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REVIEW PAPER

Revolutionizing waste management: nanoparticle synthesis from fruit Peels, applications and challenges

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Abstract
Nanoscience is fast evolving and has applications in food science, biotechnology, and nanobiotechnology. The global problem of handling non-biodegradable garbage, which is expensive and hard to dispose of, requires novel solutions. Nanotechnology and other innovative technologies can make biodegradable trash useful. Recent research has focused on sustainable nanoparticles (NPs) production from biodegradable trash. Over the past decade, biogenic synthesis of metallic nanoparticles (MNPs) has been considered a viable alternative to conventional approaches. Its biocompatibility, environmental friendliness, and ease of use make this strategy recommended. Industrial fruit waste, rich in bioactive phytoconstituents, may be used to cap and reduce NPs. These bioactive compounds facilitate the synthesis of nanoparticles and exhibit antibacterial, antioxidant, and anti-inflammatory activities. Silver nanoparticles derived from fruit waste, when incorporated into food coatings, have been shown to inhibit microbial growth by approximately 95–99%, thereby extending the shelf life of food products by 7–10 days. Similarly, the incorporation of zinc oxide nanoparticles into biodegradable packaging materials enhances UV protection by nearly 80% and improves mechanical strength by about 30%. Quantitative benefits demonstrate their sustainability and efficiency as preservative and plastic alternatives. Fruit peel nanoparticles show promise in practical applications. This review article discusses biogenic NPs made from fruit waste, their types, extraction methods, functional features, pharmacological potential, industrial applications, and future advances and examines sustainable nanotechnology's current advances by turning fruit peels into therapeutic nanomedicines.

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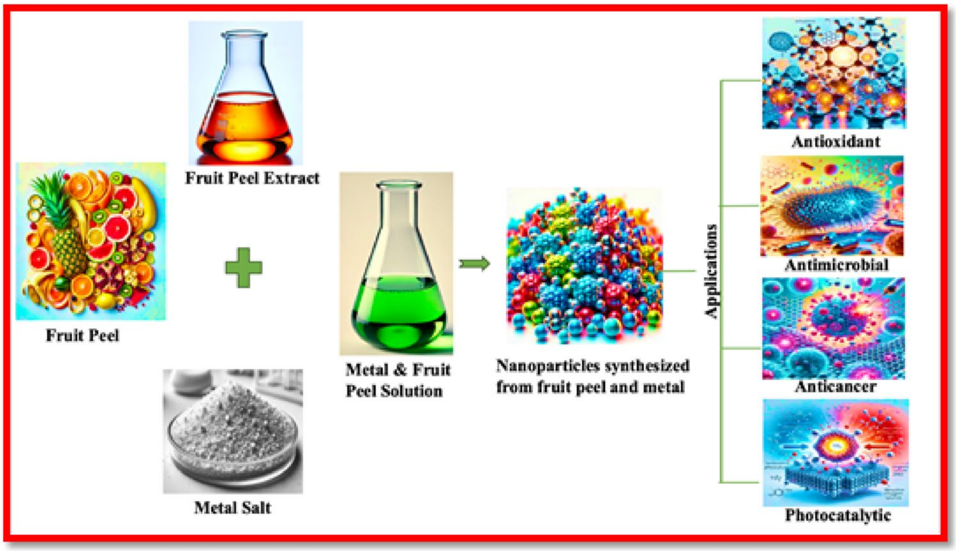
Graphical Abstract



Keywords Fruit waste · Extraction · Nanoparticle synthesis · Biological potential · Industrial aspects

Introduction

The economy, environment, and human health are all severely impacted by food waste, which is a major worldwide problem that has to be addressed [1]. The supply of sustainable food is a huge problem for developing countries. India, which is ranked 105th out of 127 nations, is a prime example of the challenge of food security. When seeking to address this issue, nations and regions like the European Union and India face several obstacles [2]. According to estimates from the United Nations Environment Programme, families in India generate around 68.76 million tons of food waste annually, with each individual producing an average of 50 kg of food waste. Similarly, the European Union claims that over 59 million tons of food waste or 131 kg per person occur each year [3]. The World Health Organisation (WHO) estimates that foodborne pathogens are responsible for 420,000 associated deaths and about 600 million instances of foodborne disease (WHO, 2016) [4]. This problem may be reduced by the employment of numerous measures, such as enhancing the management of supply chains, boosting consumer understanding about food preservation, and repurposing food waste into commodities with better functionality [5]. Recently, there has been a lot of interest in the idea of a circular economy, which seeks to create value from waste materials. With 2.32 million tonnes of household food waste produced yearly in developing countries, this strategy is especially relevant there (UNEP Food Waste Index Report, 2021). Food waste in the supply chain is estimated to have an annual economic effect of around R 61.5 billion, or 2.1% of the country's GDP in 2011 [6]. Phytochemicals and bioactive substances found in fruit waste (FW) are abundant and may find use in functional foods, dietary supplements, and cosmetics. These substances may exist in many different forms. However, FW may include potentially dangerous substances including pesticides and heavy metals, depending on the production and processing procedures [7]. It is essential to confirm that FW is safe for use in these applications before beginning to extract bioactive components. By reducing food waste and using it to make valuable commodities, significant economic benefits may be achieved while concurrently addressing environmental and public health concerns. The bioactives derived from FVW may be used to successfully synthesize metal and metal oxide nanoparticles (NPs) [8]. Due to their reducing agent properties and interactions with metal ions, these substances produce metallic nanoparticles with unique properties. Phenolic substances like tannins and catechins, together with amino acids like tyrosine and tryptophan, have been used to create gold and silver nanoparticles, respectively [9]. Over 75 million tonnes of trash are produced each year by grapes, the world's biggest fruit crop (International Organisation of Vine and Wine [OIV], 2017) enzymes, such as lactase and peroxidase, are crucial for stabilizing metal ions, stopping their aggregation, and promoting their reduction to nanoparticles. Furthermore, polysaccharides such as chitosan and alginate function as stabilizing and reducing agents when nanoparticles (NP) are being synthesized [10, 11].

The literature indicates that around 60% of medications that are sold commercially originate directly or indirectly from natural reservoirs such as minerals, plants, and animals [12]. The biomolecules found in FW may influence the structure and growth of NPs by acting as templates for the creation of nanoparticles using biomimetic approaches [13]. In addition to directing the creation of nanoparticles (NPs), macromolecules including proteins, peptides, nucleic acids, and polysaccharides also serve as capping agents, stabilising and halting the aggregation of NPs. For applications in the domains of medicine, electronics, and catalysis, the stability of NPs is crucial to maintaining their unique characteristics [14]. The use of nanotechnology might leverage the bioactive potential of FW and help foster sustainable innovation in a number of industries. The synthesis of nanoparticles (NPs) from edible peel, kernel, and pericarp waste has gained popularity as an ecologically acceptable substitute for traditional techniques, which often include the use of chemical precipitation and hazardous solvents [15, 16]. According to the tenets of green chemistry, this biogenic process produces nanoparticles (NPs) with distinct physical and chemical characteristics that enable them to be used for a range of applications in pharmacology and biomedicine. Atoms and molecules are employed as building blocks that self-assemble into nanoparticles in the majority of situations, which use a bottom-up synthesis approach [17].

Despite its enormous potential, there is presently a limited amount of investigation into the utilization of horticultural and aquaculture waste for the production of nanoparticles. The need for increased study in this area is shown by the few number of investigation that have looked into the process by which such waste may be converted into products with additional value [18]. The morphology of particles is a crucial factor in assessing the effectiveness of biogenic nanoparticles [19]. Waste products from plants provide a diverse range of bioactive compounds that impact these characteristics throughout the NPs synthesis process. This analysis explores the methodologies employed in the production of biogenic nanoparticles, considering both their benefits and drawbacks [20]. There are several financial and environmental benefits to synthesizing nanomaterials from biodegradable waste. In addition to creating advanced materials for use in medical and other applications, it provides a sustainable solution to problems caused by non-biodegradable waste [21, 22].

Extraction of biologically active phytoconstituents from fruit waste

To extract bioactive chemicals from the leftovers of tropical exotic fruits, a variety of operational procedures and conditions must be met in order to maximize efficiency and output. Among the most crucial processes are grinding, solvent extraction, and drying [23]. Wet milling is often employed to enhance subsequent extraction operations, even though very fine particle sizes may cause excessive water retention, which may complicate pressing processes [24]. When evaluating various alternatives such as ethanol, petroleum ether, hexane, and acetone, it is evident that acetone stands out as the organic solvent yielding the highest output. This is due to the fact that the most used organic solvent for extracting carotenoid is acetone. Furthermore, the European Union permits the utilization of acetone in the production of food additives, guaranteeing that the material conforms with all relevant safety regulations [25]. Before extraction, fresh raw materials may be washed with water to remove soluble impurities. As a consequence, the extract's quality improves. Sequential washing with acetone helps further remove water and extract carotenoid components. For quantitative recovery, several extractions are often needed. The structure of a few flavonoids found in fruit waste is shown in Fig. 1.

After the extraction process is finished, carotenoids may be obtained as crude pigments by evaporating solvents at low temperatures, as long as any required cleaning steps have been taken beforehand. As an alternative, purification by solvent transfer to hexane would be necessary; nevertheless, hexane's restricted use in food component manufacture indicates that cautious consideration is necessary [26].

Solvent extraction may also be used to extract tocopherols, flavonoids, and other phenolic compounds associated with them. Tocopherols and other phenolic diterpenes are well extracted using nonpolar solvents like petroleum ether and hexane. However, ethyl ether and ethyl acetate are especially good in recovering phenolic acids, low-molecular-weight phenolics, and flavonoid aglycones [18]. Because of their higher polarity, ethanol and ethanol-water combinations are more effective at extracting high-molecular-weight phenolics and flavonoid glycosides. Overall polyphenol yields increase as a consequence. There are financial and safety benefits to using ethanol and ethyl acetate freely in the manufacturing of food ingredients [19]. The cost of the solvents and the requirements for effluent treatment must be considered in order for these processes to be financially feasible. In order to balance yield, cost, and environmental impact, it is critical to optimize solvent choices [27].

Dietary fiber (DF) is often recovered from tropical fruit leftovers after the extraction of proteins, carotenoids, or

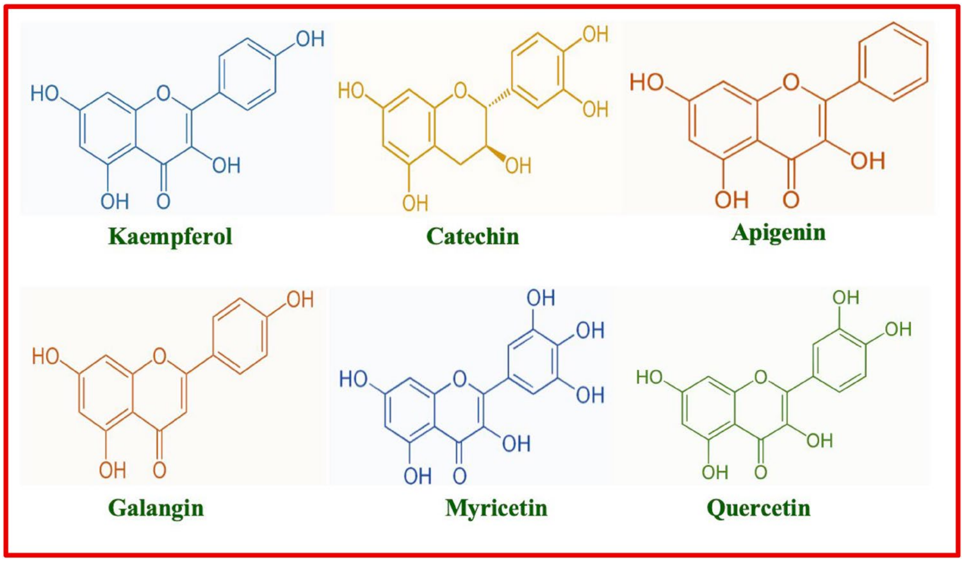


Fig. 1 Structure of some flavonoids present in fruit waste

antioxidants. As a result, the recovery process affects the dietary fiber product's composition, which in turn affects the product's nutritional and functional properties. Pectin extraction often involves the use of mineral acids like nitric or hydrochloric acid. One kind of dietary fiber with remarkable gelling properties is pectin. The pectin is precipitated using ethanol or aluminum chloride solutions after the extract has been separated from the solid leftovers [21]. Extraction of pactin may occur after other bioactives have been recovered, or it may occur directly from the raw byproduct after extraction of juice. Enzymatic extraction is one method that seems promising as a substitute for the traditional methods of processing dry and coarsely ground raw materials. This method may more successfully recover pectin and pactic oligosaccharides, which are known to enhance gut health, change the human microbiome, and have anticancer properties [28]. Fig. 2 shows the structure of some Alkaloids present in fruit waste.

Utilising green-synthesised AgNPs to preserve food products

Silver has garnered a lot of attention lately due to their broad-spectrum antibacterial properties. Accordingly, they may prove to be a useful instrument for fruit and vegetable preservation. Silver nanoparticles (AgNPs) may be used in food preservation by submerging the item in the mixture or by including them into packaging materials such as edible coatings or wrapping sheets. These methods guarantee that the quality of food products is maintained throughout storage in addition to enhancing their antibacterial activity [29].

Plant-derived AgNPs have shown efficacy in reducing weight loss in immersion treatments while preserving the nutritional components. AgNPs derived from tea leaf extracts, for instance, were able to minimize weight loss in tomatoes while maintaining levels of vitamin C, titratable acid, and total soluble solids respectively [24]. Similar to this, orange fruits treated with AgNPs made from leaf extracts of *Fatsia japonica* exhibited a 50% reduction in deterioration rate. Bananas treated with a solution containing 0.01% silver nanoparticles showed reduced morphological changes and delayed ripening [30].

These films are used to wrap fruits and vegetables, creating an antibacterial barrier without coming into direct contact with the food. They are a component of wrapping films. Studies have shown that when silver nanoparticles (AgNPs) are incorporated into low-density polyethylene (LDPE) sheets for the packaging of fresh-cut carrots, there are no detectable silver residues on the fruit [26]. When applied directly to the produce's surface, edible coatings ensure that the antibacterial qualities are felt across the whole surface. The application of these coatings, which may be consumed together with the agricultural produce, is thought to be a sustainable and ecologically beneficial preservation technique [31].

Both approaches aim to extend food's shelf life while concurrently addressing worries about microbial growth and quality degradation. For instance, after 14 days of storage at 20 degrees Celsius, papayas coated with hydroxypropyl methylcellulose containing 0.25% silver nanoparticles showed no symptoms of fungal growth, thus extending their shelf life [28]. In particular, the manufacturing of edible coatings uses materials including locust bean gum, agar, carrageenan, chitosan, and alginate. These coatings' effectiveness depends on their properties, including their ability to evenly disperse silver nanoparticles (AgNPs) and stick to the fruit or vegetable's surface. Because it is simple and

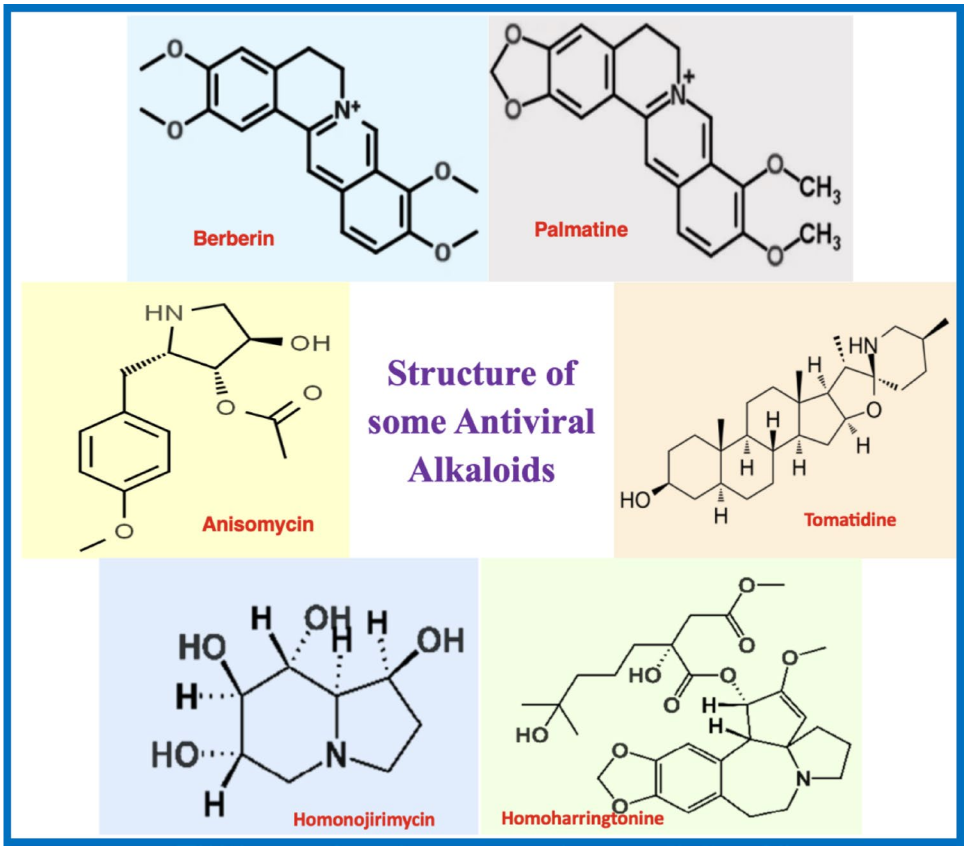


Fig. 2 Structure of some antiviral alkaloids present in fruit waste

effective, chitosan has become a popular choice among these materials. The combination of AgNPs with chitosan has the ability to completely inhibit fungal spore germination while also promoting the growth of treated seeds, according to study by Gowda and Sriram (2023) [32]. In general, the use of silver nanoparticles (AgNPs), especially in edible coatings, is a technique that is safe for the environment and efficient in increasing fruit and vegetable preservation, lowering spoilage, and maintaining quality.

Fruit waste components used as reducing agents in nanosynthesis

Phytochemicals, another name for bioactive compounds, are found in abundance in fruits. These two phrases describe secondary metabolites produced by plants. The presence of these compounds is crucial for the protection of plants against environmental challenges, illnesses, and predators, which in turn serves to improve their resilience and guarantee their continuing survival. Since these phytochemicals have so many potential uses in industries including agriculture, medicine, food production, and nanotechnology, their significance extends well beyond plant defense [30]. Grapes are the most widely farmed crop in the world, producing around 75 million tons of by-products annually. By-products that are frequently considered trash include grape seeds, peels, and marc. These by-products do, however, include vital elements such proteins, fats, carbs, vitamins, minerals, and polyphenolic substances. These components are linked to a number of health benefits, and there are opportunities for their sustainable use. Parallel to this, apples, which are consumed worldwide, along with other fruits like mangoes, pineapples, papayas, and coffee, are rich in essential nutrients and are in high demand in the industrial sector because of their significant nutritional worth [33].

Exotic fruits include particularly high levels of phenolic compounds, vitamins, carotenoids, and dietary fiber. The pulp, seeds, and peels of exotic fruits are among the several parts that have these qualities. Because these bioactive compounds are present, fruit by-products may be used to biosynthesize metal-based nanoparticles. For example, fruits like apples, grapes, and citrus contain polyphenols, which comprise flavonoids, tannins, and phenolic acids. The reducing properties of these polyphenols are strong. These substances are essential for redox metabolic processes and aid in the creation of nanoparticles [34]. A subgroup of polyphenols called flavonoids has shown efficacy as reducing agents and has been effectively used in the creation of nanoparticles. For example, flavonoids extracted from lemon peels were used to create stable, antibacterial silver nanoparticles. Terpenoids are another family of phytochemicals that may be found in fruits like pineapples and oranges. They also contain characteristics that enable them to diminish. These materials have been used to create zinc oxide (ZnO) and other nanoparticles that are helpful for medicine delivery [35].

These bioactive compounds' redox characteristics are essential for lowering metal ions and stabilising the nanoparticles produced throughout the synthesis process. These attributes provide control over the size, structure, and properties of nanoparticles by varying reaction parameters including pH, precursor concentration, and reaction duration. Although other phytochemicals including alkaloids, terpenoids, and vitamins also have a major function in this process, polyphenols are often emphasised for their participation in it [36]. An additional category of phytochemicals that has the potential to be exploited in the development of nanoparticles is alkaloids. These alkaloids include nitrogen in their structural makeup. Metal-based nanoparticles have been successfully synthesized using alkaloids, which are derived from fruit by-products like banana peels. Fruits like bananas and a variety of berries may contain these alkaloids [37]. Utilizing fruit-derived bioactive compounds to create nanoparticles suggests that these materials have the capacity to promote sustainability by converting agricultural waste into valuable resources and innovation in a range of fields.

Synthesis approaches of biosynthesis of metal oxide nanoparticles utilising fruit waste extracts

Nanomaterials have achieved significant acclaim for their remarkable adaptability and efficacy across several domains, including biotechnology, healthcare, and agriculture. Conventional methods for synthesising nanomaterials, such as chemical and physical techniques, often encounter challenges [38]. This encompasses the utilisation of hazardous chemicals, elevated impurity levels, substantial prices, and restricted reduction opportunities. Organic solvents and reducing agents, such as sodium borohydride and hydrazine, are often used in the synthesis of iron nanoparticles, both of which pose significant risks to environmental and human health [39].

Although physical techniques such as ball milling have been used to manufacture high-purity nanomaterials on a large scale, these processes need costly equipment, significant energy consumption, and extensive operating space. Analogous to this, synthetic methodologies, such as hydrothermal methods, provide control over the material's dimensions and morphology; nevertheless, they often exhibit deficiencies in dependability and repeatability. Consequently, biosynthesis has arisen as an alternative approach for the production of ecologically sustainable nanomaterials [40].

The use of plant extracts for the biosynthesis of nanomaterials offers several benefits, including elevated purity, economic viability, time efficiency, and ease of use. Plant-derived formulations are increasingly used for the synthesis of metal oxides. This is mainly due to the fact that these formulations may generate nanoparticles with requisite properties while simultaneously reducing their environmental effect [41]. This environmentally sustainable synthesis process employs plant extracts as stabilising and reducing agents. They promote the reduction of metal ions to their elemental or oxide states and prevent the agglomeration of nanomaterials via interactions with their phytochemical contents. Plant extracts include a variety of bioactive compounds, including alkaloids, flavonoids, polyphenols, tannins, saponins, terpenoids, and vitamins [42]. These chemicals play a vital function in the reduction and capping of metal ions during nanoparticle synthesis. These chemicals may be found in many plant parts, including the leaves, roots, stems, fruits, and flowers. Polyphenols are generally considered significant contributors to the bio-reduction of metal ions to metal oxides. This method is referred to as bio-reduction [43].

The process of reducing metal precursors to create atoms is called activation. Small particles combine to form larger clusters during Ostwald ripening. We call this process nucleation. In addition to increasing the stability of the nanoparticles, encapsulating plant extracts onto them defines their morphological and structural characteristics. We call this process stability and growth [44]. However, the precise oxidation-reduction mechanisms that are accountable for the plant-mediated synthesis of nanoparticles remain unclear despite a great deal of research being done in this area. However, the potential for using fruit waste in this context is increasingly becoming clear. For instance, it has been demonstrated that using fruit waste materials to create metal oxide nanoparticles with unique physicochemical properties works well [45]. In addition to encouraging environmentally conscious waste management, this innovative technique offers an efficient and environmentally friendly way to produce functional nanomaterials that have a variety of potential uses. A comparative analysis of green synthesis and conventional synthesis methods, highlighting their advantages, disadvantages, and scalability, is presented in Table 1.

Table 1 Comparative analysis of green synthesis and conventional synthesis methods highlighting Advantages, Disadvantages, and scalability

Aspect	Green Synthesis	Conventional Synthesis	References
Cost	Typically diminished because of a decreased requirement for costly reagents and energy.	Increased expenses related to reagents, energy consumption, and waste management practices.	[46]
Energy Consumption	Reduced energy demands; frequently performed under ambient conditions.	Increased energy usage resulting from severe reaction conditions.	[47]
Environmental Impact	Environmentally conscious; utilizes sustainable materials and steers clear of harmful substances.	Frequently entails the use of hazardous substances and produces considerable waste.	[48]
Product Quality	Exceptional purity and consistency; frequently excels in biological applications.	The quality may fluctuate and could necessitate further purification processes.	[49]
Reproducibility	Variability may occur based on biological origins; achieving standardization can present difficulties.	Ensuring high reproducibility through meticulously controlled processes and standardized protocols.	[50]
Safety	Enhances safety for both operators and end-users, reducing the risk of exposure to hazardous materials.	Increased danger associated with the utilization of hazardous and combustible substances.	[51]
Scalability	Possesses the potential for scalability, yet may encounter difficulties regarding consistency and control.	Robust scalability accompanied by reliable quality assurance.	[52]

Types of nanoparticles from fruit waste

Titanium dioxide (TiO_2) nanoparticles

TiO_2 is widely valued for its low toxicity, low cost, stable, high refractive index, λ_{max}, and antimicrobial properties. It is widely used in many industries, including as building, electronics, food, cosmetics, and medicine [53]. It is extensively used as a result. The efficacy of biopolymer-based composites, consisting of chitosan, sago starch, hydroxypropyl methylcellulose, gelatin, whey protein isolate, and gellan gum, is augmented by the incorporation of TiO_2 into active packaging films within the food packaging industry. Titanium dioxide nanoparticles have been approved for use as food additives by the US Food and Drug Administration (FDA) [54].

The growth of microorganisms that cause food degradation is inhibited by titanium dioxide nanoparticles, which serve as photocatalysts and antibacterial agents in food packaging. Lipid peroxidation results from the manufacturing of ROS by these molecules when they are exposed to light and UV radiation. Galstyan et al. (2018) claim that the hydroxyl radicals generated harm the bacteria's DNA, which eventually leads to the cells' demise [55]. Because of its exceptional transparency, hydrophilicity, resistance to bacterial growth, and UV protection, TiO_2-based bio-nanocomposites are used in the packaging of oxygen-sensitive food goods. Moreover, it is used in the packaging of oxygen-sensitive food products. Bodaghi et al. (2013) demonstrated that incorporating TiO_2 nanoparticles into low-density polyethylene (LDPE) sheets effectively inactivates yeasts and Pseudomonas spp. in pear packing. Furthermore, titanium dioxide (TiO_2) may be included into polymer films to create nanocomposites that provide defense against UV and oxygen [56].

A study shown that a Gel/Grape Seed Extract/TiO_2 coating has significant UV barrier properties, antioxidant activity, and antibacterial activities against *L. monocytogenes* and *E. coli*. A range of food products, including as cheese, shrimp, and strawberries, have been shown to benefit from nanocomposite coatings, which help preserve quality and prevent deteriorating [57]. Some films have positive affects on certain food items.

Silica (SiO_2) nanoparticles

Silicon dioxide nanoparticles, often referred to as nano-SiO_2, have emerged as a very adaptable material for food packaging in recent years. This is mostly due to their distinctive attributes. Due to silicon's status as one of the most prevalent elements on Earth, nano-SiO_2, also referred to as silica, is derived from silicon. The development of nanocomposites for packaging purposes has garnered significant interest. For instance, it has been shown that adding nano-SiO_2 to polylactic acid (PLA) sheets may enhance packaging performance. To do this, PLA films infused with nano-silicon oxide are created using precursors such as 3-isocyanatopropyltriethoxysilane and tetraethoxysilane as coupling agents. The resulting biodegradable packaging has superior gas barrier capabilities, outperforming PLA sheets that have not been altered while retaining its transparent features. With the use of such improvements, food products' freshness and shelf life may be preserved [58].

Successful use of nano-SiO_2 in laminated packaging materials has also been shown. It improves package performance by increasing tensile strength, decreasing gas permeability, and reducing solvent absorption from inks when used with polypropylene (PP) layers [59]. Furthermore, nano-SiO_2 has properties that inhibit enzymes and antimicrobials, which enhance food safety and preservation. Because of its many properties, nano-SiO_2 is an essential innovation in the creation of advanced food packaging solutions. Because of these characteristics, nano-SiO_2 may satisfy consumer demands for greater safety and longer shelf life [60].

Silver nanoparticles (AgNPs)

Although there are many methods for creating silver nanoparticles, or AgNPs, most of them involve turning silver nitrate ($AgNO_3$) into nanoparticles by the application of reducing agents [61]. The techniques outlined have made use of a wide range of reducing agents. Techniques that are classified as physical techniques include γ-irradiation, laser ablation, and ultraviolet radiation. Chemical reduction involves the use of substances like triethanolamine, sodium nitroprusside dihydrate, sodium citrate, sodium borohydride, gallic acid, and L-tyrosine. The biological reduction method uses a variety of natural agents, such as agar, chitosan, microorganisms, and plant extracts. With these methods, AgNP production may be customized for a broad range of uses.

The reduction of $AgNO_3$ and the subsequent modification of nanoparticle properties are significantly influenced by external physical conditions, including stirring, heating, sunlight exposure, ultrasonication, microwave irradiation, and hydrothermal reactions, in addition to reducing agents. It is also plausible that these conditions might impact AgNPs' antibacterial potential. For example, studies have shown that, in contrast to other methods like sunlight or microwave-assisted techniques, ultrasonication-assisted synthesis may produce nanoparticles with better antibacterial efficacy at lower concentrations [62].

Zinc oxide (ZnO) nanoparticles

Zinc oxide nanoparticles, or ZnO NPs, have been the subject of much research for many applications. Biological imaging, antidiabetic therapies, anti-inflammatory agents, antibacterial compounds, antifungal treatments, antioxidants, cancer prophylaxis, wound repair, drug delivery, and targeting represent many of these applications. Upon application of ZnO nanoparticles to plant surfaces and subsequent exposure to light, reactive oxygen species (ROS) are generated. Superoxide anions (O_2^-), hydroxyl radicals (•OH), and hydrogen peroxide (H_2O_2) exemplify these reactive oxygen species (ROS). In order to stop bacteria from growing and to help preserve perishable food items, reactive oxygen species (ROS) may effectively break down the cell walls of microorganisms. ZnO nanoparticles have also been included into food packaging materials due to their broad-spectrum antibacterial activity. When integrated with polymeric components throughout the manufacturing process, they augment the safety and functionality of packaging materials. Their properties such as their ability to stop the development of germs, non-toxicity, thermal stability, and photocatalytic activity make them particularly significant. ZnO nanoparticles may also be used as reinforcement materials for polymer matrices, enabling them to increase surface area, improve mechanical properties, and utilize their crystalline structure all along the way [63].

In one study, Tensile properties, extension at breakage, and antibacterial efficacy against foodborne pathogens were significantly enhanced by the incorporation of ZnO NPs to a pectin/alginate film matrix. *A. niger*, *S. cerevisiae*, *E. coli*, and *C. gloeosporioides* were among these pathogens [64]. Food preservation and safety during storage and transportation were successfully enhanced by these films, which also reduced the amount of moisture absorbed, the solubility of water, the permeability of aqueous vapour, the transmission of ultraviolet light, and the permeability of oxygen [65].

Copper oxide nanoparticles (CuO NPs)

CuO nanoparticles, or copper oxide nanoparticles, have garnered significant attention because to their unique features. These features include a small band gap energy of 1.2 eV, non-toxicity, and low production costs. Their strong antibacterial properties have further raised the prospect of their use in food packaging. In contrast to expensive noble metals like silver, CuO nanoparticles offer a less expensive substitute with comparable benefits. Among these advantages are their great stability and ease of integration into polymer matrices [66]. Upon exposure to visible or ultraviolet light, CuO nanoparticles may generate reactive oxygen species (ROS). These reactive oxygen species may impair cellular organelles, disrupt cell membranes, and finally annihilate bacterial cells. They are very potent antibacterial agents because they have this property. Among the many benefits that CuO nanoparticles have over their chemical counterparts are their biodegradation, biocompatibility, and exceptional efficacy even under conditions of elevated pH and temperature [67].

These characteristics have made CuO nanoparticles a potentially valuable resources for development of antimicrobial food packaging, which might improve food safety and prolong the shelf life of food products. The fact that they can efficiently replace more expensive materials while maintaining their high degree of effectiveness highlights its potential for extensive use in the food sector [68].

Gold coated nanoparticles (AuNPs)

Materials designed for use in biomedical applications must have both non-toxic and biocompatible qualities. Therefore, assessing the cytotoxic effects of nanoparticles is crucial when considering their use in medicine. The biocompatibility and cytotoxicity of Pi-AuNPs (gold nanoparticles made from pineapple peel) and Pa-AuNPs (gold nanoparticles made from passion fruit peel) were examined using the MTS test for cell viability[116]. Normal Vero cells and MCF-7 breast cancer cells were exposed to varying concentrations of these nanoparticles (50 mg/mL, 100 mg/mL, 200 mg/mL, and 400 mg/mL) for 24–48 h. The results proved their biocompatibility, showing no significant adverse effects even at the highest dosage (400 mg/mL). The study's findings demonstrated that, in comparison to the controls, there were no statistically significant differences in cell viability ($P > 0.05$) [69].

These findings are in line with previous research, even though earlier research has shown that gold nanoparticles derived from fruit peel extracts may have anti-cancer properties in vitro. Musa paradisiaca peel extracts were used to create the gold nanoparticles, which showed cytotoxic activity against A459 lung cancer cells [14]. For instance, HepG2 liver cancer cells were successfully inhibited by nanoparticles derived from Annona muricata peel. Some of the factors that might affect the cytotoxic effects of gold nanoparticles include their size, shape, and surface charge. Several studies have shown that positively charged functional groups enhance cytotoxicity and cellular interaction. Zeta potential experiments, however, reveal that the surface charges of Pi-AuNPs and Pa-AuNPs are negative. This produces surface coatings that are biocompatible and non-toxic. They are ideal for use in medical applications such as drug delivery and molecular imaging because of their stable and safe profiles, which may be advantageous because of their suitability for these uses [70].

Applications of nanoparticles derived from fruit waste

Metal oxide nanoparticles derived from fruit waste and their biological applications

The various health benefits that can be obtained from the production of Metal oxide nanoparticles (MONPs) synthesised from fruit waste are mostly due to the bioactive compounds that are naturally found in fruits. The biocompatibility of the resulting nanoparticles is enhanced by these substances, which include vitamins, flavonoids, and polyphenols [71]. Because of these secaondart metabolites nanoparticles are particularly well-suited for use in biomedical applications including food technology, tissue engineering, imaging, and medication administration. Since these phytochemicals are derived from natural sources, it is reasonable to believe that they are generally safe for biological systems, which reduces the possibility of cytotoxicity and unintended reactions [72]. Fig. 3 represents the applications of nanoparticles synthesised from fruit waste in different sectors.

In the process of pharmaceutical production, natural sources such as plants, minerals, and animals have played a key role throughout history. It is believed that over 60% of currently used drugs originated in these reservoirs. This demonstrates that medicinal plants, particularly bioactive compounds derived from fruit, may provide nanoparticles synergistic biological properties. As shown in applications like chemotherapy, where progressive drug release, extended half-life, and enhanced efficacy are crucial elements, this technique enhances the therapeutic efficiency of nanomaterials [73]. Bioactive substances have a function in improving the stability, biological activity, and compatibility of metal oxide nanoparticles in addition to simplifying their production. These phytochemicals enhance the functionality of the nanoparticles while also lessening their toxicity via their interactions with other chemical entities on their surface [74]. One special benefit of fruit-mediated nanoparticle production is that it blends medicinal potential with biocompatibility. This benefit comes on top of the practical and financial benefits of using plant-based resources, which include their affordability, accessibility, and scalability [75]. The biological features of these nanoparticles, well described in research, include antioxidant, anti-inflammatory, antibacterial, antiviral, and anticancer capabilities. Because of this, they are particularly significant for a broad range of applications in medicine and beyond, underscoring the fact that they have the possibility of becoming an alternative that is both sustainable and successful to existing techniques [76]. Table 2 represents diverse categories of bioactive chemicals derived from fruit by-products.

Metal oxide nanoparticles derived from fruit waste used as antibacterial agents

The proliferation of globalisation and the growing intricacy of food production have led to the emergence of foodborne pathogens, which today pose a significant threat to world health. The World Health Organisation (WHO) reports that these bacteria are responsible for around 600 million instances of foodborne disease and 420,000

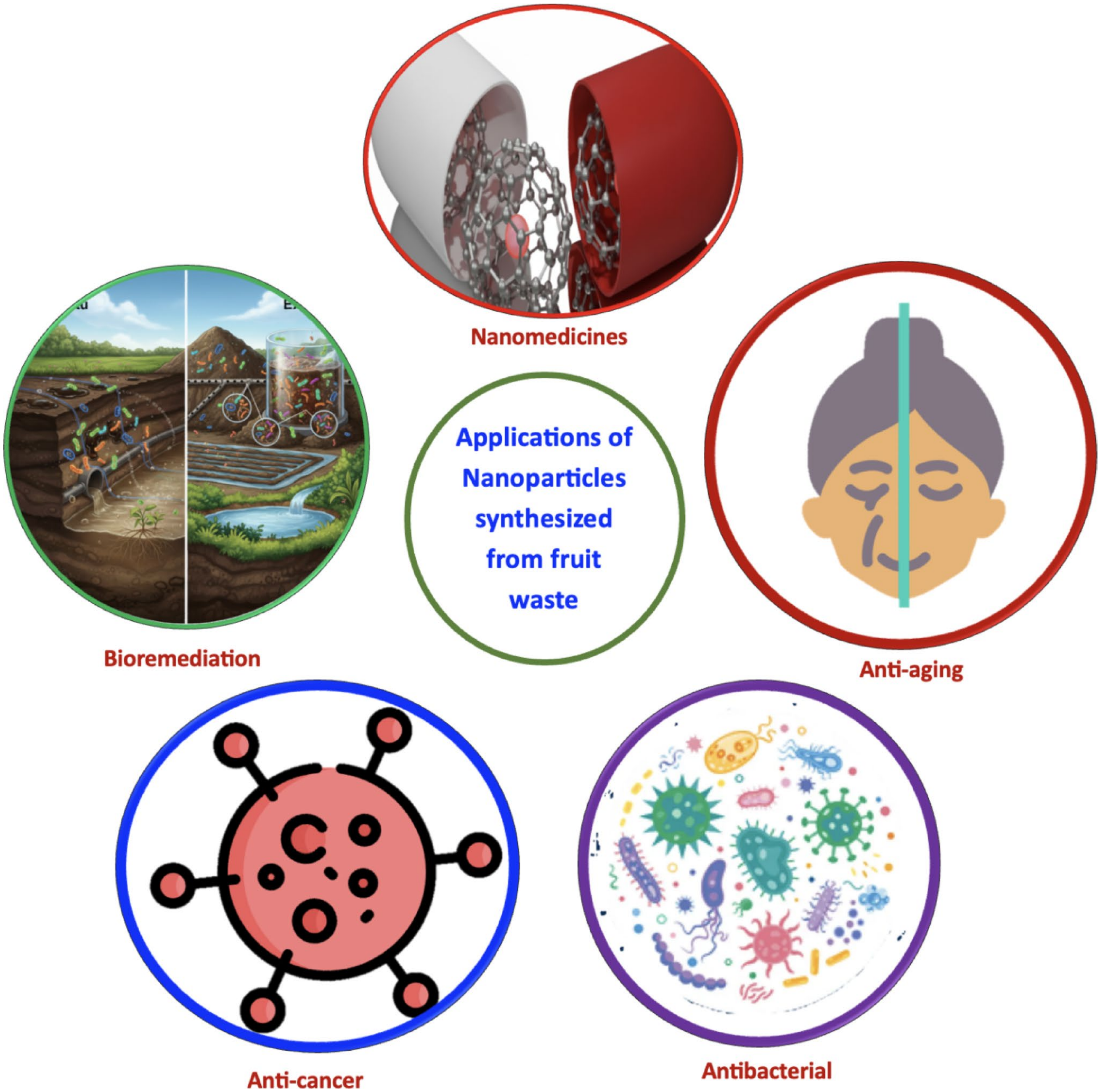


Fig. 3 Applications of nanoparticles synthesised from fruit waste in different sectors

associated fatalities per year in the United States [82, 83]. Consequently, the management of dietary-related illnesses has garnered considerable attention. A component of the defence against foodborne pathogens is the use of silver nanoparticles (AgNPs). These nanoparticles have shown the capacity to generate an excessive amount of reactive oxygen species (ROS), which compromise cellular proteins, alter antioxidant levels, and disrupt mitochondrial function, ultimately leading to apoptosis in vitro [84]. Moreover, silver nanoparticles have antimicrobial properties over a wide range, demonstrating efficacy against moulds, yeasts, both Gram-positive and Gram-negative bacteria, multi-resistant Staphylococcus aureus, and some viruses. This broad antibacterial impact is caused by AgNPs' ability to target a broad range of microbial pathogens and impede their adaptation and resistance processes [85]. Fig. 4 represents the antibacterial potential of Silver nanoparticles derived from fruit waste.

Depending on the kind of pathogen, AgNPs have varying effects on microorganisms. For example, by creating holes, increasing permeability, and causing structural damage, AgNPs might compromise the integrity of bacterial cell

Table 2 Diverse categories of bioactive chemicals derived from fruit by-products

Fruit Waste	Phytoconstituents	Extraction method	References
Apple	Phenolic compounds	Extraction using supercritical fluids	[77]
Grape marc	Polyphenols, Pectin	Extractions using enzyme assistance, ultrasound support, supercritical fluids, microwave technology, and pulsed electric fields. Ultrasound-assisted extraction	[78]
Grape Pomace	Anthocyanins Phenolic compounds	Extraction of solid-liquid phases utilizing an ionic liquid solution. Extraction of enzymes utilizing the biomass from brewery yeast Extraction process of enzymes	[79]
Grape Skin	Phenolic compounds	Natural solvents with profound eutecticity exhibit unique properties that can be influenced by high-voltage electrical discharges.	[23]
Mango Peel	Phenolic, carotenoids, and flavonoids	Supercritical CO2 extraction, succeeded by pressurized ethanol treatment of the residual material from the initial phase. Pulse electric fields and high voltage electrical discharges.	[80]
Orange Peel	Pectin, essential oils, polyphenols Ferulic acid	Microwave and ultrasound extraction extraction of solids from liquids by use of deep eutectic solvents	[81]

membranes. Additionally, they may cause the cell to die by causing the loss of vital enzymes, ATP, and cytoplasmic components [55]. The majority of foodborne illnesses are brought on by eating tainted food that was produced during the production, distribution, or serving of food. These illnesses have the potential to significantly impact global economies as well as public health. Certain bacteria are known to cause serious illnesses, including renal failure, gastrointestinal problems, and pneumonia [56]. The symptoms of foodborne illnesses might vary depending on the amount of contaminated food consumed, but they often include nausea, diarrhea, and upset stomach. Additionally, medication can be necessary [86]. The addition of silver nanoparticles, or AgNPs, to the recipe improves the antibacterial properties of film materials. The incorporation of AgNPs into a ZnO-chitosan coating markedly enhanced its efficacy against *Shewanella putrefaciens* and *Pseudomonas aeruginosa* compared to chitosan or ZnO-chitosan coatings alone [87]. Gowda and Sriram (2023) observed that the combined effects of chitosan and silver nanoparticles enhance antibacterial activity when used together [32]. Thus, this aids in managing diseases such as Colletotrichum truncatum that are transmitted by seeds. Moreover, when integrated with nano selenium-AgNPs, nanocomposite films derived from aqueous solutions of furcellaran and gelatin exhibited significant antibacterial efficacy against E. coli, multi-resistant *S. aureus* [88].

The development of antibiotic resistance in bacterial strains has reached a significant turning point, increasing the need for more potent antibacterial medications. The management of bacterial infections faces significant challenges as a result of the ongoing expansion of antibiotic-resistant organisms, which limits available treatments [89]. This is true even if opposition has been fought using a variety of strategies. This has resulted in a rise in the use of nanomaterials to treat and diagnose bacterial illnesses, with encouraging outcomes against a range of harmful pathogens. It has been shown that nanoparticles have significant antibacterial action, despite the fact that the exact mechanisms behind this activity are still unclear [90]. One of the suggested methods, is the binding of nanomaterials to vital biological constituents such DNA, enzymes, liposomes, and ribosomes. This results in protein inactivation, disruption of the electron transport chain, and an excess of reactive oxygen species (ROS), all of which contribute to cellular oxidative stress [91]. The efficacy of plant extracts, particularly those derived from fruits and their byproducts, in the biosynthesis of nanomaterials for biological purposes has been investigated. Fruit extracts have antibacterial properties against foodborne pathogens such as *Salmonella typhimurium*, *Escherichia coli*, *Staphylococcus aureus*, and *Yersinia enterocolitica*, and have been used to transform metal salts like zinc acetate into ZnO nanoparticles [92]. Additionally, ZnO nanoparticles derived from banana peels were assessed for their efficacy against *Salmonella enterica*, *Staphylococcus aureus*, *Bacillus cereus*, and *Klebsiella pneumoniae*. The results indicated that ZnO nanoparticles exhibited the least inhibition against K. pneumoniae and the highest inhibition against S. aureus ATCC 26,923 [93].

Transmission electron microscopy (TEM) analysis and inhibitory tests on fungal cells have shown that AgNPs cause cytoplasmic leakage, cell death, and deformation in Penicillium italicum. When AgNPs and chitosan coating were applied to Botrytis cinerea, the mycelial shape altered, causing fungal hyphae to lyse, cell walls to shrink and become more flexible, and spores to be detached from the conidiophore. AgNPs at concentrations of 10, 20, 40, and 80 µg/mL may impede the proliferation of Fusarium

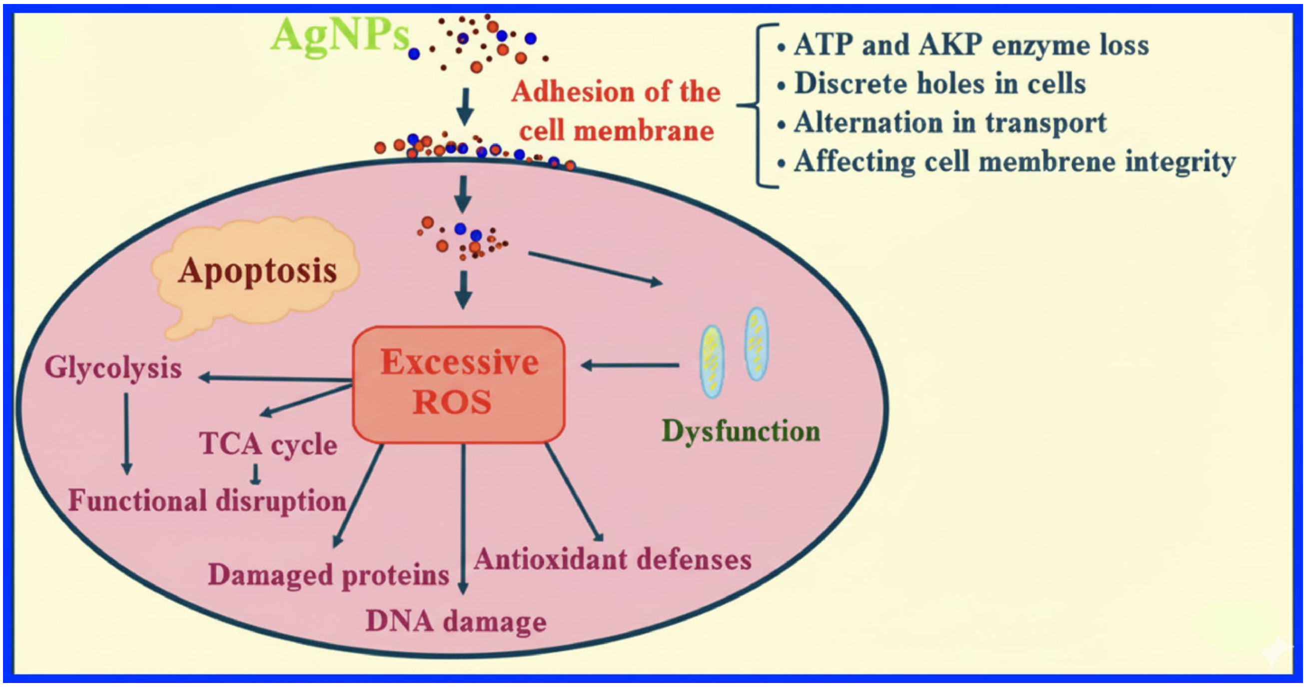


Fig. 4 Antibacterial potential of Silver nanoparticles derived from fruit waste

fungus mycelia and induce the mortality of fungal hyphae. Zhang et al. (2018) found that AgNPs substantially distorted the mycelium of P. italicum, resulting in membrane impairment and ultimately inducing cell death. Zhang et al. (2019) reported that Aspergillus niger spores were eradicated or disintegrated after treatment with molybdenum disulfide-chitosan-AgNPs (MoS-Cs-Ag), resulting in the disappearance of certain spores [94, 95]. A limited quantity of AgNPs was seen near the cell wall. This was the result of the therapy. Moreover, Nejad et al. (2024) discovered that AgNPs at a dosage of 40 µg/mL entirely suppressed the germination of Alternaria alternata spores, resulting in the onset of soft rot on sweet cherry fruits [96]. Dastjerdi and Montazer (2010) state that the breakdown of the cell membrane, which happens as a consequence of the buildup of nanomaterials within the cell wall, is probably part of the process that causes these effects. Superoxide ions (O_2^-) and toxic hydrogen peroxide (H_2O_2) are produced as a consequence of this buildup [97]. Moreover, the deterioration of bacterial cell walls and proteins which ultimately leads to the cell's death and lysis has been linked to interactions between Zn^{2+} cations and negatively charged biomolecules like nucleic acids and enzymes [98]. Because of their strong antibacterial properties, ZnO nanoparticles (NPs) are used across several domains, including bio-imaging, implant coatings, metal surface treatment, tissue regeneration, and biomedical applications [99].

Another metal oxide with antibacterial properties is copper oxide (CuO), which is used to treat a variety of bacteria and fungi. Nanoparticles of titanium dioxide are also widely employed as antibacterial agents. When they come into touch with the cell wall, they are thought to produce superoxide (O_2^-) and hydroxyl (OH) radicals, which is how they work [100]. Table 3 represent the nanoparticles derived from fruit waste and their potential uses.

Metal oxide nanoparticles derived from fruit waste used as antioxidant agents

One of the most often studied biological activities of a broad range of substances and materials, including nanomaterials, is their antioxidant properties. The reason for this is the prospective applications of these substances and materials in fields including agriculture and medical [138]. Neutralizing potentially harmful free radicals, which cause oxidative stress and cell damage, is one of the most crucial roles of antioxidants. Reactive oxygen species (ROS) may be effectively neutralized by antioxidants, which include essential minerals, vitamins, and enzymes. Reactive chemicals known as ROS have the potential to cause oxidative damage [139].

ROS need to be maintained in balance for cells and the body to be healthy. Experts assert that antioxidants play a crucial role in regulating excessive ROS, thereby mitigating oxidative stress and lowering the risk of diseases such as cancer, neurological disorders, and hypertension. Common methods employed to evaluate the antioxidant capacity of materials, including nanomaterials, encompass the ABTS,

Table 3 Nanoparticles derived from fruit waste and their potential uses

Fruit Waste	Nanoparticle Type	Method of synthesis	Properties	Applications	References
Apple peel	AgNPs	Green synthesis	Antioxidant, antimicrobial	Biomedical gels, food safety	[101]
Averrhoa bilimbi fruits	CuO	Green reduction	Antioxidant	Biomedical	[102]
Abelmoschus esculentus fruit	CuO	Green co-precipitation	Antioxidant	Biomedical	[103]
Apple peel extract	CuO	Green reduction	Antioxidant	Biomedical	[104]
Andean blackberry	CuO	Green co-precipitation	Antioxidant	Biomedical	[105]
Banana peel	AgNPs	Green synthesis	Antioxidant, antimicrobial	Medical bandages, antimicrobial agents	[106]
Custard apple peel	Fe_2O_3	Aqueous extract	Magnetic, photoactive	Catalytic degradation of dyes	[107]
Fig peel	TiO_2	Sol-gel	Photocatalytic, UV stable	Photocatalysis, coatings	[108]
Grape skin	AgNPs	Polyphenol-rich extract	Antioxidant, cytotoxic	Cancer treatment, imaging	[109]
Guava peel	AgNPs	Green reduction	Broad-spectrum antimicrobial	Herbal antibacterial creams	[110]
Kiwi peel	ZnO	Microwave-assisted green	UV shielding, antimicrobial	Active packaging, personal care	[111]
Lemon peel	TiO_2	Sol-gel, green	UV-filter, antibacterial	Sunscreen, photocatalyst	[112]
Litchi peel	AuNPs	Polyphenol-assisted	Plasmonic, biocompatible	Bioimaging, diagnostics	[113]
Mango seed	AgNPs	Plant extract method	Antibacterial	Active food packaging, coating	[114]
Myristica fragrans fruit extract	CuO	Green synthesis	Antimicroial	antimicrobial agents	[115]
Orange peel	ZnO	Precipitation, green	UV absorbent, photocatalytic	Textile UV shielding, sunscreen	[116]
Papaya peel	CuO	Microwave-assisted	Antifungal, semiconducting	Agrochemicals, antifungal sprays	[117]
Passion fruit peel	ZnO	Green synthesis	Photocatalytic, UV resistance	Sunscreen agents, cosmetics	[118]
Pineapple peel	AuNPs	Aqueous extract synthesis	Plasmon resonance, catalytic	Cancer diagnostics, colorimetric sensors	[119]
Pomegranate peel	Fe_3O_4	Green co-precipitation	Magnetic, reusable	Targeted drug delivery, wastewater treatment	[120]
Punica granatum peels	CuO	Aqueous extract synthesis	Antibacterial		[121]
Sapota seed coat	AgNPs	Extract-mediated	Antibacterial	Oral care, medical dressings	[122]
Sweet lime peel	AgNPs	Plant extract	Antibacterial	Food wrap films, packaging	[123]
Tamarind shell	CuO	Combustion/green synthesis	Catalytic, low-bandgap	Dye degradation, solar energy harvesting	[124]
Tomato peel	AgNPs	Polyphenol-mediated	Antibacterial, catalytic	Antimicrobial agents in agriculture	[125]
Watermelon rind	ZnO	Hydrothermal, green	Photocatalytic, UV protection	Wastewater remediation, cosmetics	[126]
Carica papaya fruit	CuO/SnO2	Green synthesis	Antioxidant	UV shielding, sunscreen	[127]
Orange peel waste	NiO	Green synthesis	Antioxidant Antibacterial	Biomedical	[128]
Citrus paradise	SnO_2	Green synthesis	Antioxidant Antibacterial	Biomedical	[129]
Orange fruit waste	TiO_2	Green synthesis	Antioxidant Antibacterial	UV shielding, sunscreen	[130]
Capsicum annuum	ZnO	Green synthesis	Antidiabetic Antioxidant	Biomedical	[131]
Ziziphus jujuba	SnO_2	Green synthesis	Antioxidant Antibacterial	Biomedical	[132]
Cavendish bananas	ZnO	Green synthesis	Antidiabetic Antioxidant	Biomedical	[133]
Litsea cubeba fruits	SnO_2	Green synthesis	Antioxidant Antibacterial	Biomedical	[134]

Table 3 (continued)

Fruit Waste	Nanoparticle Type	Method of synthesis	Properties	Applications	References
Rosa canina fruit extract	Cuo	Green synthesis		UV shielding, sunscreen	[135]
Citrus aurantium seed oil	ZnO	Green synthesis	Antidiabetic Antioxidant	Biomedical	[136]
Punica granatum	ZnO	Green synthesis	Antidiabetic Antioxidant	Biomedical	[137]

DPPH, and FRAP assays [140]. Researchers assert that these strategies include the use of spectrophotometric measures to evaluate antioxidant activity and the utilisation of radical cations to chelate metal ions. Recent developments in these approaches have facilitated precise and rapid evaluations of antioxidant capacity [141]. Recently, nanoparticle-based antioxidants have emerged as a novel treatment strategy. In 2019, Ajmal et al. found that TiO_2 nanoparticles synthesised from fruit peel extracts, such as kiwi, plum, and peach, exhibited significant DPPH and H_2O_2 radical scavenging activity within a concentration range of 10–100 µg/mL [142]. TiO_2 nanoparticles measuring 47.1 and 63.21 nanometres had the greatest radical scavenging ability across all concentrations. In both DPPH and H_2O_2 tests, NiO nanoparticles derived from residual orange peel exhibited dose-dependent radical scavenging activity [143]. Hong and Jiang's 2017 study indicates that SnO_2 nanoparticles derived from Litsea cubeba fruits has the ability to suppress free radicals, with an IC_{50} value of 2257.4 µg/mL. The findings of these investigations indicate that the phytochemical constituents in fruit extracts and their byproducts may engage with nanomaterials to enhance their capacity to convert unstable radicals into stable molecules [144].

Metal oxide nanoparticles derived from fruit waste used as anticancer agents

Cancer persists as one of the most difficult illnesses to cure because to its capacity to develop into a complex, multidimensional structure that proliferates uncontrolled. Estimates project an additional 27.5 million cancer cases over the next forty years, making it one of the primary causes of mortality globally [145]. This underscores the need of developing more effective treatment modalities. Chemotherapy, radiation, and surgery exemplify conventional cancer therapies that might entail considerable side effects and be excessively expensive. This has resulted in an increasing need for non-toxic, affordable alternatives with little adverse effects. Nanotechnology has emerged as a promising domain for the enhancement of cancer therapy options in recent years. Researchers have investigated a range of nanomaterials to determine their potential anticancer properties [146]. It has been shown that using eco-friendly production techniques enhances the anticancer efficacy of nanoparticles, particularly ZnO. Pomegranate peel powder was used to synthesise biogenic zinc oxide nanoparticles, which shown efficacy against colorectal cancer cells (HCT116) and normal colon cells (CCD112). These nanoparticles may eliminate between 60 and 70% of cancer cells at concentrations of 31.25 mg/mL [147]. Copper oxide nanoparticles have been shown to selectively target cancer cell lines, causing chromosomal abnormalities, cellular leakage, and DNA breaks, which eventually end in cell death.

Application of metal oxides in food packaging materials

Conventional food packaging materials, such as plastic, have been extensively used because to their ease of processing, practicality, and cost-effectiveness. Alharbi et al. (2024) assert that while these materials were originally designed to protect objects, their increasing use in marketing has markedly altered their attractiveness to consumers [148]. Nonetheless, concerns about non-biodegradability, non-renewability, carcinogenic effects, and their adverse environmental impact have been raised. The manufacture of plastic packaging requires the combustion of fossil fuels, exacerbating the adverse environmental and climatic impacts of this process [149]. This has resulted in a need for natural, renewable, and environmentally sustainable alternatives that are also more convenient, possess a longer shelf life, and are more economical. This has generated interest in biopolymer-based packaging materials [150]. Polymers are often derived from renewable resources such as flora, fauna, or microbes. These materials possess essential physicochemical qualities, such as mechanical strength, gas barrier performance, optical clarity, and biocompatibility [151]. Furthermore, these materials undergo biodegradation. Furthermore, biopolymer packaging may be developed to extend the shelf life of perishable goods. Moreover, the use of oxygen scavengers, antioxidants, or antimicrobial agents may facilitate the creation of active or intelligent packaging solutions that improve food quality, minimise waste, and prevent spoilage [152]. Issues such as inadequate mechanical and water barrier qualities often limit the use of biopolymer-based materials in packaging applications. Biopolymer-based products often encounter difficulties despite these benefits. The characteristics may be enhanced by including nanofillers, like plasticisers and metal oxide nanoparticles, into the material [153]. Recent studies have concentrated on incorporating nanoparticles into biopolymer matrices. This research aims to enhance the mechanical strength, water and gas impermeability, as well as the biological attributes, including antibacterial and antioxidant characteristics, of biopolymers. Nanoparticles, particularly metal oxides, exhibit exceptional electrical, catalytic, thermal, and antibacterial capabilities attributable to their quantum effects and substantial surface-to-volume ratio. The sector evolved during the 20th century due to advancements in food packaging capabilities enabled by the unique qualities of nanomaterials, including enhanced surface area and reactivity. Presently, biopolymer-based active packaging films include metal oxide nanoparticles, such as copper oxide, titanium dioxide, and zinc oxide. These nanoparticles have shown biological features, including antimicrobial characteristics [154].

Recent use of metal oxide nanoparticles in perishable fruits

This makes fresh fruits and vegetables more perishable due to microbial activity and lipid degradation. Approximately 40% of the food produced ends up in the hands of consumers before it is eaten, causing spoilage and significant financial losses. Bioactive packaging materials have been developed to address this problem. These substances have the capacity to both prolong food's shelf life and stop microbial contamination [155].

The use of microwave-assisted extraction of aqueous Clitoria ternatea flower extract has been highlighted in a recent work concerning the green manufacture and characterization of gold (CT-Au NPs) and cobalt oxide (CT-Co_2O_2 NPs) nanoparticles. The nanoparticles are safe and biocompatible due to this ecologically friendly process since they don't include any potentially hazardous chemical reductants or capping agents. The manufacturing process, which takes less than an hour to finish, depends on natural stabilizers such phenols, flavonoids, and alkaloids [156]. These nanoparticles shown a great deal of promise as photocatalysts for the breakdown of organic dyes like bromocresol green (BCG) and bromophenol blue (BPB) when subjected to sodium borohydride and visible light. They also succeeded in reducing 4-nitrophenol (4-NP). Cobalt oxide nanoparticles are suitable for scalable wastewater treatment since they are less expensive and harmful to the environment than other nanoparticles. Effectiveness is shown by both nanoparticles [157].

Additionally, in the realm of food preservation, edible coatings have grown in popularity. These coatings are put on the surface of product and are made up of a thin polymer membrane. Coatings operate as barriers to gases and vapors, prevent the growth of microbes, and maintain the antioxidant properties and aesthetic appeal of fruits and vegetables. Metal oxide nanoparticles have been added to biopolymers such agar, chitosan, Gum Arabic, starch, and zein to improve functional properties like UV protection, gas permeability, and microbiological resistance [158]. For example, pineapples were coated with chitosan and aloe vera gel containing zinc oxide (ZnO) nanoparticles and stored at 25 °C for 15 days. This coating postponed ripening, stopped oxidative degradation, and reduced weight loss by 5%. Salama and Abdel Aziz's 2020 study found that carboxymethyl cellulose (CMC) in combination with titanium dioxide (TiO_2) nanoparticles and guanidinylated chitosan effectively prevented green bell peppers from losing weight by 10% over a fifteen-day period [159].

In order to effectively control organic pollutants and reduce food waste, the latest advancements in bioactive coatings and nanoparticles provide highly promising solutions. Further investigation into scalable green synthesis methods and their applications in food preservation and environmental remediation is required.

Before their widespread use in biomedical, food, and environmental sectors, fruit peel nanoparticles must be understood toxicologically. The toxicity evaluation of fruit peel–mediated nanoparticles has been studied in vitro, in vivo, and ADME investigations, although the data is still fragmented and shows several gaps. Silver nanoparticles from fruit extracts have an IC_{50} of 25–40 µg/mL against cancer cell lines including HeLa and MCF-7, while sustaining over 80% viability in normal fibroblast cells at concentrations below 20 µg/mL [160]. Research indicates that ZnO nanoparticles made from citrus peel can increase ROS formation by 30–50% at concentrations over 100 µg/mL, indicating dose-dependent oxidative stress. In mice, oral green AgNPs at doses of 10 to 50 mg/kg did not cause weight loss or hematological changes after 14 days. However, doses above 100 mg/kg increased liver enzymes (ALT, AST) by 20–25%, suggesting hepatic stress. In a separate study, ZnO nanoparticles from fruit peels administered orally to rats at 200 mg/kg/day for 28 days showed less than 5% liver and kidney accumulation, with most excreted via feces, suggesting minimal long-term retention [161]. While limited, ADME profiling shows that radiolabeled AgNPs mostly accumulate in the liver and spleen, with 40–60% uptake within 24 h and more than 70% elimination within a week, mostly through feces. These findings are promising, but most cytotoxicity studies are conducted over 24–72 h, chronic low-dose exposure has not been thoroughly investigated, and fruit peel nanoparticle half-life, bioavailability, and metabolic fate data are lacking. These gaps must be filled with established methodologies and prolonged investigations to ensure food, biomedical, and environmental safety [162].

Limitations and suggestions for the use of metal oxide nanoparticles

Metal oxide nanoparticles provide several benefits in culinary applications, especially when used as additions in food packaging. These nanoparticles enhance many packaging characteristics, including prolongation of shelf life and antimicrobial qualities. Nonetheless, significant safety and legal issues are raised by its use. Adeyemi and Fawole (2023) assert that a limited number of metal oxide nanoparticles have shown enough safety for use in food-related applications [163]. Regulatory bodies have enacted measures to guarantee environmental safety in response to these issues. The United States Food and Drug Administration (FDA) has published guidelines for the use of nanotechnology in food and cosmetics. These guidelines seek to examine and mitigate the possible impacts of nanotechnology on the nutritional value and bioavailability of food. Similarly, the European Food Safety Authority (EFSA) has instituted limitations, restricting the permissible concentration of titanium dioxide (TiO_2) nanoparticles in PET bottles at 20 mg/kg. The aforementioned initiatives demonstrate a commitment to regulate the use of nanoparticles in food packaging materials to guarantee consumer safety [164]. Moreover, European legislative frameworks have developed to facilitate the commercialisation of innovative technology in the packaging industry. Prior until 2004, the market adoption of active and intelligent packaging was sluggish due to insufficient regulatory frameworks governing their use. The implementation of European Union Regulation No. 1935/2004 and European Union Regulation No. 450/2009 established a comprehensive legal framework for the use and advancement of these technologies [165]. A significant concern associated with the use of metal oxide nanoparticles in food applications is the possibility of unanticipated health consequences. The physicochemical characteristics of these particles alter owing to their nanoscale dimensions, possibly resulting in behaviours and interactions that diverge from those of their bulk counterparts. Due of this property, regulatory agencies have been doing ongoing study to determine permitted nanoparticle kinds and acceptable usage parameters to safeguard environmental and human health [166]. Titanium dioxide nanoparticles (TiO_2 NPs), often used in food colouring and UV-blocking coatings, have elicited concerns over their safety owing to their heightened reactivity and bioavailability at the nanoscale. As a result, there is an increased likelihood that these nanoparticles may migrate from the packing materials into the food, especially under circumstances of elevated humidity and warmth. This movement raises concerns over the accumulation of nanoparticles in the human body and its implications for long-term health, according to McClements et al., (2022). Regulatory bodies such as the European Food Safety Authority (EFSA) and the United States Food and Drug Administration (FDA) have established criteria to evaluate the safety of nanoparticles to mitigate these issues [167]. Examples of this include the need for manufacturers to conduct comprehensive toxicity assessments and the establishment of permissible exposure levels. Research is now being conducted on the bioavailability, absorption, distribution, metabolism, and excretion of metal oxide nanoparticles inside the human body. This study aims to elucidate the potential dangers linked to the use of metal oxide nanoparticles in culinary applications [168]. Toxicological evaluations, including in vitro assays and animal models, are crucial for detecting possible adverse effects. It is essential to achieve a balance between the advantages of metal oxide nanoparticles and associated safety concerns. Tighter regulations and thorough testing procedures are necessary, even if they can impede food packaging innovation. Manufacturers must spend in research to either create safer substitutes or improve the safety profiles of already available nanoparticles [169]. One method that provides a good substitute for traditional chemical processes like sol-gel synthesis is green synthesis, which is ecologically safe and reasonably priced. Farmers, academics, and business may work together to lower the cost of making metal oxide nanoparticles. This will increase the sustainability and accessibility of these technologies. It is feasible for researchers, businesses, and farmers to collaborate to create customized synthetic methods that can address the particular needs of agricultural operations and solve the issues faced by small-scale farming. This collaboration might promote knowledge transfer, information exchange, and capacity-building to enable on-site nanoparticle production. The efficiency and sustainability of producing nanoparticles might be significantly increased by using novel methods including solar-assisted synthesis and the use of microorganisms [170].

However, there are a number of problems with using nanoparticles in postharvest activities for a long time, such as the potential for diseases to become resistant to the nanomaterials, which might eventually lessen their effectiveness. Despite the obstacles that have been encountered, the science of nanotechnology still holds great promise for improving food security and sustainability [171]. Notwithstanding the significant benefits of using metal oxide nanoparticles in food-related applications, apprehensions persist over safety and regulatory adherence. Comprehensive research and evaluation are necessary to address these concerns and confirm that nanoparticles are safe for food contact and do not provide any health hazards. Achieving a balance among innovation, safety, and affordability necessitates cooperation among manufacturers, researchers, and regulatory authorities [172]. To mitigate the potential health concerns linked to metal oxide nanoparticles, the use of safe preparation processes is necessary. A crucial first measure in guaranteeing the safety of nanoparticles for biological applications is the formulation of biocompatible synthesis methods that adhere to green chemistry principles and use non-toxic substances. A thorough characterization of nanoparticles is also necessary, including figuring out their stability, size, shape, and surface charge. This is required to assess the potential for toxicity and predict the behavior of nanoparticles in biological systems [173].

Dose-response analyses are essential for assessing toxicity and comprehending the relationship between MONPs exposure levels and any negative consequences. To account for a range of toxicological effects, this procedure compares several dose-response curves. Investigating the material's distribution and metabolism inside the body is also crucial, with a focus on the absorption, distribution, metabolism, and excretion (ADME) processes [174].

Industrial aspects of fruit peels

In an attempt to reduce food waste, some nations have required improvements in food supply networks. It is expected that using packaging materials with antioxidant or antibacterial properties would enhance food's shelf life, decrease food waste, and boost the food industry's profitability. Both the cultivated area and agricultural output have increased in the horticulture sector to meet the global need for food. An estimated 800,000 tons of fresh fruits and vegetables are generated annually as a result of the increase in production, which results in the manufacture of massive volumes of plant commodities. Any losses or waste that arises during the preparation of the product are not included in this calculation. One important objective for countries looking to use low-waste technologies in their agriculture sector is the full exploitation of horticultural products [175].

On many instances, fresh tropical exotic fruits are not consumed right once; instead, they undergo treatment to extract useful components from other plant parts. For example, byproducts from tropical fruits such as papaya, mango, macadamia, and coffee are often used in secondary procedures to extract bioactive components. The process of processing coffee involves removing the desired beans from leftovers, such as the "coffee cherry," which is made up of the fruit's skin and other parts that are not edible. In a similar vein, macadamia nuts are extracted from tropical fruits that have an outer and inner shell [175]. The process of separating the main product, the valuable nut, from byproducts like shells is a typical processing step. Similarly, fruits like pineapple, taro, papaya, and mango are prized for their edible flesh, but during processing, byproducts like skins and seeds are produced. These byproducts may find use in the realm of nutrition. For example, it has been proposed that leftovers from various fruits and vegetables, including papaya, taro, mango, macadamia nuts, and coffee cherries, could be utilized as sources of essential nutrients [176].

Fruit byproducts, such as grapes and citrus fruits, may be harvested for their bioactive chemicals, which can be profitable. Citrus fruits, one of the most widely produced commodities in the world with an annual production of over 88 million tons, are processed extensively for the manufacture of juice and other products including jams and canned goods. Approximately one-third of the citrus crop is subjected to industrial processing, producing leftovers that make up half of the fruit's weight [177]. The chemical industry extracts flavonoids and essential oils from these wastes and utilizes them for their own purposes. Similar to grapes, which are one of the biggest fruit harvests in the world, grapes are mostly employed for the manufacturing of wine, which results in the creation of huge byproducts such as seeds. Grape seeds are a valuable resource for oil extraction and other uses because of their high concentration of phenolic compounds and unsaturated fatty acids, especially linoleic acid [178].

A substantial portion of the weight of papaya, pineapple, and mango is made up of byproducts that are created during processing; this ratio may range from 10% to 60%. Some minimally treated fruits have byproducts that may exceed the weight of the edible component, and the ratios of these byproducts vary by fruit type and processing method. Certain fruits produce byproducts from fruits that are seldom treated. Research has focused on the possibilities of such byproducts [179]. A patented extract made from passion fruit skins serves as one illustration of this. This extract showed hepatoprotective, anti-inflammatory, and antioxidant properties, as well as lowering blood pressure and serum nitric oxide levels. The increased interest in recycling and using agricultural leftovers has led to a significant expansion in the scope of byproduct sources that have been studied. The agri-food industry's focus on sustainability and the identification of active chemicals are the main drivers of this interest [180].

Challenges and future directions

Fruit peels as biogenic precursors for nanoparticle synthesis are popular worldwide because to their low cost, eco-friendliness, and capacity to value agro-waste. Despite its potential, the field faces many challenges that prevent it from moving from lab study to commercial and social use. Raw material unpredictability, process optimization, stability, scalability, environmental safety, legal frameworks, and application-specific challenges are among these issues. Flavonoids, phenolics, terpenoids, alkaloids, tannins, and reducing sugars are abundant in fruit peels. These molecules reduce and cap, but their quantities vary widely among species. Orange peels are rich in flavonoids and ascorbic acid, while banana peels are high in starch and polyphenols [181]. Metabolite levels depend on climate, soil type, cultivation methods, and harvest season. Indian mango peels may yield nanoparticles with different characteristics than Brazilian mango peels. Precursor chemistry variability affects particle size, shape, and stability, making research repeatability and scalability difficult. Experimental factors include Critical parameters, Morphological variety, Non-linear scaling, and Limited mechanistic understanding affect fruit peel nanoparticle synthesis. Nanoparticle nucleation and growth depend on reaction pH, temperature, precursor concentration, extract-to-metal ion ratio, and incubation duration. Even small pH or temperature changes can change nanoparticle shape from spherical to rod-like or create extensive polydispersity. Because mixing, heat transport, and concentration gradients behave differently at greater volumes, laboratory-size optimal conditions rarely work at pilot or industrial scale. Metabolite roles in nanoparticle reduction and stability are uncertain, limiting systematic optimization [182]. Advanced methods like TEM, SEM, XRD, and DLS are necessary, but they are expensive and scarce in resource-poor areas with lots of fruit peel waste. Bioactive chemicals on nanoparticle surfaces complicate characterization. Overlapping FTIR peaks and complex zeta potential profiles make capping agent identification difficult. Characterization occurs mostly after synthesis, and nucleation and growth monitoring techniques are scarce, making process control difficult. Biosynthesized nanoparticles often have short shelf life and storage due to poor capping or steric stabilization. Particle aggregation reduces surface area and activity. Temperature, humidity, oxygen, and light can damage nanoparticles. Citrus peel-derived silver nanoparticles lose stability after weeks. Lyophilization and encapsulation are necessary for stability but expensive and complicated. Fruit peel-derived nanoparticles' effects on cells, tissues, and ecosystems are unknown [183]. Long-term persistence, bioaccumulation, and ecotoxicity need study. Metal ions and damaged capping agents may seep into soil and water. Biosynthesis' environmental benefits are sometimes exaggerated without life cycle assessments (LCA) of its energy, water, and chemical impact. Nanoparticles require expensive and time-consuming toxicological and pharmacokinetic studies for medicinal or diagnostic use. Biosynthesized nanoparticles' varied properties impede clinical approval. Although successful in lab settings for dye degradation or pollution removal, nanoparticle recovery, recyclability, and reusability remain issues. Continuous operation systems require immobilized or recyclable nanostructures. Fruit peel nanoparticles lack precision and uniformity, which are needed for advanced applications including solar cells, sensors, and semiconductors. Their performance is below chemically produced counterparts. Establishing international biosynthesized nanoparticle size, purity, and safety standards. Eco-labeling sustainable nanomaterials to increase consumer and industry acceptability. Government grants, subsidies, and tax incentives to build fruit peel-based nanoparticle industries. Establishing transparent criteria for natural resource ownership and equitable use to benefit local communities and agricultural producers [184].

Ecologically, using fruit peels for nanoparticle synthesis is promising, but standardization, optimization, scalability, safety, and regulation must be addressed. These difficulties require collaboration amongst chemistry, nanotechnology, toxicology, environmental science, and policymaking. At that point, this novel laboratory concept can only become a sustainable industrial waste valorisation solution [185].

Fruit peel-mediated nanoparticle production must overcome its current limitations to move from lab to industry. Focused domain advancements can achieve this. Fruit peel biochemical content varies greatly, so raw materials must be standardized. We can increase repeatability by establishing metabolite profiling methods using HPLC, LC-MS, and NMR and creating worldwide databases of phytochemical content across species, growing circumstances, and maturity stages. Combining extracts with synergistic metabolites may improve synthesis consistency. Using microfluidic continuous-flow systems and artificial intelligence and machine learning to predict the effect of synthesis factors on nanoparticle morphology can reduce trial-and-error and improve scalability. Hybrid green-chemical technologies using fruit peel extracts and microwave irradiation or sonochemistry could increase uniformity, yield, and stability [186]. In-situ monitoring using real-time spectroscopic or microscopic methods, molecular docking and simulation studies to reveal phytochemical–metal ion interactions, and surface-sensitive methods like XPS for capping agent identification will improve mechanistic understanding and process control. Encapsulating nanoparticles in natural biopolymers like chitosan or alginate, lyophilization and cryopreservation, and natural stabilizers from agro-waste sources will improve shelf life and be eco-friendly. Pilot-scale reactors are needed to integrate fruit-processing and nanomaterial manufacturing into a continuous supply chain. Using renewable energy for extraction and synthesis reduces expenses, and turning remaining biomass into biofertilizers or biogas is waste-free. To address safety concerns, systematic toxicological studies, life cycle evaluations that consider the entire environmental impact, and safe-by-design nanoparticle engineering practices to prevent bioaccumulation are necessary [187]. Regulating biosynthesized nanoparticles using established guidelines is also necessary. To encourage adoption, eco-certification, ethical intellectual property frameworks, and government incentives should be provided. Biomedicine should use nanoparticles for precise drug delivery and antimicrobial coatings; environmental remediation should use recyclable nanostructures for pollutant degradation; energy should examine photocatalysis, supercapacitors, and solar cell integration; and sustainable food systems should use nanoparticles in biodegradable smart packaging. To translate laboratory discoveries into practical applications, these fields will need strong collaboration across chemistry, materials science, toxicology, environmental engineering, and policy-making, as well as industry-academia partnerships. Local nanoparticle production hubs in underdeveloped nations with abundant fruit waste can boost the economy and reduce environmental impact. Fruit peel waste could become a renewable resource in the future, supporting sustainable nanotechnology innovation while addressing waste management, environmental protection, and advanced material uses [188].

Conclusion

The global production of 2.32 million tonnes of food waste highlights the need for sustainable and creative waste management techniques. Lack of disposal, storage, and processing facilities requires innovative technology. Fruit waste is rich in bioactive chemicals that reduce and stabilize metal oxide nanoparticles, making it a possible green substitute for chemical approaches. Biopolymer-based food packaging can improve physicochemical qualities, shelf life, antioxidant, and antibacterial capabilities with such nanoparticles. Edible coatings and films help preserve food and reduce global food waste. Adoption requires overcoming various obstacles despite these benefits. Potential nanoparticle migration, scale-up issues, synthesis and characterization process heterogeneity, and uneven safety evaluations remain obstacles. Industrial application is complicated by commercial viability and yield volatility. Nanotechnology, food science, and environmental management researchers must collaborate to solve these obstacles. Large-scale production requires synthesis process optimization, reaction parameter control, and more stable and useful nanomaterials. To maintain consumer safety and public confidence in nanoparticle-based food preservation technologies, robust regulatory frameworks, including uniform safety assessments and explicit labeling, are needed. Scaling-up, interdisciplinary research, regulatory control, and commercialization can lead to sustainable, efficient, and safe fruit-waste-derived nanoparticle applications.

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