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Valorization of Fruit and Vegetable Waste as Functional Ingredients: A Comprehensive Review across Different Sectors

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***Abstract*: Fruit and vegetable wastes (FVWs) are rich sources of valuable bioactive compounds, including antioxidants, phenolic compounds, dietary fibres, vitamins, proteins, lipids, and minerals. These constituents possess significant nutritional and health-promoting properties and have considerable potential for application in the development of functional foods, nutraceuticals, and food additives. Food processing industries generate substantial quantities of waste and by-products that remain under-utilized despite their high content of valuable bioactive components. This has stimulated growing interest in sustainable technologies for the efficient recovery and utilization of these compounds. This review examines the composition and nutritional potential of bioactive compounds present in various fruit and vegetable wastes. It highlights strategies for the valorization of FVWs through their incorporation into food products to improve nutritional quality and functional properties. Furthermore, this review discusses the current applications of fruit and vegetable waste (FVW) derived ingredients across a wide range of sectors, including the food, bakery, meat, pharmaceutical, cosmetic, and packaging industries. In addition, it addresses key challenges associated with their utilization, such as economic feasibility, sensory acceptability, processing constraints, and food safety considerations. Overall, the review emphasizes the sustainable utilization of fruit and vegetable processing waste as a valuable source of health-promoting compounds, contributing to waste reduction, environmental sustainability, and the development of value-added products.**

Keywords: Antioxidants, bioactive compounds, dietary fibre, fruit and vegetable waste, value addition

I. INTRODUCTION

About one-third of the food produced for human consumption is either lost, or is wasted, which leads to an economic loss of approximately $940 billion annually. This inefficiency aggravates food insecurity, consumes a quarter of agricultural water, requires land equivalent to the size of China, and contributes 8% to global greenhouse gas emissions [1]. Thus, conserving food is essential to reduce cost of production, increase the efficiency of the food system, improve food security and nutrition, and to ensure environmental sustainability. Report on Sustainable Development Goal (SDG Target 12.3), evaluates efforts to halve the global food waste among retailers and consumers and reduce food losses in production and supply chains by 2030[2]. Addressing food waste effectively requires coordinated actions across all levels of the food system, from production to consumption.

India ranks as the second-largest producer of vegetables and fruits globally, with its food processing industry projected to reach $535 billion by 2025-26[3]. Despite this impressive production capacity, a significant challenge persists in the form of food loss and waste resulting from biotic factors. This waste is generated from unutilized parts of living organisms such as pulp (pomace), peel/skin, seeds, stems, husks, rinds, and other organic and inorganic materials. In developing countries, including India, the lack of appropriate processing technologies leads to more than 50% of nutritional components being wasted. The food production and processing sectors generate substantial waste, with 25–30% of fruit processing output discarded annually. This amounts to over 100 billion tons of vegetable and fruit waste. The high moisture content of this waste prevents incineration, contributing to environmental pollution [4]. The World Wildlife Fund 2021[5] estimated that global food waste amounts to approximately 2.5 billion tonnes annually, which is about 1.2 billion tonnes higher than earlier estimates [6]. Effective utilization and conversion of this waste into useful products is essential. The sheer volume of byproducts generated presents a significant global challenge, necessitating innovative solutions to mitigate environmental impacts and enhance sustainability. Food waste encompasses various items, including cereals like rice and wheat, whose processing produces brans, husks, stems, and leaves that can be repurposed as fertilizers, building materials, or fibre additives.

Innovative strategies such as microbial fermentation, single-cell protein production, microbial oil production, volatile fatty acid production, and enzyme production offer promising alternatives to conventional landfilling methods for mitigating the negative impacts of food waste [7,8]. Among these approaches, the valorisation of food waste through the recovery of bioactive compounds has emerged as an effective pathway for generating value added products with significant health and economic benefits (Figure 1). Although food waste can provide an ideal environment for the growth of pathogens and other microorganisms, leading to environmental pollution and public health concerns, it also represents a rich source of valuable biomaterials, including proteins, lipids, phytochemicals, minerals, micronutrients, and dietary fibre [9]. These compounds can be extracted and utilized as functional ingredients in food, nutraceutical, and pharmaceutical applications. In particular, the recovery of dietary fibre from fruit and vegetable waste has gained considerable attention due to its well-established health benefits and therapeutic potential. Fruit-processing by-products such as peels, pomace, and pulp from apples, grapes, cherries, citrus fruits, pineapples, and guavas are abundant sources of dietary fibre, while fruit and vegetable processing residues are also rich in bioactive compounds such as antioxidants, phenolics, flavonoids, and carotenoids [10]. These compounds can enhance the nutritional quality and functional properties of food products. Consequently, numerous studies have focused on converting agri food and food processing by products into high-value dietary fibre and other functional ingredients, thereby reducing food waste, minimizing environmental impacts, and supporting the transition toward more sustainable and circular food systems.

Several extraction techniques have been developed to isolate these bioactive compounds. These wastes can be utilized in the food industry through technologies like supercritical fluid extraction (SFE), ultrasonic-assisted extraction (UAE), high hydrostatic pressure (HHP), and microwave-assisted extraction (MAE) [11,12]. Nowadays, green extraction techniques, such as nano-emulsions, are also used to enhance the yield [13-14]. Dietary fibre concentrates retrieved from the by-products of agricultural industry have shown practical characteristics and applications as carriers for probiotics. Green extraction techniques to obtain bioactive compounds, from fruit and vegetable waste have proven effective. Additionally, bio-refinery methods such as anaerobic digestion (AD), fermentation, hydrothermal carbonization, and pyrolysis can convert these wastes into biofuels [15]. Over the past decade, a diverse range of by-products have been generated from these bio-wastes, creating a huge market. Some of these co-products are used as biofuels: biogas and bioethanol are used as energy sources in the fuel industry. Enzymes and Nutraceuticals are also extracted from them. Nowadays, several biodegradable products such as bio-plastics, bio-pesticides, bio-fertilizers, bio-surfactants, and bio-fabrics are being developed and used by various industries such as packaging, fertilizers, apparel, and cosmetics.

Over the past four decades, numerous studies have demonstrated the significant health benefits of dietary fibre, including its role in reducing the risk of hypertension [16], diabetes [17-18], colon cancer, constipation, irritable bowel syndrome, and cardiovascular diseases [19-20]. Consequently, nutritionists and regulatory agencies recommend a daily dietary fibre intake of 25–35 g for a 2,000-kcal diet, or approximately 14 g per 1,000 kcal. Fruit and vegetable processing wastes represent abundant sources of dietary fibre, polyphenols, carotenoids, and other bioactive compounds that can be utilized to enhance the nutritional and functional properties of food products. The incorporation of these by-products into food formulations can improve physicochemical, microbial, sensory, and textural characteristics, particularly in meat products, by inhibiting oxidation and microbial growth, thereby extending shelf life. As the food industry increasingly seeks innovative and sustainable ingredients, the development of value-added products from fruit and vegetable waste presents a promising opportunity. Such ingredients not only contribute to improved nutritional quality but also offer economic and environmental advantages through efficient resource utilization, enhanced product functionality, and reduced food waste.

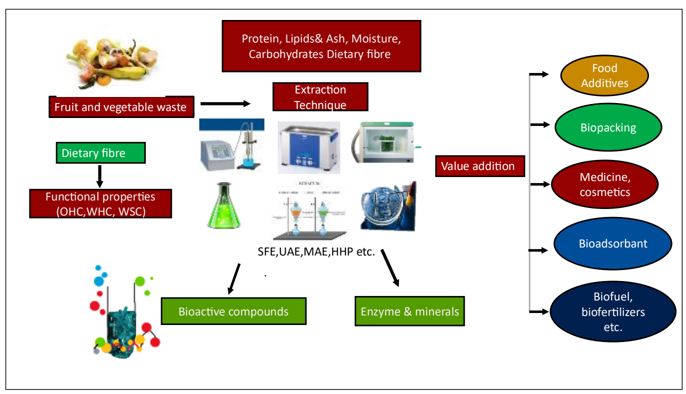

Figure 1: Extraction of FVWs and development into value-added products

Analysis and Properties of FVWs

Fruit and vegetable wastes (FVWs) is an important by-product of the food industry, which is often disposed off in landfills, leading to pollution of the environment. However, these wastes have large quantities of bioactive compounds, particularly antioxidants, antimicrobial and phenolic compounds which have numerous health benefits. Common bioactive compounds found in FVW include Catechin – a strong antioxidant, protects from inflammation and cardiovascular diseases; Cyanidin-3-glucoside – supports eye health; Epicatechin – improves blood flow besides having antioxidant and anti-inflammatory properties; Galangin – antimicrobial properties; Gallic acid – help against cancer; Kaempferol – anti-inflammatory, anticancer properties; and Chlorogenic acid – regulates blood sugar levels and supports weight management [21].

Antioxidants

Antioxidant molecules (such as Catechin, Epicatechin, Gallic acid, etc.) help our immune system by shielding it from oxygen-free radicals that cause oxidative stress, which is associated with a variety of chronic and degenerative disorders. Their primary tasks include scavenging reactive cellular species, protecting lipids, proteins, and nucleic acids, and ultimately hindering cell disintegration [22]. Key antioxidant components include phenolic compounds, carotenoids, and vitamins C and E. For the antioxidant activity, three different analytical assays were used (ABTS, DPPH, and FRAP). In ABTS (2,2′-azino-bis- (3-ethylbenzothiazoline-6-sulfonic) acid assay, antioxidant sample reduces the ABTS radical to its colourless form and the extent of decolourization is measured. DPPH (α, α-diphenyl-β-picrylhydrazyl) assay measures the ability of antioxidant to reduce DPPH radical from deep violet to yellow coloured compound. In FRAP (Ferric Reducing Antioxidant Power), antioxidants reduce Fe^{3+} to Fe^{2+}. Change in colour due to formation of ferrous complex is a measurement of amount of antioxidant. Fruit and vegetable wastes, such as grape seeds and buckwheat hulls, are rich sources of polyphenol content and exhibit strong antioxidant activity [23-24].

The citrus sector generates a significant quantity of residues from seeds and peels. These leftovers make up almost half of the fruit in its whole and are a significant source of flavonoids, vitamin C and phenolic compounds. Apple pomace contains significant amounts of polyphenols and flavonoids, and grape pomace is known for its resveratrol, catechins, and proanthocyanidins content. Flavonoids (flavonols, flavanones, flavones, flavanonols, isoflavones, flavanols, and anthocyanidins), stilbenes, and lignans were identified in various fruit wastes, with the greatest phenolic concentration found in grape, apple, pomegranate, and citrus (lemon, orange) wastes, and vegetables like tomato, lettuce, coriander, olive and white goosefoot (sticks). Mango peel and sweetsop peel contain high amounts of total phenolic content (TPC), and seeds of various fruits like grapes, avocado, and mango have the highest TPC. Furthermore, the phenolic content of the peels of several fruits, including pomegranates, bananas, pears, apples, and peaches, is higher than that of the edible parts [25]. The main phytochemicals present in banana peels are Epicatechin, Gallocatechin, and Catechin.

Pomegranate juice production generates waste high in Ellagitannins, Punicalin, and Punicalagin, all of which have strong antioxidant properties [26]. Similarly, apple peels are rich in polyphenols and possess antibacterial, anticancer, and cardio-protective qualities [27]. The antioxidant, and antibacterial activities of the peels of sweet orange (*Citrus sinensis*) and pomegranate (*Punica granatum*), and mineral content have been studied, showing antimicrobial effects against various microbes such as *Pseudomonas aeruginosa, Escherichia coli, Serratia marcescens, Staphylococcus aureus, Bacillus cereus, Bacillus subtilis,* and *Klebsiella pneumoniae* [28]. Natural phenolic compounds and carotenoid derivatives are increasingly being used as additives for the functionalization of materials intended for applications in the cosmetic industry and biomedicine. The flavonoid and total phenolic contents of onion skins from 15 Indian cultivars were evaluated. [29].

Antimicrobial Compounds

In the food industry, preventing microbial spoilage, enhancing nutritional value, and expanding the shelf life of food products is crucial. There is growing interest in natural antimicrobials, such as extracts and powders as a food processing by-product, fruit and vegetable peels, spices, herbs, and flowers, due to their bioactive compounds [30-31]. These natural antimicrobials can improve the shelf life and quality of bakery, meat, and dairy products while also boosting their nutritional value. However, the effectiveness and sensory impact of natural antimicrobials must be carefully considered [32-33].

The antimicrobial activity of fruit and vegetable waste is attributed to bioactive compounds like polyphenols, flavonoids, and essential oils. For instance, compounds such as catechins, epicatechins, gallic acid, and procyanidins in grape waste, and apigenin, catechin, and quercetin in other wastes, are key antimicrobial agents [34]. Extracts from orange, yellow lemon, and banana peels exhibit significant antimicrobial activity, with yellow lemon peel showing the highest effectiveness, particularly against gram-negative bacteria like Klebsiella pneumoniae. Pineapple, jackfruit, durian, coffee, mangosteen, and cacao pod peels, as well as certain vegetable wastes, demonstrate robust antimicrobial properties against both gram-negative and gram-positive bacteria [35].

Grape industry by-products and banana peel extracts both have promising potential in inhibiting pathogenic food-borne bacteria due to their bioactive compounds. Grape pomace, seeds, and skins, which are by-products of winemaking, contain high levels of polyphenols, flavonoids, and tannins which possess strong antimicrobial and antioxidant properties [36]. Studies indicate that extracts from grape by-products can inhibit the growth of various pathogenic bacteria, such as *E. coli, Listeria,* and *Salmonella*. Banana peels are rich in bioactive phytochemicals, including carotenoids, phenolic compounds, and flavonoids. Research has demonstrated that banana peel extracts can effectively inhibit the growth of common food-borne pathogens like *Staphylococcus aureus* and *Pseudomonas aeruginosa*. Additionally, potato peel extract shows antifungal activity along with antimicrobial properties [37]. Jabuticaba waste extracts, rich in anthocyanins, and grape residue, high in antimicrobial phytochemicals, show potential for application in meat products, inhibiting various bacterial strains without affecting sensory qualities [38]. The use of these natural by-products could offer a sustainable and eco-friendly alternative to synthetic preservatives in the food industry.

Dietary Fibre

Dietary fibre is the indigestible fraction of plant material, including hemicellulose, pectin compounds, cellulose, mucilages, gums, and lignin. Based on solubility, dietary fibre is classified into two primary groups: insoluble dietary fibre (IDF) and soluble dietary fibre (SDF). IDF includes lignin (found in vegetables and aromatic alcohols), hemicellulose (present in wheat bran and grains), and cellulose (in root vegetables). SDF includes gums (from legumes and beans), pectin (in legumes and grains), and mucilage [39]. SDF dissolves in water, forming a gel-like substance that slows digestion and helps control blood sugar levels. IDF promotes regular bowel movements by increasing stool volume. Both types of fibre are vital for gut health and the prevention of chronic illnesses [40]. The functionality of dietary fibre is described in Table 1. Dietary fibres can be extracted via physical methods such as high hydrostatic pressure and high-pressure homogenization, as well as chemical and enzymatic methods. The type and quantity of fibre depend and may vary on the basis of food source and the unutilized portion of waste. For example, banana peel has a high content of insoluble dietary fibre, which has desirable qualities like the ability to hold water, oil, and glucose [41].

TABLE 1
Sources and functionality of Dietary fibre developed by food variable wastes [45,46]

Dietary fibre	Features	Sources	Functionality
Soluble fibre			
Pectin	It is galacuronic acid, rhamnose, arabinose and high content of galactose	Whole grains, apples, legumes, cabbage, root vegetables	Lower cholesterol, hypoglycemic effect
Gum	Monomers of hexose and pentose	Oatmeal, legumes and haricot beans carrots, Strawberries	Adhesive, delayed digestion and absorption and fermentation by gut bacteria
Mucilages	Compounds which is synthesized in plants that it is contain of glycoprotein	Food additives, fennel seeds Psyllium seed	Regulate blood glucose, lower cholesterol and detoxifiers
Beta glucan		Oats, barley, mushrooms	Reduces cholesterol levels, enhances immune function, and supports gut health through fermentation.
Inulin	β-1-2 fructans residues backbone	Chicory root, garlic, onions, leeks, asparagus	Acts as a prebiotic, aids in calcium and magnesium absorption, and contributes to improved blood sugar control.
Psyllium		Psyllium husk, seeds of Plantago ovata	Reduces cholesterol levels, helps manage blood glucose levels,
Oligofructose	β-Fructo-oligosaccharides (FOS), α-galactooligosaccharides (GOS),	Chicory root, Jerusalem artichokes, onions	Manage sugar level, gut health
Insoluble Fibre			
Cellulose	Indigestible dextrins Waxes	Whear flour, Cabbage, Peas, Apples, Carrots, unprocessed bran	Food additives, medicine,bio-adsorbents, thickening agent
Lignin		Bran cereals, green beans, radishes, Eggplant	Bioplastics, biofuels, food packing, carbon fibres
Hemicellulose	Hemicellulose Resistant maltodextrins	Whole grains, bran cereals, beet root, brussels	Edible films, biodegradable packing, gut microbiota

Utilizing dietary fibre from vegetable and fruit waste not only boosts the nutritional content of food products but also offers significant environmental and economic benefits by reducing waste and creating valuable products. Successful applications, such as the use of apple pomace fibre in bread and citrus peel fibre in dairy products, demonstrate the potential of this approach. Dietary fibres from fruit and vegetable waste can improve gastrointestinal health by regulating digestion, absorption, transit time, stool formation, and gut microbiota composition. Additionally, these fibres exhibit antioxidant properties, which can protect cells from oxidative stress and improve overall health [40,42]. In addition, they directly affect human micro-biota and supply probiotic growth with energy and nourishment.

The structure of polysaccharides, particle size, extraction conditions, vegetable source, and water-holding capacity all affect the functional characteristics of fibres. Vegetable processing bio-residues are comprised of fibre-rich seeds and depleted skin. These residues may also be used in innovative processed foods as they serve as low-cost, non-caloric thickening and bulking agents, as well as water and oil retainers that can enhance emulsion or oxidative stabilities. Food items undergo changes in their textural, rheological, nutritional, and sensory attributes when dietary fibres are added. In addition to its functional and technological benefits for the packaging industry, dietary fibres offer an environmental friendly option for qualities including swelling, viscosity, gel-forming, chelating capability, water and oil retention, and glucose retardation index [43]. Dietary fibre concentrates recovered from by-products of the agriculture industry have demonstrated promising functional properties. These fibres can serve as carriers for probiotics, aiding in their stability and delivery [44].

Further research is needed to optimize extraction techniques, ensure product stability, and explore new applications, solidifying the role of fruit and vegetable waste in the development of value-added dietary fibre products.

Protein and Lipid

Plant-based protein isolates and concentrates can be derived from various wastes such as potato peels, tomato seeds, and carrot pomace. These proteins exhibit functional properties like emulsification, foaming, and water-holding capacity, making them suitable for food applications. Protein has been found in their waste and the inedible portions of many fruits and vegetables. Citrus peels have a protein level ranging from 2.5% to 9.0%. Fruit and vegetable pomace, carrot pomace, green pea peels, sweet lime peel, pineapple peel, mango peel, cabbage leaves, orange peel, banana peel, tomato solid waste, potato solid waste, and cauliflower were among the sections of fruits and vegetables that contained varying concentrations of protein [47]. Fruits and vegetable seeds have great quantities of protein whose hydrolysis with pharmacological activity favours the release of bioactive peptides [48]. Similarly, tomato seed protein, with high nutritional value and antioxidant properties, is a promising ingredient for functional foods [49]. Utilizing these waste-derived proteins not only enhances food sustainability but also adds economic value to the food processing industry. Since protein has several uses in the food sector, numerous studies have been done to create bioplastics utilising it as a fundamental component [50].

The derivation of fats and lipids from fruit and vegetable waste, including seeds, peels, pulps, kernels, and pomace, presents a valuable opportunity for both the food and cosmetic industries. Several types of fruit and vegetable wastes are rich in valuable lipids. [51]. Mango kernel fat, which contains high levels of stearic and oleic acids, continues to find use in confectionery and cosmetic products due to its stable and emollient characteristics [52]. Similarly, tomato seed oil, with its abundance of linoleic and oleic acids, is gaining attention for its potential in dietary supplements and functional foods. Grape seed oil, a by-product of the winemaking process, remains a source of polyunsaturated fatty acids and antioxidants, which are beneficial in both nutritional and skincare products [53]. The utilization of these lipid-rich wastes not only promotes sustainability by reducing food waste but also adds economic value by creating high-demand products from otherwise discarded materials. Moreover, these lipids often contain bioactive compounds that enhance their functional properties, providing additional health benefits when incorporated into various products.

Vitamins and Minerals

Fruit and vegetable waste, including parts like kernels, pomace, seeds, peels, and sticks, are rich sources of vitamins and minerals, providing valuable nutrients that can be repurposed for various applications. These waste components often contain great quantities of vitamins like, vitamin C, vitamin A, and B-complex vitamins, along with essential minerals like potassium, calcium, magnesium, zinc, sodium and iron. For instance, citrus peels are abundant in vitamin C and flavonoids, which have antioxidant properties and can be used in dietary supplements and fortified foods [54]. Mango peels and seeds have plentiful of polyphenols, carotenoids, and vitamins A and E, which are beneficial for skin health and are utilized in cosmetic formulations [55]. Tomato pomace, which includes skins and seeds, is a good source of lycopene, potassium, and magnesium. These components can be derived and used in the development of functional foods and Nutraceuticals, aimed at promoting cardiovascular health [56]. Carotenoids are a class of pigments found in various fruits and vegetables, providing health benefits as antioxidants. Lycopene – a carotenoid, predominantly found in tomato peels, making up about 90% of the total carotenoids is known for its strong antioxidant properties and potential health benefits, which include reducing the risk of certain cancers and heart diseases. Another carotenoid - Beta Carotene in tomato seeds is a precursor to vitamin A, which is important for good vision, skin health, and immune function. Lutein and Zeaxanthin carotenoids are generally found in green leafy vegetables, known for their roles in protecting against age-related macular degeneration. Tomato peels have a very high concentration of carotenoids on a dry-weight basis. This highlights the potential value of tomato by-products in producing natural antioxidants and nutritional supplements. Peels or skin of pumpkin and carrots also contain a large amount of carotenoids.

Grape pomace, a by-product of the winemaking industry, has great quantities of resveratrol, vitamin E, and essential minerals. This nutrient-rich by-product has been effectively utilized in creating antioxidant supplements and functional beverages [57]. Additionally, banana peels are high in potassium, dietary fibre, and various vitamins, making them suitable for creating enriched flours and animal feed [58]. The high mineral content of banana peel powder also suggests its potential to fortify foods and improve nutritional profiles [59].

Avocado seeds contain a significant amount of potassium, magnesium, and antioxidant vitamins, which have been explored for use in health supplements and cosmetic products [60]. Utilization of these waste parts not only provides a sustainable approach to waste management but also enhances the nutritional value of food products. By extracting and repurposing these vitamins and minerals, industries can create high-value products that meet consumer demand for health and wellness. The continued research and development in this area emphasize the potential of these waste materials to contribute to food security and sustainable economic development.

Valorization of fruits and vegetable wastes into Value-Added Products

Fruit Vegetable waste (FVWs) can be converted into value-added products in the food industry and pharmaceuticals, biofuel, bio-packing etc. The circular economy can benefit from strategies that convert food waste (FVWs) into high-value food additives by encouraging sustainability and reducing waste. This review summarises diverse applications across food additives, biofuels, bio-adsorbents cosmetics and pharmaceuticals and many more:

Food Additives

The reuse of food-variable wastes (FVWs) as food additives in the food industry reduces significant losses and waste in the fresh produce and processing sector, addressing nutritional, economic, and environmental concerns. Dietary fibres from fruit and vegetable waste can be incorporated into various food products, including meat products, cakes, and other baked goods, to enhance their nutritional profile and functional properties [61-62].

Bakery

Incorporating FVW byproducts into bakery goods not only adds economic value but also contributes to developing innovative and eco-friendly formulations with improved health effects [63]. Studies have shown that fruit and vegetable wastes can be used to create bakery items like cakes and cookies, providing gluten-free options and enhancing the fibre content, mineral composition, and protein levels of the products. Abu El-Hassan and co-workers added varying amounts of banana peel powder to butter cakes, finding that the cakes' specific volume increased compared to the control. The supplemented cakes had higher protein, fibre, ether extract, and ash content. After the storage period, the cake with 16% banana peel powder had the lowest microbial load (96 ± 8.7 cfu) and peroxide value (0.99 ± 0.1 meq peroxide/kg fat) [64]. Hameed et al. investigated papaya seed powder (PSP) and papaya seed oil (PSO) as valuable by-products with significant physicochemical properties and antimicrobial activity. PSP analysis revealed 39 bioactive compounds with broad-spectrum antimicrobial effects. Incorporating PSP into chocolate cupcakes enhances their nutritional content and quality, showing their potential as functional food ingredients and natural additives [65].

Meat products

Microbial deterioration is a significant concern in animal-based foods like meat and poultry. To address this, meat producers are seeking natural and cost-effective additives derived from food waste to enhance the health benefits and extend the shelf life of their products. Various researches propose using natural antibacterial compounds obtained from food waste to prevent microbial deterioration and increase the shelf life of animal-based goods. Citrus peel powder (orange and lemon) improves the microbial and chemical properties of raw minced beef at refrigerator temperature (4±10 ºC). At 5% concentration, it reduces microbial load and preserves sensory properties, while 10% affects sensory scores [66]. Nahed et al. tested quercetin-rich extracts and powders from red and yellow onion skins on beef burgers, finding increased antioxidant, flavonoid, and phenolic content. There was no noticeable increase in microbial load after 15 days of storage, and no sensory changes in the burgers [67]. These natural antimicrobial extracts are recommended as additives in beef patties.

Ghimire et al. extracted polyphenol-rich peels from various pomegranate varieties and found the Ganesh variety exhibited the highest antioxidant activity. Treating buffalo meat with 1% and 1.5% Ganesh pomegranate peel extract (PPE) improved storage stability during refrigeration, effectively controlling peroxide value (PV), TBARS value, and total plate count [68]. PPE prevents oxidation and harmful microbes, enhancing food stability during processing, storage, or digestion. Marinating buffalo meat in PPE helps maintain freshness at 5°C [69]. Additionally, adding PPE to grape seed oil improves stability during storage, though not as effectively as BHA (Butylated hydroxyanisole) [70]. Mokbel and coworkers studied the effects (biochemical quality, oxidative stability, sensory analysis) of 1% lemon, orange, grapefruit, and banana peel powders on chicken patties stored at -18°C for three months. Lemon peel powder had the highest bioactivity with 90.5 mg gallic acid/g total phenolics, 35 mg rutin/g total flavonoids, and 90% antioxidant activity. Banana peel powder increased protein (22.18 g/100 g) and decreased fat content (10.52 g/100 g) [71]. All peel powders showed strong antioxidant and antibacterial properties. Banana residues, containing malic and succinic acids, inhibited both Gram-negative (*E. coli*, *Salmonella*) and Gram-positive (*S. aureus, Bacillus)* bacteria, while palmitic acid had minimal impact [72]. These findings suggest that fruit peels could be used to develop new antibiotics. Further research is needed to evaluate their effectiveness against various pathogens, yeast, and fungi.

Pharmaceutical and Cosmetics

Potential target markets for recycling and using natural bioactive chemicals from food by-products are the cosmetic and pharmaceutical industries. Fruit and vegetable waste is a major source of bioactive compounds with applications in the food, health, and pharmaceutical sectors. These compounds include carotenoids, polyphenols, dietary fibres, vitamins, and oils. Fruit and vegetable waste contains bioactive chemicals with anti-inflammatory, anti-tumour, anti-cancer, anti-allergenic, and anti-atherogenic qualities that are beneficial to health.

Bioactive component quercetin, which has been proposed as a viable therapeutic option for the treatment or amelioration of several health conditions, mostly related to the nervous system and cardiovascular systems [73]. Agri-food waste from apple, pear, and sugar beet waste can provide bioactive molecules to protect endothelial function and its complications, potentially aiding in the prevention of cardiovascular diseases [74]. Numerous studies have highlighted the nutritional and health benefits of citrus fruits, noting their antimicrobial, anticancer, antidiabetic, antiplatelet aggregation, and anti-inflammatory properties. Citrus fruit waste, including seeds, peels, pomace, membrane residues, secondary juice, and leaves, holds significant economic value. These wastes can be utilized as sources of bioactive compounds for food preservation and as renewable energy sources in the food, pharmaceutical, and cosmetic industries [75]. Recently, Eman et al. reported that orange peel extract has a chemo-preventive effect against cyclophosphamide-induced organ toxicity in an in vivo model [76]. Tomatoes (*Solanum lycopersicum*) are widely consumed and rich in bioactive compounds, offering health benefits that may help prevent oxidative stress-related diseases like cancer and cardiovascular diseases. According to Kumar et al., tomato seed wastes from processing contain significant bioactive compounds with health-promoting properties. Studies have shown that tomato seed extracts exhibit antiplatelet, antioxidant, anticancer, anti-mutagenic, antimicrobial, and neuro-protective effects in both in vitro and in vivo animal models [77-78].

The by-product of pear processing contains bioactive ingredients, carbs, and fibres that can be used in industrial settings. Pear pomace has several potential applications, including serving as a substrate for the coproduction of pear vinegar and bacterial cellulose, providing antioxidants and fibre to reduce obesity and oxidative stress in animal trials, and other uses. A comprehensive analysis of pear bioactive compounds has demonstrated the existence of polyphenols, including tri-terpenes, flavonoids, and phenolic acids. Compared to pear pomace, the seed and peels are found to be rich in phenolic compounds. Sugar beet by-products are a promising source of bioactive compounds that can help prevent cardiovascular diseases. The sugar beet root has significant antioxidant activity, which can help prevent cancer, cardiovascular illnesses, osteoporosis, and neurological diseases [74]. Polyphenolic compounds extracted from different fractions of apple pomace (AP) using subcritical water extraction (SCW) and ethanol extraction, evaluating their properties. subcritical water extraction resulted in a higher total polyphenolic content (TPC) of 39.08 mg GAE/g db compared to ethanol extraction with 10.78 mg GAE/g db, indicating the effectiveness of SCW in extracting polyphenolics from AP [79]. They also observed that all ethanolic extracts were found to be cyto-compatible with human fibroblast and salivary gland acinar cells, indicating the potential biomedical applications of the polyphenolic compounds extracted from AP.

Wang et al. induced type 2 diabetes in mice using a high-fat diet and streptozotocin to study the effects of banana peel dietary fibres. After 5 weeks, they found that the fibres decreased food intake, increased body weight, and lowered blood lipids and glucose levels. Fasting insulin and GLP-1 levels rose, and liver and pancreatic damage was reduced [41]. Lin et al.'s research also showed that milled and dried bananas helped control blood sugar and improved diabetes symptoms in animal models [80]. A recent review by Messinese et al. discussed adding bioactive components from fruits and grains (rice, oranges, and oat bran) to cosmetics. They raised concerns about synthetic chemicals causing side effects and bacterial resistance. Due to their anti-cancer, anti-diabetic, neuroprotective, cardiovascular, antimicrobial, and anti-inflammatory properties, these natural components are suggested for use in pharmaceuticals [81].

Bio-packing

A few research also looked at the creation of new environmentally friendly materials such coatings, edible films, and bio-composites made from recovered components made from agro-industrial byproducts. Among the most common bioactive found in food and agri-food byproducts are phenolic chemicals, carotenoids, and dietary fibres. As a result, bioactive compounds might be used in a variety of industrial settings as useful elements to encourage the reuse and recycling of biomasses that were often intended for landfilling, animal feed, or fertiliser [82].

The use of bioactive compounds derived from processing food residues and agri-food by-products can provide active edible coatings and films that promote environmentally responsible packaging while preserving food quality and shelf life. Gomes et al. examined coatings derived from phenolic-rich extracts from acerola and jaboticaba by-products and were successful in preventing *Lasiodiplodia species*-caused papaya root rot [83]. A recent study used agri-food by-products like onions, artichokes, and thistles as bioactive additives in alginate-based films to create edible food contact materials. The positive results were attributed to the antioxidant properties of the bioactive compounds added to the films [84].

Bio-adsorbents

Agricultural residues such as coconut shells, sawdust, rice straw, sugarcane bagasse, banana peels, and orange peels are common examples of agricultural waste. These materials are rich in cellulose and contain a wide variety of functional groups, including amine, amide, imidazole, thioether, sulfonate, carboxyl, sulfhydryl, phosphodiester, phenolic, and phosphate groups [85]. The adsorption capacity of agricultural waste-based adsorbents is largely influenced by the presence of these functional groups, which attract the cationic components of pollutants and facilitate the adsorption process. Researchers have investigated the rind, cortex, and peel portions of fruit and vegetable wastes for the removal of hazardous contaminants, including pesticides, heavy metals, and dyes. Nguyen reviewed several studies on the use of durian fruit waste as an adsorbent for water treatment and reported its effectiveness in removing various contaminants. The conversion of agricultural waste into value-added products has become an important area of research, as these materials are renewable, inexpensive, and environmentally friendly. The adsorption capacity of such biosorbents depends on several factors, including adsorbate concentration, adsorbent dosage, contact time, biosorbent particle size, agitation speed, temperature, and pH [85].

Biofertilizer and Biofuels

Fruit and vegetable wastes (FVWs) and by-products have significant potential applications in the production of biofertilizers and biofuels. FVW contains bioactive compounds that can be utilized for various purposes, including the production of biofuels like bioethanol, biohydrogen, biodiesel, and biogas. Additionally, these wastes can be used in biorefinery processes to generate valuable products such as biochar, biosorbents, and organic fertilizers. FVW, being rich in lignocellulosic biomass, is considered a second-generation feedstock for biorefinery, offering a renewable and sustainable source for bioenergy production. By employing eco-friendly technologies like anaerobic digestion, fermentation, and hydrothermal carbonization, fruit and vegetable waste can be effectively converted into biofuels and biofertilizers, contributing to a more sustainable and circular bioeconomy [86-87].

Verma et al. reviewed how food and agricultural waste, like fruit peels (e.g., orange, pineapple, banana, pomegranate, tangerine), can be processed into valuable products. Orange peel contains D-limonene, pineapple waste offers cellulose, hemicellulose, pectin, lignin, and sugar, while banana peels are rich in polysaccharides, proteins, fibres, and pectin. These non-edible parts present opportunities for bioconversion into valuable products, such as biofuels, bio-plastics and fertilizers. For example, passion fruit and orange peels can be turned into methane fuel through anaerobic digestion. Pomegranate and orange peels serve as biosorbents for wastewater treatment and can also produce bioelectricity, bio-pigments, and biofertilizers. Pineapple waste is used for ethanol, antioxidants, citric acid, lactic acid, biogas, and fibre production. Banana peels can yield biochar and single-cell proteins [88]. Additionally, peels from fruits like pomegranates, sweet lime, bananas, and tangerines are used to create biofertilizers and biogas.

Challenges and Future Research

Fruit waste valorisation plays a vital role in achieving sustainable development goals by reducing carbon footprints, minimizing greenhouse gas emissions, and promoting the circular economy. Although fruit and vegetable by-products are often considered waste, they are rich sources of bioactive compounds with valuable functional properties, including antioxidant, antimicrobial, and anti-inflammatory activities, making them attractive for applications in the food, pharmaceutical, cosmetic, and nutraceutical industries. However, the effective utilization of these compounds faces several challenges, such as inefficient extraction technologies, economic constraints, safety concerns, regulatory requirements, and difficulties associated with large-scale production. Conventional extraction methods are often time-consuming and resource-intensive, whereas emerging green technologies and environmentally friendly solvents offer improved sustainability and extraction efficiency. Advanced extraction techniques, including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and pulsed electric field (PEF) processing, have shown significant potential for recovering bioactive compounds from fruit waste. Furthermore, innovative approaches such as nano-encapsulation and metabolic engineering can enhance the stability, bioavailability, and controlled release of these compounds. To maximize the industrial utilization of fruit waste-derived bioactives, interdisciplinary research integrating food chemistry, food technology, biotechnology, and molecular biology is essential. Addressing challenges related to toxicity, sensory quality, regulatory compliance, and economic feasibility will be critical for their successful incorporation into functional foods and nutraceutical products. Future developments are expected to focus on biorefinery-based approaches, sustainable processing technologies, and value-added product development, thereby transforming fruit waste into a valuable resource that supports environmental sustainability, human health, and industrial innovation.

II. CONCLUSION

To sum up, the fruit processing sector produces a lot of waste, which is a rich source of antimicrobials and antioxidants agents. These beneficial bioactive substances are recovered from food waste have significant uses in the pharmaceutical, medical, food, agriculture and packing industry. Along with bioactive compounds, they are good sources of minerals, proteins, lipids, and dietary fibre, making them significant as food additives. They can be incorporated into various food categories such as cakes, biscuits, dairy products, and bakery goods.

Food-based natural antimicrobials play a vital role in the food industry by extending the shelf life of processed products and protecting them from microbial spoilage. These antimicrobials enhance food safety and preservation while boosting nutritional quality with added antioxidants. In agricultural applications, natural antimicrobials act as eco-friendly pesticides, combating plant diseases and reducing reliance on chemical pesticides. Additionally, their potential as therapeutic agents in medicine and pharmacology highlights their importance in developing new drugs and treatments.

Significance of Study

The valorization of fruit and vegetable waste has gained considerable importance in recent years due to its potential to address both environmental and societal challenges. On one hand, the disposal of large quantities of organic waste poses significant environmental concerns, including greenhouse gas emissions, soil and water contamination, and the increasing burden on landfills. On the other hand, there is a growing demand for dietary fibre, antioxidants, polyphenols, and other bioactive compounds that promote human health and well-being. Transforming fruit and vegetable processing waste into value-added products provides an effective solution to these interconnected issues by converting low-value waste streams into valuable resources. Such an approach not only supports waste reduction and environmental sustainability but also contributes to the development of a circular bio-economy, where resources are efficiently utilized and reused.

From a societal perspective, the valorization of fruit and vegetable waste can improve food and nutritional security through the development of affordable functional ingredients and nutraceutical products. It also creates opportunities for innovation, entrepreneurship, and employment in the food processing and waste management sectors, thereby contributing to economic growth. Furthermore, the abundance and low cost of fruit and vegetable waste make it an attractive and sustainable raw material for the production of dietary fibre and other bioactive compounds. In a country like India, where rapid urbanization, population growth, and industrial expansion have led to increasing volumes of organic waste, sustainable waste management has become a critical priority. The widespread practice of disposing organic waste in open dumps and landfills not only wastes valuable resources but also exacerbates environmental degradation. Therefore, the recovery and utilization of bioactive compounds from fruit and vegetable waste represent an environmentally responsible and economically viable strategy that aligns with the principles of sustainable development. By transforming waste into valuable products, fruit and vegetable waste valorization serves as a practical example of resource efficiency and circularity, demonstrating how environmental protection, public health, and economic development can be achieved simultaneously.

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