Role of Fruit Peels In Reducing Food Waste: A Circular Economy Approach

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Abstract

Fruit peel waste has become a significant global issue, resulting in substantial environmental and economic consequences. As the population grows, the demand for food increases. Approximately 42% of fruit and vegetable waste originates from households, 38% comes from the food processing sector, and other areas in the food industry produce the remaining 20%. Among the by-products of fruits, peels constitute about 50% of the total waste. These discarded peels are rich in phenolic compounds, proteins, lipids, and polysaccharides, all of which contribute to their high antioxidant properties and nutritional value. The escalating problem of fruit peel waste requires urgent solutions. One promising approach to address this issue within a circular economy framework is the use of fruit peels. By repurposing fruit peels, we can reduce waste, lower the environmental impact of disposal, and create a sustainable value chain. Integrating fruit peels into a circular economy necessitates innovations in waste management technologies, as well as changes in consumer perceptions and policy frameworks to encourage waste reduction. This review explores the role of fruit peels in reducing fruit peel waste through the circular economy approach. It analyzes the bioactive compounds, nutrients, and beneficial properties present in fruit peels, discusses their valorization in various industrial sectors, and examines their applications as additives and preservatives. Furthermore, the paper addresses the use of fruit peels in creating eco-friendly packaging alternatives and sustainable materials, and their role in wastewater management. Finally, it outlines challenges associated with their commercial utilization.

Keywords: *Food industry, By-products, circular economy, preservatives, eco-friendly packaging*

1. Introduction

Since industrialization, economies have largely followed a linear take use

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dispose model characterized by minimal recycling and significant resource depletion. This approach has intensified environmental degradation alongside increasing production and waste generation. According to Cladeira et al., nearly 30 million tons of uneaten food waste are generated annually in Europe during food processing, and the global food processing market is projected to reach 4.1 trillion dollars by 2024, growing at a compound annual rate of 4.3 percent from 2019 to 2024 [1]. Fruit peel waste constitutes a major portion of this loss. The Food and Agriculture Organization reported in 2019 that 14 percent of global food production is lost after harvest, while the United Nations Environment Programme Food Waste Index report of 2021 estimated 931 million tons of food waste annually [2]. The fruit and vegetable sector generates a comparatively higher proportion of waste, with peels accounting for 25 to 30 percent, followed by seeds, pulp, skin, and pomace. Approximately 42 percent of this waste is produced at the household level, 38 percent during food processing, and 20 percent along the supply chain. Specific contributions include mango peel at 45 percent, banana peel at 35 percent, citrus peel at 50 percent, pineapple peel at 27.7 percent, and apple peel at 20 to 30 percent. Overall, peels constitute nearly 50 percent of total fruit waste in both domestic and commercial sectors [3]. Waste is generated during harvesting, transportation, processing, and consumer stages. Chemically, fruit peels are rich in flavonoids, phenolic compounds, proteins, dietary fiber, pectin, polysaccharides, and antioxidants. Their structure is mainly composed of cellulose and lignin and contains functional groups such as hydroxyl, carboxyl, carbonyl, aldehyde, ether, and ester groups. These constituents contribute to strong antioxidant capacity and nutritional value, making peels valuable for food, pharmaceutical, and packaging industries [2]. The Circular Economy model, illustrated in Figure 1, replaces the linear system by promoting reuse, recycling, and recovery to extend material life cycles [4]. Valorization strategies such as producing biodegradable films from orange and banana peels and extracting natural dyes from pomegranate and beetroot reduce dependence on synthetic plastics and petroleum based colorants. This review report highlights the role of fruit peel valorization in advancing sustainable industrial practices and supporting environmental protection [4].

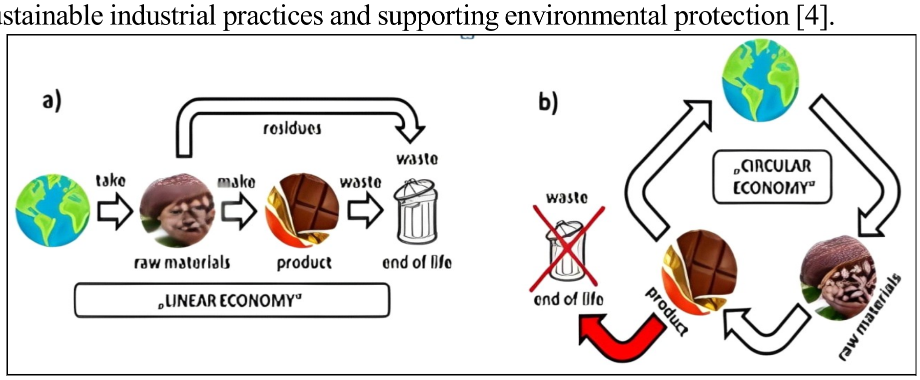


Figure 1:The basic principle of linear economy and circular economy [5]

2. Bioactive Compounds Found in Fruit Peels

Bioactive components are intriguing natural compounds found in small amounts in our food that can help enhance our health or ward off potential issues. These wonderful substances, like bioactive peptides, terpenoids, phytosterols, fibers, fatty acids, polyphenols, carotenoids, alkaloids, and vitamins, play a crucial role in managing various metabolic processes in our bodies, such as neutralizing free radicals, influencing gene expression, and supporting the activity of receptors and enzymes. As a result, these amazing compounds are becoming key players for many food industries and innovative startups, inspiring them to create products that cater to the growing demand for wholesome, nutritious, and affordable options [6]. These are essential for survival but they can positively influence health, prevent diseases and promote overall well-being. Some of the common bioactive compounds present in peels of fruit are shown in Figure 2. Fruit skins, the outer layer typically thrown away as waste, are actually a source of nutrients and bioactive compounds. They possess a high amount of dietary fibers, vitamins and minerals, often exceeding the nutritional content found in fruit peels. Abundant in antioxidants such as flavonoids, polyphenols and carotenoids, these peels provide potential health advantages including anti-inflammatory and anti-microbial effects. From the vibrant essential oils in citrus peels to the powerful antioxidants in pomegranate peels, each type of peel has unique properties that can be harnessed.

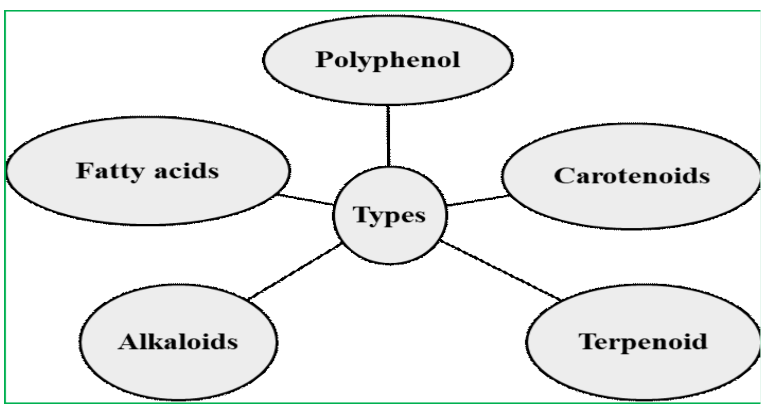


Figure 2: Types of Bioactive Compounds

Various bioactive compounds and its nutritional and functional properties present in fruit peels are discussed below.

2.1 Apple peel

The peel of an apple makes up about 10% of the fruit's total weight, and it's packed with goodness, providing 41% of all the flavonoids found in an apple and

31% of its phenolic content [3]. Apple peel is known to possess anti-oxidative, anti-proliferative, and anti-carcinogenic properties, in addition to exhibiting anti-inflammatory effects. The compounds epicatechin, catechin, and procyanidins play a significant role in reducing LDL cholesterol and demonstrate considerable antioxidant activity. Chlorogenic acid is recognized for its strong alkyl peroxyl radical scavenging activity; since alkyl peroxyl radicals can promote tumor formation and carcinogenesis, chlorogenic acid contributes to cancer protection. Quercetin has been shown to be beneficial in combating heart disease and cancer, as it inhibits tyrosine kinase and reduces mutant expression in breast cancer cells. Furthermore, apple peel contains high levels of pectin, which has gained importance for various industrial applications, including as biofuel precursors and as a food ingredient [7]. Structural representation of some common bioactive compound present in apple peel is shown in Figure 3.

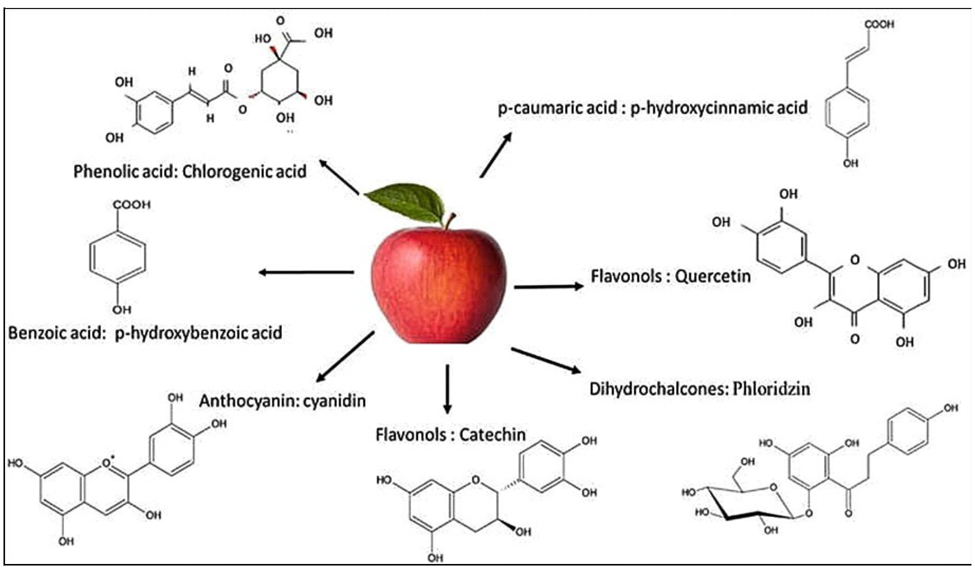


Figure 3: Structure of Bioactive compounds present in apple peel

2.2 Mango peel

Mango peel, a major by-product of mango processing (15–20% of fresh fruit weight), is a chemically rich biomass with significant functional value. It contains key phenolic compounds such as protocatechuic acid, gallic acid, ferulic acid, catechin, quercetin 3-O-galactoside, and the xanthone mangiferin, along with carotenoids, predominantly beta-carotene [8]. These phytochemicals possess multiple hydroxyl groups and conjugated aromatic systems that enable radical scavenging, metal chelation, and modulation of inflammatory pathways, contributing to antimicrobial, antidiabetic, anti-inflammatory, and anticancer activities. Mangiferin, in particular, enhances insulin sensitivity and exhibits strong antioxidant capacity due to its C-glucosyl xanthone structure.

Nutritionally, mango peel contains 20–30% carbohydrates along with proteins, amino acids, lipids, organic acids, and substantial dietary fiber (10–28% soluble and 29–50% insoluble), supporting gastrointestinal health. It also provides vitamins A, C, and E, and essential minerals (Ca > K > Mg > Na > Fe > Mn > Zn > Cu). The high beta-carotene content contributes provitamin A activity, while tocopherols (vitamin E) enhance oxidative stability. The major bioactive constituents of mango peel are summarized in Figure 4 [8].

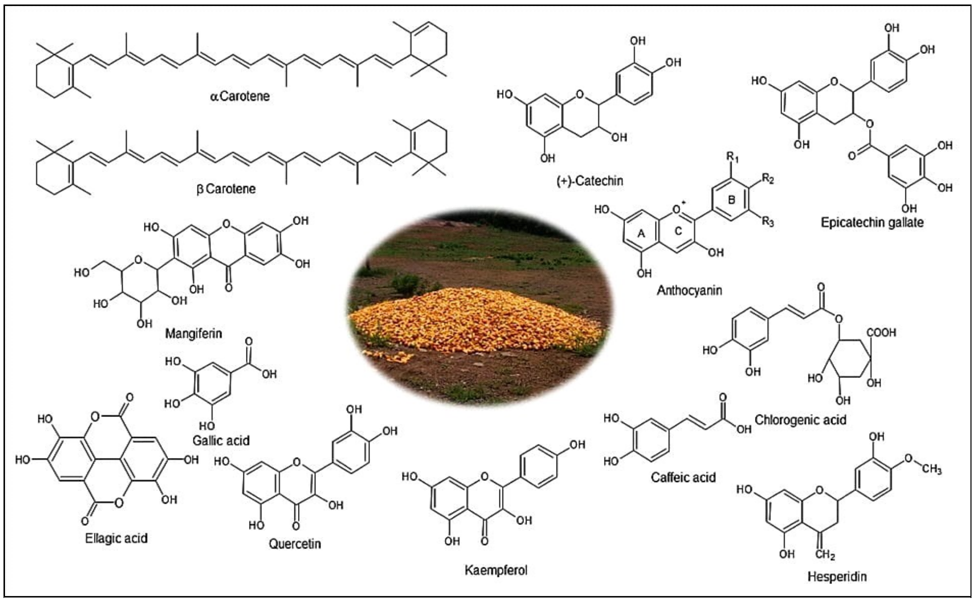


Figure 4: Structure of bioactive compounds present in mango peel [9]

2.3 Banana Peel

Banana peel, a major by-product of banana processing (~35% of fruit weight), is a chemically valuable biomass rich in phenolics and structural polysaccharides [3, 10]. It contains flavonols, flavan-3-ols, hydrocinnamic acids, catecholamines, gallic acid, epicatechin, catechin, anthocyanins, and high levels of rutin (mainly quercetin glycosides and 3-rutinosides) [3]. The abundance of hydroxylated aromatic structures enables strong free radical scavenging and redox activity. Notably, gallocatechin content is significantly higher than in pulp, reinforcing its antioxidant potential [12]. Banana peel also contains elevated levels of dopamine and L-dopa, contributing to its bioactivity. Structurally, it is composed of cellulose, hemicellulose, and pectin bearing carboxyl, hydroxyl, and amine functional groups, which facilitate metal binding and adsorption processes. It is additionally rich in polyunsaturated fatty acids (omega 3 and 6), minerals (Ca, Fe, Mg, Zn, Na, P, Cu) [11], and carotenoids such as alpha-carotene, beta-carotene, and lutein, a xanthophyll known to inhibit lipid oxidation [13]. These constituents underlie its reported antioxidant, hypoglycemic, hypolipidemic, and gastroprotective effects. Owing to its high carbon content and functional groups, banana peel also serves as an efficient biosorbent for pollutant removal. The major bioactive compounds present in banana peel are illustrated in Figure 5.

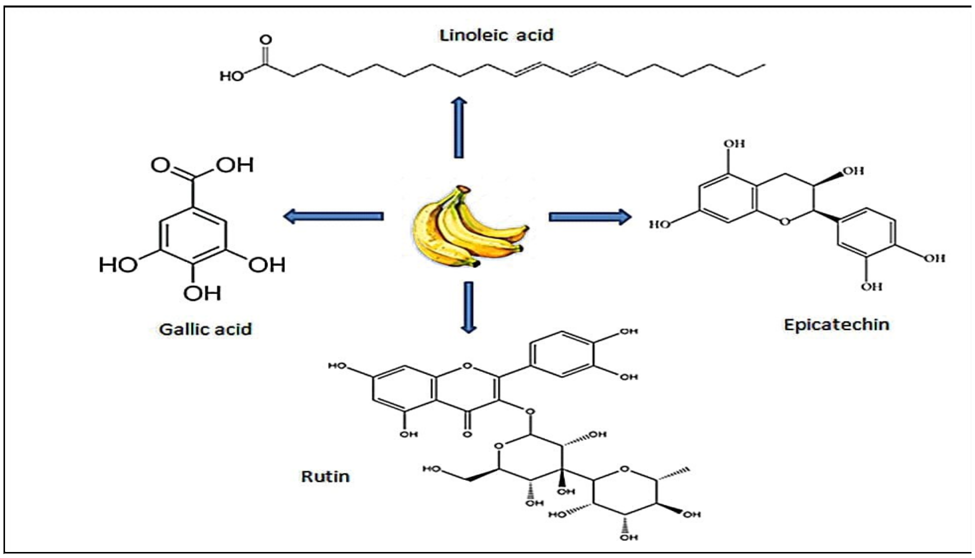


Figure 5: Bioactive compounds present in banana peel

2.4. Pomegranate peel

Pomegranate peel, often discarded as waste, is a concentrated source of polyphenols and structurally diverse bioactive compounds [14]. It is particularly rich in ellagitannins such as punicalagin and punicalins, along with ellagic acid, flavonoids (quercetin, kaempferol), catechins, and anthocyanins including delphinidin, cyanidin, and pelargonidin. The abundance of hydroxyl groups and conjugated aromatic systems in these molecules enables efficient free radical scavenging, metal chelation, and modulation of inflammatory pathways, accounting for strong antioxidant, anti-inflammatory, and antimicrobial activities.

The lipid fraction contains linoleic acid and punicic acid, a conjugated linoleic acid associated with anti-inflammatory and anticancer potential. Minor constituents such as alkaloids and terpenoids further enhance chemical diversity. In addition, the peel provides dietary fiber, supporting gastrointestinal health and glycemic regulation. Owing to this rich phenolic and lipid profile, pomegranate peel exhibits significant therapeutic and industrial potential [14]. The major bioactive compounds present in pomegranate peel are summarized in Figure 6.

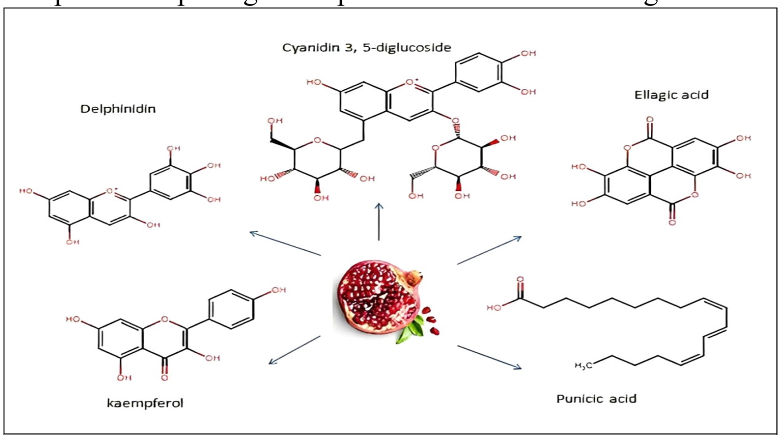


Figure 6: Bioactive compounds present in pomegranate peel

2.5 Citrus peel

Citrus fruits such as oranges, mandarins, lemons, grapefruits, and pomelos belong to the genus Citrus and are widely consumed both fresh and processed. However, domestic consumption and industrial juice production generate large quantities of by-products, mainly peel, pulp residues, and seeds, collectively referred to as pomace. Figure 7 illustrates some common citrus fruits highlighting the diversity within the Citrus group and the proportion of peel relative to the edible portion, which explains the significant volume of peel waste generated during processing.

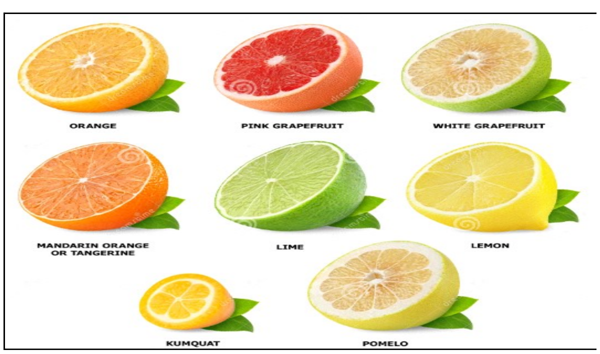


Figure 7: Common citrus fruits

Citrus peel is a rich source of essential oils, carotenoids, pectin, flavonoids, and other bioactive constituents with strong antioxidant and health promoting properties. The dominant flavonoids are hesperidin and naringin, with rutin and neohesperidin also commonly detected; mandarins are particularly abundant in these compounds and exhibit high antioxidant potential. Hesperidin and naringin are considered the principal bioactive flavonoids responsible for the functional properties of citrus peel [15]. Compared with the edible pulp, the peel contains higher levels of polyphenols and antioxidants. Its phenolic profile includes caffeic acid, p coumaric acid, ferulic acid, and sinapic acid, which act as antioxidants by donating electrons or hydrogen atoms to neutralize free radicals, thereby protecting cells from oxidative stress and lowering the risk of chronic diseases. Polymethoxylated flavones are of notable commercial interest due to their pharmacological activities and applications in functional foods and nutraceuticals. Figure 8 illustrates the major bioactive compounds in citrus fruits, including flavonoids (hesperidin, naringin, rutin, neohesperidin), phenolic acids, carotenoids, pectin, and essential oil volatiles, highlighting the chemical diversity underlying the peel's biological and industrial importance. In addition to phenolics, citrus peels are rich in essential oils, complex mixtures of volatile aromatic compounds, which are being investigated as economical and eco friendly alternatives to synthetic preservatives such as sodium nitrate and sodium benzoate in food systems [16].

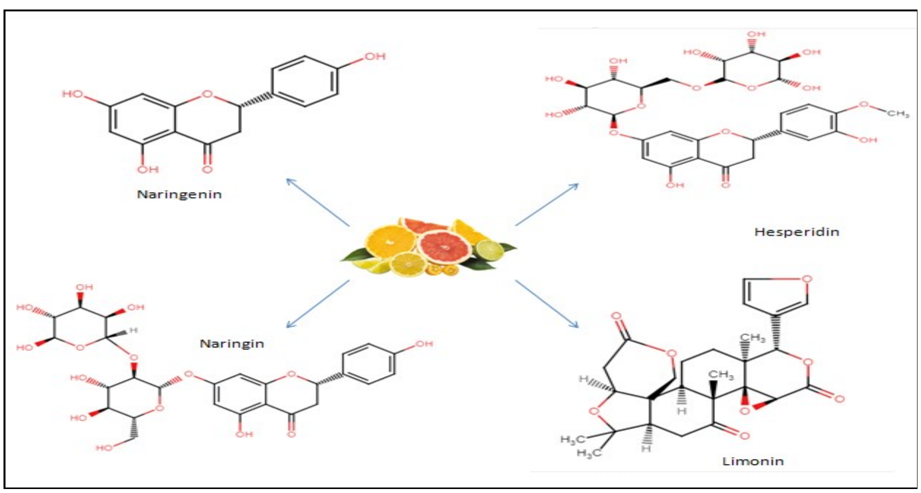
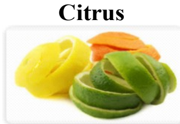


Figure 8: Bioactive compounds present in citrus peel

Thus, fruit peels are a rich source of diverse bioactive compounds, including polyphenols, flavonoids, carotenoids and dietary fibers, which contribute to their potential health benefits and functional properties. A summary of bioactive compounds present in different peels is presented in Table 1.

Table 1: Fruit peels and their bioactive compounds

Fruit peel	Bioactive compounds	References
Apple 	Quercetin, Chlorogenic acid, Epicatechin, Catechin, p-hydroxycinnamic acid, Procyanidins, cyanidin, p-hydroxybenzoic acid	[7]
Mango 	Protocatechuic acids, Mangiferin, beta-carotene, Quercetin 3-O-galactoside, Gallic acid, Ferulic acid, Catechin	[8]
Banana 	Hydrocinnamic acids, Flavon-3-ols, Catecholamines, Gallic acids, Epicatechin, Catechin, Anthocyanins, Rutin, Gallocatechin, Alpha-carotene, Beta-carotene, Lutein	[12, 13]
Pomegranate 	Punicalagin, Punicalins, Ellagic acid, Anthocyanins(delphinidin, cyanidin, and pelargonidin), Quercetin, Kaempferol, Catechins, Linoleic acid, Punicic acid	[14]
Citrus 	Hesperidin, Naringin, Rutin, Neohesperidin, Pectin, Caffeic acid, p-coumaric acid, Ferulic acid, Sinapic acid	[15, 16]

3. Valorization of Fruit Peels

Waste valorization has emerged as a strategic alternative to landfilling, focusing on the reuse, recycling, composting, or industrial transformation of waste into value-added products or energy. It involves converting residues and by-products into secondary raw materials and reintegrating them into production cycles [17]. Within a circular economy framework, fruit by-products, particularly peels, are increasingly recognized as rich sources of bioactive compounds, contributing both to environmental sustainability and economic value creation [18]. Fruit peels often contain higher concentrations of phenolic compounds than edible pulp, reflecting their protective role against biotic stress. These phenolics exhibit antioxidant, anti-inflammatory, and antimicrobial activities and are associated with reduced risks of cardiovascular, neurodegenerative, and certain chronic diseases. The composition and concentration of polyphenols vary among fruit types; apple, banana, and citrus peels are especially well documented. Green extraction strategies are widely employed to recover these compounds while minimizing solvent use, toxicity, and processing costs [17]. Multiple valorization routes are applied depending on the target product. Mechanical treatments (drying, grinding, pressing) convert peels into fiber-rich powders for functional food applications. Biological approaches include anaerobic digestion for biogas and fertilizer production, fermentation for bio-based chemicals and biofuels, and enzymatic hydrolysis for generating simpler bioactive molecules. Selective extraction and purification enable the recovery of natural pigments, antioxidants, and pectin. For example, citrus peel waste rich in pectin is processed into gelling agents used in the food and pharmaceutical industries [20]. Recent advances emphasize green (non-conventional) extraction technologies due to higher efficiency, shorter processing times, and reduced environmental impact. Techniques such as enzyme-assisted extraction, pressurized liquid extraction, microwave-assisted extraction, ultrasound-assisted extraction, pulsed electric field extraction, and supercritical fluid extraction are extensively explored for recovering peel-derived bioactives [21]. Microwave-assisted hydrodistillation has proven effective for essential oil recovery from wet citrus peels [22], while flavonoids and tannins from apple peel are commonly isolated via Soxhlet extraction using methanol or ethanol as solvents [23]. Figure 9 illustrates Isolation workflow of bioactive compounds from fruit peels.

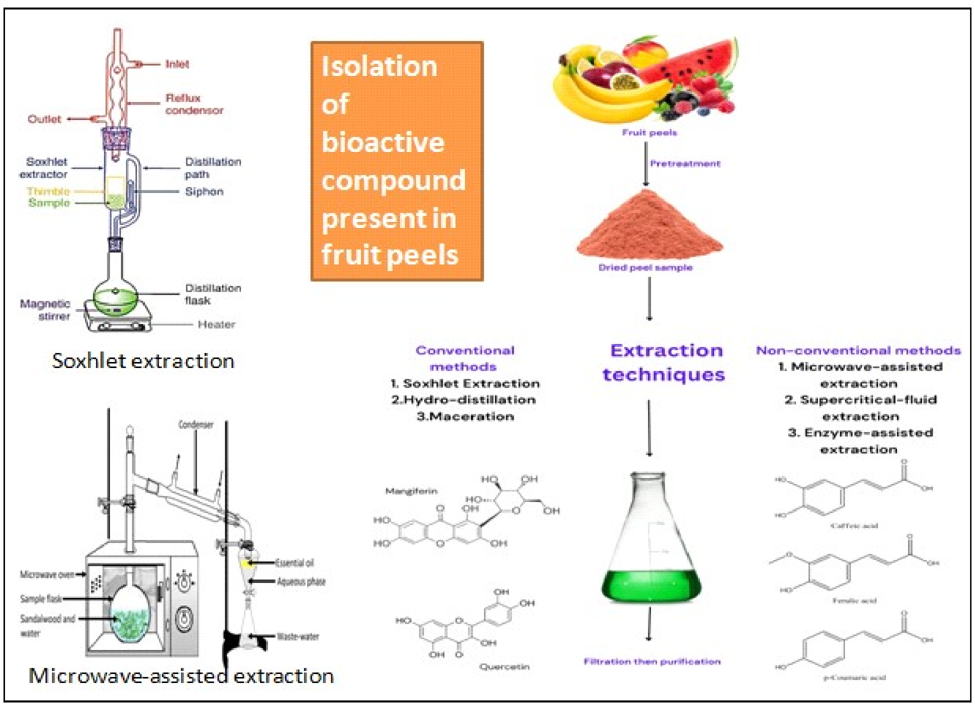


Figure 9: Isolation workflow of bioactive compounds from fruit peels.

4. Environmental Benefits of Utilizing Fruit Peels

Fruit waste contributes significantly to environmental problems, particularly through greenhouse gas emissions. When fruit is sent to landfills, it breaks down anaerobically, releasing methane (CH_4), a greenhouse gas approximately 25 times more potent than CO_2. Additionally, fruit cultivation consumes large quantities of water, land, and energy, which are wasted when produce is discarded, and improper disposal can result in nutrient runoff that causes eutrophication, affecting aquatic ecosystems. Fruit peels offer an environmentally friendly solution due to their high content of bioactive compounds, including dietary fibers, polysaccharides, flavonoids, and phenolic acids [24]. These peels enhance compost quality by supplying nutrients such as nitrogen and potassium, maintaining a balanced carbon-to-nitrogen ratio, stimulating microbial activity, and reducing methane emissions. The functional groups on peels (-COOH, -OH, -PhOH) enable them to act as biosorbents, removing pollutants from water through ion exchange, complexation, and electrostatic interactions. Notably, banana and orange peels have been demonstrated to remove chromium (Cr) from wastewater [25]. Furthermore, structural components like pectin, cellulose, lignin, and hemicellulose allow peels to be converted into bioplastics, films, or coatings, providing sustainable alternatives to synthetic plastics [26]. By applying these strategies, fruit peels can be transformed from waste into valuable resources, reducing environmental harm and supporting sustainable industrial applications.

5. Applications of Fruit Peels

Fruit peels, once considered agricultural waste, are now recognized as valuable resources in the food industry due to their applications as natural food additives, preservatives, and sources of dietary fiber, enhancing nutritional value and promoting sustainability. Food additives serve specific technological functions and are categorized into six groups: preservatives, nutritional additives, coloring agents, flavoring agents, texturizing agents, and miscellaneous agents, with preservatives further classified as antimicrobial, antioxidant, and anti-browning agents. Antioxidants, in particular, prevent oxidative degradation, such as lipid peroxidation, which can alter flavor, color, texture, and nutritional quality while generating toxic compounds, making them crucial in food preservation [18]. Fruit peels are rich in dietary fibers, vitamins, minerals, acids, and phytochemicals, which can be incorporated into products like biscuits, bread, cookies, noodles, sausages, and patties to enhance their functional and nutraceutical properties. Adding bioactive compounds from peels to food packaging can extend shelf life and reduce waste, while essential oils and extracts from peels provide antibacterial and antioxidant properties, supporting growth in food, cosmetic, and pharmaceutical industries [3].

Specifically, banana peels have multiple applications: as a source of enzymes like amylase and cellulose for brewing, juice production, and baking; as a functional ingredient to improve meat and poultry products, enhancing water retention, tenderness, color, and fiber content; and as an ingredient in yogurt and noodles, boosting phenolic content and antioxidant activity. Banana peel-derived extracts and gels also have skincare applications, including moisturizers and treatment of heel fissures, due to their hydrophilic and organic composition [11]. Pomegranate peels enhance the antioxidant and antimicrobial properties of products such as wheat cookies and chicken/meat items, extending shelf life and controlling oxidative rancidity; encapsulated peel phenolics also improve ice cream's antioxidant activity and alpha-glucosidase inhibition [27]. Mango peels are used as food preservatives, meat tenderizers, and functional beverage ingredients, with proteolytic extracts improving beef collagen solubilization and tenderization by 35%; peel powders are also used as substitutes for flours and pulps in baked goods, pasta, tortillas, and chips [28]. Citrus peels are a primary commercial source of pectin, widely applied as a gelling agent, emulsifier, and fat replacer in jams, baked goods, and pickled products, while their essential oils are utilized in beverages, confectioneries, cosmetics, and household items due to their aromatic and functional properties [18,29].

5.1 Fruit Peel in Biodegradable Packaging and Biomaterials

Increasing environmental concerns over non-biodegradable plastic packaging and consumer demand for high-quality food have driven interest in biodegradable materials derived from fruit peel [26]. In line with circular economy principles, edible coatings and films made from industrial fruit waste have gained importance. Fruit peels, rich in antioxidants, antimicrobial compounds, pectin, and cellulose, can be used to develop edible films and coatings that protect perishable foods, extending shelf life and preventing enzymatic browning, texture breakdown, and off-flavor development [3,26]. Pineapple peel fiber, with high cellulose content (70–80%), provides strength and stiffness, reinforcing composites with polyester, low-density polyethylene (LDPE), or biodegradable plastics for lightweight, strong packaging. Starch from banana peel is suitable for biodegradable plastics, and the plasticizer propane-1,2,3-triol improves material quality [30]. Apple peel polyphenols incorporated into chitosan-based edible coatings enhance antioxidant and antimicrobial properties, improve film density, thickness, and opacity, and extend the postharvest life of strawberries while reducing industrial waste [31,32]. Mango peel can be converted into bioplastics through enzymatic hydrolysis and fermentation, serving as eco-friendly substitutes for conventional plastics [33]. Overall, fruit peel-derived materials offer sustainable packaging solutions that reduce plastic waste, enhance food preservation, and promote circular economy practices

5.2. Fruit Peel in Wastewater Treatment & Bio-Eenergy Production

Fruit peels, usually treated as waste, are emerging as sustainable resources for wastewater treatment and bioenergy, supporting circular economy practices. Rapid industrial growth has increased freshwater demand and wastewater production, which often contains hazardous organic and inorganic pollutants, including heavy metals such as chromium (Cr), lead (Pb), mercury (Hg), uranium (U), selenium (Se), zinc (Zn), arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), and nickel (Ni), dyes, phenolic compounds, and pesticides. Organic pollutants raise biological oxygen demand (BOD) and chemical oxygen demand (COD), leading to oxygen depletion and eutrophication, threatening aquatic life. Many phenolics are water-soluble but poorly biodegradable. Dyes, visible even in trace amounts, pose ecological risks. Various natural and non-conventional methods, including bioadsorbents like fruit peels, are used to remove these contaminants [35].

5.3 Fruit peels as a biosorbents

Fruit peel waste is an efficient, low-cost biosorbent for removing heavy metals, dyes, and organic pollutants from wastewater [34]. Biosorbents are biological materials that passively adsorb contaminants from aqueous systems. Peels of apple, banana, mango, orange, and pomegranate contain functional groups such as phenolic –OH, carboxyl –COOH, amine –NH, , and aromatic moieties, which facilitate adsorption through ion exchange, complexation, hydrogen bonding, and electrostatic interactions. Although their surface area is lower than commercial activated carbon, the abundance of acidic sites enhances metal binding [Figure 10].

Powdered banana peel effectively removes Rhodamine B, while banana and orange peels adsorb carcinogenic Cr(VI) from effluents [25]. Adsorption efficiencies up to 88% have been reported for Pb, Cd, Ni, and Cu using peel-based materials [35]. Chemical modification of orange peel, rich in cellulose, pectin, hemicellulose, and lignin, improves Pb removal capacity [36]. Phosphoric acid-treated mango peel efficiently adsorbs methylene blue [37]. Peel-derived activated carbon and iron oxide-impregnated materials further enhance reusability and pollutant removal. Overall, fruit peels provide sustainable and effective materials for heavy metal and dye remediation in wastewater systems [38].

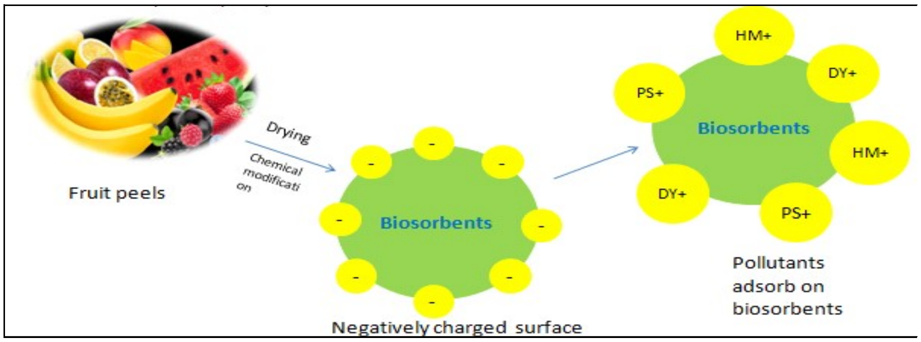


Figure 10: Fruit peel biosorbent and pollutant adsorption mechanism.

5.4 Fruit peels as source of bio-energy production

Global warming and climate change are the outcome of excessive use of fossil fuels. As a result, a push is underway to replace fossil fuels with cleaner, renewable fuels like bioethanol and biodiesel. Fruit peel waste contains a lot of sugars and carbohydrates that can be collected and used to make bioethanol. Gasoline is used on a massive basis all over the world. If bioethanol is to replace gasoline, a large amount of bioethanol would have to be produced. Fruit waste such as banana peel, orange peels and pineapple peels are known for their ability to produce total reducing sugars (TRS), pentose sugars (PS) and bioethanol [39]. Bioethanol is an alcohol made by microbial fermentation, mostly from carbohydrates produced in sugars or starch-bearing plants such a lignocellulosic biomass. Lignoecellulosic biomass is an alternative source of the renewable energy system and utilizing it to produce biofuels may help to reduce CO_2 emission [40]. Bioethanol production includes 3 steps which are depicted in the Figure 11.

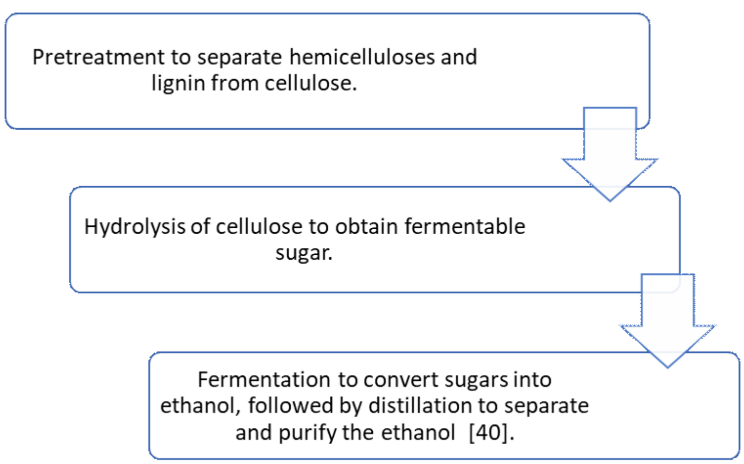


Figure 11: Bioethanol Production Flowchart

Banana peel provides essential carbohydrates and protein and deficient levels of anti-nutrients such as phytates, alkaloids and phenolics that act as biodegradation inhibitors. Mango and apple peels, rich in carbohydrates, can serve as effective feedstocks for bioethanol production. These peels are collected, cleaned, and pretreated to break down complex carbohydrates into simple sugars through enzymatic or chemical hydrolysis. The resulting sugars are fermented by microorganisms, such as *Saccharomyces cerevisiae* (yeast), to produce ethanol. After fermentation, the ethanol is purified through distillation. This process not only utilizes organic waste effectively but also provides a sustainable and eco-friendly source of renewable energy, reducing reliance on fossil fuels and contributing to waste management. Mango peels contain higher levels of reducing sugars up to 40%. Bio-ethanol content was only 5.4 % (v/V) during direct fermentation of mango peels . Citrus peel waste is a valuable lignocellulosic feedstock for bioethanol production due to its richness in fermentable sugars and low lignin content [41]. Additionally, waste from pineapple such as the fruit peel and crown, are rich in fiber and contain lignin, hemicelluloses and cellulose. Papaya peel, which is produced in vast quantities globally in the fruit juice industry contains phenolic compounds and sugars. Therefore, these wastes have been used to manufacture biofuels especially for bioethanol production [40].

6. Miscelleneous Applications of Fruit Peels

6.1 Repurposing of orange peel as a green reductant for recycling of spent lithium-ion batteries

The development of environmentally benign hydrometallurgical processes to treat spent Lithium-ion batteries is a critical aspect of the electronic-waste circular economy. Herein, as an alternative to the highly explosive H_2O_2, discarded orange peel powder is valorized as a green reductant for the leaching of industrially produced Lithium-ion batteries scraps in citric acid lixiviant Lithium- ion batteries are used currently in wide range of electronic products. As the demand for lithium-ion batteries continue to grow at a rapid pace, so does the pile of spent lithium-ion batteries waste. The majority of the spent lithium-ion batteries often end up in landfills or incinerators, which are environmentally unfriendly and economically unwise. Fruit peel waste is rich in a plethora of redox active molecules, such as dietary fibers, catechins, phenolic acids and flavonoids. Researchers have begun to explore the possible use of this class of "waste material" as a low-cost and sustainable approach to recycle lithium-ion batteries. Using pulverized orange peel as a prototypical fruit peel waste, the efficacy and safety of orange peel as a green reductant for the acid leaching of valuable metals like Co, Li, Mn, and Ni from lithium-ion batteries cathode materials were examined. The key is the cellulose found in orange peel, which is converted into sugar under heat during extraction process. These sugars increase the recovery of metals from battery waste. Naturally occurring antioxidants found in orange peel, such as flavonoids and phenolic acids, may also contribute to this enhancement. The selective recovery of $Co(OH)_2$ can be achieved using the orange-peel inspired leaching system. Thus, the use of fruit peel waste to recover valuable metals from spent lithium-ion batteries is an effective, eco-friendly, and sustainable strategy to minimize the environmental footprint of both waste types [43]. The process of how orange peel is helpful in extracting metals from spent lithium-ion batteries is shown in [Figure 12].

Figure 12: How extraction of metals from spent lithium-ion batteries takes place using orange peel

6.2 Green synthesis of metal Nanoparticles using fruit peels

Fruit peel extracts function as biogenic reducing and capping agents in the green synthesis of nanoparticles (1–100 nm), offering a safer alternative to conventional physicochemical routes that rely on toxic solvents and stabilizers. Fruit peels are rich in polyphenols, flavonoids, terpenoids, and phenolic acids bearing redox-active hydroxyl (–OH) groups. These groups donate electrons to reduce metal ions such as Agz and Zn²z into metallic or metal oxide nanoparticles, while simultaneously stabilizing the surface via adsorption and coordination interactions [44]. Using fruit peel extracts, diverse nanomaterials, including CuO, Fe, O*f* , TiO,

, Mn_3O_4, and ZnO, have been synthesized. The mechanism involves electron transfer from phenolic constituents, initiating nucleation and nanocrystal growth; concurrently, surface-bound phytochemicals prevent agglomeration through steric and electrostatic stabilization. For example, flavonoids and terpenoids from orange peel enable the formation of stable Ag nanoparticles with strong antimicrobial activity [45]. Pomegranate peel, enriched in gallic acid and ellagitannins, facilitates the biosynthesis of Ag and Au nanoparticles by mediating metal ion reduction and regulating particle size and morphology [46]. Banana peel extract, containing lignin, cellulose, hemicellulose, and pectin, serves as both reductant and stabilizing matrix for Ag and Pd nanoparticles and has been applied in mesoporous silica nanoparticle preparation for adsorption of methyl orange and phenol, highlighting environmental remediation potential [45]. Figure 12 depicts ZnO nanoparticle synthesis using orange peel extract. Zinc acetate dihydrate dissociates to yield Zn^{2+} ions (A). Upon mixing with peel extract (B), phytochemicals complex with Zn^{2+} (C). Subsequent addition of NaOH generates $Zn(OH)_2$ as an intermediate, which upon thermal dehydration converts into crystalline ZnO nanoparticles (D) [46]. Throughout the process, plant metabolites act dually as reducing and capping agents **[Figure 13].**

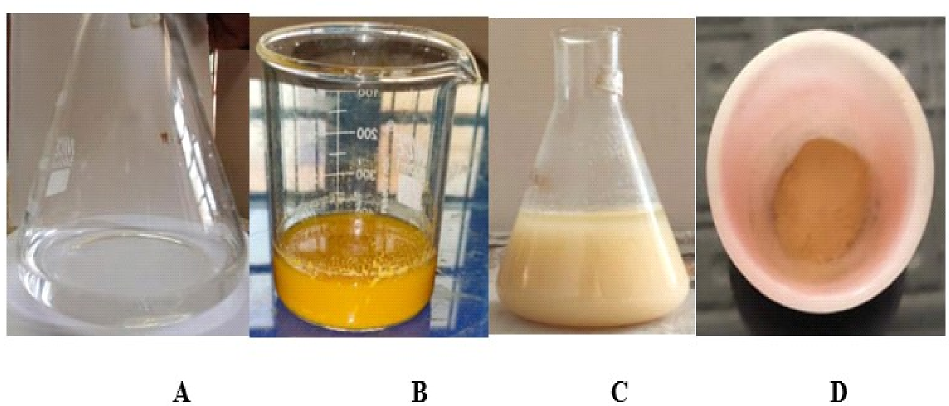


Figure.13.Preparation of ZnO-NPs from orange peels

7. Conclusion

The traditional "take–use–dispose" economic model has led to excessive resource consumption and growing waste, with fruit peels alone making up nearly 25–50% of global food waste. Although often discarded, these peels are rich in valuable bioactive compounds such as polyphenols, flavonoids, carotenoids, dietary fiber, pectin, cellulose, and essential vitamins. These compounds exhibit strong antioxidant, anti-inflammatory, and antimicrobial activities. For instance, apple peels contain flavonoids that support cardiovascular health, mango peels provide bioactive phytochemicals with antidiabetic and anticancer potential, banana peels are rich in dopamine and phenolics, citrus peels supply essential oils and antioxidants, and pomegranate peels contain ellagitannins known for their chemo preventive effects. Rather than treating fruit peels as waste, the circular economy approach views them as valuable resources. Through sustainable technologies such as enzymatic hydrolysis and microwave-assisted extraction, these by-products can be converted into biodegradable packaging, natural dyes, functional food ingredients, cosmetics, pharmaceuticals, and even biofuels. Beyond product development, fruit peels also contribute to composting, wastewater treatment through biosorption of heavy metals and dyes, and bioenergy generation. Compounds from orange peels have even been used as eco-friendly reducing agents to recover metals like cobalt, lithium, manganese, and nickel from spent lithium-ion batteries. Additionally, fruit peel extracts are being used in green nanoparticle synthesis, reducing dependence on hazardous chemicals. Although large-scale implementation requires better collection systems and biorefinery infrastructure, fruit peel valorization offers an environmentally responsible pathway that supports sustainability and strengthens the circular bioeconomy.

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