

NANOPARTICLES IN FUTURISTIC TRENDS: UNVEILING THE NEXT GENERATION OF MATERIALS

Abstract

Recently nanoparticles (size 1 to 100) nanometers have attracted numerous attention from a wide range of industries because of their unique characteristics. Nanoparticles provide exciting opportunities for innovation and sustainability in various fields, including energy, electronics and medical and healthcare. In biomedicine, nanoparticles exhibit significant promise for a myriad of applications, including therapeutic interventions, diagnostic imaging and personalized drug delivery. Furthermore, they have the potential to completely transform energy systems by improving energy storage and acting as fuel cell catalysts. Efforts to develop environment-friendly synthesis processes are underway, aiming to ensure sustainable production methods. Overcoming these obstacles will unlock the full potential of nanoparticles, shaping a future characterized by innovation and sustainable technological advancements. In the context of nanotechnology, this chapter examines the transformational potential of nanoparticles. This also explores the frontiers of nanoparticle science, emphasizing the remarkable optical, electrical, magnetic and catalytic capabilities of these tiny particles.

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I. INTRODUCTION

Significant progress has been made in nanotechnology in recent years, ushering in a new era of materials and technologies (Bayda *et al.*, 2020). Nanotechnology is the study of structures, devices, and systems that exhibit novel properties and functions as a result of the arrangement of their atoms on the 1-100 nm scale. Nanoparticles, which have emerged as adaptable entities with tremendous promise in numerous scientific and industrial sectors, are among the important actors in this sphere. Nanoparticles, thanks to their novel nanoscale features, have promising prospects for revolutionizing several fields, from medicine and electronics to power generation and environmental protection (Joudeh and Linke, 2022). Future predictions show that nanoparticles will play a crucial role in reshaping the technological environment, fueling innovation, and radically altering our way of life (Malik *et al.*, 2023). There is now a lot of study being done and investigation being done in the field of using nanoparticles in future trends. The purpose of this chapter is to investigate the cutting edge of this discipline, and to illuminate the next generation of materials and technologies that will be made possible by nanoparticles. Nanoparticles are amazing for several reasons, one of which is the astonishing capacity of nanoparticles to show one of a kind features and capabilities at the nanoscale. This phenomenon has garnered a significant amount of interest from researchers all around the world, which has led to the development of ground-breaking discoveries and technologies. Nanoparticles have shown excellent optical, electrical, magnetic, and catalytic capabilities, amongst others, which may be adjusted by precisely controlling their size, shape, and composition (Khan *et al.*, 2019). Nanoparticles have also been shown to exhibit antibacterial properties. These characteristics open up a broad variety of possibilities for the development of innovative materials and gadgets with capabilities that have never been seen before. Nanoparticles have recently attracted a great deal of attention in the fields of medicine and healthcare owing to the possibilities that they provide for targeted medication delivery, diagnostic imaging, and therapeutic intervention. According to Nathan Banerjee (2013), nanoparticles have a high surface-to-volume ratio, the capacity to interact with molecular or cellular processes, and the potential to alter the activities of biological systems. These characteristics make nanoparticles particularly appealing for use in a variety of biomedical applications. When lipid-based, polymeric, and metal nanoparticles are made in more and more specific ways, they can be optimized for drug delivery in a more personalized way (Mitchell *et al.*, 2021). Nanoparticles may also be utilized as powerful imaging agents (Han *et al.*, 2021), which makes it simpler to see how biological structures function and locate disorders. These kinds of developments offer a great deal of potential for both personalized treatment and better results for patients. Nanoparticles also have a lot of promise to change how energy systems are made as they can be used to make clean and sustainable energy solutions (Banin *et al.*, 2021). For example, they can be used to store and collect energy more efficiently and as catalysts in fuel cells. Nanoscale materials, such as graphene and quantum dots, have proven remarkable electrical and optical capabilities, opening the way for next-generation electronic devices with improved performance, miniaturization, and flexibility (Nguyen and Nguyen, 2016). Graphene and quantum dots are two examples of nanoscale materials that have shown exceptional electrical and optical qualities. Nanoparticles have a tremendous amount of potential to play a role in the developments of the future, nevertheless several obstacles need to be addressed first, including their synthesis, characterization, scalability and safety (Suppiah *et al.*, 2023). There are now efforts being made to create environmentally friendly and sustainable synthesis

processes that will minimize the effect on the environment and guarantee that the production of nanoparticles can be scaled up.

I. ADVANCEMENTS IN NANOPARTICLE SYNTHESIS

Nanoparticles, which serve as the basic building blocks of nanotechnology, are distinguished from other particles in terms of their size, shape and composition, all of which contribute to their one of a kind qualities and capabilities. The capacity to accurately manage these parameters has opened up new avenues for designing nanoparticles with desired features, allowing a broad range of applications in a variety of sectors. These new paths have been made possible by the ability to perfectly control these parameters.

1. Bottom-Up and Top-Down Approaches : In recent developments in nanoparticle synthesis, both bottom-up and top-down techniques have played key roles in generating nanoparticles with specific characteristics (Wang and Xia, 2004). These breakthroughs have been made possible by recent advancements in nanoparticle synthesis. These methods have been used to attain a level of exact control over the size, shape, composition, and surface characteristics of nanoparticles. The bottom-up strategy entails the construction or development of nanoparticles from smaller building blocks or precursor materials. This strategy is also known as the additive manufacturing strategy. There have been several applications of chemical synthesis techniques, including coprecipitation, hydrothermal synthesis, chemical vapor deposition, and sol-gel synthesis (Abid *et al.*, 2021). By modifying the reaction conditions and the constituents of the precursors, these methods make it possible to synthesize nanoparticles with precisely regulated qualities.

Techniques of self-assembly have also been used in the bottom-up approach, which is a method in which nanoparticles organize themselves into ordered structures by the action of molecular interactions. The use of DNA or peptides as building blocks for self-assembly has emerged as a potentially useful method for the production of complicated nanoparticle assemblies (Calais *et al.*, 2018). The top-down strategy, on the other hand, entails the reduction of bulk materials to produce nanoparticles. (Chen *et al.*, 2016) describes the process of reducing bigger particles into nanoparticles as one that may be accomplished by the use of mechanical grinding and milling processes such as ball milling, attrition milling and high-energy milling. With these methods, the size, form and location of the particles can all be changed. The top-down method for making nanostructures uses many different methods, such as photolithography, laser machining, nanocontact printing, scanning lithography, nanosphere lithography, colloidal lithography, soft lithography, diffusion, scanning probe lithography, deposition, nanocontact printing, and ion implantation (Kumar *et al.*, 2017). Creating nanoparticle structures may be accomplished by a variety of procedures, some examples of which include focused ion beam milling, electron beam lithography and photolithography. These are only a few of the many possibilities (Fu *et al.*, 2018). These patterned materials may then be etched using further techniques to generate nanoparticles. Laser ablation has also been used as a top-down strategy, whereby laser pulses are used to vaporize a bulk target material, which then results in the production of nanoparticles. This method has been established and developed, especially in the past few years as an alternative method for the synthesis of nanoparticles with desired physicochemical and structural properties. In

the same way that other methods such as colloidal chemistry, electrochemistry, spark current decomposition, and others are used for that purpose (Semaltianos 2015), this method is an alternative method for the synthesis of nanoparticles with desired physicochemical and structural properties. Recent developments in nanoparticle synthesis have seen substantial improvement in both bottom-up and top-down techniques.

- 2. Green Synthesis Methods:** Green synthesis methods of nanoparticles involve environmentally friendly approaches that utilize natural, sustainable, or benign materials and conditions for nanoparticle synthesis (Huston *et al.*, 2021). According to Ying *et al.*, (2022), green synthesis is more useful than conventional chemical synthesis because it is less expensive, it reduces pollution, and it enhances the safety of both the environment and human health. Plant extracts that include bioactive components such as polyphenols and flavonoids have the potential to function as reducing and stabilizing agents during the manufacturing of nanoparticles (Ahmad *et al.*, 2019). The environmentally friendly synthesis of silver nanoparticles using plant extracts has been extensively documented (Vanlalveni *et al.*, 2021). This synthesis uses aqueous extracts of plant components such as the leaf, bark, and roots, among other plant parts. Synthesis of nanoparticles often takes place in biological factories comprised of bacteria, fungi, and yeast. According to Rana *et al.*, research from 2020, they have naturally occurring reducing and capping agents, which make it easier for nanoparticles to develop. Producing nanoparticles by the cultivation of microorganisms under controlled circumstances and using appropriate metal precursors is possible. For example, microbes such as *Bacillus methylotrophicus* have been used in the environmentally friendly production of silver nanoparticles (Wang *et al.*, 2016; Javaid *et al.*, 2018). According to Karpagavinayagam and Vedhi's 2019 research, flower extracts from *Avicennia marina* were used to synthesize iron oxide nanoparticles, which were then used for the degradation of colors. Extracts of the cactus *Opuntia ficus-indica* and the microalga *Dunaliella salina* were used in the synthesis of gold and lithium nanoparticles respectively (Singh *et al.*, 2019). Extracts of *Stevia rebaudiana* and *Capsicum annum* were used to create ZnS and Ag nanoparticles, respectively (Alijani *et al.*, 2019). These green synthesis techniques provide sustainable and ecologically friendly alternatives to classic synthesis processes. As a result, they make it possible to produce nanoparticles that have a less negative effect on the environment and have the potential to be used in a variety of contexts.

II. NANOPARTICLES IN MEDICINE AND HEALTHCARE

Recent years have seen a rise in the amount of focus placed on nanoparticles within the medical and healthcare sectors. This may be attributed to the unique qualities possessed by nanoparticles as well as the diverse array of applications to which they may be put. The use of nanoparticles in targeted drug delivery systems has a significant amount of untapped potential for enhancing treatment results, lowering the risk of adverse effects, and facilitating the development of personalized medicine techniques. Ongoing research is aimed at perfecting the design of nanoparticles, as well as their surface fictionalization and drug release kinetics, to further improve the targeting effectiveness of these particles and their use in therapeutic settings. The numerous ways in which nanoparticles may be used in medicine and other areas of the healthcare industry are outlined in the following condensed list:

- 1. Targeted Drug Delivery Systems :** Recently, nanoparticles have gained attention as a promising platform for the creation of individualized medication delivery systems. When compared to conventional approaches, this particle-based approach to medication delivery has several advantages. Because healthy cells may absorb chemotherapy just as well as cancer cells, current chemotherapy-based cancer treatments are typically accompanied by significant side effects (Rosenholmet *et al.*, 2010). Nanotechnology's use in diagnostics has revolutionized disease detection, tracking, and the use of tailored medication.

Here's an overview of how nanoparticles are utilized in targeted drug delivery:

- **Enhanced Permeability and Retention (EPR) Effect:** Nanoparticles can take advantage of the EPR effect, which is when blood vessels in tumors leak more than they should. Due to their small size, nanoparticles can passively collect in tumor tissue through blood vessels that are leaking. This means that the nanoparticles stay there longer and there is more medicine at the target spot(Shinde *et al.*, 2022)
 - **Surface Modification:** Surfaces of nanoparticles may be modified with ligands or targeting moieties, allowing them to recognize and bind to particular receptors or markers that are located on the surface of the cells or tissues that are being targeted. Many scientists have found that surface modification of such polymeric nanoparticles can improve the applications of nanoparticles. Surface modification also enables nanoparticles to carry specific drug molecules and disease or tumor-specific antibodies, both of which refine and improve drug delivery (Pathak, 2019).
 - **Multifunctionality:** It is possible to provide nanoparticles with multifunctional features via the use of genetic engineering, which enables them to carry out a variety of functions in parallel. They may, for instance, combine the capabilities of medication delivery with imaging agents to provide real-time monitoring of the distribution and effectiveness of the medicine. The integration of these tasks improves the effectiveness of treatment and makes personalized medicine easier to implement (Patra *et al.*, 2018).
- 2. Diagnostic Applications :** Diagnostic applications have been completely transformed by the use of nanoparticles due to their increased sensitivity, specificity, and multiplexing capacities.

The following is an outline of the many diagnostic applications that make use of nanoparticles:

- **Biosensors and Point-of-Care Testing:** For the detection of biomolecules, pathogens, or environmental analytes, biosensing systems often make use of nanoparticles as an active ingredient. Biosensors that are based on nanoparticles provide increased sensitivity, faster reaction times, and an intuitive user interface. To selectively capture and detect target analytes, they may be functionalized with specialized recognition molecules such as antibodies, aptamers, or DNA probes. These biosensors have applications in the detection of illness, monitoring the

environment, ensuring the safety of food, and testing patients at the point of care (Malhotra and Azahar2017).

- **Molecular Imaging and Targeting:** Nanoparticles can be made to bind to particular cell surface marks or receptors by adding targeted ligands, antibodies, or peptides. This active targeting makes it possible to see and find certain groups of cells or signs of disease. Molecular imaging with tailored nanoparticles lets illnesses like cancer, heart disease, and neurological diseases be found and tracked without harming the patient. nanoparticle-based contrast agents used in most common biomedical imaging techniques, such as fluorescence imaging, MRI, CT, US, PET, and SPECT, with a focus on their structure-related traits, benefits, and drawbacks (Xiangjun *et al.*, 2019).
- **Nucleic Acid Detection:** Nanoparticles are utilized in nucleic acid-based diagnostic assays, such as polymerase chain reaction (PCR), isothermal amplification, or next-generation sequencing. They can be employed as probes for the detection of specific DNA or RNA sequences. Nanoparticle-based nucleic acid detection methods offer improved sensitivity, specificity, and multiplexing capabilities, facilitating genetic testing, pathogen identification, and personalized medicine (Tange *et al.*, 2020).
- **Lateral Flow Assays:** Nanoparticles are utilized in lateral flow assays, commonly known as rapid diagnostic tests or point-of-care tests. In these assays, nanoparticles conjugated with antibodies or antigens serve as detection probes. Lateral flow immunoassay (LFIA) is the most representative point-of-care testing (POCT) technology that has been widely used in various fields (Lou *et al.*, 2022). Lateral flow assays are simple, portable, and cost-effective diagnostic tools used for a range of applications, including infectious disease testing and pregnancy detection (Hao *et al.*, 2022).

III. NANOPARTICLES IN ENERGY AND ENVIRONMENT

Nanoparticles have been shown to have a lot of potential in the fields of energy and the environment because of their unique properties and abilities. Putting nanoparticles in systems that collect and store energy makes it possible to use energy more safely and efficiently. Ongoing study focuses on improving the efficiency of energy conversion, the amount of energy that can be stored, and the creation of next-generation energy systems by optimizing nanoparticle qualities, surface changes, and integration strategies. The following are how nanoparticles are used in applications relating to energy and the environment:

1. **Energy Harvesting and Storage:** Nanoparticles play a significant role in energy harvesting and storage systems, enabling advancements in renewable energy technologies and energy storage devices.

Here's an overview of how nanoparticles are utilized in energy harvesting and storage:

- **Solar Energy Harvesting:** Nanoparticles are used in solar cells and other photovoltaic systems. Examples of these nanoparticles include semiconductor

quantum dots and metal oxide nanoparticles. The use of nanotechnologies to improve the performance of these solar systems in many different ways and combinations is probably talked about more than any other method (Wang *et al.*, 2022). These nanoparticles have several advantageous properties, such as adjustable bandgaps, increased charge carrier movement, and enhanced light absorption. According to Hu P. *et al.*, 2015 nanoparticles make it possible to convert sunlight into electricity in an effective manner, which results in improved power conversion efficiencies and the possibility of solar energy harvesting that is inexpensive, flexible, and lightweight.

- **Energy Storage:** Nanoparticles find their way into a variety of different energy storage technologies, such as batteries and supercapacitors. Nanomaterials such as nanowires, nanotubes, or nanosheets may increase the surface area and offer shorter diffusion paths for ions, which can contribute to better energy storage capacity, quicker charging/discharging rates, and longer cycle life (Yu *et al.*, 2018). The development of high-performance energy storage systems that have higher power density and energy density is helped by the use of electrode materials that are based on nanoparticles. In sustainable nanotechnologies, the usage of supercapacitors as components of energy conversion and storage systems is becoming more common (Maksoud *et al.*, 2020).
- **Hydrogen Production and Storage:** In today's technology for producing hydrogen and storing it, nanoparticles play an important role. Nanoparticles made of metals or metal alloys may serve as catalysts for the production of hydrogen via a variety of processes, including water splitting and reforming. The development of nanomaterials for the production of renewable energy demonstrates that nanotechnology plays an essential role. In recent years, nanomaterials have garnered a lot of attention because of the remarkable mechanical, electrical, electronic, optical, and magnetic characteristics that they exhibit. These characteristics have resulted in substantial repercussions for the processes of energy generation, storage, and use (González *et al.*, 2021)

IV. ENVIRONMENTAL REMEDIATION

Nanoparticle-based remediation technologies are emerging and becoming vital to sustainable environmental management techniques. Nano-adsorbents, nano-filtration, nano-photocatalysts, magnetic nanoparticles, and nanosensors are some of the methods developed using nanotechnology to treat water and wastewater, air and pollutant detection:

1. **Water Treatment:** In the past 10 years, nanotechnology has led to new water treatment membranes. Nanomaterials have been added to membranes by blending or surface grafting to make membranes with desirable structures and new functions, such as high permeability, catalytic reactivity, contaminant degradation, and self-cleaning (Pendergast and Hoek, 2011). Nanoparticles, like iron oxide nanoparticles, can be used to remove heavy metals from water sources by holding on and attracting them. Auffan *et al.*, 2008 found that these nanoparticles have a lot of surface area and can bind to heavy metals

well, making it easier to get rid of them in water. Photocatalytic qualities can be seen in nanoparticles like titanium dioxide (TiO₂) and zero-valent iron (ZVI). They can also be combined with other technologies, such as photo-excitation, to improve the effectiveness of disinfection (Hossain *et al.*, 2014). So, many nanoparticles, such as metal and metal oxide nanoparticles (Dizaj *et al.*, 2014), have been recommended to control the growth of bacteria and kill different types of microorganisms in water. Silver nanoparticles can kill bacteria, viruses and other pathogens, so they can be used to clean water by killing bacteria, viruses, and other pathogens.

- 2. Soil Remediation:** Nanoparticles, such as nano zero-valent iron (nZVI), may be utilized to immobilize and stabilize pollutants in soil, hence preventing the contaminants from migrating and leaking into groundwater (Ibrahim *et al.*, 2016). According to the findings of the experiments, the introduction of nanoparticles into the soil was able to remove a wide variety of organic, inorganic, and metal contaminants. According to Madhura *et al.*'s 2019 research, the application of nano-zerovalent iron and magnetite nanoparticles resulted in the quick degradation of organic contaminants in the soil. Nanoparticles of TiO₂ (n TiO₂) and PEI-copper nanoparticles lowered the half-lives of phenanthrene and atrazine, respectively. These findings were published in the journal *Nanoscale* (Kalidhasan *et al.*, 2017). Certain nanoparticles, such as those based on carbon, have the potential to improve sorption and microbial interactions in soil, therefore speeding up the process by which organic pollutants in the soil are degraded.
- 3. Air Pollution Control:** Nanoscience and nanotechnology are getting better and better, which is having a big impact on environmental monitoring and sensing. A lot of nanoparticles have been used to find and get rid of a wide range of contaminants in both gaseous and liquid media (Andreescu *et al.*, 2009; Theron *et al.*, 2008, 2010). Nanosensors with high selectivity and sensitivity have been studied for monitoring different gases in the air (Zhou *et al.*, 2015) to prevent explosions or poisoning. Air pollution has been controlled more effectively with the help of nanosensors (Brahmkhatri *et al.*, 2021). Niccolai *et al.*, 2019 say that the main goal of making smart dust is to make a set of advanced devices in the form of very light nanocomputers. It is easy for these nanosensors to stay in the air for hours.

V. NANOPARTICLES IN AGRICULTURE AND FOOD SCIENCE

Nanoparticles are now being studied and used a lot in agriculture and food science to solve some problems and increase production. Because of their flexibility and uniqueness, they could be used to increase the farming output, safety, and quality of the food. At the start of the 21st century, nanotechnology and nanoparticles were used in agriculture for the first time (Fraceto *et al.*, 2016). Since then, more than 230 nano-products have been used in different farming tasks (Rajput *et al.*, 2022). As our understanding of nanoparticles grows, their use to improve and protect crops will likely play an increasingly important role in the movement toward food security and healthy agriculture.

Some of the ways nanoparticles are used in agriculture and food science are listed below

1. Crop Enhancement and Protection : Nanoparticles are gaining significant attention in the field of crop enhancement and protection due to their unique properties and potential to revolutionize agricultural practices. The antimicrobial characteristics of metal nanoparticles are known and widely used in agriculture directly or indirectly for managing plant disease and germination (Thakur *et al.*, 2018). By harnessing nanotechnology, researchers and agriculturalists aim to address various challenges in agriculture, such as improving crop productivity, increasing resistance to pests and diseases, and reducing the environmental impact of agrochemicals.

Here are some ways nanoparticles are used in crop enhancement and protection:

- **Nanopesticides:** Nanoparticles are utilized to develop more efficient and targeted pesticide formulations. Nano-sized pesticide particles can adhere better to plant surfaces, leading to improved coverage and reduced runoff. This targeted delivery enhances the effectiveness of pesticides while reducing the overall amount needed, minimizing environmental contamination and potential harm to non-target organisms. The preference for nano pesticides is because of their smart delivery system and increased life span by releasing pesticides in a timely and controlled manner. They improve water solubility protect agrochemicals from environmental degradation, and control crops' pathogens, weeds, and insects. They are adopted in agriculture and food industries to reduce the unnecessary use of other harmful pesticides and ensure plant safety & crop development (Pradhan and Mailapalli, 2020).
- **Nanofertilizers:** Nanotechnology enables the development of nanofertilizers that provide controlled and slow release of nutrients to plants. This ensures a steady and sustained nutrient supply, enhancing plant growth and nutrient uptake efficiency. There are three main classes of nanofertilizers: nanoscale additives, nanoscale coating, and nanoscale fertilizers (Mikkelsen, 2018). Nanofertilizers are efficient as they slowly release nutrients throughout the plant's life cycle. They reduce the risks of adsorption, decomposition, leaching, and surface runoff (Joshi *et al.*, 2019). This results in reduced use of pesticides, less pollution of the environment, cheaper costs for farms, and greater crop yields without the need to clear up polluted grounds and water or guard against a wide variety of insect pests and bacterial illnesses (Prasad *et al.*, 2017). According to Iavicoli *et al.*, (2017), nano-fertilizers may enable a targeted or controlled release of agrochemicals, to achieve their maximum biological efficiency without administering an excessive dose.
- **Disease Management:** The use of nanoparticles as vehicles for the delivery of bioactive compounds, such as antibacterial drugs and plant growth regulators, to address plant diseases is now under investigation. They can protect crops from infections and increase the crops' inherent defense systems, both of which are beneficial. Nanoparticles are increasingly being used for fertilizer despite the lack of studies on the treatment of plant diseases. Some examples of nanoparticles are copper and titanium dioxide (Worrall *et al.* 2018). According to Sadeghi *et al.* (2017), the use of titanium dioxide nanoparticles in fertilizers has been shown to inhibit the growth of viruses and inhibit bacterial growth.

- **Seed Treatment:** The germination rate, the vigor of the seedlings, and the overall performance of the crop may all be improved by covering seeds with nanoparticles. Nano-preparing is a new way of priming seeds that helps improve sprouting, growth, and output by making plants more resistant to different pressures. Nano-priming is a much better way to get seeds to grow than any of the other methods. The most important things about nanoparticles in seed preparation are that they improve electron exchange and the ability of different parts of plant cells and tissues to respond on the surface (Nile *et al.*, 2022). Agro-nanotechnology is a good way to improve seed sprouting, plant growth, and food output through the use of nanomaterials. Nanoparticles used to coat seeds may help seeds sprout by allowing plants to take in nutrients faster and grow better (Guleria *et al.*, 2023).
2. **Environmental Stress Mitigation:** Nanoparticles can be used to mitigate the adverse effects of environmental stresses, such as drought, heat, and salinity. They can help regulate water uptake, maintain cellular stability, and reduce oxidative damage in plants. Nanomaterials-induced responses are involved in defense against various environmental stresses in plants. These plants' responses to nanomaterials depend upon the type of nanoparticles, species of plants, their growth, and stages of development (Zulfiqar *et al.*, 2019). The optimum nanomaterials concentration alters the stress-responsive gene expression and RNA gene expression for improved plant stress tolerance. Recent studies revealed that nanomaterials enhance the accumulation of proline and amino acids, absorption of water and nutrients, and the activity of antioxidant enzymes, improving plants' tolerance to extreme conditions (Elsakhawy *et al.*, 2018)

VI. FOOD PACKAGING AND PRESERVATION

Nanotechnology has brought forth an innovative food packaging solution for the food business (Dasgupta *et al.* 2015). Nanofood is described as food that is produced using nanotechnology in the production, processing, storage, and packaging of food (Onyeaka *et al.*, 2022). Because of their one-of-a-kind qualities, nanoparticles have recently emerged as a potentially useful technology in the field of food packaging and preservation. These nanoparticles have the potential to increase the shelf life, safety, and quality of food items. Researchers and food producers are hoping to solve a variety of issues relating to the deterioration, contamination, and waste of food by integrating nanomaterials into the materials used for food packaging.

The following are some examples of how nanoparticles are used in the process of preserving and packaging food:

- **Enhanced Barrier Properties:** Fruits and vegetables play a significant part in maintaining a healthy diet due to the vitamins, minerals, antioxidants, and fibers that they contain. As a result, consumers place a high priority on buying these foods. Increasing the barrier qualities of packing materials against oxygen, moisture, and other gases may be accomplished by the use of nanocomposite films and coatings that incorporate nanoparticles. Perishable food products have a longer shelf life as a result

of this because it stops oxidation, which in turn slows the process of going bad (Jafarzadeh *et al.*, 2021).

- **Antimicrobial Properties:** Incorporating antibacterial inorganic nanoparticles such as metals (Ag, Cu, Au) and metal oxides (TiO₂, SiO₂, ZnO) into food packaging compounds is conventional. Instead, intelligent food packaging can detect rotting and dangerous microbes (Anvaret *et al.*, 2021). Silver nanoparticles are often employed in food packaging due to their low volatility, high-temperature stability, and great toxicity to various bacteria (Ahari *et al.*, 2020; Kavakebi *et al.*, 2021). Antimicrobial nanoparticles include silver and metal oxides. These nanoparticles may prevent bacteria, molds, and other microbes from growing on food when added to packing materials.
- **Smart Packaging:** The development of nanosensor technology and the incorporation of nanosensors into food packaging are two important factors that will determine the state of food security in the future. The supply chain as a whole may benefit from the detection, monitoring, tracking, recording, and communication capabilities of this innovative packaging solution. Nanosensors that are included in the materials used for packaging can detect changes in the temperature, humidity, and gas composition that occur inside the container. According to Fuertes *et al.* (2016), this information may be put to use to monitor the quality and freshness of food in real time, which in turn enables customers and merchants to make educated judgments regarding the product's fitness for eating.
- **Flavor and Aroma Preservation:** By inhibiting the passage of volatile substances through the packing material, nanoparticles may be used to assist in the preservation of the flavor and scent of food goods. This helps maintain the food's freshness as well as its overall appeal to the senses. Nanosensors can detect pesticides, poisons, and microbiological contaminants in foodstuffs and transform these findings into observer-readable signals such as taste generation and color development (Onyeaka *et al.*, 2022). This enables consumers to be notified immediately if their food has been tainted or has gone bad.
- **Active Packaging:** Active packaging is when particles added to the packing material interact directly with the food and protect it from UV, air, ethylene, or bacterial contamination (Nikolic *et al.*, 2021). Active packaging systems can be put into two groups: active scavenging systems (absorbers) that remove unwanted things from the product, like moisture, carbon dioxide, oxygen, ethylene, and smell; and active releasing systems that release things into the packaging, like antioxidants, carbon dioxide, or antimicrobial compounds (Yildirim *et al.*, 2018).
- **Biodegradability:** Biodegradable polymers or biopolymers have emerged as an alternative to non-biodegradable plastic in a variety of industrial applications (Shaikh *et al.*, 2020). Nanoparticles are used as reinforcements to improve the barrier and mechanical properties of polymers, resulting in packages with less demand for raw materials that are more sustainable and when applied to biopolymers, their production

and use becomes feasible, reducing the reliance on petroleum-based materials (Souza and Fernando, 2016).

VII. NANOTECHNOLOGY AND SUSTAINABLE AGRICULTURE

Nanoparticles are an important part of nanotechnology and sustainable agriculture because they offer new ways to solve problems that modern agriculture faces. The goal of using nanotechnology in agriculture is to make better use of resources, reduce damage to the environment, and encourage healthier farming practices. In general, nanotechnology and nanoparticles provide exciting prospects to convert agriculture into an industry that is less dependent on natural resources and more respectful of the environment.

Here are some of the most important ways nanoparticles are used in sustainable farming:

- **Enhanced Nutrient Delivery:** It is possible to employ nanoparticles themselves as carriers to transport nutrients, fertilizers, and micronutrients straight to the roots of plants (An *et al.*, 2022). This tailored nutrient delivery method improves the efficiency with which nutrients are taken up by the plant, decreases the amount of fertilizer that is wasted and increases crop yields.
- **Soil Remediation and Water Management:** Based on nanosensors, smart watering systems are made with the help of nanotechnology. These sensors measure the amount of water in the soil and how much water crops need in real-time. This helps farmers use water more efficiently and save water resources (Banotra *et al.*, 2017). The removal of contaminants and heavy metals from polluted soils may be accomplished with the use of nanoparticles, which are used in soil remediation. Nanoscale materials have the potential to efficiently immobilize or decompose pollutants, enhancing the health of the soil and preventing plants from absorbing them. Zero-valent nanoscale iron is the nanomaterial that has seen the most widespread use for the removal of pollutants from soil. In the cleaning process, nanoparticles like tiny zeolites, metal oxides, carbon nanotubes, and so on could also be used. Nanoparticle screens can remove organic particles and poisons like dichlorodiphenyltrichloroethane, endosulfan, and malathion from water (Srivastava *et al.*, 2018).
- **Disease Detection and Control:** Nanoparticles can also be employed as pesticides, which can improve the efficiency of nutrient management. According to Chinnamuttu and Kokiladevi's (2007) research, nanoparticles are useful for weed control. The regulated release of plant growth regulators by nanotechnologies, such as hormones or signaling molecules, may optimize plant growth and development, particularly in tough situations (Abdul Wahab *et al.*, 2023). To identify plant illnesses and pathogens in their earliest stages, scientists are turning to nanosensors and nanomaterials. This enables prompt intervention and the tailored administration of remedies, which in turn minimizes the amount of pesticides used and reduces the amount of produce that is lost. Nanoparticles may be utilized as a carrier material for herbicides, particularly for herbicides like paraquat, according to Silva *et al.* (2011).

- **Environmental Monitoring** The use of nanosensors in the environment allows for the monitoring of the quality of both the air and the water, as well as the detection of pollutants and pesticide residues. This information assists in the evaluation of the influence on the environment and assures compliance with sustainable agricultural practices (Bet *al.*, 2022).

VIII. CONCLUSION

In conclusion, nanoparticles are on the verge of ushering in a new age of materials and technology, which will propel futuristic trends across a variety of industries. Because of their one-of-a-kind characteristics and functions, they are fundamental components of any innovative or forward-thinking endeavor. We may obtain significant insights into the future landscape of materials science and technology if we investigate the most recent breakthroughs in nanoparticle technology as well as the prospective uses of nanoparticles. However, to guarantee responsible development and make the most of the advantages that nanoparticles may bring to society, special attention must be given to the difficulties and safety issues related to the use of nanoparticles. Nanoparticles have an essential position to play in driving forward technological development, and the enormous potential they represent for the future cannot be overstated. As we start down this path, we must address the difficulties involved with the synthesis, characterization, and use of these compounds. In addition, it is of the utmost importance to give careful thought to issues of health, safety, and the environment. Unlocking the full potential of nanoparticles to contribute to the creation of a better, more sustainable future is possible if we encourage cooperation across disciplines and push for responsible technological advancement.

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