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Zero waste food processing: Valorization of by-products into nutraceuticals and functional ingredients

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Abstract

Discarding food residues from agriculture and food processing in landfills lead to soil pollution, biogas emission and contributes to climate change. To lessen the environmental harm of food waste disposal, the zero waste food processing approach aims to reduce food loss and waste during production and foster sustainability. Sustainable food production requires efficient resource use, reduced environmental footprint, economic viability and minimized food wastage. By-products from food industries such as pomace, peels and seeds of fruits and vegetables are repurposed to isolate phytochemicals. Phytochemicals are plant derived bioactive molecules with nutritional or therapeutic potential to prevent or treat certain illnesses. Bioactive groups including polyphenols, phytosterols, dietary fibre and flavonoids exhibit nutritive and pharmacological actions against chronic and metabolic disorders such as cardiovascular diseases, cancer, diabetes, obesity and oxidative stress. These molecules are increasingly recovered by green extraction technologies rather than by conventional approaches, since traditional methods are time consuming and green techniques can often achieve higher recovery. Bioactive compounds such as polyphenols, carotenoids and phytosterols can be recovered using green extraction technologies including supercritical fluid extraction, ultrasound-assisted extraction, microwave-assisted extraction and pressurized-liquid extraction. A key principle of green extraction is the replacement of toxic petroleum based solvents with environmentally friendly alternatives such as water, ethanol and supercritical CO_2, enhances extraction efficiency while ensuring safety for nutraceutical and food applications. The recovered compounds can be incorporated into value-added products like functional ingredients, fortificants, edible coatings and dietary supplements.

1. Introduction

Food loss and waste (FLW) refers to the reduction in both the quantity and quality of food occurring along the supply chain, from production and postharvest handling to distribution and retail. Food discarded at the consumer level is specifically termed food waste. FLW can be broadly classified into three major categories of by-products: residues from crop cultivation, by-products generated during postharvest handling and leftovers produced during food processing (Boruah and Ray, 2024). These agricultural by-products often pose environmental hazards and are frequently treated as biohazards. Therefore, adopting sustainable strategies to minimize food waste and effectively utilize these by-products has become a global priority. Globally, the scale of food waste is alarming. According to the Food and Agriculture Organization (FAO), approximately 1.3 billion tonnes of food valued at nearly USD 750 billionis wasted annually (FAO, 2017; Sahoo *et al*., 2023). In India, with a population exceeding 1.3 billion, about 0.5 kg of organic waste is generated per person each day (Paulraj *et al*., 2019; Sahoo *et al*., 2024). Major contributors include hostels, supermarkets, residential complexes, restaurants, airline catering services and the food processing sector. The United Nations Environment Programme (UNEP) Food Waste Index Report (2021) further indicates that annual per capita food waste in India is 90 kg among high-income groups, 68 kg among middle-income groups and 63 kg among low-income groups (Chaudhary *et al*., 2021; Sahoo *et al*., 2024). Food waste accounts for approximately 22% of combusted municipal solid waste and 24% of landfill waste, generating nearly 4.4 gigatons of carbon dioxide annually,accounting for around 8% of total anthropogenic greenhouse gas emissions (Kohli *et al*., 2024).

Reducing food waste is a key objective of the United Nations 2030 Agenda for Sustainable Development due to its profound social, economic and environmental implications. Socially, minimizing food loss addresses ethical concerns and improves food security. Economically, farmers, manufacturers and consumers experience direct financial losses due to wasted resources. The US Environmental Protection Agency highlights that food industry stakeholders can achieve significant cost savings by reducing waste through lower disposal costs and reduced procurement expenses (Iacovidou *et al*., 2012). Similarly, UNEP emphasizes that improved resource efficiency creates financial gains, business opportunities, job creation and

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enhanced competitiveness (UNEP, 2011). From an environmental perspective, food waste disposed in landfills generates methane and carbon dioxide, contributing substantially to climate change. Land filled food waste alone contributes about 7% of global greenhouse gas emissions, primarily as methane, which has a significantly higher global warming potential than carbon dioxide (Papargyropoulou *et al.*, 2014).

Building on the growing concern over food waste and environmental sustainability, zero waste has emerged as a global strategy to eliminate food waste, a concept that originally developed within the industrial sector. It is framed as an ethical, economic, practical and visionary approach that promotes lifestyles aligned with sustainable natural cycles, in which waste streams are repurposed as resources for future generations. The zero waste approach seeks to prevent or reduce food waste by converting inedible or underutilized food fractions (such as peels, seeds and pomace) into nutraceuticals rich in bioactive compounds and other functional ingredients. However, food processors face significant challenges in the disposal of agro industrial waste due to biogas emissions, landfill dependence and the risk of soil and water contamination. Consequently, the agricultural and food sectors are increasingly shifting toward zero waste food processing through the valorization of food waste into nutraceuticals and functional components to achieve sustainability (Bogusz *et al.,* 2021).

Nutraceuticals and functional foods provide health benefits beyond basic nutrition. Nutraceuticals are bioactive elements with nutritional and pharmaceutical properties beneficial to human health, while functional foods provide physiological benefits that support growth and wellbeing. It is often marketed as capsules, tablets or extracts, while functional foods offer physiological benefits that support overall wellbeing. Azmir *et al.* (2013) stated the bioactive compounds such as polyphenols, phytosterols and carotenoids can be extracted from food by-products using green technologies, including supercritical fluid, ultrasound-assisted, microwave-assisted and pressurized liquid extraction. The efficiency of these techniques largely depends on solvent selection (Figure 1).

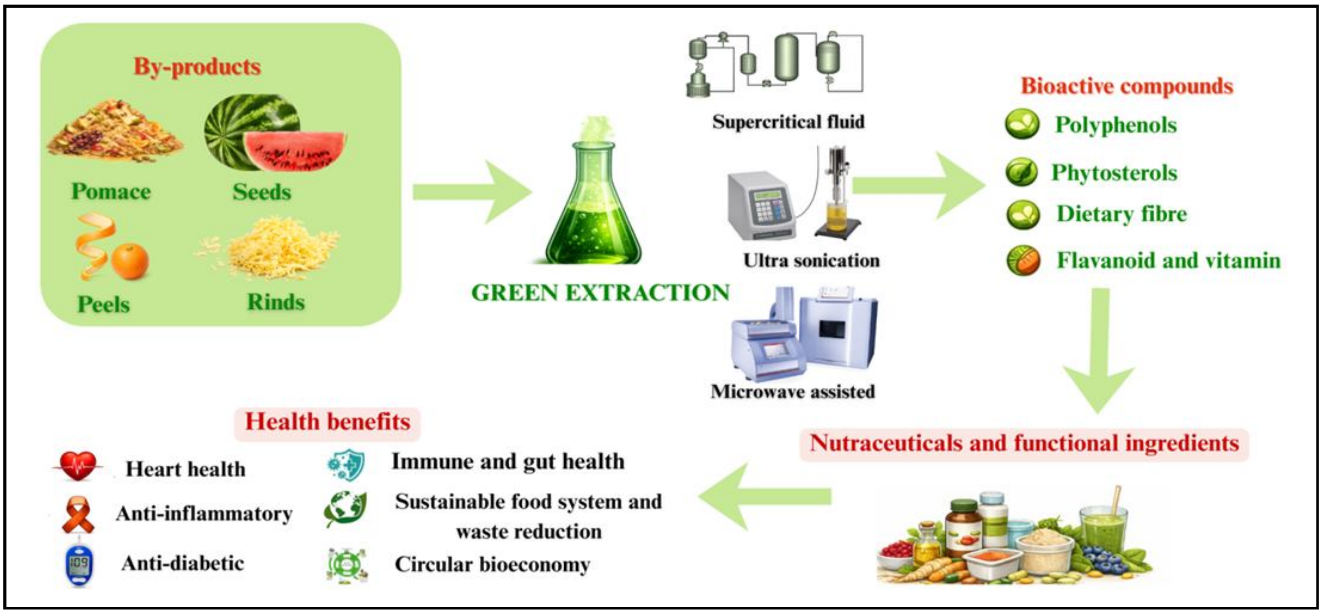

Figure 1: Zero waste approach.

2. Valorization of fruit processing by-products

2.1 Apple (*Malus domestica* (Suckow) Borkh.)

Apple pomace is the solid residue remaining after apples are milled and pressed to produce juice, cider or puree. It consists mainly of peel, seeds, core, calyx and stem material left after juice extraction. Apple pomace is commonly utilized to produce pectin and as animal feed (Varzakas *et al.,* 2016). Apple pomace, including seeds, is a rich source of bioactive compounds, particularly phloridzin along with catechins, hydroxycinnamates, phloretin glycosides, quercetin glycosides and procyanidins. Due to its high dietary fibre and pectin content, apple pomace is increasingly utilized in fibre enriched foods, dairy products, confectionery and bakery applications as a natural emulsifier, fat replacer and antioxidant ingredient. Fermentation and advanced processing techniques further enhance its fibre content and functional properties highlighting, its potential as a sustainable food ingredient. These applications demonstrate the significant potential of apple pomace as a value added by-product in nutraceutical formulation (Ezzat *et al.,* 2022).

Celiac disease is an autoimmune condition triggered by gluten ingestion that damages the small intestine. Gluten free alternatives help celiac disease affected individuals. In gluten free cake formulations, adding 10% apple pomace produced a denser cake with firmer texture but higher fibre and acceptable sensory quality. Adding apple to cookies lowered the glycemic index by about 10%, making apple pomace a useful ingredient for GI focused products. Incorporating 3 to 9% apple pomace with brown rice in gluten free crackers increased mineral content, antioxidant activity, boosting total phenolic and flavonoid levels. Thus, apple pomace is a promising nutritional and functional ingredient in bakery items (Ezzat *et al.,* 2022).

Most polyphenolic antioxidants in apples are concentrated in the skin; therefore, a substantial amount of these compounds remain in apple pomace after processing. Apple by-products contain flavanols, hydroxycinnamic acid derivatives, flavonols, dihydrochalcones and anthocyanins, all of which exhibit strong radical scavenging activity and highlight the value of apple residues as dietary antioxidants. Apple peel also contains triterpenic acids located in epidermal cells and epicuticular wax, which are often discarded during processing. These compounds possess antioxidant, anti-inflammatory and antimicrobial properties, making them attractive for multifunctional health applications. In addition, apple seeds and peels contain unsaturated fatty acids such as oleic, linoleic and linolenic acids, contributing to antioxidant, antimicrobial and antiproliferative activities. Apple pomace has therefore been identified as a potential source of apple seed oil rich in unsaturated fatty acids beneficial for cardiometabolic health (Walia *et al.,* 2013).

2.2 Grapes (*Vitis vinifera* L.)

Grapes are primarily processed for winemaking, generating approximately 20% grape pomace on a dry weight basis. This by-product retains significant amounts of dietary fibre and polyphenols due to incomplete extraction during processing. These polyphenols exhibit antioxidant, antimicrobial and anti-inflammatory properties making grape pomace a cost-effective source of bioactive compounds. Grape skin and pulp extracts have also been used as substrates to produce pullulan, an industrially valuable α-glucan through fermentation with *Aureobasidium pullulans*. In addition, grape seeds are processed to obtain oil rich in linoleic acid, vitamins and antioxidants, which contribute to cholesterol-lowering and cardioprotective effects (Varzakas *et al.,* 2016).

Recently, micro and nano-delivery systems have been explored to enhance the stability, bioavailability and targeted activity of grape by-product derived compounds. Nano-scale carriers provide larger surface areas and enable controlled delivery of therapeutic agents, thereby improving efficacy. Clinical evidence suggests that resveratrol and grape seed extracts are beneficial for skin health, including aging, wound healing, acne and redness. Among nano-carriers, liposomes are particularly promising due to their ability to protect bioactives from degradation, enhance transport to target skin layers and support skin barrier restoration (Castro *et al.,* 2023).

2.3 Banana (*Musa paradisiaca* L.)

Banana processing generates substantial biomass waste from pseudo stems, rhizomes, bracts and peels, which can be valorized as sources of nutritional and nutraceutical compounds. Banana bracts are rich in anthocyanins and are therefore suitable as natural colourants. Banana peel, which constitutes approximately 30% of the fruit, represents a major disposal concern but is a valuable by-product due to its high dietary fibre, phenolics and carotenoids with strong antioxidant activity (Mishra *et al.,* 2022). Banana peel has also been explored for oral health applications as a natural tooth whitening aid and a source of potassium that supports dental remineralization. Furthermore, banana peel extracts have demonstrated anticancer activity with the viability of MCF-7 breast cancer cells decreasing from 91.14% to 24.7% as extract concentration from Nendran banana peel increased from 20 to 200 µg/ml. Banana peel extracts have also been incorporated into carboxymethyl cellulose based gels for the treatment of heel fissures, showing improved wound healing and sustainability compared with conventional ointments (Bhavani *et al.,* 2023).

Banana peel powder (BPP) is increasingly used as a natural colourant and flavouring agent in foods, beverages, confectionery and dairy products, providing an alternative to synthetic additives. The peel can be processed into powder or puree and incorporated into baked goods to improve moisture, texture, aroma and nutritional value, while carotenoids and anthocyanins impart natural yellow to red hues. BPP has multifunctional applications in yellow noodle production as a partial wheat flour substitute, enhancing potassium, vitamin C and vitamin B_6 content while offering a gluten free option (Zaini *et al.,* 2020; Ramli *et al.,* 2009). In addition, BPP incorporation in jelly has been shown to improve hardness, chewiness and springiness with higher levels producing more pronounced textural changes (Wani and Dhanya, 2025). Yogurt fortified with banana peel extract has demonstrated increased total phenolic content, antioxidant capacity and antidiabetic potential (Kabir *et al.,* 2020). Moreover, banana peel fibre incorporated into synbiotic camel milk yogurt improved viscosity, probiotic viability (*Lactobacillus casei* and *L. gasseri*), consistency and sensory attributes (Safdari *et al.,* 2021; Wani and Dhanya, 2025).

2.4 Kiwi (*Actinidia deliciosa* A. Chev.)

Kiwi fruit by-products particularly skin and seeds are rich sources of bioactive compounds. Kiwi fruit skin contains high levels of vitamin E, anthocyanins, quinic acid, catechins and flavonoids, which exhibit strong antioxidant, anticancer and antibacterial activities (Alim *et al.,* 2019).

Kiwi seeds are a valuable source of proteins that may serve as an alternative to soy protein due to their improved digestibility and balanced amino acid composition. Extraction of kiwi seed oil has demonstrated multiple health promoting properties including antioxidant, antidiabetic and anti-obesity effects (Chamorro *et al.,* 2021). Additionally, kiwi fruit by-products can be utilized to obtain citric acid, pectin, phenolic compounds and actinidin. Citric acid is widely used as an acidulant and flavour enhancer in food and pharmaceutical applications, while actinidin, a cysteine protease is commonly employed as a natural meat tenderizer (Chamorro *et al.,* 2021).

Furthermore, the high dietary fibre and pectin content of kiwifruit support immune function and may help prevent chronic conditions associated with constipation by exerting a prebiotic effect on gut microbiota. Kiwi fruit has been shown to selectively stimulate beneficial lactic acid bacteria such as *Lactobacillus* and *Bifidobacterium,* while inhibiting *Clostridium* and *Bacteroides* species, highlighting its potential role in gut health (Ilie *et al.,* 2022).

2.5 *Citrus* L. fruits

Citrus processing generates substantial waste including pith, albedo, seeds and flavedo, which are rich in flavonoids, dietary fibre, citric acid, pectin, protein, cellulose, hemicellulose and lignin. These residues are widely utilized by the chemical and food industries for the extraction of citric acid, pectin, lignin and flavonoids, often using hydro alcoholic solvents (Marin *et al.,* 2007; Mahato *et al.,* 2018). Inedible citrus components can also be incorporated into value-added products such as herbal teas, medicinal decoctions for colds and digestive disorders and food products including ice cream and yogurt. Additionally, preservation of citrus with herbs such as ginger, rosemary and ginseng enhances flavour, aroma and nutritional value (Mahato *et al.,* 2018). Citrus peel pectin has gained importance in nanotechnology as an encapsulating agent, where polymer blends are used to improve stability and encapsulation efficiency (Panwar *et al.,* 2021). Citrus seeds are also recognized as potential sources of essential oils and proteins (Berk, 2016; Suri *et al.,* 2022).

Citrus peel is further utilized in the production of citrus infused olive oil enriched with bioactive compounds such as carotenoids, naringenin, tyrosol and hydroxytyrosol, which are associated with numerous health benefits (Ascrizzi *et al.,* 2018). With the global rise in neurodegenerative disorders, citrus polymethoxylated flavones and flavanones such as nobiletin, tangeretin, and hesperidin have attracted attention for their neuroprotective effects. Clinical studies indicate that flavonoids derived from citrus peels and extracts may improve cognitive function and reduce the risk of dementia and depression, highlighting their potential role in promoting cognitive health (Maqbool *et al.,* 2023).

2.6 Mango (*Mangifera indica* L.)

Mango by-products particularly the seed kernel and peel are valuable sources of functional compounds. Mango seed kernel fat is widely used as a cocoa butter equivalent due to its similar fat and triglyceride profile, while its phenolic constituents, including gallic acid, ellagic acid and gallates contribute to strong antioxidant activity (Sagar *et al*., 2018). Mango peel is rich in gallotannins, benzophenone derivatives and flavonol O- and xanthone C-glycosides, with kaempferol and quercetin as predominant flavonoids (Kabir *et al.,* 2017). Mango peel flour has been incorporated into bakery and pasta products such as cakes, breads, noodles and macaroni, improving cooking, nutritional and sensory qualities (Ajila *et al.,* 2010). The presence of gallate compounds in both peel and kernel further enhances radical scavenging activity, while extraction of carotenoids, phenolics, dietary fibre and vitamin C from mango by-products supports their use in nutraceutical and functional food applications (Jahurul *et al.,* 2015).

Mango peel powder (MPP) incorporated into noodles provides polyphenols, anthocyanins, flavonoids and carotenoids. Notably, MPP contains polyphenols with α-glucosidase inhibitory activity, which may help regulate postprandial blood glucose levels and contribute to antidiabetic effects (Kabir *et al.,* 2024).

2.7 Pineapple (*Ananas comosus* (L.) Merr.)

Pineapple processing generates substantial waste including the peel, core and crown, which contributes to environmental implications. To address this, pineapple by-products are increasingly utilized to produce ethanol, bromelain and the extraction of bioactive compounds (Polania *et al.,* 2022). Pineapple peel contains catechin and epicatechin, which help protect the skin from oxidative stress, inflammation and damage, while bromelain exhibits notable therapeutic properties. According to Polania *et al.* (2022), phenolic compounds extracted from pineapple waste demonstrate antioxidant, antiallergenic, antimicrobial, anti-inflammatory and antithrombotic activities and are commonly obtained using conventional solid-liquid extraction with organic solvents.

Phenolic acids such as caffeic, coumaric, ferulic and chlorogenic acids are abundant in pineapple peel and stem flours and are often bound to dietary fibre. During gastrointestinal digestion and fermentation, these bound phenolics are gradually released, creating a sustained antioxidant environment in the gut. This controlled release supports beneficial microbiota such as *Lactobacillus* and *Bifidobacterium* indicating prebiotic potential. The interaction between phenolics and fibre improves bioaccessibility and gut health and is associated with reduced risk of chronic conditions such as colon and cardiovascular diseases (Campos *et al.,* 2020). Additionally, pineapple pomace contains phenolics, tannins and alkaloids with anti-inflammatory and antioxidant properties that may help lower the risk of non-communicable diseases (Kumari *et al.,* 2020).

2.8 Dates (*Phoenix dactylifera* L.)

Date seeds are a notable natural source of bioactive compounds with strong antioxidant potential and have been investigated for their role in preventing metabolic, dermatological and neurological disorders. They exhibit inhibitory activity against tyrosinase and α-glucosidase, highlighting their relevance in cosmetic and antidiabetic applications (Djaoudene *et al.,* 2019). Date seed powder contains carotenoids, catechins, dietary fibre, alkaloids, anthraquinones, saponins, tannins and terpenoids, which are associated with reduced risk of cardiovascular disease, cancer and support immune function. Additionally, phytosterols derived from date seeds have demonstrated potential in managing hormone-related conditions (Allaqaband *et al.,* 2022).

Date fruits are also rich in bioactive compounds, including polyphenols, flavonoids, carotenoids, phytosterols, fatty acids, amino acids, vitamins and minerals, which contribute to antioxidant, anti-inflammatory, cardioprotective, neuroprotective and bone strengthening effects. Mechanistically, these phytochemicals inhibit inflammatory mediators such as TNF-α and IL-6, reduce amyloid-β plaque formation, modulate blood pressure through ACE-II inhibition, lower LDL cholesterol and support bone mineralization. Experimental studies indicate that dietary inclusion of dates or date seeds may enhance memory and cognition, reduce oxidative stress and hyperlipidaemia, prevent bone loss and support cardiac repair. These findings suggest that dates have strong potential as functional foods for age related conditions, although further clinical studies are required to confirm therapeutic applications (Albishi, 2024).

2.9 Papaya (*Carica papaya* L.)

Papain a proteolytic enzyme obtained from papaya latex has wide applications in the textile, pharmaceutical and food industries. In pharmaceuticals, papain is used to treat digestive disorders, support wound healing and assist in vaccine formulations for deworming livestock. In the food industry, it is commonly applied as a meat tenderizer and beer clarifier. Papaya seeds have demonstrated efficacy against helminthic infections and have been explored for potential applications in sickle cell anaemia and renal disorders, largely due to bioactive compounds such as carpaine (an alkaloid) and carpasemine (a glycoside) responsible for antihelminthic activity (Okeniyi *et al.,* 2007). Papaya seeds also contain carotenoids, phenolic acids, flavonoids, saponins, tannins and alkaloids associated with diverse biological activities (De Farmacia, 2021).

Abdel-Hameed *et al.* (2023) evaluated the physicochemical and antibacterial properties of papaya seed oil (PSO) and papaya seed powder (PSP) and their use as unconventional food ingredients in cupcakes. Using the well diffusion assay, PSP and PSO were tested against several pathogens, including *Salmonella typhimurium, Bacillus cereus, Staphylococcus aureus, Enterococcus faecalis, Pseudomonas aeruginosa, Vibrio fluvialis, Vibrio damsela,* and *Bacillus subtilis*, with PSP showing stronger antibacterial activity than PSO (Abdel-Hameed *et al.,* 2023). Unripe papaya powder (UPP), another processing by-product, contains phenolics, dietary fibre and antioxidants that inhibit cholesterol micellization and bind bile acids. Compared with wheat flour, UPP demonstrates superior hydration properties, reduces starch hydrolysis index in pancakes and increases resistant starch content, highlighting its potential as a functional ingredient (Joymak *et al.,* 2021).

2.10 Jackfruit (*Artocarpus heterophyllus* Lam.)

Jackfruit seeds are a valuable source of oil rich in linoleic and linolenic acids, which exhibit notable antioxidant activity against free radical oxidation (Kumoro *et al.,* 2020). The seeds also contain phenolic acids, flavonoids, tannins, gallic acid and stilbenes, along with essential minerals such as potassium, calcium, magnesium and sodium (Kumoro *et al.,* 2020). Jackfruit phytonutrients have demonstrated anticancer potential by neutralizing free radicals associated with chronic diseases. Saponins have shown anticancer effects by inhibiting colon cancer and inducing mitotic arrest in leukaemia cells, thereby supporting potential therapeutic applications (Oktavia *et al.,* 2017).

The peel, the major inedible portion of jackfruit is widely used for pectin extraction and is rich in calcium. Peel extracts exhibit higher total phenolic and flavonoid content than the pulp, seeds and flakes (Zhang *et al.,* 2017). Jackfruit shell has also been identified as a potential source of â-carotene, ascorbic acid and polyphenols such as catechin and chlorogenic acid (Sharma *et al.,* 2015). Additionally, jackfruit contains appreciable dietary fibre, which supports bowel regularity, prevents constipation and may help protect the colon mucosa by facilitating the removal of carcinogens (Amadi *et al.,* 2018; Shedge *et al.,* 2022).

2.11 Coffee (*Coffea arabica* L.)

Coffee processing generates husk as a major by-product, which varies in composition depending on the processing method. Husk from the dry method consists of skin, pulp, parchment and mucilage and is rich in insoluble fibre and phytochemicals such as anthocyanins and proanthocyanidins. In contrast, husk from the wet method mainly contains skin and pulp and is rich in phenolic acids (hydroxycinnamic acids), flavanols, flavonols and anthocyanidins. These bioactive compounds can be extracted for nutraceutical applications and dried coffee husk is already used as an infusion ingredient in non-alcoholic beverages (Rebollo-Hernanz *et al.,* 2023).

Bioactive compounds derived from coffee by-products have shown promising health benefits, particularly antioxidant activity, supporting their use in functional foods and nutraceuticals to meet increasing consumer demand for health-oriented products (Peluso, 2023). Abdel-Mohsen *et al.* (2023) reported hepatoprotective effects of aqueous extracts from phenolicrich green coffee beans against oxidative stress induced damage, highlighting the pharmacological potential of coffee residues. Additionally, caffeine present in coffee by-products exhibits antifungal and antibacterial properties (Dziki *et al.,* 2015).

3. Valorization of vegetable processing by-products

3.1 Potato (*Solanum tuberosum* L.)

Potato peels are the principal by-product of potato processing. They contain carbohydrates (notably starch), vitamins, minerals and phytochemicals such as carotenoids and phenolic compounds. Peels have been used as natural antioxidants to prevent lipid and protein oxidation in minced mackerel (Farvin *et al.,* 2012). Phenolics present include chlorogenic, gallic, protocatechuic and caffeic acids, which have antioxidant activity and potential tumor inhibiting and glycemic index lowering effects (Ezekiel *et al*., 2013). Potato peel extracts have also shown protective effects in biological systems, such as shielding erythrocytes from oxidative damage induced by ascorbate and $FeSO_4$ (Singh and Rajini, 2008). Bread enriched with potato peels have higher dietary fibre than standard wheat bread (O'Shea*et al.,* 2012).

3.2 Tomato (*Solanum lycopersicum* L.)

Tomato by-products typically comprise dried, crushed skins and seeds; 3 to 7% of raw material is lost as waste during juice pressing. Lycopene, the major carotenoid responsible for red color concentrates in the skin and is extracted effectively by supercritical CO_2 extraction. Lycopene intake is associated with reduced risk of prostate, pancreatic and stomach cancers. Lycopene is the most effective antioxidant with comparatively higher plasma levels than β-carotene (Machmudah *et al*., 2014). Ranveer *et al.* (2013) reported lycopene concentrations (μg/g dry weight): tomato peel (376), industrial processing waste (176), whole tomato (84) and pulp (48). Tomato by-products also contain lutein, an oxygenated pigment with antioxidant properties due to its conjugated polyene chain, contributing to free radical detoxification (Saini *et al.,* 2018). Incorporating tomato peel powder into fermented sausages raises lycopene content (Calvo *et al.,* 2008). Tomato pulp has been used as a thickener in ketchup to maintain color and texture, potentially substituting hydrocolloids (Farahnaky *et al.,* 2008).

3.3 Onion (*Allium cepa* L.)

Industrial peeling of onion (*A. cepa*) bulbs yields by-products such as brown skin, outer fleshy leaves and bulb tops or bottoms that are rich in flavor compounds, fibre and particularly quercetin glycosides (Sharma *et al.,* 2016). Major flavonoids in mature bulbs are quercetin 3,4-diglucoside and quercetin 4-O-monoglucoside, constituting over 85% of total flavonoids. Quercetin from onions is rapidly absorbed and slowly eliminated, contributing to antioxidant defense (Azeem *et al*., 2023). Onion flavonoids have been associated with anti-inflammatory, cardioprotective and anticancer effects and some anti-HIV activity. Organosulfur compounds present in onion by-products further add pharmacological interest, underlining the underutilized potential (Lanzotti, 2006).

3.4 Carrot (*Daucus carota* L.)

Carrot (*D. carota*) pomace is a natural source of α- and β-carotene and can serve as a nutraceutical and functional ingredient. Pomace has been incorporated into beverages to raise phenolic content (O'Shea *et al.,* 2012). Unlike fruit pomaces that may contain seeds, carrot pomace can be added to products without adverse functional or flavor effects while retaining phytochemicals, making it an attractive ingredient (Chantaro *et al.,* 2008).

3.5 Cauliflower (*Brassica oleracea* L. var. *botrytis*)

Cauliflower is rich in glucosinolates, flavonoids and phenolic acids. Glucosinolates have been linked to reduced tumor incidence in reproductive organs and the inhibition of breast cancer cell growth. Cauliflower by-products such as stems, contain significant phytochemical levels similar to other fruits and vegetables (Ahmed and Ali, 2013).

3.6 Olive (*Olea europaea* L.)

Olive oil extraction produces black water or vegetation water containing olive husk (skin and stones). The husk can be reprocessed to extract olive husk oil. Olive mill wastewater is rich in hydroxytyrosol derivatives, potent scavengers of superoxide radicals and have potent antitumor property (Visioli *et al.,* 2000; Imran *et al*., 2018). Valorizing olive processing waste focuses on recovering bioactive from wastewater. Various technologies for extracting fine chemicals and producing enzymes have been evaluated (Federici *et al.,* 2009). Ramos *et al.* (2013) examined the phenolic composition, antioxidant and antiproliferative activity of methanol/water extracts from olive pomace and dry olive mill residue.

3.7 Avocado (*Persea americana* Mill.)

Avocado peels and seeds, often treated as waste are sources of bioactives with anti-inflammatory, antioxidant, antithrombotic, neuroprotective and cardioprotective effects. Identified phenolics in avocado by-product extracts include epicatechin, procyanidin B_2, 5-O-caffeoyl-quinic acid, procyanidin trimers, kaempferol and quercetin derivatives, myricetin 3-rhamnoside, gallic and chlorogenic acids (Zaki *et al.,* 2020). Avocado seed extracts have been shown to lower triglycerides, blood pressure and glycemic levels suggesting benefits for cardiovascular health and cholesterol reduction (Marra *et al.,* 2024).

3.8 Garlic (*Allium sativum* L.)

Garlic by-products are processed into powders, granules, minced or chopped fractions, extracts and oils for industrial use. Rising global interest in garlic derivatives is driven by bioactive compounds that support medicinal and functional benefits. Regions with advanced processing facilities convert raw garlic into products such as freeze dried extracts, essential oils, black garlic and dehydrated powders. Market drivers include sustainable processing and bio-waste valorization. Garlic bioactives confer antioxidant, anti-inflammatory, antimicrobial and cardioprotective activities. Extraction techniques like supercritical fluid extraction (SFE) and ultrasound-assisted extraction (UAE) have improved bioavailability and stability of these compounds (Jain *et al.,* 2025).

4. Extraction of bioactive compounds

Various extraction approaches are employed to recover bioactive compounds from fruit and vegetable by-products and the choice of method depends on the desired purity, physicochemical characteristics of the target compounds, their localization within the plant matrix (free or bound), cost effectiveness and intended end use. Prior to extraction, pretreatment operations such as washing, cutting, size reduction and drying are essential to enhance extraction efficiency and yield by increasing surface area and improving solvent penetration (Gong *et al.,* 2020; Patra *et al.,* 2022). Traditional extraction methods are generally time consuming and solvent intensive; therefore, modern techniques including solvent extraction, enzyme-assisted extraction, ultrasound-assisted extraction, microwave-assisted extraction and supercritical fluid extraction are increasingly adopted due to their improved efficiency, selectivity and reduced processing time (Belwal *et al.,* 2020; Patra *et al.,* 2022).

The primary objectives of extraction include isolating target bioactive from complex plant matrices, enhancing the selectivity of analytical methods improving the sensitivity of bioassays by concentrating the compounds of interest, converting bioactives into forms suitable for detection and separation and ensuring reproducible and robust procedures independent of matrix variability. In solvent based extraction, the process generally follows four key mechanisms: solvent penetration into the solid matrix, dissolution of target compounds in the solvent, diffusion of solubilized compounds out of the matrix and collection of the extract for further processing (Azmir *et al.,* 2013). These optimized extraction strategies are essential for the effective valorization of food processing by-products into nutraceutical and functional ingredients.

4.1 Supercritical fluid extraction (SFE)

To avoid degradation of thermo labile compounds, supercritical fluid extraction (SFE) has gained popularity as a green extraction technology. SFE is an advanced extraction method typically operated at pressures of 200 to 400 bars and temperatures of 40 to 60°C (Pinto *et al.,* 2020). A substance becomes supercritical when temperature and pressure exceed its critical point (Tc, Pc), where distinct liquid and gas phases no longer exist. Supercritical fluids combine liquid like density and solvating power with gas like diffusivity, low viscosity and low surface tension, enabling rapid mass transfer and higher extraction efficiency (Azmir *et al.,* 2013).

Among supercritical fluids, carbon dioxide (CO_2) is the most widely used solvent for food and nutraceutical applications due to its non-toxicity, non-flammability, low cost and easy removal from extracts. CO_2 possesses a relatively low critical pressure (74 bar) and critical temperature (31°C), allowing extraction under mild conditions that preserve heat sensitive bioactive compounds (Azmir *et al.,* 2013). However, the low polarity of supercritical CO_2 limits the extraction of polar compounds; therefore, small amounts of food grade co-solvents such as ethanol or water are often added to enhance solvent polarity and improve extraction efficiency.

SFE has been successfully applied to obtain fatty acid rich oils from food processing by-products. For instance, guava seed oil extracted using SFE contained high levels of linoleic and oleic acids along with bioactive compounds such as phytosterols and tocopherols (Narvaez-Cuenca *et al.*, 2020). Pumpkin seed oil obtained by SFE under optimized conditions showed higher yields of linoleic, oleic and linolenic acids compared with ultrasound-assisted extraction using n-hexane (Cuco *et al.*, 2019). Similarly, SFE has produced higher oil yields from apple seeds than Soxhlet extraction. Overall, SFE is increasingly recognized as a sustainable and efficient technique for recovering lipophilic bioactive compounds from food by-products. Compared with conventional solvent extraction, SFE offers higher selectivity, shorter extraction times and solvent free extracts making it highly suitable for food, nutraceutical and pharmaceutical applications.

4.2 Subcritical fluid extraction

Subcritical fluid extraction has become a more affordable green alternative because supercritical fluid extraction can be expensive. In subcritical extraction, the solvent is maintained between its boiling point and critical point. Among subcritical techniques, subcritical water extraction (SWE) is widely used as a green method because water is non-toxic, inexpensive, readily available and eliminates the need for organic solvents.

Under subcritical conditions (typically 100 to 250°C under sufficient pressure to maintain the liquid state), the physicochemical properties of water change significantly. Increasing temperature reduces water's dielectric constant, viscosity and surface tension, allowing it to behave like an organic solvent and improving the solubility of moderately polar and non-polar compounds. These changes enhance mass transfer and promote extraction through convection, diffusion and partitioning mechanisms. Despite its advantages, SWE may cause degradation or hydrolysis of heat sensitive compounds such as pectin under severe conditions (Essien *et al.,* 2020).

In addition to water, subcritical propane extraction has gained attention as a green technique for oil recovery because propane is a low toxicity solvent that can be easily removed after extraction and is considered a safer alternative to conventional organic solvents used in oil extraction (Azmir *et al.,* 2013).

4.3 Microwave assisted extraction

Microwave-assisted extraction (MAE) employs microwave radiation to transfer soluble compounds into a solvent from diverse matrices. Microwaves (300 MHz-300 GHz) generate oscillating electric and magnetic fields, where ionic conduction and dipole rotation convert electromagnetic energy into heat (Tripti Jain *et al*., 2009). Heat is generated due to resistance of the medium to ion movement and collisions caused by rapidly changing field directions. The MAE extraction mechanism involves: (1) Solute separation from active sites under elevated temperature and pressure, (2) Solvent penetration into the matrix, and (3) Mass transfer of solutes from the matrix into the solvent (Alupului, 2012).

MAE is considered a green extraction technique because it significantly reduces extraction time, solvent consumption and energy use compared with conventional extraction methods. In food applications, solvents such as water and ethanol are commonly preferred due to their safety and environmental compatibility. For example, avocado seed residues rich in phenolic acids, procyanidin dimers, epicatechin and catechin showed maximum recovery using MAE with ethanol (71.64°C, 14.69 min), while acetone was also effective under optimized conditions (Araujo *et al*., 2020). Similarly, pineapple peel pectin and polyphenols were efficiently extracted by MAE at 420 W for 30 min compared with 60 min required for conventional extraction (Rodsamran and Sothornvit, 2019).

4.4 Ultrasound assisted extraction (UAE)

Ultrasound-assisted extraction (UAE) uses sound waves (20 to 100 kHz) to generate acoustic cavitation and enhance mass transfer between plant matrices and solvents (Belwal *et al*., 2020; Saifullah *et al*., 2020). Cavitation involves the formation, growth and implosion of microbubbles during alternating compression and rarefaction cycles, which disrupts cell walls, improves solvent penetration and facilitates the release of intracellular compounds (Grassino *et al*., 2020).

UAE is considered a green extraction technique because it operates at lower temperatures, reduces solvent consumption and shortens extraction time compared with conventional methods. In food and nutraceutical applications, water and aqueous ethanol are commonly used as environmentally friendly solvents. Optimization of solvent type, temperature and extraction time has improved the recovery of anthocyanins and phenolics from grape peel (Ghafoor *et al*., 2011). Similarly, UAE outperformed conventional and soxhlet extraction for jamun seed powder, yielding bioactive compounds with 1.2 fold higher antioxidant activity under optimized conditions (Mahindrakar and Rathod, 2020).

4.5 Enzyme assisted extraction (EAE)

Some phytochemicals are tightly bound to plant cell walls and resist conventional extraction; therefore, enzyme assisted extraction (EAE) is used to improve the release of bioactive compounds. Enzymes such as cellulase, α-amylase, protease and pectinase hydrolyse structural components of the lignocellulosic cell wall matrix, breaking glycosidic and proteolytic bonds and facilitating the liberation of target compounds (Grassino *et al*., 2020). EAE is considered a green extraction technique because it operates under mild conditions, reduces solvent consumption and employs biodegradable, food grade catalysts.

Two main EAE approaches are enzyme-assisted aqueous extraction (EAAE) and enzyme-assisted cold pressing (EACP). EAAE is widely used for oil and bioactive compound extraction using water as the extraction medium, while EACP involves enzymatic pretreatment of seeds prior to mechanical pressing, providing a non-flammable and non-toxic alternative to solvent-based extraction. Enzyme application significantly increased phenolic antioxidant recovery from raspberry processing waste compared with non-enzymatic controls (Laroze *et al*., 2010). Gomez-Garcia *et al*. (2012) reported Novoferm as the most effective enzyme among those tested for releasing phenolics from grape waste. Similarly, pectin extraction from passion fruit peel using protopectinase achieved a 40% higher yield than chemical extraction under optimized conditions (Vasco-Correa and Zapata, 2017). Xu *et al*. (2014) demonstrated that enzyme combinations (cellulase, pectinase and β-glucosidase) produced higher yields of pectin and phenolics from grape peel in shorter extraction times compared with conventional solvent extraction.

4.6 Pulsed electric field assisted extraction (PEF)

Pulsed electric field assisted extraction (PEF) is an environmentally friendly, non-thermal technique characterized by low energy consumption and minimal solvent use (Andreou *et al*., 2020). The process is based on electroporation, where short high voltage pulses create nanopores or micropores in cell membranes, facilitating the release of intracellular bioactive compounds. Electric pulses promote the migration of ions and molecules toward the cell membrane, thereby enhancing mass transfer and extraction efficiency (Patra *et al*., 2022).

PEF is often applied as a pretreatment prior to conventional or green solvent extraction to improve yield and reduce processing time. Studies on apple peels showed that extraction efficiency depends on electric field intensity and the cell disintegration index, with higher intensities (*e.g.,* 1200 V/cm) significantly improving soluble matter recovery (Wang *et al*., 2020). Guderjan *et al*. (2005) reported that PEF pretreatment increased phytosterol recovery from maize by 32.4% and isoflavonoid recovery from soy by 20 to 21%. Patra *et al.* (2022) demonstrated that using PEF on grape by-products not only boosts anthocyanin extraction but also, when applied prior to maceration, reduces required maceration time and enhances the stability of anthocyanins and polyphenols throughout the vinification process.

4.7 Pressurized liquid extraction

Pressurized liquid extraction (PLE), also known as highpressure solvent extraction (HSPE), enhanced solvent extraction (ESE), accelerated solvent extraction (ASE) or pressurized fluid extraction (PFE), is a green extraction technique that uses elevated pressure to maintain solvents in the liquid state above their normal boiling points (Li *et al.*, 2022). The application of high pressure and temperature enhances solubility and mass transfer while reducing solvent viscosity and surface tension, thereby accelerating extraction. Automation further reduces extraction time and solvent consumption. Using this technique, anthocyanins can be extracted within minutes (Herrero *et al.*, 2012).

PLE significantly reduces solvent consumption and extraction time compared with Soxhlet extraction and is considered an effective alternative to supercritical fluid extraction for polar compounds (Rehman *et al.*, 2020). Importantly, PLE is compatible with water and aqueous ethanol, making it suitable for food and nutraceutical applications. The technique has been applied to extract heat stable organic contaminants from environmental matrices and bioactive compounds from marine sponges (Montero *et al.*, 2023). PLE is widely regarded as a green extraction technology due to its efficiency and reduced requirement for hazardous organic solvents. For instance, adapted PLE outperformed hot solvent extraction, MAE and UAE in extracting lycorine and galanthamine from *Narcissus jonquilla*. Under optimized conditions (40°C, 1500 psi, 15 min), phenolic compounds such as gallocatechin, catechin, epicatechin gallate, caffeic acid, chlorogenic acid and myricetin were successfully recovered from *Anatolianpropolis* (Patra *et al.*, 2022). Overall, pressurized liquid extraction represents a rapid, efficient and environmentally friendly technique for the recovery of polar and semi polar bioactive compounds from food and agro industrial by-products. Compared with conventional solvent extraction, PLE offers improved extraction efficiency, reduced solvent consumption and shorter processing time.

4.8 Combination of extraction processes (CE)

Combination of extraction processes has emerged as an effective strategy to overcome the limitations of individual extraction techniques. Integrating multiple methods can shorten extraction time, improve mass transfer, enhance yield and reduce solvent and energy consumption. In many cases, agro-industrial by-products are first pretreated using enzymes, microwaves or ultrasounds to disrupt cell walls and increase solvent accessibility prior to the main extraction step. Common hybrid approaches include SFE combined with UAE, MAE coupled with solvent extraction, enzyme pretreatment followed by PEF and sequential processes such as SFE followed by MAE or conventional solvent extraction (Patra *et al.*, 2022). Such integrated processes are increasingly applied to improve the efficiency of bioactive compound recovery from food processing by-product (Table 1).

Table 1: Comparision of green extraction techniques

Techniques	Recovery efficiency	Environmental impact	Economic feasibility	Industrial scalability	Limitations	References
Ultrasound-assisted extraction (UAE)	High yield due to cell disruption by cavitation	Very low solvent and energy requirement	Medium cost; equipment relatively simple	High potential for scaleup	Less effective for very large particle matrices	Chemat *et al.*, 2017
Microwave-assisted extraction (MAE)	Very high due to fast internal heating	Reduced solvent consumption	Moderate investment cost	Moderate scala-bility	Risk of degradation of heat sensitive compounds	Picot-Allain *et al.*, 2021
Supercritical CO_2 extrac-tion (SFE)	Excellent selectivity and purity of extracts	Environmentally benign solvent (CO_2)	High capital and operating cost	Moderate scalability	Requires high pressure and speci-alized equipment	Picot-Allain *et al.*, 2021
Enzyme-assisted extraction (EAE)	High due to targeted cell wall break-down	Biodegradable and eco-friendly process	Enzyme cost increases processing expenses	Moderate industrial feasibility	Longer processing time and enzyme stability issues	Patra *et al.*, 2022
Pressurized liquid extra-ction (PLE)	High extraction efficiency with less solvent	Reduced solvent usage and faster processing	Moderate cost	Good potential for industrial adoption	Elevated tempera-ture affects heat-sensitive compounds	Picot-Allain *et al.*, 2021
Combination extraction techniques	Very high due to synergistic effects	Lower energy and solvent requirements	Moderate cost with optimi-zation	Emerging industrial application	Process optimiza-tion still required	Rutkowska *et al.*, 2017

5. Economic and environmental benefits

Zero waste food production is founded on the premise that resource use and economic growth can be partially decoupled through integrated farming systems. This approach enhances resource efficiency through business models that conserve materials, increase production efficiency and recycle waste streams. For example, a closed loop system integrating aquaculture, composting and organic vegetable cultivation in straw bales created a regenerative industrial flow that converts residues into higher-value products (Nenciu *et al.*, 2022).

Such systems provide significant economic and environmental benefits, including a 12% increase in energy efficiency, an 18% rise in food output and a 25% reduction in operating costs. They also reduce aquaculture impacts on water bodies, mitigate eutrophication and transform non-value residues into nutrient sources, thereby promoting industrial symbiosis and sustainable agriculture (Nenciu *et al*., 2022). Zero waste processing further lowers greenhouse gas emissions and resource losses by minimizing disposal costs and improving machinery efficiency (Kumar *et al*., 2022).

Conversely, poorly managed food processing by-products can cause aquatic toxicity, water contamination, soil phytotoxicity and foul odors due to high organic load and microbial instability. Valorization of these residues offers an environmentally sound waste management strategy by converting them into functional food ingredients and bioactive compounds. This process enables the recovery of proteins, polysaccharides, dietary fibres and phytochemicals for use in food and pharmaceutical applications, thereby reducing reliance on fresh raw materials and supporting a circular food economy (Boruah and Ray, 2024). Overall, zero waste food production and by-product valorization represent key pillars of sustainable food systems. By transforming waste streams into value-added ingredients, these approaches simultaneously address environmental concerns, improve economic efficiency and support the development of functional foods. Consequently, integrating circular economy principles into food processing is increasingly recognized as essential for future sustainable and resilient food production systems.

6. Conclusion

Zero waste food production valorizes by-products into nutritionally valuable products such as nutraceuticals and functional food ingredients. Zero waste processing reduces environmental disposal of food waste reduces biogas emissions and supports sustainability. By-products are transformed into functional ingredients and bioactive compounds. Extraction of these bioactives from industrial food waste preferentially employs green techniques supercritical fluid extraction, enzyme assisted extraction, ultrasound assisted extraction, microwave assisted extraction and combined extraction processes. These methods use solvents to separate bioactives from biological matrices and should aim for maximal recovery. Extracted compounds can be formulated as supplements, integrated into functional foods or incorporated into other products to enhance nutritional value. Utilizing agricultural by-products increases production efficiency and advances sustainability.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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