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From waste to resource: fruit by-products deserve a second life

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Editorial

Reducing environmental impact, increasing resilience to climate change, and recovering and valorizing waste from production processes are among the main objectives of the UN 2030 Agenda and the European Green Deal.[1]

The fruit sector represents one of the largest agricultural industries worldwide. Millions of tons of apples, citrus fruits, grapes, berries, bananas, mangoes, pineapples, peaches, pears, and tropical fruits are cultivated every year for fresh consumption and industrial processing. Yet during farming, harvesting, storage, transportation, and transformation, enormous quantities of biomass, such as imperfect and damaged fruits, peels, seeds, pomace, pulp residues, become waste, therefore, millions of tons of fruit by-products are discarded worldwide, every year. It has been estimated that approximately 50% of the 88 Mt of food waste produced in Europe each year is due to fresh fruit and vegetables, and that between 30% and 60% of the original fruit mass is discarded as residue of several industrial processes.[2,3] For decades, these waste products were considered economically and environmentally insignificant, and their disposal in the fields, in the open, or through low-value applications, such as composting, was seen as the most obvious solution. Yet these materials are far from useless. In an era defined by climate change, resource scarcity, the traditional linear model of production, i.e. produce, consume, discard, is increasingly unsustainable, and the urgent need for sustainable production models with the reuse and recycling of fruit by-products represent not only an environmental necessity, but also an economic and social opportunity. The concept behind this transformation is based on a system in which waste is minimized and resources remain in use for as long as possible. In this framework, fruit by-products are no longer considered refuse, but secondary resources capable of generating additional value. This approach reduces environmental impact, lowers disposal costs, and creates new business opportunities for farmers, food processors, and innovative startups.[3-5]

Fruit by-products fit perfectly into this model because they retain significant biological and economic value even after industrial transformation. Fruit residues contain dietary fibers, polyphenols, antioxidants, natural pigments, essential oils, enzymes, fermentable sugars, vitamins, and structural biomolecules that can be reintegrated into industrial production systems. Scientific research has demonstrated that these compounds can be transformed into food ingredients, pharmaceuticals, nutraceuticals, cosmetics, biofuels, biodegradable materials, animal feed, fertilizers, and innovative biomaterials. For example, fruit peels and seeds are rich in bioactive compounds, antioxidants, dietary fibers, essential oils, and natural pigments. Citrus peels can be transformed into pectin for the food industry, natural fragrances for cosmetics, or bio-based cleaning agents. Apple pomace can be reused in bakery products to enrich foods with fiber, while grape residues from wine production contain polyphenols with significant nutraceutical and pharmaceutical potential. Even tropical fruit waste, such as mango or pineapple peels, can be converted into biodegradable packaging materials or biofuels.[6-8]

The reuse of fruit by-products can play a strategic role in food security and sustainable agriculture. Recovering edible compounds from processing waste contributes to a more efficient use of natural resources such as water, land, and energy. It also encourages innovation in the agri-food sector, fostering the development of functional foods, eco-friendly materials, and renewable energy sources.

Consumers have long been increasingly preferring natural additives over synthetic chemicals. Therefore, from this perspective, reusing food waste is not only an environmental strategy but also a response to changing market trends and consumer expectations, to which industries are responding by exploring fruit-based alternatives for preservatives, colorants, flavorings, and stabilizers.[9] The nutraceutical and pharmaceutical sectors show increasing interest for sustainable ingredients derived from agricultural residues. In the cosmetic industry, Fruit extracts are increasingly used in anti-aging creams, moisturizers, exfoliants, and haircare products due to their antioxidant and regenerative properties. This trend demonstrates how environmental sustainability can coexist with economic profitability and industrial innovation. Fruit by-products are also widely used in livestock nutrition. Dried pomace, peels, and pulp residues can serve as cost-effective feed ingredients rich in fiber and nutrients. This practice reduces feed costs while simultaneously diverting waste from landfills. However, nutritional composition, digestibility, and shelf stability must be carefully managed to ensure safe animal nutrition. Another important field of application concerns renewable energy production. Fruit waste is rich in organic matter and fermentable sugars that can be converted into bioenergy through anaerobic digestion and fermentation processes. Biogas, bioethanol, and biohydrogen can all be produced from fruit-processing residues, reducing dependence on fossil fuels and contributing to climate mitigation strategies. Anaerobic digestion also generates digestate that can be used as organic fertilizer, creating integrated circular systems in which waste from one process becomes input for another.[10]

Fruit waste has also emerged as a promising source of biodegradable materials and sustainable packaging solutions. Plastic pollution has become one of the major environmental crises of the twenty-first century, encouraging researchers and industries to seek alternatives to petroleum-based plastics. Fruit peels, fibers, starches, cellulose,

and pectin can be transformed into bioplastics, edible films, and compostable packaging materials. Banana fibers, pineapple leaves, and citrus pectin have demonstrated strong potential for developing biodegradable composites and eco-friendly packaging systems.[11]

The technological evolution of fruit waste valorization has been accelerated by the development of green extraction methods and advanced biotechnologies. Traditional extraction techniques often required large quantities of solvents and energy, limiting environmental sustainability. Modern technologies such as ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, and enzyme-assisted extraction improve efficiency while reducing environmental impacts. Biotechnology and microbial fermentation further enable the production of enzymes, organic acids, biopolymers, and biofuels from fruit residues.[5,12]

Digital technologies are also beginning to play an important role in circular economy systems. Artificial intelligence, machine learning, and blockchain technologies can improve waste tracking, supply-chain transparency, resource optimization, and production efficiency. Smart systems may help industries identify waste streams, optimize logistics, and create more efficient circular production networks.[13]

However, despite these promising developments, significant challenges remain. the transformation required is not solely technological or economic; it is also cultural. Society must fundamentally rethink the concept of waste itself. Nature operates through circular systems in which every residue becomes part of a new cycle. Human production systems, by contrast, have often treated waste as an inevitable and disposable consequence of economic growth. Reusing fruit by-products challenges this mentality and promotes a vision of industry based on regeneration, efficiency, and responsibility.

Educational institutions and universities also have an important role to play. Future professionals in agriculture, engineering, food science, and business must be trained to integrate circular economy principles into industrial systems and product design. Consumer education is equally important to overcome misconceptions about recycled food ingredients and promote acceptance of sustainable products.

The future of fruit by-product valorization appears highly promising. Growing environmental awareness, technological progress, and evolving consumer preferences are creating favorable conditions for the expansion of circular bioeconomy systems. Integrated biorefineries capable of converting fruit waste into multiple high-value products may become central components of sustainable industrial ecosystems. Innovative startups and established companies alike are increasingly exploring new business models based on upcycling and waste valorization.

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Conflict of Interest

All authors declare that there is no conflicts of interest.

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