging waste biomass sources, including pine needles, wood bark, and poultry manure, along with their valorization processes. Further research is needed to enable their comprehensive valorization through the integration of experimental investigations and robust LCA approaches. Future studies should adopt harmonized methodological frameworks that include product-oriented functional units, comprehensive system boundaries, transparent allocation procedures, and solvent and energy management strategies, alongside scale-up and sensitivity analyses to improve the robustness, comparability, and industrial relevance of sustainability assessments.

## INTRODUCTION

According to recent estimates, food waste remains a predominant problem worldwide. The United Nations Environment Programme (UNEP) has reported that some 1,052 million tons of food waste have been produced in 2022,[1] of which 60% came from households. This negative trend was also confirmed by more recent estimations from across the world (Figure 1),[2] even if some inefficiencies are also concentrated in the post-harvesting phases.

The situation in Europe (EU) does not appear to be any better. In 2006, a scientific report from the EU commission revealed that the amount of food waste per capita was equal to 179 kg.[3,4] In Figure 2, the primary production of food waste across the EU is shown. The cumulative values (dashed red line in Figure 2A) highlight a descendent trend after some years of plateau (2016–2018) as a consequence of a fast increase following the 2012–2014 economic crisis. According to Figure 2B, the major contributors (>10%) are Spain (average 23%), Italy (average 19%), and France (average 11%).

Food losses mean failing to contribute to the fight against poverty and, consequently, to reducing mortality. Today, over 820 million people still suffer from hunger worldwide; this is about one in nine.[5] No poverty and zero hunger correspond to the first and second goal of the Agenda 2030,[6] the fundamental document released in 2015 with the aim of setting pillars of sustainability for nations and industries by using common framework and simple language.

Food waste arises not only from agricultural harvesting and primary processing but also significantly from the food and feed industries, as well as from post-consumer sources. Therefore, the efficient and expanded use of such wastes, by-products, and co-products (even referred to as side-streams) from agriculture and related sectors is essential for the production of value-added chemicals and materials. The main challenges in converting biowaste into valuable products are largely posed by the composition and origin of the waste itself, rather than by technological limitations. Existing technologies, originally designed for fossil-based resources, can be indeed adapted and optimized for biowaste processing. Nonetheless, food waste presents specific challenges: despite being largely available, its contamination and low energy density often make large-scale conversion processes economically unattractive.[7]

Food-waste recycling transforms residues, which would otherwise be discarded, into valuable resources such as renewable energy. This process reduces landfill volumes and associated greenhouse gas emissions, while enabling the production of biofuels, fertilizers, animal feed, or electricity from biogas. By substituting fossil-based resources, food-waste valorization contributes to lowering environmental impacts. Life cycle assessment (LCA) can be used to quantitatively evaluate the environmental burdens of these technologies and support the development of technological advances aimed at mitigating environmental threats.[8] Within the water-food-energy nexus, such strategies also promote efficient resource uses across sectors, enhancing sustainability and resilience in agricultural systems.

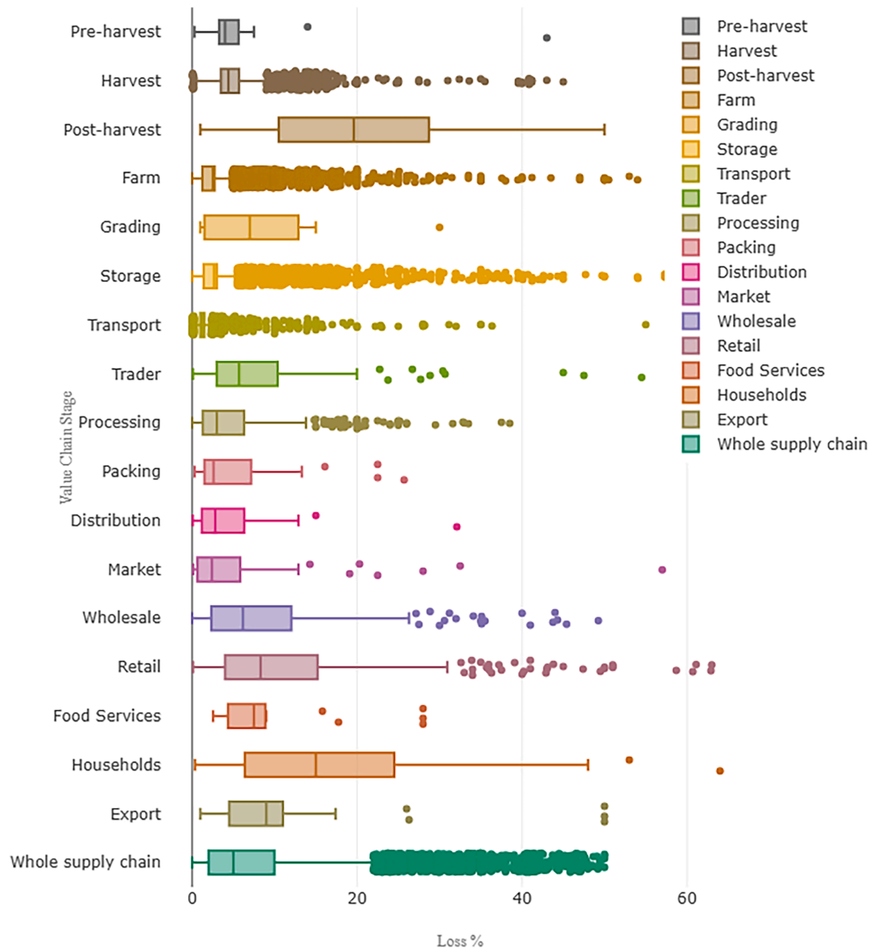


**Figure 1. Worldwide food loss (%) per value chain stage (1965–2024)**
The boxplots show the distribution of reported food loss percentages for each value chain stage. Boxes represent the interquartile range, the horizontal line indicates the median, and whiskers extend to the minimum and maximum values. Data optained from the literature.[2]

Considering the extensive body of literature on agricultural waste valorization,[9–13] this review highlights emerging strategies to transform diverse biomasses into value-added chemicals, emphasizing sustainable extraction techniques, environmental impact assessment via LCA, and future research directions within a circular-economy framework. The selected studies are related to recent developments in agricultural waste valorization, focusing our investigation on those published during the last 5 (mainly) to 10 years. The biomass feedstocks considered in this review were selected to highlight major findings related to both well known (i.e., grape pomace, shrimp shell, and coffee grounds) and less considered starting biomasses for the preparation of functional materials, including chestnut shells, walnut shells, pine needles, wood bark, and poultry manure.

## VALORIZATION OF AGRICULTURAL BY-PRODUCTS

### Extraction of secondary metabolites as value-added chemicals

#### *Grape pomace*

Agricultural by-products, usually regarded as a bulky burden to dispose of, can turn into valuable sources of precious healthy compounds, whose chemical synthesis can be either tricky or too costly. Grape pomace, also referred to as marc, is a clear example. Grape pomace is a major wine-making by-product whose composition is strictly entwined not only with the grape variety but even with the soil nature and wine-making procedures, as well. Generally, it consists of variable quantities of residual pulp, skins, seeds, and stalks. Although a number of possible reuses have been investigated, this biomass still represents a serious economic and environmental issue for wineries. To valorize grape pomace and convert it into an a value-added product, distillation procedures have been largely employed for the production of spirits.[14] As a feed for farm animals, pomace has turned out to be detrimental to livestock health on account of its high amounts of fibers and tannins, which have negative impacts on the animal digestion.[15] Alternatively, this material has been studied as a possible fertilizer to improve the soil content in nitrogen and minerals; but the occurrence of phytotoxic and anti-microbial molecules has been identified as a factor that impairs germination.[16] Thus far, the most promising reuse of grape pomace has been based on the recovery of healthy compounds endowed with many bioactivities ranging from the antioxidant to the vasodilatory, anti-thrombotic, cardioprotective, anti-inflammatory, anti-cancer, and anti-microbial ones.[17–19] All of the above-mentioned properties have been linked to specialized metabolites, mainly polyphenols, such as anthocyanins and their derivatives, flavanols, condensed tannins, stilbenes, and lignans. These compounds have been widely used not only in the pharmaceutical sector but even in the food industry to delay food spoilage and extend the aliments shelf-life.[20] However, it is unlikely that all of the bioactivities shown by grape pomace extracts can be attributed exclusively to polyphenols. Additionally, the secondary metabolism pathways in plants usually lead to several classes of compounds differing from each other by chemical architecture and consequently by different biological roles. This hypothesis has been recently corroborated by the detection of impressive quantities of a triterpenoid, namely oleanolic acid, in the Aglianico (*Vitis vinifera*) red grape pomace.[21,22] Oleanolic acid is a major component of the grape berry cuticle with anti-tumor, antibiotic, and antiviral properties.[23] Also, this molecule is

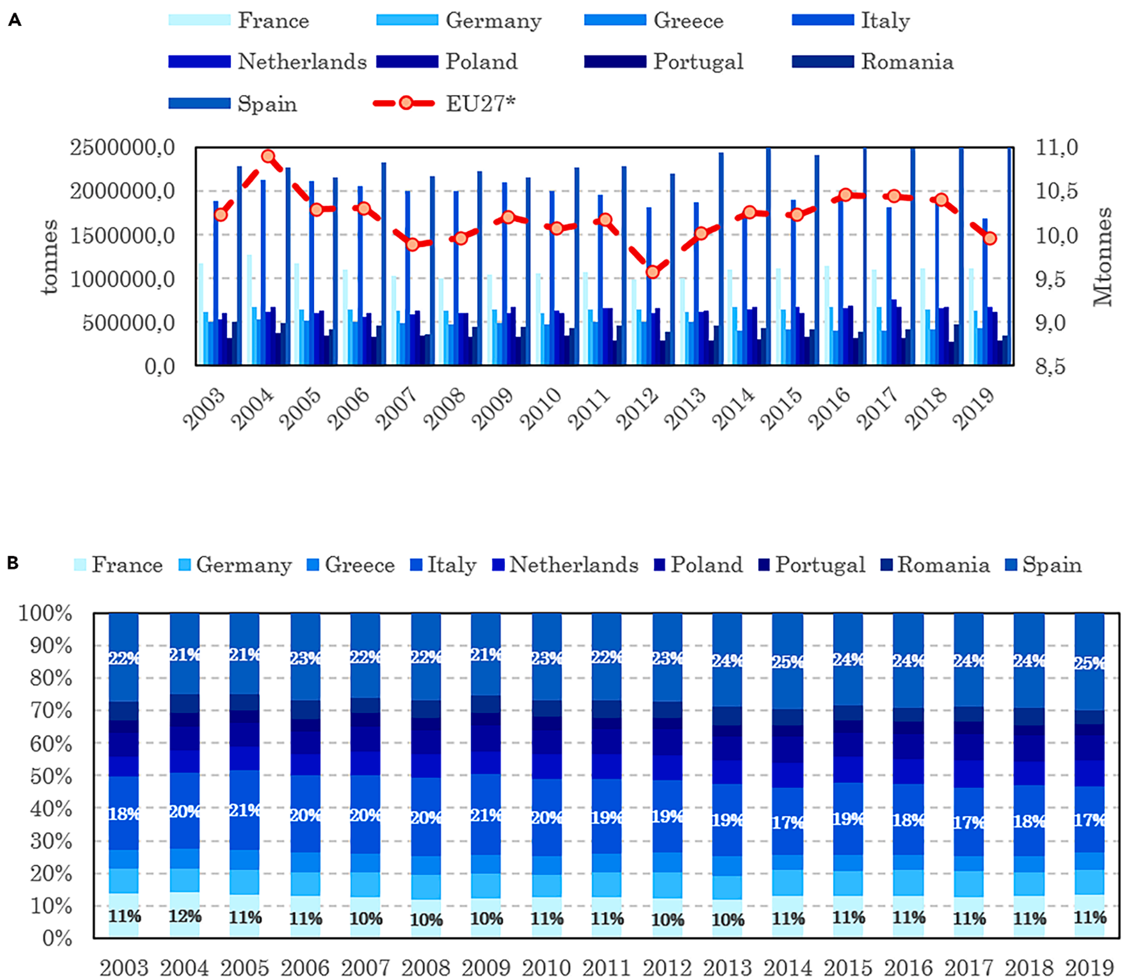


**Figure 2. Food-waste primary production**

(A) Absolute value, per States (tons) and in EU (Mt).

(B) Member States contribution (cut-off >10%). Adapted from EU bioeconomy monitoring system dashboards, Knowledge Centre for Bioeconomy. Available at https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system-dashboards_en (accessed October 1, 2025).

capable of targeting many end points of anti-diabetic relevance.[24] The study of Castellano et al.[24] has highlighted the need to conduct a comprehensive chemical characterization of the matrix under investigation, in addition to a typical targeted analysis, to minimize the risk of overlooking major compounds possibly present. The following logical step is the development of efficient and, at the same time, environmentally friendly extraction methods to recover the detected molecules. In general, some techniques, including microwaves, ultrasound, high hydrostatic pressure, pulsed electric fields, enzymes, and green solvents have been investigated, sometimes even in combination. Yet, their industrial uses are still a long way off from being implemented. In future works, there is a need to study how to reuse residual pomaces after the extraction of the target molecules in other winery practices. In this regard, their potential as adsorbents for the removal of hazardous materials from waste waters could be explored, including heavy metals and other organic components that significantly reduce their biodegradability and reuse.

### *Walnut shells*

The market for walnuts (*Juglans* spp.) has been steadily increasing worldwide. The only edible part of the fruit is the kernel that is rich in nutrients including polyphenols, polyunsaturated fatty acids, amino acids, peptides, dietary fibers, vitamins, and minerals.[25] Consequently, the shell and husk, the external fleshy component of the fruit, are mainly discarded as crop waste. The walnut shell is primarily made up of lignin (52.3%), followed by remarkable quantities of cellulose (25.5%) and hemicellulose (22.2%). Also, it has been reported that extracts from shells are characterized by the presence of both essential oils and fatty acids. Among the latter, palmitic acid, arachidic acid, and stearic acid were the most abundant, along with some unsaturated fatty acids such as oleic acid and linoleic acid. Linoleic acid, in particular, is of great interest on account of its ability to lower the amount of low-density lipoprotein cholesterol. Similar to grape pomace, this biomass is also rich in polyphenols, especially flavanol-based tannins and quercetin. Further compounds identified in walnut shell extracts are salicylic acid, hydroxybenzoic acid, hydroxycinnamic acid, vanillic acid, *trans*-resveratrol, and gallic acid.[26] As a consequence of the rich selection of molecules occurring in walnut shells, it is not surprising that such a biomass has been extensively reused in a variety of industrial sectors. By way of example, lignin extracted from shells has been employed for the production of adhesives and activated carbons.[27] Also, other researches[28] have utilized walnut shell waste for the production of ceramics bricks featuring high water absorption and specific heat capacity. Once reduced into ashes, shells have been proven to be able to eliminate heavy metals such as copper, chromium, and lead from groundwaters[29] or even pesticides from the soil.[30] Some scientists have used walnut shells as a green catalyst for the chlorination of acetylene[31] in the wake of the current efforts to develop eco-friendly catalysts. Finally, shells are also employed in the food industry to preserve the product quality[32] or in the pharmaceutical sectors due to their anti-bacterial, antioxidant, and anti-cancer properties.[33] As stated above, in addition to shells, husks also represent a significant by-product of walnut processing. Green husks have been largely used in food industries to produce renowned liqueurs appreciated for their pleasant sensory attributes and contents of healthy compounds.[34] This has consequently prompted careful analysis of the metabolic contents of walnut husks. Extracts obtained by supercritical carbon dioxide turned out to contain interesting unsaturated fatty acids including linoleic acid and eicosenoic acid, as well as polyphenols, hydrolyzable tannins, juglones.[35] Walnut husk extracts are already used in the agricultural, food, and textile industries. They have also proven to be quite useful as mordants in the dyeing industry[36] or adsorbents of heavy metals such as chromium and cadmium from industrial effluents.[37,38] In the food industry, walnut husk extracts have been proven to lengthen the shelf-life of pecans, fresh-cut apples, rainbow trouts, among others.[39–42]

### Chestnut shells

The processing of chestnuts also leads to the production of bulky by-products being accumulated in industrial plants and/or in orchards where they can affect tree health by promoting the growth of deleterious insects.[43] Major by-products deriving from chestnut processing are leaves, burs, shells, and inner shells. The peeling process alone produces solid waste constituted essentially by burs and shells accounting for over 15% of the chestnut weight.[44] As in the case of most waste materials from the food or agriculture industries, the above-mentioned matrices hold a great potential to be reused in line with the principles of circular economy. Spiny burs have been proposed for the development of edible products on account of their polyphenol contents.[45] More interesting is the metabolic profile of shells, in which phenolic acids, flavonoids, and condensed and hydrolyzable tannins, such as castalagin and vescalagin, have turned out to be abundant.[46–48] Hence, it is not surprising that shell extracts feature high antioxidant effects and are able to inhibit lipid peroxidation.[49] Similar bioactivities have been discovered also in chestnut inner shell extracts. More specifically, in addition to antioxidant properties, *in vivo* and *in vitro* studies have ascertained anti-cancer, anti-inflammatory, and even anti-diabetic and anti-obesity activities.[50–55] Across East Asia, inner shells have long been employed even as cosmetics, for their anti-wrinkle properties.[50] As previously stated, another bulky by-product deriving from the chestnut processing is constituted by leaves that fall abundantly during the harvest season. Flavonoids, such as quercetin, flavan-3-ols, rutin, and cirsiliol have been identified along with phenolic acids and lignans in leaf extracts.[56] In traditional medicine, chestnut leaves have been used to prepare hot beverages to alleviate cough and diarrhea.[57] Of particular interest is chestnut leaf anti-microbial activity. In fact, leaf extracts are able to delay the growth of lactic acid bacteria as well as of *S. aureus* and *Pseudomonas* spp.[58] Given that bacteria are responsible for food spoilage, such extracts could be investigated for possible use as natural preservatives to elongate food shelf-life. Further potential applications of chestnut by-product extracts include their use as colorant thanks to their rich contents in pigments.[59]

### Shrimp shell

Global crustacean production reached 185 Mt in 2022.[60] The solid waste biomass produced by the crustacean processing industry constitutes 50%–60% of the total production volume, amounting to around 3.8 Mt per year worldwide.[60] The management of such a huge volume of this kind of waste is quite challenging, not only from a logistical standpoint but also economically and environmentally. Conventional strategies for shrimp waste disposal mainly involve incineration and landfilling. These practices, in addition to being a financial burden for companies, can cause serious environmental problems and health risks due to bacterial contamination and strong odors during decomposition, which release volatile organic compounds (VOCs) into the atmosphere. Incineration, if not properly controlled, can also generate toxic by-products such as dioxins and furans. Furthermore, the indiscriminate disposal of shrimp waste leads to the loss of several value-added molecules, as no effort has been made for their recovery and valorization.[61] While plant-derived by-product biorefinery only yields carbon, hydrogen, and oxygen-based platform molecules, shell waste provides appealing feedstock for compounds that naturally contain nitrogen with high potential for biomedical, pharmaceutical, and nutraceutical applications. The three predominant fractions in the shell waste include chitin, which is the main component of shrimp and crab exoskeletons, proteins, and an inorganic moiety ($CaCO_3$), in addition to a smaller fraction of secondary metabolites (lipids and pigments).[62,63] Traditional attempts to shell waste valorization have been mainly devoted to the recovery of chitin.[64] Chemical treatments for the extraction of chitin include demineralization, deproteination, and discoloration by using strong acid or alkali solutions, causing both environmental and safety concerns along with raised costs and resource wastage.[65] As matter of fact, an alternative, cost-effective, and environmentally friendly extraction protocol has been proposed.[61] This method yields high-purity chitin (over 90%) by using hot water and carbonic acid ($CO_2$ and $H_2O$) in an autoclave for deproteination and demineralization, respectively. Furthermore, techno-economic and life cycle analyses estimated a reduction of the total operating cost related to the extraction method proposed in that work compared to the traditional one, beside a remarkable reduction of the associated carbon footprint from 283 to 17.1 kg $CO_2$ equiv.[61] In the context of shell waste biorefinery, to achieve a comprehensive utilization of the biomass, a growing interest has been devoted to the extraction and recovery of secondary metabolites,[66–68] including proteins and carotenoids, mainly astaxanthin (ASX). ASX is widely used in food, pharmaceutical, and cosmetics industry and also exhibits high antioxidant and anti-cancer activity.[69] Thanks to its superior biological activity, great interest has been devoted to the development of cutting-edge processes for ASX extraction from crustacean wastes. First attempts involved chemical extraction using conventional fossil-based solvents (hexane and acetone at a ratio of 1:1), yielding 8.4 mg/g waste, and comparable results have been obtained by pretreating the shrimp shells with *S. cerevisiae* before the chemical extraction.[70] In this context, efforts have been devoted to design more sustainable extractions of ASX from shrimp shells. For example, Chandra Roy and co-workers proposed an ultrasound-assisted natural deep eutectic solvents (NaDESs) extraction protocol. Among various choline chloride-based NaDESs investigated, the choline chloride/lactic acid DES yielded the highest ASX extraction (69 μg/g).[71] Alternatively, green technologies employing edible oil (sunflower oil) or its methyl ester as extracting medium have been recently developed. However, the ASX yields for these systems ranged between 20 and 35 μg/g of wet mass.[72] Therefore, although few examples of green extraction of ASX from crustacean shells have been reported in the literature, there is still a lack of knowledge in the field to improve the efficiency of the extractions and attain competitive yields compared to those obtained with fossil-derived solvents.

#### Coffee grounds

Globally, coffee is one of the most popular beverages, with an estimated 10.4 Mt consumed in 2022/23.[73] Through its entire life cycle, from cultivation of green coffee cherries to the final product, coffee production generates an impressive amount of waste (51.8 Mt per year).[73] Spent coffee grounds (SCGs), the solid residue obtained after the brewing process, account for about 6 Mt annually. Usually, the conventional fate of this waste is municipal landfilling or composting. Following a circular-economy approach to relieve the environmental burdens associated with the disposal of such a high amount of waste, the reuse of SCGs has been proposed in several applications. Soil amendment to reduce the use of chemical fertilizers is one of the most well-established potential reuses of coffee grounds. However, the studies published in the literature have so far shown controversial results. For example, the positive impacts of coffee powder on plant growth have been found to depend on both the plant species and application rate.[74] On the other hand, adverse effects of coffee grounds on plant growth have been observed, possibly due to the phytotoxic effect of polyphenols released.[73] Further employments of untreated SCGs include their use as cementitious additives that can be incorporated after geopolymerization to reduce the high carbon footprint associated to the production of Portland cement,[75] or as adsorbent materials for the removal of heavy metals (Cu (II), Pb (II), and Cr (VI)) and basic dyes from aqueous matrices.[76] Brewed coffee grounds are also a suitable feedstock for various integrated biorefinery pathways including anaerobic digestion to biogas, fermentation to bioethanol, and pyrolysis to bio-oil.[77–79] Notwithstanding their good performances as biorefinery feedstock, SCGs are a source of valuable compounds that are retained after the brewing process. Exhaustive characterizations reported in the literature have demonstrated the presence of a wide variety of bioactive compounds, including carbohydrates, fibers, proteins, lipids, antioxidants (caffeine), polyphenols, flavonoids proanthocyanidins, carotenoids, melanoidins, terpenes, and vitamin precursors.[80–82] Thus, the development of effective methods for the recovery of these valuable biomolecules has drawn the attention of the scientific community. In this context, microwave-assisted (ME) and enzyme-assisted liquid extractions have been proposed as green strategies for the design of a potentially feasible integrated biorefinery. In these studies, polyphenols and antioxidant mixtures have been regarded as priority targets, for their potential in the production of nutraceutical and functional products.[82–84] The most important metabolites extracted from each waste biomass considered in this review were reported below in Figure 3.

In the context of waste biomass valorization, the valuable extractable compounds are typically secondary metabolites present in low quantities, making further exploitation of the post-extraction residue necessary. This can be achieved through the preparation of carbonaceous materials, including through pyrolysis and hydrothermal treatment for the production of biochar and hydrochar, respectively.

Indeed, the complete valorization of agricultural waste through a circular economy is a virtuous yet under addressed approach. In general, the main investigated routes are biomass extraction for valuable chemicals and biomass processing for functional materials. Figure 4 highlights relevant routes for converting agricultural waste into carbonaceous materials for various applications including wastewater treatment, catalysis, and energy storage.[85–91] We suggest the integration of biomass extraction to obtain chemicals of interest or biomass processing to prepare functional materials to fully valorize the initial biomass.

## ENVIRONMENTAL IMPACTS: ANALYSIS OF THE SELECTED FOOD-WASTE VALORIZATION THROUGH LCA STUDIES

Several LCA applications addressing valorization strategies of the aforementioned waste residues have been proposed in the literature. Moon et al. reported the potential usage of hazelnut as a carbon precursor for anodes in sodium-ion batteries.[91] Various carbon precursors can be used to produce hard carbon (HC) materials. However, conventional options such as sugars and polymers, along with their synthetic processes (e.g., acidic/basic treatments), often suffer from high costs, low yields, and limited environmental sustainability; factors that significantly hinder the viability of sodium-ion batteries. Therefore, biowaste materials are attractive and hazelnut shells were selected by the authors due their low price (0.15–0.25 $/kg) and abundance: the hazelnut production worldwide is estimated to be 1.2 Mt.[92] Hazelnut shell-derived-HCs have been prepared at laboratory scale through four different post-synthesis treatments: unwashed HC, acid-treated HC, water-washed HC ground into 1 mm particle size and < 32 μm particle size. Two of them (acid treated and water washed with <32 μm particle size) were selected for a LCA analysis, following a cradle-to-gate approach and selecting two functional units (FUs): 1 kg of HC and 1 mAh

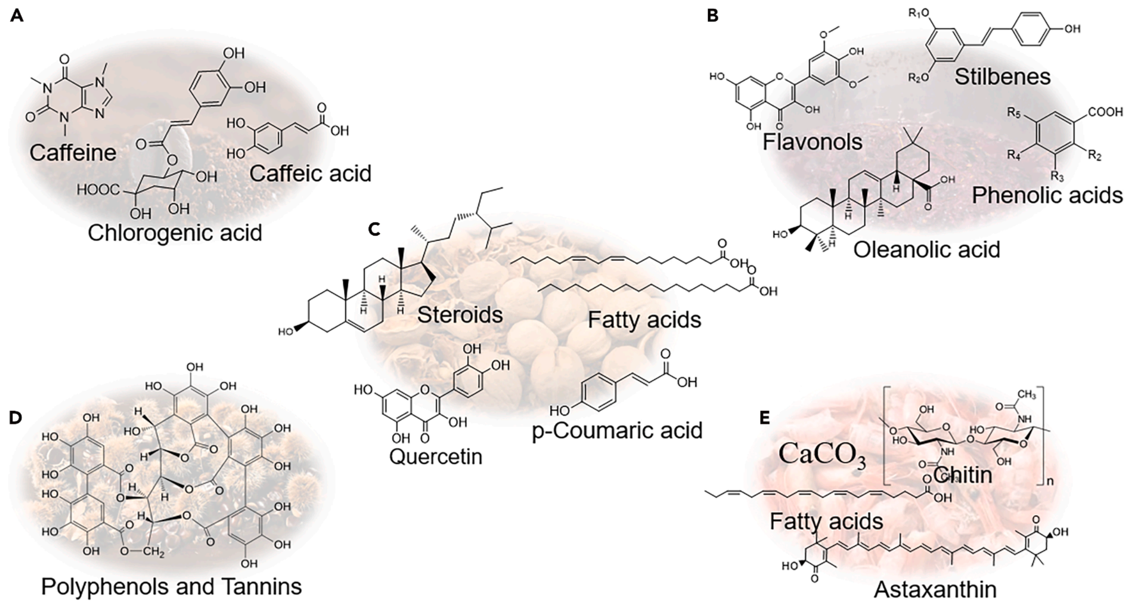


**Figure 3. Chemical structures of the most relevant added value compounds extracted from each of the waste biomasses addressed in this review**
(A) Coffee grounds, (B) grape pomace, (C) walnut shells, (D) chestnut shells, and (E) shrimp shells.

$Na^{+}$ storage capacity of HC anodes. In both cases, the water-washed shell-derived-HC samples with <32 μm particle size exhibited the best environmental performance due to the avoided usage of acid, which enables greener synthetic conditions.[91]

Chestnut-derived tannins have also been widely explored as a renewable alternative to conventional chemicals in various applications, showing consistent environmental advantages.[93,94] In graphene production via liquid-phase exfoliation (LPE), tannins can replace toxic solvents such as N-methyl-2-pyrrolidone (NMP), reducing human toxicity potential impacts while also improving dispersion and stability of graphene sheets.[93] LCA results confirm that tannin-based processes outperform the conventional NMP route, with high-shear exfoliation (HSWT) emerging as the most sustainable option from an environmental point of view due to energy efficiency and low waste generation. In contrast, ultrasound exfoliation (UWT) requires significantly higher energy inputs (+79%) and generates more waste (+78%), leading to greater impacts in categories such as climate change, fossil resource depletion, and acidification.[93]

Similarly, in the production of tannin-based coagulants from chestnut shells, LCA comparisons of extraction methods (solid-liquid vs. ME) show comparable environmental performances, with no clear advantage of one technique over the other.[94] In both cases, electricity consumption (particularly during the drying phase) dominates the environmental profile, accounting for more than 90% of total impacts. Sensitivity analyses further highlight the strong influence of the electricity mix on overall results.[94]

Overall, these studies underline two consistent trends: the environmental benefits of replacing fossil or toxic-based chemicals with bio-based tannins, and the dominant role of energy consumption (especially in drying and processing steps) as the main environmental hotspot.

Another interesting field of application of LCA is in the evaluation of the feasibility of extracting chitin and its derivative from crustaceous shells. The usage of shrimp shells alone,[95–100] in combination with crab shells[101,102] or with other substrates,[103] as well as the usage of lobster and spider crab shells,[104] has

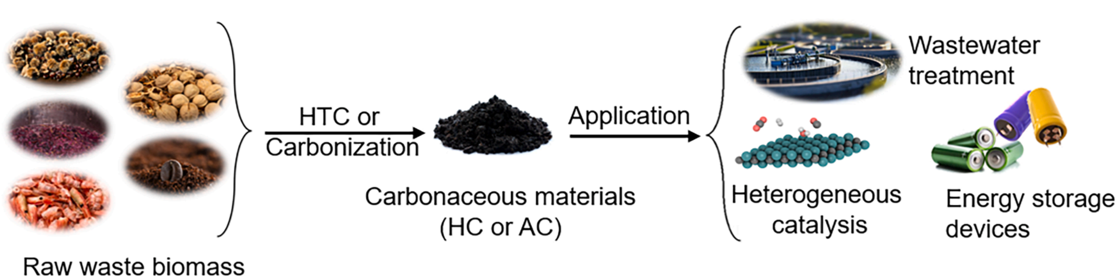


**Figure 4. Representative scheme for carbonaceous material production and application**
HC, hydrochars; AC, activated carbons.

been widely discussed in the literature. This interest is due to the impressive amount of waste produced each year and to the chitosan (CS) market, one of the major products obtained from chitin. In the case of shrimps approximately 72,000 tons of shell waste are produced annually.[99] The CS market reached a notable value of USD 10.88 billion in 2022 and is projected to grow steadily at a compound annual growth rate (CAGR) of 20.1% from 2023 to 2030.[99]

LCA studies on chitin and CS production from shrimp shell waste consistently identify chemical use and energy demand as the main environmental hotspots, while also highlighting opportunities for process optimization.[99,100] In conventional extraction (CE) pathways, reagents such as sodium hydroxide and ethanol, together with electricity consumption, dominate the environmental burdens, contributing significantly to impact categories such as human non-carcinogenic toxicity and marine and freshwater ecotoxicity.[99] For instance, reducing NaOH concentration from 50% to 30% can decrease toxicity-related impacts and freshwater eutrophication by 10%–20%, demonstrating substantial improvement potential through chemical optimization.[99] Reported carbon footprints also vary geographically, with values around 59 kg $CO_2$-equiv/kg of CS in Ecuador, higher than that of India (approximately 27 $CO_2$-equiv/kg) but lower than the values for Europe (approximately 76 $CO_2$-equiv/kg).[102,105]

In contrast, alternative extraction technologies that minimize or eliminate chemical inputs show clear environmental advantages. Processes based on steam explosion and supercritical $CO_2$ (SE-SCDM-HDP) avoid the use of harsh reagents (e.g., NaOH and HCl), reduce electricity consumption, and shorten processing times, resulting in significantly lower impacts. In particular, these approaches can achieve up to a 39% reduction in carbon footprint compared to conventional acid-base methods.[100] These studies emphasize that reducing chemical intensity and improving energy efficiency are key strategies for lowering the environmental impacts of chitin and CS production from crustacean waste.

Shrimp shells have also been used in combination with cellulose nanofibril (cross-linked with citric acid) to produce nanofibril-reinforced CS composite films for packaging applications.[103] A comprehensive cradle-to-gate LCA of CS-cellulose nanofibril (CNF) composite films, developed as sustainable alternatives to conventional fossil-based packaging materials, was also presented. The composite films are produced using CS derived from shrimp shell waste and CNF extracted from softwood pulp (derived from chips), with citric acid as a cross-linking agent and glycerol as a plasticizer. The results in terms of carbon footprint show that the CS-CNF composite films have a lower carbon footprint (3.9 kg$CO_2$-equiv) than those derived from low-density polyethylene (LDPE), polypropylene (PP), and bio-based polymers-like polylactic acid (PLA) and starch. Among the three sub-processes including CNF and CS manufacturing and film casting, the CNF manufacturing process has the lowest environmental impact contribution. The film-casting process contributes up to 90% of the total climate change indicator, primarily due to the energy-intensive drying stage. Sensitivity analysis confirmed that deproteination and demineralization steps, along with overall energy use, are critical parameters influencing environmental outcomes. The use of sodium hydroxide in the deproteination of shrimp shells emerged as the most sensitive factor across multiple impact categories, indicating a significant opportunity for environmental improvement through alternative extraction methods. The increase of the CNF loading from 10% to 20% was shown to enhance mechanical and barrier properties without significantly affecting the potential impacts, suggesting that performance improvements can be achieved without compromising environmental sustainability.

Ng et al.[98] presented the application of a cradle-to-gate LCA to a novel class of bioinspired composites made from chitin and cellulose: fungal-like adhesive materials (FLAMs). These materials are designed to be biodegradable, renewable, and regionally producible, offering a sustainable alternative to conventional petroleum-based materials like rigid polyurethane (PUR) foam. The FU was set as 1 kg of end material. The LCA evaluates four production scenarios: (1) international sourcing of raw materials, (2) regional sourcing, (3) use of recycled cellulose fibers, and (4) local production of CS from black soldier fly (BSF) biomass, within a geographical radius of 50 km. The results show that FLAMs, even in their current state, have lower environmental impacts than PUR foam across most midpoint indicators, including climate change, fossil depletion, and terrestrial acidification. However, the study identifies key environmental hotspots. In detail, in case of international sourcing of raw materials, long-distance air freight and the use of sodium hydroxide in CS extraction have been identified as the major contributors to environmental burdens. Alternatively, in case of regional sourcing of raw materials ($\leq$3,000 km), the transportation-related impacts and the cumulative burdens resulted significantly reduced compared to those of rigid PUR foam production on most midpoint indicators. Moreover, the use of recycled cellulose fibers does not substantially alter the environmental profile compared to virgin fibers, due to the efficiency of modern pulping technologies. The only category that is reduced was agricultural land occupation. The lab-scale BSF-based CS production instead shows increased impacts due to inefficient chemical use (sodium hydroxide and hydrochloric acid), highlighting the need for optimized biomass fractionation methods. Monte Carlo simulations were used to assess uncertainty, revealing that technological differences in CS extraction methods (especially between lab-scale and industrial processes) are the primary source of variability. The study concludes that regional production and improved extraction technologies are essential for maximizing the sustainability potential of FLAMs. It recommends exploring alternative chitin sources, such as fungi and BSFs, and adopting enzymatic or fermentation-based extraction methods to reduce chemical use.

Another study of Oliveira Silva and co-workers[96] compares a conventional heating method (heating plate [105 °C—4 h], D-H) and a ME method (400 W—6 pulses of 5 min [D-M1], 400 W—2 pulses of 8 min (D-M2), 500 W—2 pulses of 8 min [D-M3]) for CS production from shrimp shells, focusing on yield, physicochemical properties, and environmental impacts. LCA showed microwave methods drastically reduced environmental impacts in terms of fossil resource scarcity, climate change potential, human non-carcinogenic toxicity, and terrestrial ecotoxicity by using ReCiPe midpoint (H) method. Electricity use dominated environmental impacts (>96%), especially in pretreatment and drying stages, even if Brazilian energy mixes was used for modeling (with hydroelectricity comprising 55%). NaOH was identified as a major contributor to toxicity and climate impacts, suggesting that recovery strategies are needed. The study concludes that D-M3 offers the best balance of yield, quality, and environmental performance. ME deacetylation is a viable alternative for sustainable CS production.

The usage of ME methods for extracting CS from shrimp waste was also addressed by Mohammadi et al.[95] They conducted a comparative LCA of three CS extraction methods from shrimp waste: CE, ME, and conventional under microwave irradiation (CEM). The latter proved to be the most cost efficient, with a production cost of 7.9 USD/kg. The authors use two FUs: the CS production yield ($FU_{PY}$) and the CS anti-bacterial activity ($FU_{AA}$). Using the $FU_{PY}$, the CEM method demonstrated the lowest cumulative environmental impact, outperforming CE and ME. This advantage was primarily due to reduced consumption of sodium hydroxide and electricity, which lowered impacts across multiple damage categories. When assessed the $FU_{AA}$, CE emerged as the best-performing method (229 Pt), attributed to its superior CS yield and anti-bacterial effectiveness. These findings underscore the critical influence of FU selection on LCA studies. The most significant contributors to human health impacts were hydrochloric acid, electricity, and sodium hydroxide.

Finally, a study of Fernádez-Marín et al.[104] explores the valorization of lobster and spider crab shell waste into high-performance biopolymers, focusing on chitin nanocrystals (ChNCs) and CS. ChNCs were obtained via acid hydrolysis, while CS was produced through deacetylation, both yielding materials with high purity and crystallinity. The resulting CS/ChNC films exhibited enhanced mechanical properties, UV shielding, and transparency, making them viable alternatives to fossil-based plastics. The results of the carbon footprint indicator per 1 kg of material produced (dry basis) show that the electricity consumption is the dominant contributor (77%–94%). ChNCs had the highest environmental impact (618 kg $CO_2$-equiv/kg), followed by CS (296 kg $CO_2$-equiv/kg), and chitin (77 kg $CO_2$-equiv/kg). Transitioning to a 100% renewable energy mix significantly reduced the carbon footprint value of CS/ChNC films to 80 kg $CO_2$-equiv/kg. Other impact categories, such as freshwater ecotoxicity and terrestrial acidification, also decreased under renewable energy scenarios by emphasizing the importance of energy sourcing and process optimization in reducing environmental burdens.

Another well-investigated waste source is SCGs. Several strategies of valorization have been described, such as the production of biofuel, lubricants, photothermal composite, and hydrothermal biochar as a filler in concrete. LCA studies on biofuel production from SCGs highlight trade-offs between process efficiency, energy demand, and environmental performance, with consistent advantages for simpler and less energy-intensive pathways.[106,107] Transesterification routes, including both conventional and *in situ* processes, generally produce fuels with higher heating values (up to 40.1 MJ/kg) but are associated with higher costs and $CO_2$ emissions due to low extraction efficiencies, complex separation steps, and significant energy demand (e.g., methanol recovery).[106,107] In contrast, pyrolysis emerges as a more environmentally and economically favorable option, despite yielding fuels with lower heating values (~32.2 MJ/kg), as it avoids solvent-intensive steps and reduces overall process complexity.[106] Specifically, pyrolysis shows lower $CO_2$ emissions per MJ of biofuel unless transesterification efficiency exceeds 38%, a threshold rarely achieved in practice.[106]

Comparisons between centralized conventional processes and decentralized *in situ* transesterification for biodiesel production from SCGs further underline the importance of system configuration.[107] While conventional methods can reduce energy use by up to 43%, *in situ* approaches may become advantageous under specific conditions, such as long transportation distances (>180 km), and can offer benefits in impact categories like respiratory health and land occupation.[107] Overall, these studies indicate that process simplification, reduced chemical use, and minimization of energy-intensive steps are key factors driving the environmental sustainability of SCG-based biofuel production.

Pichler et al.[108] explore the usage of SCGs oil (SCGsO) as a lubricant or additive. The authors conduct a detailed physicochemical and tribological characterization of SCGsO, comparing it to polyalphaolefin 8, a conventional synthetic lubricant. SCGsO exhibits comparable thermal stability and viscosity but contains more ester and acid functional groups, which enhance its friction-reducing properties (may cause faster oxidation). LCA results, obtained from SimaPro[109] software and ILCD 2011 midpoint +, identify hexane-based extraction process as the main environmental concern, in particular for the human toxicity (non-cancirogenic and cancirogenic effects), freshwater eutrophication and freshwater ecotoxicity categories. Ethanol is suggested as an alternative for the extraction since it could lead to lower environmental burdens. Regarding energy consumption, the drying pretreatment of the SGCs feedstock has the most significant impact on electricity usage.

Jie et al.[110] explored the transformation of SCGs into hydrothermal biochar (SCGs-HTC) for use in concrete, with the aim of enhancing performance and reducing carbon emissions. SCGs-HTC was produced via hydrothermal carbonization. Several characterization stages were applied, showing the SCGs-HTC improved workability, mechanical strength, permeability resistance, and freeze-thaw durability. A cradle-to-gate LCA study quantified a 7.9% reduction in carbon emissions compared to conventional concrete, primarily due to carbon sequestration in the composite system and reduced natural sand usage. The analysis showed that SCGs-HTC preparation contributed negative emissions due to biogenic carbon fixation.

Finally, a study presented by Zheng et al.[111] presents the development and environmental evaluation of a novel photothermal composite made from CS and SCG, designed for efficient solar-driven water evaporation and fabricated using a low-energy process involving acid hydrolysis and UV photocrosslinking. The carbon footprint of 1 g of composite was estimated through the use of IPCC 2021 GWP100[112] method, revealing a value of 0.71 kg $CO_2$ equiv/g, significantly lower than comparable materials such as graphene (0.9 kg $CO_2$ equiv/g) and multiwalled carbon nanotubes (1.0 kg $CO_2$ equiv/g). This reduction was primarily attributed to the elimination of energy-intensive heating and the use of freeze-drying and hydrolysis instead. Compared to previous SCGs-based photothermal materials, the reported method achieved a 7.8% reduction in energy demand. Additionally, the composite design eliminated the need for petrochemical-based insulating layers commonly used in traditional evaporation systems, further enhancing sustainability. The CS/SCG composite demonstrated excellent durability, maintaining performance after multiple reuse cycles, aging tests, and exposure to harsh chemical environments.

## EMERGING AGRICULTURAL BIOMASS FEEDSTOCKS FOR VALORIZATION

### Poultry manure

Food-waste composts and livestock manures have generally attracted less interest in literature, yet they show enormous potential as starting materials for phosphorous (P) recovery. Herein, instances are discussed in which the organic fraction is favorably used to generate thermal energy. However, several drawbacks related to the conversion of these bioresources need to be overcome to make the process more accessible. In detail, their massive volume makes transportation difficult and expensive, and the presence of pathogens, heavy metals, and other contaminants poses a huge risk for the environment and human health.

Bontempi et al. investigated the valorization of poultry litter ash through ME thermochemical treatment aimed at enhancing P recovery.[113] The work provides a relevant contribution to the circular management of agricultural and livestock residues by converting an abundant waste stream into a valuable nutrient source. The authors demonstrate that microwave heating can improve the extractability of phosphorus, offering a potentially more efficient alternative to conventional thermal or chemical recovery processes. Given the growing global concern over phosphorus scarcity and the environmental burden associated with manure-derived residues, the proposed approach aligns with current strategies for resource efficiency and nutrient recycling. The study also highlights important considerations for future development, including energy optimization and ensuring the agronomic quality of the recovered product. Overall, this research represents a promising example of how advanced thermochemical technologies can support the sustainable upcycling of agricultural waste into high-value fertilizing materials.

The same research group has also reported a zero-waste strategy to recover phosphorus and silica from rice-husk poultry litter ash.[113] The authors applied a design of experiments (DoE) to optimize acid leaching parameters, finding that a hydrochloric acid concentration of $\sim$ 0.34 mol $L^{-1}$ and a liquid-to-solid (L/S) ratio of 50 achieved the best balance between P recovery and minimized zinc contamination. Sustainability metrics were also assessed, and the results confirm that the treatment process embodied energy reached $\sim$128 MJ $kg^{-1}$ dry extract (DE) and carbon footprint $\sim$6 kg $CO_2$ $kg^{-1}$ DE, compared to raw treatment values of embodied energy_raw $\sim$99 MJ $kg^{-1}$ DE and carbon footprint_raw $\sim$10 kg $CO_2$ $kg^{-1}$ DE. Although recovery of $SiO_2$ was deemed unviable at the ash's current silica content (below the threshold of $\sim$80% $SiO_2$), the authors argue that P recovery from such ashes remains a promising loop closing the resource cycle for this critical raw material in agriculture.[113]

An integrated approach for both chemicals' extraction for fertilizers production as an alternative to thermal incineration of poultry manure was reported by Izydorczyk et al.[114] The authors explored the valorization of poultry-slaughterhouse waste by converting it into fertilizer via thermochemical and hydrothermal treatment routes, thereby addressing both waste management and nutrient recovery. The authors reported meaningful reductions in greenhouse gases and $NO_x$ emissions when substituting incineration with the proposed process pathway. They demonstrated that the resulting fertilizer product exhibits adequate agronomic properties (e.g., N, P, and K content) for field application, enhancing circularity in the livestock-agriculture interface. A key contribution lies in framing the process as a value-chain integration from slaughterhouse residuals to fertilizer, rather than mere disposal. Overall, the work adds a relevant case of circular economy applied to agro-industrial waste streams.[114]

### Pine needles

Pine needles represent a widely available forest resource due to the extensive distribution of coniferous species across Europe, North America, and Asia. The market for pine needle-derived products, particularly essential oils, is estimated at approximately USD 16–20 million (2024–2025), with a moderate projected annual growth rate of 2%–5%.[115] However, supply is subject to seasonal collection, variability in chemical composition, and logistical challenges associated with remote forest locations. Integrating pine needles into a biorefinery context requires sustainable forestry strategies to ensure consistent volume, quality, and traceability. These factors make pine needles a promising feedstock for high-value applications, provided efficient processing and supply chain models are implemented. Pine needles, rich in lignin (>30 %), can provide significant economic benefits if converted through effective valorization pathways. Studies have explored their use for electricity generation via gasification, showing costs comparable to or lower than coal, with substantial $CO_2$ emission reductions when carbon taxes are considered. In addition to energy, pine needles have been utilized in biorefineries to produce enzymes, bioethanol, and fuel pellets. For example, 1 kg of pine needles can yield 9,970 FPU of cellulase and 1 gallon of bioethanol at a production cost of $0.19 per gallon, while pelletization of fermented biomass increases calorific value by 8.5 % due to higher lignin content. These findings indicate that multi-product valorization strategies enhance economic feasibility and sustainability for pine needle biomass.[116]

A study by Velentini et al. reported the efficient synthesis of a pine needle-based adsorbent obtained from biomass carbonization and functionalized with $-SO_3H$ groups by treating with $H_2SO_4$, significantly enhancing its affinity toward methylene blue. Surface sulfonation markedly improved adsorption capacity compared with non-functionalized biochar. Kinetic, isotherm, and thermodynamic analyses confirmed that the removal mechanism is dominated by chemisorption. An effective regeneration protocol was also demonstrated, allowing recovery of up to 94% of the ethanol used for desorption. Overall, the work highlights the potential of pine-needle-based materials as low-cost, sustainable adsorbents for water purification applications.[117]

Very recently, the work of Roy et al. has investigated, through a comprehensive techno-economic analysis (TEA), a hypothetically scaled up system (1.5 ton per day), focusing on three pathways (torrefaction, pyrolysis, and anaerobic digestion) based on energy input, biofuel yield, and economic viability.[116] The main findings of this analysis confirmed that pine needles held substantial potential for sustainable biofuel production. Pyrolysis, torrefaction, and anaerobic digestion of pine needles all demonstrated strong technical and economic feasibility, with profitability comparable to other renewable energy routes. The TEA incorporated mountain-specific constraints and showed that measures such as polyhouse drying, briquetting of torrefied needles, and small floating-drum digesters can significantly reduce costs and improve returns.[116]Anaerobic digestion offered promising fuel production potential, though logistical and operational challenges remain.

Future work should optimize pretreatment, identify low-cost catalysts, and include full life-cycle assessments to support commercialization. Sustainable exploitation of pine needle biomass will require integrated policies, environmentally compliant harvesting practices, and community-based management to enhance rural energy access, promote local livelihoods, and contribute to forest-fire mitigation.

### Wood bark

Bark is generated in very large volumes globally as a by-product of forestry and timber industries. Estimates suggest that annual bark production is about 200 million $m^3$ worldwide.[118] Historically much of this bark has been used for low-value applications (e.g., combustion for energy, mulch, low-grade fuel) or disposed of/incinerated. Given the increasing interest in bio-based materials, circular-economy strategies, and biorefineries, bark is now being seen as a feedstock for higher-value valorization: extraction of phenolics, tannins, lignin, biochar, composites, and adsorbents.[119–121] Thus, valorization of wood bark offers a pathway to add value to what was once a residual stream, reducing waste and creating new material streams.

Bark is a rich source of structurally diverse secondary metabolites, which can be grouped into lipophilic and hydrophilic components. The lipophilic fraction contains compounds such as triterpenes, fatty acids, and sterols, whose distribution is strongly dependent on the species; betulin is one of the most prominent examples. Hydrophilic extracts, instead, are dominated by polyphenolic substances like phenols, proanthocyanidins, and tannins, whose yields vary according to botanical origin and extraction strategy. The recovery of these metabolites relies on the careful design of extraction processes, from classical Soxhlet methods to modern techniques such as ultrasound-, microwave-, and supercritical fluid-assisted extraction. Betulin extraction is particularly sensitive to the solvent type and temperature, while tannin isolation must account for issues of purity and co-extracted impurities. Suberin, a highly complex aliphatic-aromatic biopolymer, requires targeted depolymerization steps or the use of greener ionic liquids to preserve its structure. Stilbenoids are a class of secondary metabolites built on a 1,2-diphenylethylene backbone, which can be further substituted with hydroxyl, methoxy, or glycosyl groups to generate derivatives such as resveratrol, piceatannol, and pterostilbene. Their extraction commonly follows a two-step approach: non-polar solvents first remove lipophilic impurities, followed by polar solvents like ethanol or water to selectively recover stilbenes, often assisted by ultrasound to improve yield and purity. Analytical identification relies mainly on HPLC coupled with MS, while NMR provides detailed structural characterization. Despite their high value, large-scale extraction faces notable challenges, including the need for high solid-to-liquid ratios, which increases solvent use, energy demand, and downstream processing, and slow solvent penetration due to the complex physical structure of bark. Integrating multi-product biorefineries with existing industrial facilities can significantly enhance the economic performance of bark valorization. Techno-economic studies, though limited, indicate that extracting high-value compounds such as pectin, stilbenoids, and resins in existing pulp mills can increase profits by millions of euros. Producing value-added products like lignin-based PUR foams or cellulose composites outperforms direct sales of raw lignin and tannins due to higher market prices. Plant integration reduces production costs, as seen in black pellet production, through energy and resource synergies. Similarly, locating tannin and briquette production alongside plywood or geothermal plants lowers capital investment and utility costs while improving returns. Valorized bark can be further processed into composites, nanocellulose, adsorbents, and energy products, or used in coatings, adhesives, and pigments. Despite variations in bark composition due to environmental factors, minimal pretreatment is sometimes sufficient. Ongoing optimization of extraction, pretreatment, and product development is crucial. Overall, bark valorization offers promising opportunities for circular-economy growth, sustainable resource use, and environmental benefits.[122,123]

## FUTURE PERSPECTIVES

In this review, we have highlighted the crucial role of agricultural waste valorization as a valuable and promising route for both the extraction of high-value chemicals. In particular, the studies discussed herein demonstrate how widely available agro-industrial residues can represent strategic feedstocks for the development of sustainable chemical processes and materials. Our aim is to promote a holistic approach that enables the complete valorization of biomass resources within a circular-economy framework, minimizing waste generation while maximizing resource efficiency. In this context, the adoption of standardized assessment methodologies, such as LCA, is essential to properly evaluate the environmental impact of emerging technologies and to guide the development of more sustainable processes in both academic and industrial settings.

The use of chestnut or hazelnut shells and water-based processes represents a major advantage, enabling circularity, reduced toxicity, and avoidance of critical raw materials, as shown for tannin-based coagulants and graphene production. However, LCA results consistently highlight energy consumption—particularly electricity-intensive steps such as drying, exfoliation, or pyrolysis—as the dominant environmental hotspot, often outweighing raw material benefits. Similar results have been detected in the case of the valorization of crustacean waste into chitin-, CS-, and nanochitin-based products. LCA consistently reveals that energy consumption and the use of chemicals such as NaOH, HCl, or solvents dominate environmental impacts. Innovative strategies such as ME extraction or supercritical $CO_2$ processing can significantly reduce energy use, chemical demand, and carbon emissions, thereby improving environmental performance. Likewise, alternative feedstocks (e.g., fungi) or process optimization (e.g., solvent recycling, water regeneration) markedly decrease impacts compared to conventional acid-based routes.

Nevertheless, trade-offs remain, as greener methods may involve higher costs, lower scalability, or performance variability depending on the chosen FU and process conditions. Therefore, while these valorization pathways are promising, their sustainability ultimately depends on minimizing chemical inputs, optimizing energy sources, and integrating efficient process design at scale.

Despite the growing body of LCA studies on thermochemical conversion routes and functional carbon materials, the assessment of extraction processes remains notably underdeveloped and fragmented. The literature suggests that existing studies are largely confined to a limited set of feedstocks, such as CS/chitin or selected agro-industrial residues, and typically adopt cradle-to-gate, laboratory-scale boundaries that omit critical downstream operations. This omission is non-trivial, as steps such as solvent recovery, purification, concentration, and drying are often among the dominant contributors to environmental burdens, particularly in terms of energy demand and solvent-related impacts. Furthermore, the use of heterogeneous and sometimes activity-based FUs hinders comparability across studies and limits the robustness of broader conclusions. This gap has important implications: it risks underestimating the true environmental footprint of extraction-based valorization pathways and may bias decision-making in favor of seemingly lower-impact options that are incompletely assessed. To address these limitations, future LCA studies should also adopt harmonized, product-oriented FUs (e.g., mass of extracted product), extend system boundaries to include full downstream processing, and explicitly account for solvent use, recovery efficiencies, and energy integration strategies. Studies should also clearly define how multi-output systems are handled, particularly in cascade approaches aimed at recovering additional lower-value streams or alternatively justify the allocation method applied. Additionally, the integration of scale-up considerations and sensitivity analyses on key parameters (e.g., solvent recycling rates, energy sources) would significantly improve the relevance and transferability of results. It should be acknowledged, however, that scale-up is not straightforward and often requires process simulation tools to appropriate size equipment (e.g., number of distillation columns and trays).[124,125] Given that such expertise may not always be available, the use of simplified scaling approaches can be acceptable,[126] provided their limitations are transparently discussed. Finally, the adoption of multi-impact assessment methods is strongly recommended to avoid burden shifting and mitigate the risk of environmental trade-offs.[125]

Within this perspective, the recent "Green Chemistry for Sustainability" program launched by Paul Anastas is providing an important conceptual framework that is influencing green chemists and engineers worldwide. The adoption of green chemistry principles can therefore guide the transition toward a more sustainable society, where widely distributed waste biomasses may contribute to reducing dependence on fossil resources and mitigating geopolitical tensions related to the production of chemicals and materials. The continuous growth of the green-chemistry-based industry reflects the increasing global commitment toward sustainable development. By taking a leading role in this transition, the European Union is promoting new investment opportunities and job creation through large-scale financial initiatives such as Next Generation EU, which mobilizes €750 billion (within the €1.824 trillion multiannual financial framework until 2027), including €17.5 billion specifically dedicated to natural resources and environmental protection. Within this context, bio-based building blocks represent a sector of enormous interest, with an estimated market value of approximately $3 billion by 2030.[127]

Despite this encouraging outlook, the transition toward a sustainable chemical industry capable of integrating nexus solutions under the guidance of chemistry remains a long and complex process. Although several national and international investment plans have been developed in recent years, further coordinated strategies and stronger actions are still necessary to effectively support this ambitious transformation.[128] A critical issue is represented by the difficulties often faced by small and medium-sized enterprises (SMEs) in interacting with funding agencies and accessing available financial resources. In many cases, this challenge is associated with the absence of dedicated and trained personnel capable of preparing competitive project proposals. In this scenario, stronger connections between stakeholders, including research institutions, funding agencies, and specialized consultancy organizations, could facilitate access to funding opportunities. Such collaborations may contribute not only to industrial growth in the field of project development and investment attraction but also to a more effective valorization of national and international investments, with positive impacts on employment and innovation. The strengthening of SMEs through dedicated training programs developed in collaboration with academic institutions represents another important factor for driving sustainable innovation throughout the industrial sector. Indeed, a comprehensive transition toward greener industries cannot be achieved without fully involving SMEs, which represent the majority of industrial actors in many countries. Equally important is the need for clearer and more accessible dissemination of information regarding funding opportunities and sustainability initiatives. Making these opportunities transparent and widely accessible would allow a larger number of industries to actively participate in the transition toward sustainable production models. From an economic perspective, targeted incentives can further accelerate this process, guiding industries toward the adoption of environmentally responsible practices. As highlighted in several studies, the strong interconnection between economic, scientific, and social dimensions is essential for building a sustainable future.[129] In this context, waste reduction through benign-by-design valorization strategies represents a promising approach that should be further supported and recognized at the policy level through appropriate economic incentives, ultimately enabling these practices to become common industrial standards.

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## DECLARATION OF INTERESTS

The authors declare no competing interests.

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