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Valorization of Agricultural Food Waste as a Source of Bioactive Compounds: A Review of Applications in Nutraceuticals and Cosmetics

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ABSTRACT: Large amounts of by-products, such as peels, pomace, seeds, stalks, and spent substrates, are produced by the agri-food processing industry and are typically thrown away or, at most, recycled into compost or animal feed. However, these residues are becoming more widely acknowledged as a rich and underutilized source of bioactive substances with proven antioxidant, antibacterial, anti-inflammatory, and photoprotective qualities. These substances include polyphenols, carotenoids, dietary fiber, essential oils, and bioactive peptides. The main agricultural food-waste streams, citrus peel, grape pomace, apple pomace, tomato pomace, olive mill waste, spent coffee grounds, and banana peel, are summarized in this review, which also assesses both traditional and cutting-edge (green) extraction techniques for recovering their bioactive fractions. We look into downstream uses in cosmetics (anti-aging, UV-protective, and antibacterial formulations) and nutraceuticals (functional foods, dietary supplements), and we talk about the technological, legal, and financial obstacles that presently prevent widespread industrial use. The research indicates that, although further advancements in green extraction, standardization, and safety/regulatory frameworks are required to fully realize its promise, food-waste valorization constitutes a commercially promising and scientifically mature pillar of the circular bioeconomy.

1. INTRODUCTION

An estimated one-third of all food produced worldwide is lost or wasted during the supply chain. A large portion of this waste is concentrated into particular, chemically rich by-product streams like peels, pomace, seeds, and spent grounds thru agro-industrial processing like juicing, winemaking, oil pressing, and brewing. Since many polyphenols, carotenoids, and fibers are concentrated in skins, seeds, and pulp rather than in the main processed product, these residues—which were previously considered a disposal liability, are now recognized to retain a significant portion of the bioactive phytochemicals present in the original raw material.

Food-waste valorization is now a strategic priority within the circular bioeconomy due to the convergence of three trends: growing consumer demand for natural and sustainably sourced ingredients, stricter environmental regulation of agro-industrial waste disposal, and advancements in green extraction technology. These residues have drawn increasing attention from the nutraceutical and cosmetic industries in particular as inexpensive, renewable sources of antioxidants, colorants, emollients, and functional actives that can replace synthetic or resource-intensive substitutes.

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The objectives of this review are to: (i) Describe the main agricultural food-waste streams and their primary bioactive components; (ii) Contrast traditional and environmentally friendly extraction methods for their recovery; (iii) Examine existing and new uses in nutraceuticals and cosmetics; and (iv) Determine the technological and regulatory obstacles that need to be overcome for these methods to become commercially viable.

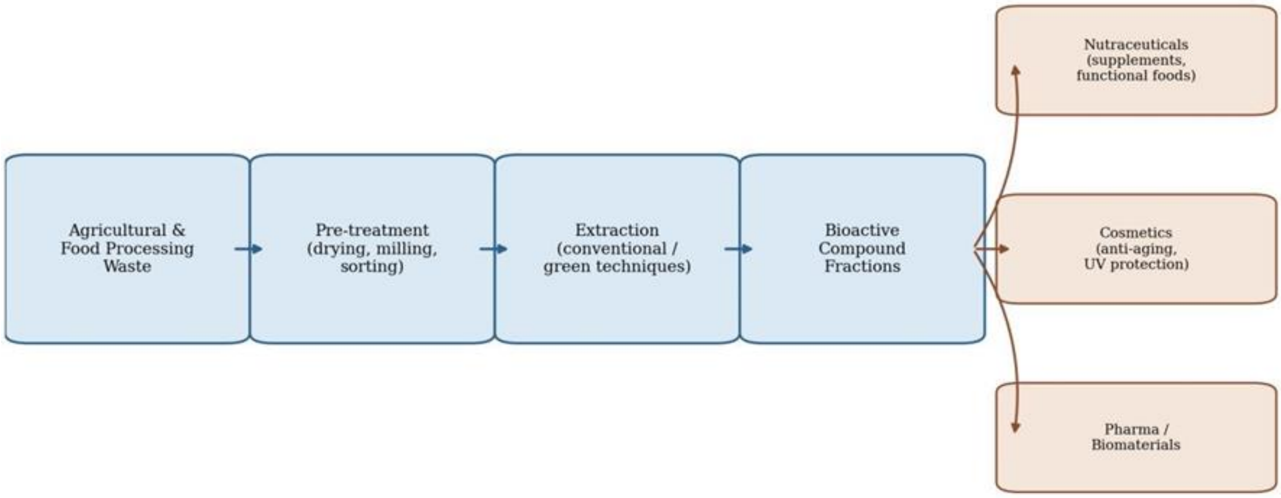

Figure 1. Generalized pathway for valorizing agricultural food waste into nutraceutical and cosmetic applications.

2. MATERIALS AND METHODS

2.1 Search Strategy

Terms including "food waste valorization," "agro-industrial by-products," "bioactive compounds," "nutraceuticals," "cosmeceuticals," and specific waste-stream names (e.g., "citrus peel," "grape pomace," "spent coffee grounds") were combined with Boolean operators in a structured search across Scopus, Web of Science, PubMed, and ScienceDirect, covering publications from the previous fifteen years.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria comprised peer-reviewed studies reporting extraction, characterization, or application of bioactive compounds from a named agricultural or food-processing by-product, recent systematic reviews and meta-analyses, and English-language full text availability. Exclusion criteria comprised studies without a defined waste stream or extraction methodology, non-peer-reviewed grey literature, and duplicate reports of the same dataset.

2.3 Data Synthesis Approach

For each included waste stream, data extracted covered source industry and generation volume, principal bioactive constituents, extraction method and reported yield, demonstrated bioactivity (in vitro, in vivo, or clinical), and documented or proposed end-use application, consistent with PRISMA 2020 reporting guidance.

2.4 Comparative Framework for Extraction Technologies

Extraction technologies identified in the reviewed literature were compared across a common set of qualitative parameters - solvent use, energy/time demand, selectivity, thermal-degradation risk, capital cost, scalability, and environmental footprint - to allow a like-for-like comparison between conventional and green methods (Section 3.2).

2.5 Statistical Analysis

Not applicable. As a narrative/comparative literature review rather than a primary quantitative study, no inferential statistical testing was performed on original data; extraction-yield ranges and qualitative technique scores reported in Section 3 are compiled directly from the reviewed literature rather than computed from a study dataset.

3. MAJOR AGRICULTURAL FOOD-WASTE STREAMS AND THEIR BIOACTIVE COMPOUNDS

3.1 Overview of Major Agricultural Food-Waste Streams

Table 1 summarizes seven of the most extensively studied agricultural and food-processing waste streams, their principal bioactive constituents, reported bioactivities, and representative extraction yields drawn from the literature.

Table 1. Summary of major agri-food waste streams and their bioactive compound profiles.

Waste stream	Source industry	Key bioactive compounds	Reported bioactivity	Typical yield*
Citrus peel	Juice processing	Flavonoids (hesperidin, naringin), vitamin C, d-limonene, pectin	Antioxidant, antimicrobial, UV-protective	~15–20%
Grape pomace	Winemaking	Resveratrol, catechins, proanthocyanidins, anthocyanins, grapeseed oil	Antioxidant, anti-aging, antimicrobial, anticancer (in vitro)	~17–18%
Apple pomace	Juice/cider processing	Chlorogenic acid, quercetin, pectin, dietary fibre	Antioxidant, prebiotic, cholesterol-lowering	~10–13%
Tomato pomace	Sauce/paste processing	Lycopene, carotenoids, tomato-seed oil, phytosterols	Antioxidant, photoprotective, anti-inflammatory	~8–10%
Olive mill waste	Olive oil production	Hydroxytyrosol, oleuropein, tyrosol	Potent antioxidant, anti-inflammatory, antimicrobial	~20–23%
Spent coffee grounds	Coffee brewing/instant coffee	Chlorogenic acids, caffeine, diterpenes, coffee oil	Antioxidant, anti-cellulite, caffeine-based cosmetic actives	~13–15%
Banana peel	Fruit processing/food service	Carotenoids, polyphenols, dopamine, pectin	Antioxidant, emollient, wound-healing (preclinical)	~10–12%

Citrus peel, grape pomace, and olive mill waste show the highest reported yields and the broadest range of documented bioactivities, while apple, tomato, and banana by-products are comparatively under-exploited relative to the volumes generated, suggesting room for further valorization research on these streams specifically.

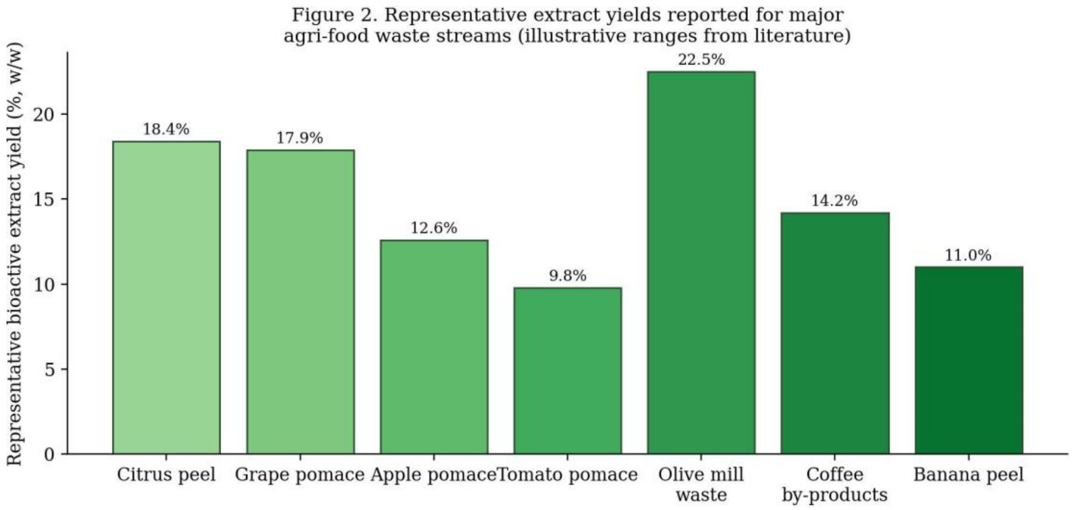

Figure 2. Representative bioactive extract yields reported for major agri-food waste streams (illustrative ranges compiled from the literature).

3.2 Citrus Peel

Large amounts of peel waste, rich in flavonoids like hesperidin and naringin, vitamin C, pectin, and essential oils dominated by d-limonene, which alone can make up the vast majority of the essential-oil fraction recoverable from orange peel, are produced during citrus processing. Because of their strong antibacterial and antioxidant qualities, these components such as, citrus pectin as a thickening for food and cosmetics, flavonoid extracts as functional food antioxidants, and d-limonene as a fragrance and solvent ingredient in personal care formulations, are economically feasible. Lipid extraction from various food matrices and adhesives are two further suggested applications.

Because citrus seed fractions, which are often ignored in favor of peel—have been shown in preclinical assays to contain biologically active compounds with antioxidative, anti-inflammatory, and anticancer-relevant properties, the potential value recoverable from citrus processing residues extends beyond the peel alone.

3.3 Grape Pomace

Grape pomace, which is composed of grape skins, seeds, and stalks left over after winemaking, is one of the most well-characterized food waste streams. Anthocyanins, proanthocyanidins, catechins, and resveratrol are abundant in it. Strong antioxidant capacity in DPPH radical-scavenging tests and antimicrobial activity against skin-relevant bacteria like Staphylococcus aureus and S. epidermidis support the use of grapeseed oil and pomace-derived phenolic extracts in anti-aging skincare products and antioxidant dietary supplements.

3.4 Apple and Tomato Pomace

Apple pomace, a byproduct of making juice and cider, contains pectin, quercetin, and chlorogenic acid. It has been shown that antioxidant-rich polyphenol fractions can be successfully recovered while retaining biological activity via hot-water and aqueous-ethanol extraction. The amount of lycopene and other carotenoids found in the seed and skin portions of tomato pomace—a byproduct of making sauce and paste—is remarkable. These substances are prized for their antioxidant properties in nutraceutical formulations and for their photoprotective and anti-inflammatory properties in cosmetic goods.

3.4 Olive Mill Waste

Tyrosol, oleuropein, and hydroxytyrosol—phenolic chemicals recognized as some of the most powerful natural antioxidants discovered to date—are found in significant solid and liquid waste streams produced during the manufacture of olive oil. Olive waste-derived extracts are becoming more and more popular for use in high-end anti-aging cosmetic formulations and nutraceutical antioxidant supplements due to their potent anti-inflammatory and free-radical scavenging properties.

3.5 Spent Coffee Grounds and Banana Peel

Coffee oil rich in diterpenes, residual caffeine, and chlorogenic acids are all retained in spent coffee grounds, which are produced in large amounts by the beverage industry. Previously, these compounds were used commercially in anti-cellulite and eye-contour cosmetic treatments based on caffeine. A typical waste of fruit processing and food service, banana peel has been investigated preclinically for its potential to heal wounds. It is made up of pectin, polyphenols, and carotenoids that have been shown to have emollient and antioxidant properties.

4. EXTRACTION TECHNOLOGIES

For the efficient, sustainable, and targeted recovery of bioactive compounds from food waste, the extraction process is essential. Conventional solid-liquid extraction, such as Soxhlet extraction employing organic solvents, is still frequently used but is increasingly viewed as unsustainable due to its unusual solvent intake, long processing times, and thermal damage of heat-sensitive compounds. By increasing extraction efficiency, lowering solvent and energy consumption, and better preserving bioactivity, green and emerging technologies—such as ultrasound-assisted extraction, microwave-assisted extraction, supercritical CO2 extraction, and enzyme-assisted extraction—have been developed to get around these restrictions.

Polyphenols, flavonoids, and tannins have been successfully recovered from a variety of waste streams, such as apple pomace, grape pomace, citrus peels, and berry skins, using green solvent systems, particularly aqueous ethanol combinations.

This aligns extraction practices with the more general sustainability objectives of circular bioeconomy models.

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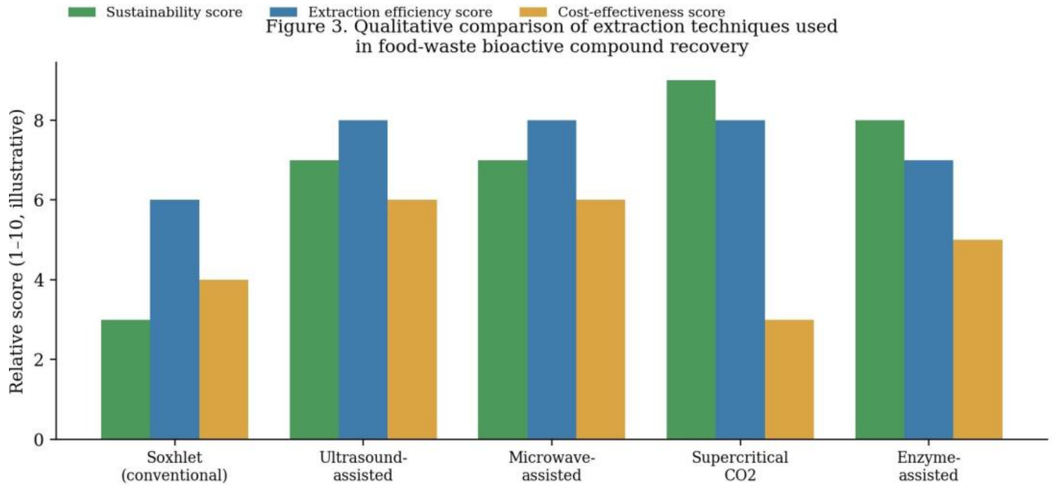

5. APPLICATIONS IN NUTRACEUTICALS

Functional meals, dietary supplements, and fortified drinks are increasingly using bioactive extracts recovered from agri-food waste. Apple and grape pomace fractions rich in polyphenols and fiber are utilized to increase the antioxidant capacity and prebiotic fiber content of dairy, beverage, and baking products. While citrus flavonoid extracts and olive-derived hydroxytyrosol are developed into capsules and functional food ingredients aimed at cardiovascular and metabolic health claims, carotenoid-rich tomato-pomace extracts are sold as natural colorants and antioxidant supplements. The promotion of nutraceuticals made from food waste as an affordable, sustainable substitute for substances typically synthesized or extracted from virgin plant material is a recurrent theme in this research.

6. APPLICATIONS IN COSMETICS

Due to customer desire for "clean label" and upcycled ingredients, the cosmetics industry has been a particularly active adopter of bioactives obtained from food waste. Citrus-derived d-limonene and flavonoids are used as fragrance and antioxidant components in skincare products; tomato-pomace carotenoids and olive-derived hydroxytyrosol are used in photoprotective and anti-inflammatory formulations; and caffeine recovered from spent coffee grounds is still a mainstay active in anti-cellulite and eye-contour products. Grape pomace and grapeseed extracts, which are rich in antioxidant phenolics and vitamin E. Cosmetic formulation is a high-value outlet that can significantly increase the financial sustainability of waste-recovery activities, and these applications exemplify a larger trend of agro-industrial by-product circularity.

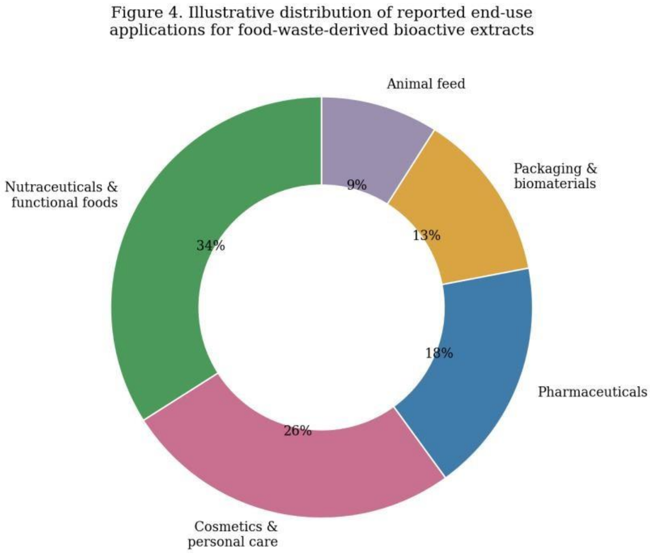

Figure 4. Illustrative distribution of reported end-use applications for food-waste-derived bioactive extracts, compiled from the reviewed literature.

7. CIRCULAR ECONOMY AND TECHNO-ECONOMIC CONSIDERATIONS

Beyond its scientific justification, the circular economy and bioeconomy models that aim to replace the conventional linear "extract–produce–dispose" paradigm with closed-loop systems that recover value from every stage of production are increasingly framing food-waste valorization. For agro-industrial processors, valorization offers a dual benefit: it converts a waste-disposal cost (landfill fees, effluent treatment, greenhouse-gas-generating decomposition) into a revenue-generating co-product stream, while simultaneously reducing the environmental footprint of the primary operation.

Techno-economic assessments of pomace- and peel-derived extract production generally identify feedstock collection and logistics, rather than the extraction step itself, as the dominant cost driver, since agro-industrial by-products are frequently generated seasonally and in geographically dispersed locations, and are prone to rapid microbial spoilage if not stabilised promptly. Co-locating extraction facilities with primary processing plants (e.g., an extraction unit integrated directly into a winery or juicing facility) has been proposed as a strategy to minimise transport costs and preserve bioactive integrity by reducing the interval between waste generation and processing.

The relative value of the recovered fraction also depends heavily on the target market: cosmetic-grade extracts, which command premium pricing and require smaller processed volumes, can often justify higher-cost green extraction methods such as supercritical CO2, whereas nutraceutical or functional-food ingredients, produced at larger volume and lower price point, may depend more heavily on lower-cost conventional or ultrasound-assisted methods to remain economically competitive.

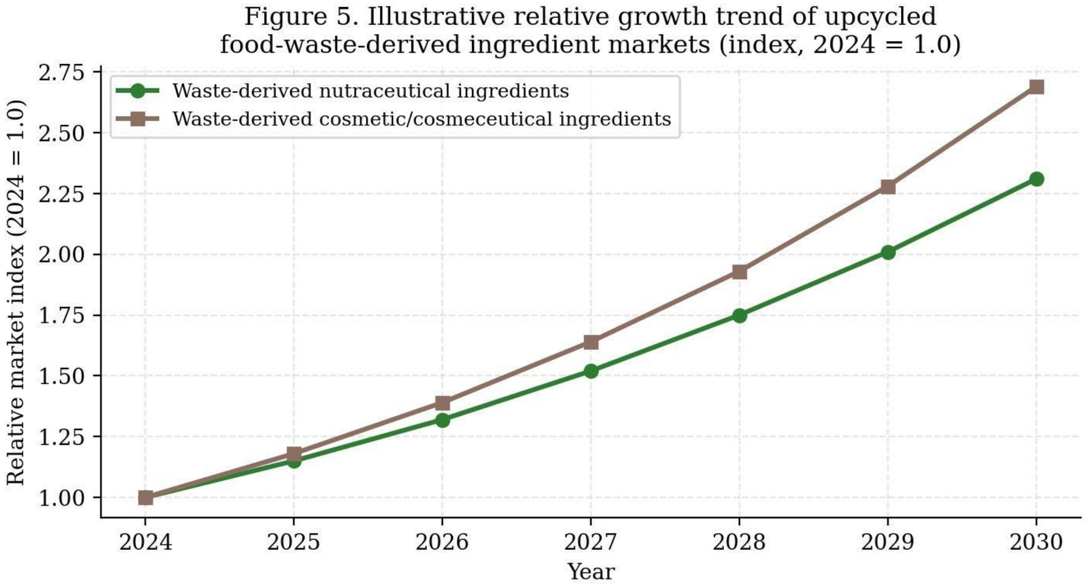

Figure 5. Illustrative relative growth trend of upcycled food-waste-derived ingredient markets, nutraceutical versus cosmetic segments, 2024–2030 (index, 2024 = 1.0).

8. SAFETY, QUALITY, AND REGULATORY CONSIDERATIONS

Agricultural food waste may have a higher risk of microbial contamination, pesticide residue accumulation (especially in peel and skin fractions), and mycotoxin development during storage because it comes from material that has already undergone primary food processing. These issues must be resolved before an extract is deemed safe for use in nutraceuticals or cosmetics. Therefore, rapid post-generation stabilization (drying, freezing, or immediate extraction), contaminant screening, and batch-to-batch quality control equivalent to that used for traditionally procured raw materials are usually necessary for good manufacturing practices for waste-derived products.

Additionally, different jurisdictions continue to have different regulatory processes for substances derived from garbage. By-product-derived extracts were not initially taken into consideration when designing novel-food or cosmetic ingredient clearance procedures in a number of nations, leading to uncertainty regarding classification, allowed concentration limits, and labeling requirements. The time-to-market for verified food-waste-derived bioactives would be significantly reduced by harmonizing various approaches, possibly through specialized "upcycled ingredient" categories that have started to emerge in some markets. The government ought to keep focusing on this problem.

9. CHALLENGES AND FUTURE DIRECTIONS

Standardization: Batch-to-batch consistency and supervisory endorsement are complicated by the important discrepancies in extract configuration and strength caused by cultivar, ripeness, processing history, and storage conditions.

Scale-up economics: Although some green extraction methods, like supercritical CO2, offer better sustainability and selectivity, their higher capital costs may prevent small and mid-sized processors from implementing them.

Safety and regulatory frameworks: new food and cosmetic ingredient approval procedures for waste-derived extracts are still inconsistent across nations, and contaminant profiling (pesticide residues, mycotoxins) needs more uniformity.

Supply chain logistics: Agro-industrial waste requires investment in stability and pre-treatment infrastructure near the site of generation since it is normally periodic, geologically dispersed, and prone to fast microbial decomposition.

Addressing these challenges through coordinated investment in green extraction infrastructure, harmonized regulatory guidance, and cross-sector cooperation between agro-industrial processors and nutraceutical/cosmetic manufacturers will be necessary to scale food-waste valorization from a promising research area into a mainstream pillar of the circular bioeconomy.

10. CONCLUSION

Left-over streams from food processing and agriculture are a basis of bioactive mixtures with clear applications in nutraceuticals and cosmetics that are both economically and scientifically authenticated. Citrus peel, grape pomace, apple and tomato pomace, olive mill waste, spent coffee grounds, and banana peel can altogether offer distinctive profiles of antioxidant, antibacterial, and photoprotective mixtures using both conventional and more in nature friendly green extraction methods. The field's path strongly supports its significance to the scope of Natural Resources for Human Health, but comprehending the full potential of this circular economy opportunity will entail continuing progress in extraction standardization, regulatory harmonization, and economically viable scale-up.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Not applicable. This review did not involve human participants, animal subjects, or primary data collection requiring ethical clearance.

DATA AVAILABILITY STATEMENT

Not applicable. This is a literature review; no new primary data were generated. All data discussed are drawn from the cited published sources.

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