

Sustainable Valorisation of Fruit and Vegetable Processing Waste: Opportunities for innovative value-added materials

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The rapid expansion of the global food industry, driven by increasing population, changing dietary patterns, urbanization and rising consumer demand, has significantly increased the production of food and agro-industrial by-products. This Substantial growth of the food industry sector is conjoined with an array of many challenges, among which the two most major issues are food safety and food waste management (Nirmal *et al*, 2023). The global fruit and vegetable processing industry generates millions of metric tons of by-products annually predominantly in the form of peels, pomace, seeds and unused pulp. The Food Waste Index Report 2021 from the United Nations Environment Program states that food waste results in the loss of 931 million tonnes per year (Râpă *et al*, 2024). According to the FAO, if food waste were a country, it would produce the third most carbon dioxide globally behind the US and China. Fruits and vegetables, which have historically been regarded as zero-value agricultural waste are predicted to be wasted at a higher rate. When these wasted streams are allowed to decay they greatly contribute to landfill accumulation and greenhouse gas emissions.

Food industry by-products are no longer just seen as waste items but as important sources of nutrients and health-promoting substances. Fruit peels like orange, mango, papaya and pomegranate peels are rich sources of dietary fibre, carotenoids, phenolic compounds, flavonoids and other phytochemicals with potential nutritional and functional properties; fruit seeds like papaya, mango and grape seeds contain valuable oils, proteins, phenolic compounds and other phytochemicals tomato pomace is a potential source of lycopene, dietary fibre and seed oil. In a similar vein, pineapple peels and cores include nutritional fibre, phenolic compounds and bromelain, while citrus peels contain essential oils and flavonoids. These components can be recovered and added to value-added products, such as functional foods, nutraceuticals, food additives and other health-related applications by using suitable processing and valorisation techniques. Using food industry by-products as

functional food ingredients can help create new and nutritionally improved foods while also reducing the environmental impact of food waste generation. Furthermore, their effective application can promote food system circularity, improve resource efficiency and boost food and nutrition security particularly in developing countries. The development of economically viable, safe and sustainable strategies for the valorisation of these underutilised resources is crucial for maximising their nutritional and functional potential while supporting sustainable food production as the sustainable utilisation and value addition of agricultural and food-processing by-products has received more attention in recent years (Nirmal *et al*, 2023).

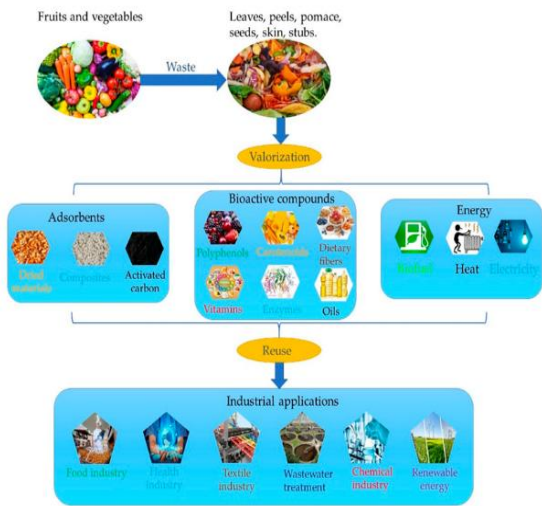


Fig: 1 Conversion of FVW into sustainable and value-added materials

Potential Uses of Some FVW as Sustainable and Value-Added Materials

Fruit and vegetable waste (peels, seeds, husks, and pomace) is an important resource for circular bioeconomy applications since it is rich in biopolymers, bioactive chemicals and structural fibres. Table1 illustrates application of different by-products from fruit and vegetable waste.

Table 1: Application of different by-products from fruit and vegetable waste

Waste Source	Bioactive/Material Component	Sustainable Value-Added Applications
Citrus Peels (Orange, Lemon)	Pectin, essential oils (limonene), cellulose	Biodegradable food packaging films, natural preservatives, pectin-based hydrogels, biofuel
Apple Pomace	Dietary fibre, polyphenols, pectin	Vegan leather alternatives (AppleSkin), bakery fortifiers, biochar for soil remediation

Banana Peels & Trunks	Cellulose fibres, starch, potassium	Sustainable textile yarns, bioplastics, heavy-metal-adsorbent water filters, paper manufacturing
Pineapple Leaves & Waste	Bromelain enzyme, high-tensile lignocellulose	Piñatex (leather alternative), enzyme extracts for pharmaceutical/food applications, structural composites
Grape Pomace & Seeds	Tannins, resveratrol, seed oils	Natural cosmetics (anti-ageing serums), organic textile dyes, bio-based antioxidant food additives
Tomato Peels & Seeds	Lycopene, cutin polymer, fatty acids	Natural food colourants, protective bio-lacquers for metal food cans, UV-blocking biodegradable packaging
Potato&Cassava Peels	Pure starch, microcrystalline cellulose	Thermoplastic starch (TPS) cutlery/bags, bioethanol production, industrial adhesives
Onion & Garlic Skins	Quercetin, cellulose, sulfur compounds	Antimicrobial packaging wraps, natural yellow-brown textile dyes, health supplements

Green Extraction Technologies Driving Industrial Feasibility

Eco-friendly, non-thermal processing techniques that protect heat-sensitive bioactive without using hazardous organic solvents are necessary to move from lab-scale extraction to commercially viable food production:

Table 2: Green Extraction Technologies and Their Applications

Technology	Principle	Potential Applications
Ultrasound-Assisted Extraction (UAE)	Ultrasound waves disrupt plant cell structures and improve mass transfer.	Phenolics, pigments, antioxidants, oils
Microwave-Assisted Extraction (MAE)	Microwave energy rapidly heats moisture and polar molecules within plant material.	Phenolics, flavonoids, pigments
Pulsed Electric Field (PEF)	Short electrical pulses permeabilize cell membranes and facilitate the release of intracellular compounds.	Juice compounds, pigments, intracellular nutrients
Pressurized Liquid Extraction (PLE)	Solvent extraction is performed under elevated temperature and pressure to enhance extraction efficiency.	Phenolics, carotenoids, antioxidants
Supercritical Fluid Extraction (SFE)	Supercritical fluids, commonly CO ₂ , selectively extract target compounds	Oils, carotenoids, lipophilic compounds
Enzyme-Assisted Extraction (EAE)	Enzymes such as cellulase and pectinase break down plant cell walls and facilitate compound release.	Phenolics, proteins, oils, pigments
Aqueous Extraction	Water is used as the extraction medium instead of conventional organic solvents.	Proteins, soluble fibres, minerals and some phytochemicals
Ethanol-Water Extraction	Food-grade ethanol combined with water is used to improve the extraction of selected compounds.	Phenolics, flavonoids and pigments

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