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Biotransformation of wastes from agro-processing industries: Sustainable pathways for development of value-added products

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Abstract- The processing of fruits and vegetables alone generates a significant amount of waste, which accounts nearly to 25–30% of the total product. Mostly seeds, peels, husk, seed coats, pomace, tops, leek, kernel, stems, leaves, and rinds are the most common agro-based byproducts which are not utilized or processed into value-added products. These agro-based wastes are the potential sources of bioactive compounds, dietary fibers, natural pigments, polyphenols, essential oils, and other nutritionally valuable components that can be used to produce value-added products. The sustainable utilization of these by-products offers multiple advantages, including reduction of environmental burden, enhancement of food security, minimizes cost in waste management, and develops functional ingredients for food, pharmaceutical, cosmetic, and bioenergy industries. Innovative processing strategies such as bioconversion, fermentation, extraction of bioactives, and the subsequent incorporation into nutraceuticals or functional foods can transform these residues into high-value commodities. This chapter emphasizes on the potential of food industrial wastes as a resource rather than a liability, while exploring new technological advancements, economic feasibility, and sustainability perspectives. A shift towards waste valorization not only aligns with main three circular economy principles (driven by principles, eliminate waste and pollution, circulate products and materials) but also contributes significantly to resource efficiency and environmental sustainability.

Keywords- Agro-based by-products, bioactive compounds, circular economy principles, value added products, waste valorization.

I. INTRODUCTION

In the European Union, about 89 million tons of food waste are generated annually, and this value is expected to increase by 40-fold in the upcoming years. According to the Food and Agriculture Organization (FAO), roughly 40% of the food produced in India goes wasted. Moreover, the Food

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Corporation of India reported this loss to be ranging between 10 to 15 percent of the total production. According to the Ministry of Food Processing Industries (MFPI) India, fruit and vegetable losses to be 12 and 21 million tons, respectively, representing to a market value of about 4.4 billion USD, with a total food value loss and waste produced of 10.6 billion USD. A broader term is "fruit and vegetable waste" (FVW), which refers to inedible parts of fruits and vegetables that are thrown away at different stages that is during collection, handling, shipping or processing. According to FAO, around 1.3 billion tons per year of edible parts from foods which are destined for human consumption are discarded and wasted worldwide (Gustavsson et al., 2011). Among all the wastes generated worldwide per year, more than 88 million tons are generated in the European Union (data for the EU-28 countries in 2012) (Stenmarck et al., 2016), and it is estimated that this value will continue to grow up to 40% in the upcoming years (Plazzotta et al., 2017). In North America (Canada, Mexico and the United States), FVW estimates that food-supply-chain waste is nearly 170 million tons (CEC, 2019).

II. LITERATURE REVIEW

Refining agro-industrial residues as feedstock is central to a central bioeconomy. Recent reviews highlights that an integrated "valorization" approach— combining physiochemical extraction, enzymatic/biological conversions, fermentation, and thermochemical routes — can produce a wide range of value-added products such as functional food ingredients, nutraceuticals, natural colorants, food-grade fibres, pectins, biofertilizers, biopolymers, single-cell proteins, enzymes, and bioenergy carriers (Šelo et al., 2021; Prado-Acebo et al., 2024). Such a wide range of 'multi-valorization frameworks' not only improve resource efficiency but also reduce greenhouse gas emissions and waste-management costs when applied at appropriate scale.

Microbial fermentation and solid-state fermentation (SSF) are the key pathways that convert sugars, oligosaccharides, and other fermentable components into products such as organic acids (e.g., lactic acid), ethanol, single-cell protein, microbial lipids, and specialty metabolites. SSF, which relies on low-moisture agro-residues as substrate, is a cost-effective method for producing bioactive compounds and enzymes for upgrading lignocellulosic material to animal feed or fertilizer (Perwez et al., 2024). Enzymatic pretreatment (e.g., pectinase, cellulase, proteases) facilitates downstream extraction and conversion of polysaccharides and bound phenolics from pomace and peels enhance yields of fermentable sucrose and speciality carbohydrates. Advancement in enzyme-cocktail design and immobilization have further improved conversion of fruit pomace into fermentation intermediates or functional biopolymers (Samad, 2025).

Non-toxic extraction techniques such as (pressurized liquid extraction, ultrasound-assisted extraction, subcritical water extraction) have got advanced in technological aspect and are frequently applied to recover antioxidants, pigments like (anthocyanins, carotenoids), and essential oils from citrus peels, berry pomace and vegetable trimmings. These recovered molecules are being reformulated as natural preservatives, colorants, or nutraceutical isolates (Shams et al., 2024; Ramzan et al., 2025). Techniques like (Anaerobic

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digestion, pyrolysis, and hydrothermal liquefaction) convert residues into biogas, bio-oils, biochar and processed heat. While these processes are well suited for energy recovery, there is growing focus in the literature on integrated strategies linking the material valorization and energy recovery (e.g., biochar as adsorbent or soil enhancer while extracted bioactives are processed separately) to increase the rate of economic return (Sarker, 2024).

Research reviews and case studies demonstrate both laboratory-scale successes and emerging commercial demonstrations. For example, fruit pomaces have been successfully transformed into pectin and dietary fiber mainly allowed for bakery and confectionery applications; citrus peels are now commonly used as feedstock for limonene extraction and pectin recovery; and grape pomace has been investigated for production of polyphenol-rich extracts, animal feed supplements, and fermentation substrates for value-added metabolites (Nirmal & Lakshmi, 2023; Nur'Aqilah et al., 2023). These cases highlight just how many different products can come from a single type of waste when the right processing is used.

Even with many clear potentials, several barriers still remain. Feedstock heterogeneity, seasonal variability, scale economics, cost of green extraction/pretreatment, regulatory hurdles for food-grade co-products, and the need for life-cycle and techno-economic assessments are recurring themes in the literature (Roy et al., 2023). The raw material can vary a lot by season and source, making it difficult to keep quality and supply steady. Integration of upstream logistics (collection, sorting, stabilization) with downstream valorization units is critical; decentralized preprocessing (e.g., at packinghouse or canning facilities) can improve transport economics and product quality. Upcycled ingredients must meet reliable testing requirements for contaminants, quality and shelf life.

Moving towards true 'cascade' use of these byproducts means taking multiple steps: (1) recovering valuable molecules, (2) converting leftover materials into bioproducts or any other value-added products, and (3) Energy recovery from what remains as leftover. Policy incentives (extended producer responsibility, green procurement), coupled with advances in low-cost enzyme technologies, microbial strain engineering, and green extraction, approaches close the loop between farm waste and new product development and will need cooperation across new technology, industry and policy to work at high scale (Prado-Acebo et al., 2024; Sarker, 2024).

III. FINDINGS

TABLE 1: POTENTIAL OF FRUIT AND VEGETABLE WASTES FOR VALUE ADDITION

Fruit/Vegetable Waste	**Bioactive Compound(s)**	**Biological Activities**	**New Products Developed**	**Research Gap / Unaddressed Work**
Apple pomace	Chlorogenic acid, Procyanidin B2,	Antioxidant, suppression of NO production; enhance	Apple pomace flour cookies, bars; pomace-based	Incomplete sensory evaluation; shelf-life stability under

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	other polyphenols	glucose uptake; improve insulin sensitivity	kombucha; probiotic drinks; jellies; scones	varying storage; impacts on texture and colour over time
Pear pomace	Arbutin, Ursolic acid, Vanillic acid, Ferulic acid	Lipid profile improvement (lower TG, TC, LDL, VLDL); modulation of ER pathway	Gluten-free cupcakes and cookies; pear pomace powder for breads; candied products	Long-term studies on obesity models; human clinical data; more on bioavailability
Orange peel	Coumaric acid, Nobiletin, Tangeretin, Ascorbic acid	Membrane stabilization; improved glucose tolerance; enhanced insulin action	Baking/cooking flavour powders; jams; zest oils; orange peel noodles; candied peel	Detoxification of undesirable hydrolysates; reduction of bitterness; scaling extraction processes
Pomegranate peel	Gallic acid, Ellagic acid, Catechin, Cyanidin	Glycogenesis enhancement; protection of pancreatic cells; anti-atherosclerotic	Peel teas; peel-powder chocolates; incorporation in dumplings, ravioli	Moisture control in fine powder; processing methods to reduce microbial load; standardization of active compound content
Grape pomace	Malvidin, Laricitrin, Syringetin, Quercetin	Improved insulin sensitivity; reduced ectopic fat deposition; antioxidant effects	Pomace powder in cereals, snack bars, yogurts; edible wine pomace products	Texture and colour stability; acceptability in different cultural settings; processing cost vs benefit
Banana peel	Gallic acid, Catechin, Isoquercitrin	Immune modulation; improve insulin resistance; increase glucose uptake in cell models	Banana peel chips; flour for breads/cookies; spread / preserves	Bitterness reduction; removal of antinutritional factors; large-scale process design

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Pineapple peel	Gallic acid, Catechin, Ferulic acid	Inhibition of lipid peroxidation; antioxidant capacity; cell protection	Fermented drinks; vinegar; probiotic beverages; peel extracts	Integrated biorefinery models; nutrient recovery in addition to bio actives; economic analysis
Mango peel	Lupeol / Fagarsterol, Magiferin, other triterpenoids and flavonoids	Anti-diabetic activity; inhibition of NO production; strong antioxidant potential	Fruit-fortified yogurts; fibre biscuits; chips; flavour-enhanced powders	Digestive behaviour with mango peel inclusion; sensory impacts; possible allergenicity or irritation
Dragon fruit shell / peel	Flavonoids, Phenolic acids, Vitamin C, Carotenoids	Prebiotic & gut-health; cardioprotective; anti-obesity potentials	Natural colorants; herbal drinks; peel tea; spreads; seed oil extraction	Comprehensive studies on spreads; shelf-life; regulatory status for food colouring; extraction yield optimization

III. CONCLUSION

Fruits and vegetables industries generate a lot of waste and approximately 25-30% of the raw materials gets spoiled. This waste contains peels, seeds, stems, and rinds, and has been discarded traditionally. Nevertheless, it is currently being perceived as a source of useful compounds such as fibers, proteins, pigments, and polyphenols.

Microbial and enzymatic processing are some of the new techniques which are assisting in converting this waste into usable products such as nutraceuticals, biopolymers, functional food ingredients, and biofertilizers. This is called a valoration strategy, as it allows the development of a circular bioeconomy through minimizing environmental damage and increasing economic performance.

Although this is advantageous, the process has challenges. These are fluctuation in the raw materials, expensive processing and regulatory challenges. These problems will be tackled by combination of techno-economic evaluations, life-cycle analysis, and supportive policies.

The most approachable is a cascade type of strategy, in which useful compounds are first of all extracted, then the rest of the materials are converted, and lastly the energy is recovered. Through integration of science and industrial operations together with governmental assistance, agro-industrial waste conversion can be a major component of sustainable products and development that would enhance the environment

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protection and economic development.

Waste food products that can be extracted and used in agriculture and agro-based industries offer a long-term way forward of minimizing environmental pressure and producing new value-added products. Industries can facilitate the transition to a circular bioeconomy by converting the residues (peels, seeds, husks, and pomace) into nutraceuticals, functional food ingredients, biofertilizers, animal food, and bioenergy. Despite the continued existence of the problems of variability in the quality of raw materials, high processing rates, and regulatory constraints, development in green extraction technologies, bioprocessing and supportive policies will make it possible to adopt on a large scale. In such a manner, strategic transformation of agro industrial waste has not only reduced the loss of resources but also enhanced sustainability of the environment, economic development and food security.

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