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REVIEW

Applications of Nanotechnology in Agriculture and Food Science: A Review

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Nanotechnology acquires great attentions in the last few years because of its broad applications in the medicines and drugs like tumor detection, cosmetics and materials. Nanotechnology is memorized as a growing technology because of its applications and functions due to nanoparticles' size range between 1-100 nm. Nanomaterials are gaining popularity as an alternative to conventional pesticides, with promising results in the roles of plant growth stimulants, insecticides and fertilizers. Nanotechnology has been applied to several areas of agriculture, including crop enhancement, plant disease detection, weed and pest management, soil, water remediation, animal health and breeding, and more. Simultaneously, nanotechnology has also become increasingly significant in the food industries too. Particularly engaging for food packaging purposes are silver nanoparticles, and nanotechnology is currently being utilized to use in the food business for purposes among them processing, quality monitoring and packaging. As a result, this review concentrates on the synthesis and uses of nanoparticles in the food and agricultural industries. Despite several studies suggesting that nanoparticles have applications in the food and agriculture industries, more studies are needed to convey the significance of nanoparticles in these fields.

Keywords: Nanotechnology, Agriculture sector, Food sector, Synthesis, Food processing.

INTRODUCTION

Nanotechnology and nanomaterials are the two fields of research that are rapidly expanding. One of six "Key Enabling Technologies" recognized by the European Commission as promoting sustainable growth and competitive advantage across a broad range of industrial application domains and being present in almost every aspect of our daily lives is nanotechnology [1]. Although there are numerous theories regarding nanotechnology in the literature, it may be summed up as a brand-new, cutting-edge and interdisciplinary branch of science that involves the development of substances and objects at the molecular and nanometric scales [2]. It deals with or involves changing its atoms and molecules to produce new materials, technologies and systems with improved properties, alternatively, it belongs to the realm of applied science and technology [3]. Nanotechnology's basic tenet is the atom-by-atom construction of new molecularly organized structures to utilize their special properties and produce cutting-edge devices [4]. However, biotechnology uses biological methods to control cellular, molecular and genetic processes to create products and services that can be used in a variety of industries, including healthcare, food and agriculture [5]. Nanobiotechnology combines nanotechnology, biotechnology, as well as chemical and physical processing, material science, system engineering and nanotechnology to create innovative items that have been altered at the nanoscale and may have better conditions than conventional materials [6]. Nanomaterials and nanoparticles have been quickly adopted by many fields, including but not limited to agro, foods, medicine, pharmacology, technology, mechatronics and energy [2,6]. They possess unique chemical, physical and biological abilities, which account for these applications.

Agriculture is among the most crucial industries and reliable industries since it generates and delivers raw resources, mostly for the animal and food feed sectors. Agriculture must advance in a way that is economically viable, environmentally friendly and successful due to the world's limited natural resources, population growth, rising food security worldwide and climate change [2,5]. The ability to modify, transform and reduce matter at the atomic and molecular levels enables the development of agricultural materials with unique qualities. High reactivity, sensitivity, increased bioavailability and bioactivity, adhesion effects and a variety of surface effects are some of the novel characteristics and applications of nanotechnology in this field [7].

Nanoscience used in the food business is identified as food nanotechnology and this term is used in this study to refer discoveries and applications breakthroughs made possible by nano-level science and engineering applied to the structure, texture and quality of foodstuffs and food-related products. Nanotechnology is used in the food industry to make nanosensors and the usage of nanoparticles like cubosomes, micelles, liposomes, nanoemulsions and biopolymeric nanoparticles to ensure food safety [8]. Pathogen detection, food processing, packaging and agricultural output depend on nanotechnology usage in the food business. The plan also calls for flavour enhancers, nutraceuticals in nanocapsules and nanoparticles with the ability to selectively bind and eliminate chemicals from food [9]. There are only a few recorded examples of novel usage in the categories of mainstream food and beverage items and it seems to be mostly concentrated on food packaging and health food products [10]. Scientists are working on food packets that include nanoparticles to alert consumers when a product is unsafe to eat. Additionally, they are creating materials with nanoparticles that can spread [11]. Surfactants in food products may allow for reductions in the amount of salt, fat and preservatives used, in addition to the creation of new or enhanced flavours and tongue sensations through the processing of food at the nanoscale [12]. This review aims to provide an analysis of the current state of knowledge concerning the synthesis, applications and potential for advancement of nanotechnology in the agro-food sector.

Approaches for synthesis of nanoparticles: Top-down and bottom-up are two general methods for the synthesis of nanoparticles as shown in Fig. 1.

Top-down approach: Top-down synthesize nanoparticles through bulk materials [13]. Soft samples cannot be processed using this procedure. Top-down is a low-cost, highly productive approach that yields nanoparticles smaller than 20 nm [14]. Fig. 2 provides a diagrammatic illustration of the Top-down approach [15,16].

Evaporation condensation: Evaporation-condensation is the most notable physical method and involves the use of a tube furnace. When tube furnaces are used, there are some drawbacks like higher environmental temperature near the source, high energy consumption [17]. Evaporation condensation works on the principle of pressure caused due to vapourizing of the metal. The evaporation condensation is done with metal evaporation through heating and then condensing of vapour for obtaining nanopowder [18].

Ionic electronic irradiation: Ion irradiation is a powerful and effective method for synthesis of nanoparticles [19-25]. Nanostructures and nanomaterials have been synthesized by the technique of electron irradiation and generally suitable for the synthesis of nanopowder based polymeric membranes [26]. Applications for ion-irradiated nanoparticles are numerous, but well-controlled mass manufacturing of these particles remains a significant difficult [27]. However, it is essential to develop well-founded techniques to synthesize nanoparticles with appropriate properties.

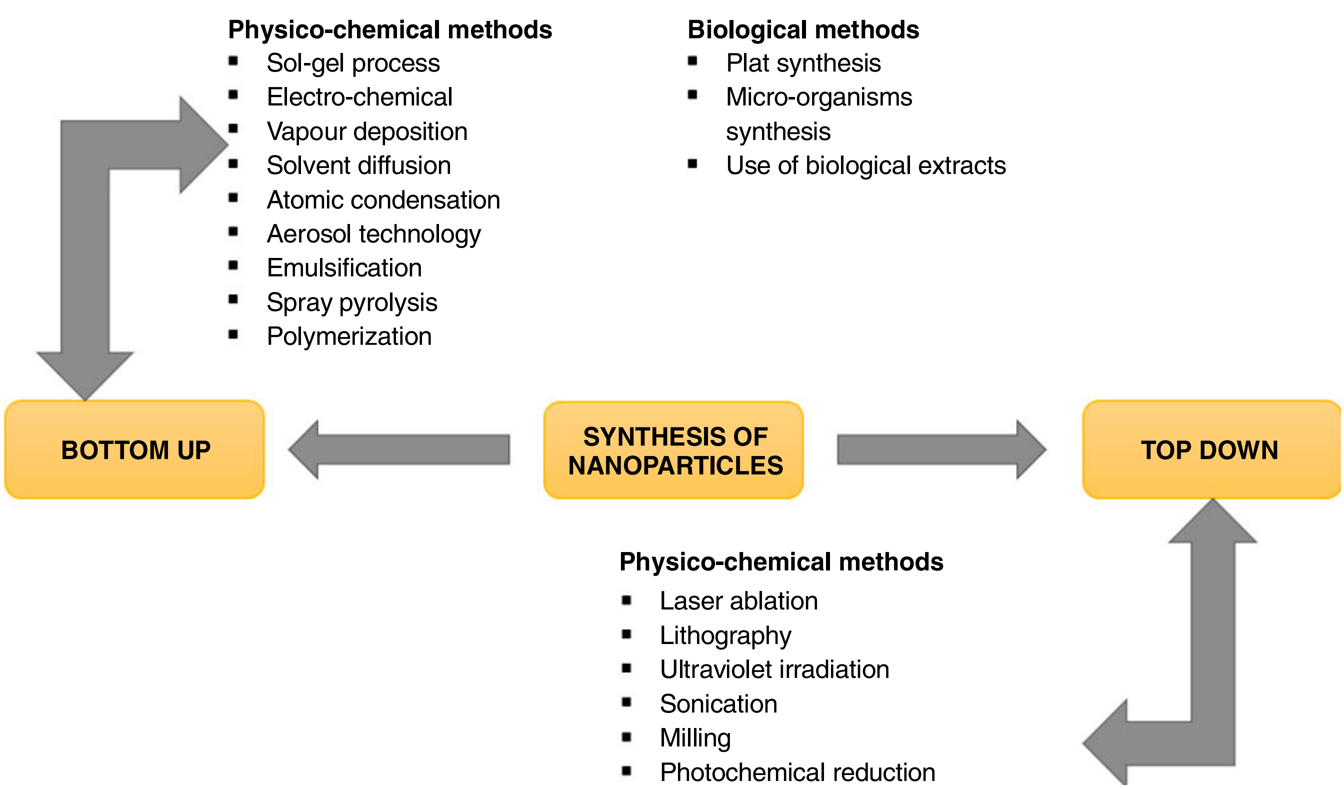

Fig. 1. Synthesis of nanomaterials *via* top-down and bottom-up approaches

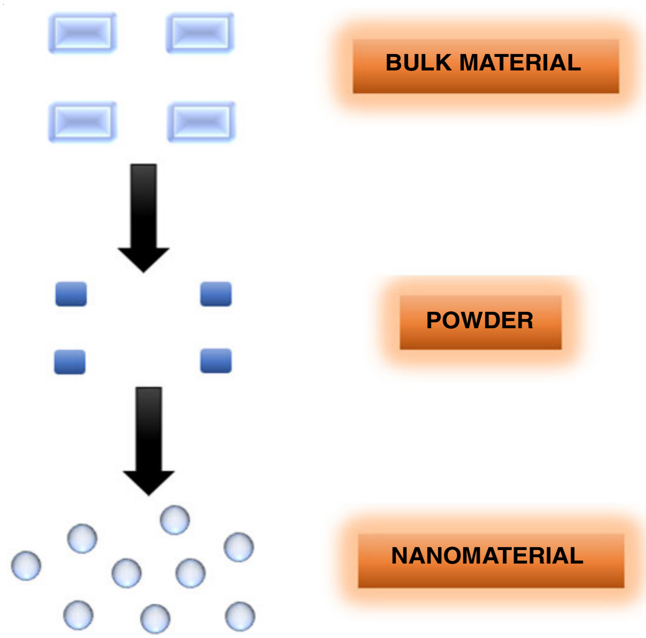

Fig. 2. Diagrammatically representation of the top-down approach

Laser pyrolysis: Vapour-phase synthesis plays a superior role in the production of nanomaterials because of advantages including product purity and scalability [28,29]. One of the useful vapour-phase techniques is laser pyrolysis. This technique involves heating a gas stream precursor with a laser beam until it breaks down [30,31]. The laser pyrolysis works on the principle of decomposition of liquid or decomposition of gas reactants due to a high-power CO_2 laser including the quenching effect [32].

Bottom-up approach: The bottom-up approach works on two main parts nucleation and growth. The nanoparticles are synthesized from the elementary level [13]. The bottom-up approach gives high precision products and high-quality products. Fig. 3 provides a diagrammatic illustration of the bottom-up approach [15,16].

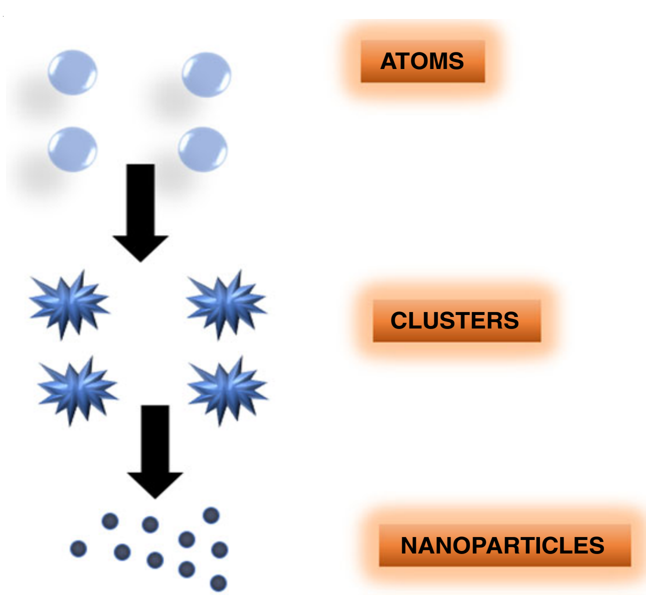

Fig. 3. Diagrammatically representation of the bottom-up approach

Sol-gel method: The wet chemical procedure known as the sol-gel method is used to prepare nanoparticles. In the sol-gel procedure, the metal alkoxide precursor is dissolved either in alcohol or water and after being heated and stirred, it becomes gel [33]. This strategy is widely used in numerous industries, and its popularity continues to grow [34-38] due to the production of high-quality nanoparticles, which exhibit unique properties [39,40].

Hydrothermal method: The hydrothermal method can generate nanoparticles which are not stable at the elevated temperatures [41]. The hydrothermal method is a soft chemical method with important advantages due to its low crystallization [42]. This technique has become a standard for preparing both organic and inorganic nanoparticles [43]. The hydrothermal method draws a large number of researchers because of its low cost, straightforward equipment and comfortable preparation circumstances [44]. For the preparation of nanoparticles with optical characteristics, this approach can be used [45].

Supercritical fluid with chemical reaction: The use of this technique in the preparation of nanoparticles has grown significantly [46]. The properties of supercritical fluid are an intermediate between gas and a liquid. Supercritical fluids are more simplified, flexible and a reduced environmental impact [47]. The supercritical fluid process has high potential in industrial level production processes [48]. Zero surface tension, rapid mass transfer and solvent elimination are only a few of the unique characteristics of supercritical fluids and their mixtures [49].

Plant extract: Plant extract is essential for the creation of nanoparticles. Green nanoparticle synthesis refers to the production of nanoparticles using various plant extracts. There are numerous uses for plant extract-based nanoparticles in the medical and environmental domains [50-52]. The usage of plants and plant extracts is compatible with the ecological sustainability.

Algae: Algae have a tremendous impact on the creation of nanoparticles. Heavy metal ions can be hyper-accumulated by algae and modified into more malleable forms [53]. These characteristics have led to the use of algae in the synthesis of nanoparticles [54]. Algae have minimal production costs and a great capacity to absorb metals and decrease metal ions. Using both living cells and cell extract of algae, nanoparticles can be synthesized [55].

Applications of nanotechnology in agriculture sector: Agricultural production is mostly affected by plant diseases and insect pests due to which there is great economic loss [56]. In agriculture, nanoparticles are utilized for disease detection, treatment, processing and storage of crops, as well as in genetic transformation to boost the plant yield [57].

Nanoparticles as fertilizers: Due to limited resources, the expansion of agriculture for higher growth is currently being managed and fertilizer management has remarkably demonstrated its significance [58,59]. By improving the soil system and applying fertilizer in a revolutionary way that uses nanoparticles, plants have been stimulated to develop in a certain manner [60]. Chemicals called fertilizers, such as urea and ammonium salts, are used to boost crop production by making it easier for plants to get the nutrients they need to thrive. But in order to produce an enormous quantity of food, farmers have turned to use traditional fertilizers at high rates and for extended durations, which is the principal anthropogenic component that causes eutrophication of freshwater and coastal ecosystems [61-64]. As a result, numerous strategies have been proposed to address this issue. The development of nanofertilizers, which are either nanomaterials capable of supplying nutrients to the plant or those that operate as enhancers of the regular fertilizers without directly providing the nutrients, is one such example. The development of biofertilizers, which use helpful microbes to transform organic debris into compounds that are nutrient-rich for the plant while also maintaining the soil's fertility and its natural habitat, is another tactic. However, this method has some limitations, including brief shelf life, a lack of appropriate carrier materials, a high temperature and desiccation sensitivity. Polymeric nanoparticles for the coating to resist desiccation, therefore, would be a great application to solve such problems [65]. For instance, researchers have studied the relationship between plant growth-promoting rhizobacteria and gold nanoparticles. Some of the strains examined, including *P. elgii*, *P. fluorescene* and *B. subtilis*, showed a considerable increase in growth, according to the data and can act as nano-biofertilizers [66].

Nanoparticles as pesticides: The ability to withstand climatic conditions like sun, heat, rain, transit through the target and enter the organism (fungus, insect, *etc.*) or the ability to withstand the pest or pathogen's defense are some of the more crucial qualities of an ideal pesticide today. However, insecticides lack such favourable chemical properties, which is why nanoparticles are now used in these goods. Additionally, it has been found that adding nanoparticles to pesticides results in more controlled modes of action, which has been shown to have positive effects on the economy, society and the environment. Another factor to take into account is the inclusion of nanoparticles, polymeric nanoparticles and nanosuspensions in pesticides [67,68]. Among the most common nanomaterials used to improve the properties of insecticides are zinc oxide, silver, nanostructured alumina, aluminum oxide and titanium oxide [69]; they are mostly used due to their simplicity in synthesis. As of right now, utilizing nano-iron oxide pesticides enhanced rice and soybean yields by 25% and 48%, respectively [70].

Insect pest management: Nanotechnology has several advantages in the area of food safety, including the ability to control insect pests [71]. One of the animal species that is most known throughout the world is the insect. A vast range of trees, including weeds, agricultural vegetation, agroforestry systems and medicinal plants, were devoured by insects. Additionally, they contaminate food and other commodities stored in bins, storage buildings, warehouses and packaging, which results in significant losses to the food that is kept there as well as a decline in food quality. Previous research has demonstrated the usefulness of metal nanoparticles against plant diseases, insects and pests. Nanoparticles can be employed to generate new pesticides, insecticides and insect-repellent compositions [63].

Nanoparticles as antifungal: Due to small dimensions, nanoparticles have been shown to be efficient in preventing the growth of certain bacteria and fungi on plants. This is because biological processes allow for their extensive penetration of cell walls and membranes. The antibacterial effects of silver ions are well recognized [72-74]. These silver nanoparticles are eco-friendly fungicidal, bactericidal and plasmonic inhibitors of plant diseases when compared to synthetic fungicides. Silver nanoparticles can damage the structural membranes wall and then thus denaturing the cell. As a result of this nanomaterial's alteration of molecular transport pathways, such as ion efflux, silver ions quickly accumulate, stopping respiration and metabolism in the cells [75,76]. The same goes for investigations into copper and copper oxide nanoparticles for the phyto-pathological field of nanotechnology have been reported as well as phytosanitary use [77]. The natural substance chitosan, which has numerous uses in biology due to its potential to be biodegradable, risk-free, non-toxic, cost-effective and beneficial to the environment, is another nanoparticle used to control fungi. Chitosan's amino groups interact with the macromolecules' negative charges on the outside of the fungal cell wall, leading some studies to conclude that it possesses antifungal characteristics [78,79].

Nanosensors in agriculture: Both biotic and abiotic factors continue to limit agricultural production. For instance, weeds, illnesses and insect pests all significantly reduce agricultural production. Regarding this, nanotechnology has made it possible to use nanosensors, which are highly developed devices that can react to physical, chemical or biological aspects and convert that response into a signal that humans can use. As a result, it is now possible to detect numerous factors related to drought, temperature, insect or pathogen pressure, or nutrient deficiency. The special and distinctive properties of nanomaterials, such as shape- and size-dependent optical properties, quick and easy surface changes and catalytic functions, are particularly helpful for signal generation and signal amplification [80,81]. Additionally, the potential for on-site monitoring allows farmers to closely monitor environmental conditions for plant growth and crop protection. This can also help to increase productivity and decrease the use of agrochemicals like antibiotics, pesticides and nutrients through early intervention. In addition, people can use inputs more effectively by indicating the nutrient or water status of crop plants over fine spatial and temporal scales [63]. These smart sensors in the agricultural industry are recognized as a potent instrument for tracking, identifying and controlling animal and plant infections since they assist in the detection of chemical pollutants, viruses and bacteria in agricultural systems as well as nutrient content and plant health. This is because they contribute in the diagnosis of diseases in both animals and plants. The micro electro-mechanical systems can sense and monitor soil temperature and moisture through micro-electronic circuits. They can also be used to diagnose oil disease, which is brought on by infected soil microorganisms like viruses, bacteria and fungi, by quantitatively measuring the difference in oxygen consumption between good and bad microbes in the soil. Additionally, photosystem II, which is known to bind a variety of chemical and herbicide groups, is used in the development of biosensors [7]. Farmers and the general populace will win from the creation of new technologies in terms of things like financial gain, decreased environmental pollution and lower labour expenses [82].

Nano-biosensors in agriculture: The development of biosensors can also take advantage of novel physical and chemical features of nanoscale materials. Biosensors use nanomaterials to increase their sensitivity and effectiveness through innovative signal transduction techniques. There are three main parts to make up typical nano-biosensors. To receive signals from the sample and send them to a transducer, the probe or biologically sensitive components such as enzymes, antibodies, tissues, microorganisms (pathogens) and nucleic acids, among others, are used. The biological receptor's physical alterations are tracked by the transducer. The gadget then converts that energy into quantifiable electrical emissions [83]. The detector receives the transducer signal, amplifies it and sends it to the CPU for analysis. Finally, the user can view the outcomes after the data has been uploaded to a display [5].

Each type of nano-biosensor has a different application depending on the analyte being detected; for instance, biosensors are used to detect phenols, polyaromatic compounds, halogenated pesticides and volatile organic compounds [84]. Their uses include the detection of numerous microorganisms and diseases as well as analytes such as urea, glucose and pesticides. One example is a cutting-edge silica nanoparticle based microbial detection method that has been reported recently. This technique has potential in the agricultural sector for the detection of plant infections since the nanoparticles 60 nm are loaded with a fluorescent dye and coupled to an antibody specific to a surface antigen of the bacterium of interest [85,86].

Disinfectants in agriculture: The first stage in any effective inquiry on *in vitro* plant tissue culture is the elimination of impurities like bacteria, fungi and viruses. Chronic microorganism contamination *in vitro* plant culture techniques is one of the main issues. Regular use of traditional antibiotics and chemotherapeutic drugs may be phytotoxic or slow down the growth of plant tissue [87]. In this respect, utilizing silver nanoparticles solution after surface sterilization has shown to have a tolerable influence on the control of bacterial infection without having any negative effects on the growth characteristics of regenerated valerian plantlets. However, using nanoparticles as a substitute for conventional plant disinfection methods has been suggested [88]. Negative electrons generated by the excitation of nanoparticles make up the mechanism of action. Additionally, this can be utilized to kill germs, as when bacteria come into contact with nanoparticles, excited electrons are pumped into their bodies, which causes the bacteria to be eliminated from the affected material, as in fruit packing and food engineering [89].

Transmission of genetic materials in agriculture: One of the main subfields of plant biotechnology is the genetic transformation. By modifying gene expression, delivery of genetic material such as DNA and short interfering RNA is crucial for the generation of pest, disease and stress-resistant strains of crop plants. The targeting of the delivery mechanism, passage across the cell membrane, uptake and destruction in end lysosomes and intracellular trafficking of DNA to the nucleus are challenges faced by gene delivery methods for plant transformation [90]. When properly functionalized, nanomaterials can transport a greater number of genes as well as substances that can turn on or off certain genes or regulate how much genetic information is released over time in plants [63]. Although Agrobacterium-mediated transformation has been shown to be effective even with a low copy number of a gene, both particle bombardment and Agrobacterium-mediated transformation are viable options for plant genetic transformation. Furthermore, plants produced from Agrobacterium-mediated transformation exhibit more consistent transgenic expression and lower transgene silencing. However, it is difficult to remove extra germs using this method following traditional antibiotic cultivation [91].

The use of carbon matrices incorporated gold nanoparticles for the delivery of DNA during the plant cells' transformation carried higher a greater proportion of genetic material than microparticles [92]. Nanoparticles had reduced compared to the commercial micrometer-sized plasmid and gold requirements particles of gold. Additionally, the nanoparticles caused minimal plant-cell damage and improved plant regeneration. The primary benefit is the site-targeted delivery and expression of chemicals and genes, respectively, as a result of the simultaneous delivery of DNA and effects or molecules to the specified places. Carbon nanofibers with plasmid DNA on their surfaces have been integrated to allow for controlled biochemical manipulations in cells [63,88]. It is also possible to think about carbon nanotubes as a possible gene delivery system for plant cells. Walled plant cell cytoplasm was accessible to single-stranded DNA wrapped around single-wrap carbon nanotubes [93]. This might be a promising finding for introducing brief dsRNA pieces into the nucleus of plant cells to activate genes *via* tiny RNAs. Another potential location for gene delivery is protoplasts, where bigger CNTs with adsorbed plasmids might be used to transfer desired genes into the plant genome [94]. Along with these vectors, cationic nanofibers, nanoparticles and nanovesicles can precipitate negatively charged DNA molecules and introduce them into cells through nonporous cell membranes. Alternatives like cationic polymers and nanoparticulate cationic liposomes are being researched. Complexes are prepared electrostatically as a result of their constant cationic charges interacting with negatively charged DNA [90]. By delivering DNA and its activators in a controlled manner, surface-functionalized mesoporous silica nanoparticles have the potential to precisely modify gene expression at the single cell level [95].

The term "bio-beads" refers to the calcium alginate beads which are a few micrometers in size and can be used to encapsulate reporter gene-containing plasmid DNA molecules [96]. The primary benefit of this method is the site-targeted delivery and expression of chemicals and genes, respectively, as a result of the simultaneous delivery of DNA and effector molecules to the targeted sites. This is how traditional genetic engineering techniques vary from nanoparticle-mediated plant transformation [3,90].

Nanolaminates in agriculture: Microorganism-induced deterioration after harvest and during cold storage is the primary source of postharvest losses in fruit and vegetable crops. Fruit, coming vegetables are often less acidic than fruits and because of their higher nutrient makeup, lower pH and higher moisture content, they are more susceptible to the attack of fungi. Bacteria typically cause spoiling. Even though it is challenging to ascertain the complete size of post-harvest losses brought on by decay. It is commonly recognized that these losses are substantial [97]. Therefore, it is believed that one of the key applications of nano-coatings is in food packaging, which is also one of the main areas of concentration for polymer nanotechnology. Different parameters like light, moisture, water vapour and gas must be met by packing materials depending on the type of food [98]. The technology of nanolamination shields food from lipids and moisture, gases, too. Additionally, they help enhance the texture and maintain the colour and odour of the meals [99]. According to studies, nanolaminates made up of polysaccharides and protein are effective against oxygen and carbon dioxide but ineffective against moisture [100]. Lipid-based nanolaminates, however, are effective at shielding food from moisture [101]. Other substances are applied continuously as the nano-coatings base ingredients a thin, amorphous coating of titanium dioxide that is 50 nm or less in thickness. Another illustration is the nano-selenium that is being offered as a tea addition [98].

The design and potential application of emulsion based nano-laminated biopolymer coatings made utilizing electrostatic deposition to prepare novel encapsulation and delivery methods to manage the bioavailability of the bioactive lipids [102]. The effectiveness of a chitosan coating to provide physical or chemical protection was one of the findings [103]. It is proposed that nano-laminate coatings' barrier characteristics are enhanced due to the increased tortuosity of their nano-structure, which is a result of the components of the nano-electrostatic laminate's interactions and also gas flow is hindered by the interpenetration of successively layered layers moving molecules through the structure [97].

Nano-remediation in agriculture: As already established, pesticides are the crucial component of agriculture. They facilitate the crop growth by shielding plants from pests that cause serious yield losses. Unfortunately, the majority of insecticides used today don't completely reach the intended recipient and any remaining substance contaminates impacts the area's land, water and air resources as well as other living things, like living things, plants and people. Examples include arsenic and chlorpyrifos [104-106]. One of the greatest challenges modern society faces is restoring degraded ecosystems to a point where they pose no threat to human health or the environment. Traditional clean-up methods, however, can be highly expensive, time-consuming and even contaminate themselves. Since it relies on specific nanomaterials, like nanoparticles, which can react with contaminants, nano-remediation has been studied as a potential substitute and may be more affordable and effective than conventional remediation of the contaminant, allowing it to change into less harmful molecules or immobilize it by adsorption [107-109]. Additionally, nano-remediation has some benefits over conventional remediation, including quicker clean-up times because the nanoparticles utilized have a smaller size and more reactive due to their greater surface area. The use of nanoparticles reduces the cost of *in situ* remediation, eliminates the need to excavate contaminated soil for disposal and eliminates the need to pump and treat groundwater [80].

Agriculture impact (benefits and drawbacks): As mentioned before, nanobiotechnology is renowned for its ability to discover and create innovative materials at the nanoscale size for usage in a wide range of applications. In light of these factors, nanotechnology offers significant benefits for the preparation of new technologies tailored to agricultural needs [110]. The transformation of food and agricultural wastes into energy and other useful byproducts for disease prevention and treatment, as well as the mitigation of the detrimental environmental consequences of pollution brought on by the overuse of pesticides and fertilizers [84]. However, using some nanosized substances in agribusiness, resource use and food intake puts the environment and human health at danger, or both issues, such as the bioaccumulation of these elements, since their longterm influence has not been established. Instead, research has shown that using nanomaterials is not necessarily dangerous. It's also critical to consider that little is known about how food crop nanoparticles can be biomagnified and transformed. Additionally, it is important to monitor the materials' presence in the food chain since, if not, the created nanomaterials may be harmful to people, the environment and animals [7]. However, it is crucial to mention that these utilization's growth in agro and food sectors has also sparked worries about how their use may affect environmental and public health security. To provide important answers about the danger, the exposure and the overall risk, the field of nanotoxicology, which studied the toxicity of primary materials with nanoscale components, has emerged [111]. Similarly, while using regulation of nanoparticles, their natural diffusion and their potential toxicity as well as the size impact of using these elements in agriculture for the creative development of innovations in the field.

Applications of nanotechnology in food sectors: Food industry can greatly benefit from the use of nanotechnology in areas such as biosensing, toxin and pathogen detection, food packaging, delivery systems, distribution of bioactive substances and protection of functional ingredients [112]. Due to the improvement in food product safety and nutritional value brought about by the use of nanotechnology, this technology may completely alter the food industry. The development of new food products that meet the demands for food quality, sensory appeal, texture and taste as well as for improving supplements and other sensory attributes, colouring, strength, processability, stability during shelf life and safety, while also being a good source of nutrients, has seen an increase in interest in nanotechnology in recent years [113-115]. Recently, Prakash *et al*. [116] found that this technology might be used for food additives, quality control and the detection of bacterial and fungal contamination.

Delivery methods for food additives and ingredients: The fundamental goal of food-related uses of nanotechnology is the creation of vitamin and supplement delivery systems and nanostructured food ingredients [117]. With the use of this technology, nutrients can be delivered to the body more effectively to produce the desired effects, as well as bioactive substances' solubility, length of time spent in the gastrointestinal tract and effective cell absorption. Omega 3 and omega 6 fatty acids, probiotics, prebiotics, vitamins, antibiotics, flavourings, preservatives and minerals have applications as bioactive molecules in food nanotechnology [118-121]. Numerous bioactive substances, which are meant to be consumed orally are non-polar substances with high melting points, low water solubilities and poor oral bioavailability. It is, therefore, vital to include certain bioactive substances into particles that promote their bioavailability because they are difficult to incorporate into commercial items, such as functional meals and beverages. In addition, due to their great stability under mild conditions, such as pH level, temperature or salt content, micelles, liposomes and nanoemulsions may be suitable possibilities. Popov *et al.* [122] recently suggested using nanoemulsion technology to make it feasible to generate aromatized beverages, juices and milk enhanced with carefully timed releases of vitamins, minerals and functional ingredients.

Nanotechnology in food processing: Significant innovations in food production, processing and packaging have been brought about by nanotechnology. Recently, the term "nanofood" was coined. The definition of a nanofood is "nanotechnology techniques or tools are used during the cultivation, production, processing or packaging of the food but not modified or produced food by nanotechnology machines [12,123]. In addition, smart packaging, on-demand preservatives and interactive foods are applications of nanotechnology [124]. The addition of nanostructures to processed foods to provide new or enhanced flavours, textures and mouth sensations. Natural food ingredients might potentially be nanostructured to require less fat while still producing tasty food products. A typical product of this technology would be a spread, mayonnaise or ice-cream with nanostructures that are low in fat but has the same "creamy" texture as its full-fat counterpart. As a result, these goods would provide consumers with a "healthy" option [10]. Food additives and supplements that are nanosized or nano-encapsulated can enhance the taste of food, increase the dispersibility of fat-soluble additives in food products, allow for hygienic food storage, reduce the need for fat, salt, sugar and preservatives and increase the absorption and bioavailability of nutrients and supplements. Examples that are now on hand include vitamins, antioxidants, colours, flavours and preservatives. Nano-sized carrier systems for minerals and vitamins have also been created for use in food products. These are based on nano-encapsulated substances in carriers made of proteins, micelles or liposomes. Additionally, some chemicals and additives are disguised in flavour or shielded from processing-related degradation using nanocarrier systems. Ascorbic acid, benzoic acid, citric acid and a synthetic version of the tomato pigment called lycopene are some examples of the food additives [10]. The primary use of metal and metal-oxide nanoparticles today is in food packaging. Examples of nanoparticles that are used in packaging are nanoclay for a gas barrier, nano-silver, nano-zinc oxide for antimicrobial activity, nano-titaniumide for UV protection, nano-titaniumide for mechanical strength, nano-silica for help in processing and nano-titanium nitride for processing assistance are all used in plastic-polymer composites. surface coatings that repel water, *etc.* In comparison to other nanomaterials utilized in various fields, the utilization of nanosilver as an antibacterial, anti-odourant and (promised) health supplement has already surpassed them all [10]. Currently, nano-silver is primarily used in health food and packaging, but a recent patent application describes its usage as an addition to antibacterial wheat flour [125].

Packaging for food using nanotechnology: Food packaging employs nanotechnology to enhance mechanical and barrier qualities. Nano-silver is used in packaging applications as a microbicide to maintain food freshness and avoid contamination [123,126]. To increase shelf life and retain quality and freshness, packaging barrier qualities are improved with nanomaterials to control the flow of gases and moisture through the packaging [121,123]. Future packaging is probably going to consist of more than just a physical container that shields food from its environment. It is necessary to further subdivide nano-packaging into packaging from which migration into the food is intentional and planned and packaging from which no nanoparticles (in any appreciable proportion) migrate. The former is less likely to develop as quickly as the latter since it will likely face more rigorous safety evaluations and unfavourable consumer opinions. The use of nanotechnologies to enhance packaging materials is likely to be highly expensive and won't be adopted until techniques are perfected and the outcomes are reliable and consistently outperform costs [127,128]. The functional qualities of packaging materials, in particular nanocomposites, could be significantly improved, extending the shelf life of packaged goods. Nanoscale structures having a distinctive shape, improved modulus and strength, as well as strong barrier characteristics, are used to create nanocomposites [129]. The packaging industry is where nanotechnology is most commonly used in the food industry. By 2015, it is anticipated that 19% of culinary applications for nanotechnology will come from this industry. This is primarily because nanotechnology has advanced significantly in this field, consumers are more accepting of the use of this technology in packaging than in food as ingredients and the regulatory requirements are less onerous than those for the existing food legislation that is in force [130]. Due to its advantages over using conventional materials, the usage of polymers as a material for food packaging has dramatically expanded during the past ten years. About 42% of the global market for polymers, which has grown from around 5 million tonnes in 1950 to almost 100 million tonnes now, is made up of packaging and containers [130].

Nanocomposites: Using methods like nanocomposite, nano-emulsification and nano-structuration, nanoencapsulation is defined as technology that packs substances in tiny containers and offers the final product capabilities, including controlled release of the core. Using this method, it is possible to protect bioactive substances including vitamins, antioxidants, proteins, lipids and carbohydrates while still producing functional foods with improved functionality and stability [131]. Nanocomposites are used in food packaging to protect food while simultaneously extending shelf life, addressing environmental issues and minimizing the usage of plastics. Most packaging materials are not biodegradable and the barrier and mechanical qualities of present biodegradable materials need to be greatly improved before they can replace traditional plastics and help manage global waste [132].

Active packaging: An innovative sort of packaging compared to conventional techniques is the active and intelligent food packaging category. An intelligent or smart system that involves interactions between the package and its components is defined as active packaging. Additionally, it fulfills consumer needs for high-quality, fresh-like and secure products by using food or an internal gas atmosphere. Active packaging, in particular, alters the state of packed food to increase shelf life, enhance food safety, improve sensory qualities or enhance colour and scent while retaining food quality [133]. It is believed that active packaging has elements that release or absorb substances in the container or in the air that come into touch with food. However, other promising uses for active packaging include oxygen captation, ethylene elimination, CO_2 absorption/emission, steam resistances, bad odors protection, antioxidant liberation, preservatives addition, additives or flavours [134]. Uptil now, active packaging has primarily been developed for antimicrobiological applications. Nanomaterials made of metals and metal oxides are employed more frequently in the creation of active packaging for antibacterial purposes. By preventing or inhibiting microbial growth, the use of nanosilver in packaging helps to preserve hygienic conditions on the surface of the food. Even though it is a biocide, its action is not that of a preservative [135].

Intelligent packaging: The idea of tracking data on the food's quality is generally referred to as the "intelligent" part of food packaging. For instance, nanosensors or nanocapsules based on nanotechnology will be able to detect food spoiling germs and cause a colour change to inform the consumer that the shelf life is about to expire or has finished [136]. This kind of function can also include the "release-on-command" idea, which will serve as the foundation for intelligent preservative packaging technology that will release a preservative if food starts to spoil. Nanotechnology can also be used in coatings or labels on packaging to provide details on the traceability and monitoring of product conditions on the outside as well as the inside across the entire food chain [137]. These applications include leaking detections for foods packed under vacuum or inert atmosphere, temperature changes (freeze-thaw-refreeze, monitoring of the cold chain by using silicon with nanopores structure), humidity variations throughout the product shelf-life or foods being spoiled are some examples of these applications. The study of pathogens transmitted by food is currently focused on sensors based on nanoparticles embedded in polymeric matrixes [138]. The technology known as the electronic tongue also needs to be highlighted. It consists of sensor arrays signaling food's state of condition. The instrument comprises an extraordinarily dense array of nanosensors able to change colour when exposed to gases generated by rotting microbes. This shows whether the food has been damaged. Additionally, DNA-based biochips. It is in the process of development that will be able to identify the presence of hazardous bacteria in fruit being harmed by fungi, beef or fish [139].

Antimicrobial nanopackaging: A novel method of preventing food from becoming contaminated by bacteria on its surface is the combination of active ingredients with food packaging ingredients. Certain nanoparticles have antimicrobial properties. Sharing a shared interface or making physical contact with the food surface is crucial for these active packaging materials. By extending the product's shelf life and improving food quality and safety, these active FCMs help reduce food waste [127].

Safety and sensing: The development of innovative antimicrobial treatments and very sensitive biosensors for disease detection are two ways that nanotechnology has benefited the field of food safety [129]. Food packaging solutions derived from nanotechnology are being developed to improve food safety and assist in reducing food waste. Nanosensors that can identify pathogenic from benign microorganisms and detect and signal the presence of rotting microorganisms are currently being developed. Additionally, better foods that can carry nutrients and drugs to various sections of the human body as well as reduce allergenic characteristics are being developed using nanotechnology. Some researchers believe that the development of nanomaterials could benefit underdeveloped nations by improving the delivery of nutrients and insecticides to crops [11]. The rapid detection of viruses, bacteria and other pathogens is made possible by a new class of ultrasmall silicon sensors called protein-coated nanocantilevers, which naturally vibrate at a specific frequency [140]. The nanocantilever may vibrate at a different frequency when impurities land on the devices, which can lead to tiny mass changes that can be swiftly identified. The identification of food pathogens is made possible by the development of synthetic tree-shaped DNA that has coloured-coded probes attached to it, known as a nanobarcode device [141]. A small, portable microbioreactor was also developed using various nanowires, specific pathogen antibodies and fluorescent antibodies for the simultaneous detection of toxins, pathogens and chemicals in foodstuffs [142]. To prevent the spread of germs and other microorganisms, silver nanoparticles have been placed into a variety of items, including bandages and freezers [143].

Food safety and nanotechnology: A significant societal concern is food safety on a national and international level despite technological advancements in the areas of cleanliness, rules and food preservation. Foodborne infections can be caused by foodborne viruses and toxins, which pose serious risks to health. Foodborne illnesses are thought to be responsible for 9.4 million illnesses annually in the US. About 13 360 illnesses, 1062 hospitalizations and 16 fatalities were caused by 818 foodborne disease outbreaks in the United States in 2013, according to the Centers for Disease Control and Prevention report [144]. To identify and detect foodborne pathogens, such as bacteria, viruses, fungus and any other potential contaminants in food products or surfaces that come into contact with food, the food industry must have a robust system in place. The food sector needs quick, accurate contaminant detection techniques that don't demand a large workforce or specialized training. Traditional detection techniques and quick molecular technologies, which are used to find and identify harmful microbes or poisons, are nevertheless costly and time- and labor-intensive. Furthermore, self-contamination during processing or accuracy issues with such conventional procedures [145-149].

The antibacterial capabilities of nanomaterials and nanosensors for the detection of foodborne pathogens and other contaminants are the primary priority of nanotech methods for food safety. Recently, society and the food business have paid greater attention as researchers have prioritized the production of nanomaterials in the realm of food security, including detection methods and nanosensor devices [150,151]. The time required for incubation and measurements is significantly shortened by nanotechnology detection techniques in addition to offering a high level of sensitivity and accuracy. For instance, one study found that after only 45 min of incubation, 88% of *E. coli* bacteria in a sample could be extracted using nanosized magnetic iron oxide particles and sugar molecules [152]. New nanotechnology techniques are therefore being developed that will improve food quality and safety, particularly in the field of microbial detection and management. Technology's growth will enable the food industry to produce safer, healthier and higher-quality food items by resolving challenges with inaccuracy and timing that affect food safety [153-155]. It was demonstrated that mixing two or even more nanoparticle materials produced a synergistic effect that resulted in a more effective antimicrobial than a single nanoparticle with regard to the antimicrobial properties of nanoparticles. For instance, titanium dioxide and carbon nanotubes combined with AgNPs were shown to be twice as efficient against *B. cereus* and *E. coli* spores [156]. Additionally, silver and sodium dodecyl sulfate nanoparticles together had a higher antibacterial effect on *S. aureus* and *E. coli* [157]. Additionally, studies have shown that combining various nanoparticles with naturally derived essential oils yields synergistic antimicrobial effects that are stronger than either nanoparticles alone or essential oils alone [158]. These nanoparticles include silver, gold, zinc, chitosan, platinum, iron and carbon nanotubes. To this end, studies have shown that eugenol and cinnamaldehyde added to poly(D, L-lactide-coglycolide) nanoparticles resulted in a potent biocidal against *Salmonella* and *Listeria* [159]. Another study reported that vacuum-packaging fresh turkey, raw beef or processed turkey deli meat with essential oils added to nanoparticles of Ag and ZnO and pullulan film for two weeks at 4 ºC inhibited the growth of *L. monocytogenes*, *S. Typhimurium*, *S. aureus* and *E. coli* [160]. Consequently, blending nanoparticles with essential oils improves the synergistic effects of antibacterial activity against several foodborne pathogens as nanoparticles lead to stronger antibacterial effects [161]. Using this kind of applications could be a highly effective method of combating multidrug resistance in the microbial world [162-166].

Due to their resistance to the majority of disinfectants, biofilms are typically difficult to eradicate. Many microorganisms, including harmful bacteria, can flourish easily in the environment found in the food industry, bacteria frequently cling to surfaces and create biofilms. The complex variety of bacteria that make up this biofilm bind together to form a biofilm that is challenging to remove off surfaces, including surfaces that come into touch with food. As a result, such biofilm becomes a source of tainted foods that can result in foodborne illnesses [167]. The findings that nanoengineered surfaces with antimicrobial coatings are one of the most efficient antimicrobial agents against biofilms has enhanced the safety of surfaces that come into contact with food as well as the safety and quality of food products themselves. In food industry, nano-coatings like nanoscale silver, TiO_2 and ZnO are applied to surfaces to serve as disinfectants [168]. Furthermore, it has been discovered that the UV-C ultraviolet light-activated TiO_2 is effective at reducing issues with biocontamination in chicken operations, processing food and transportation of food [169]. Finally, by limiting the microbial adhesion and the development of biofilms, antimicrobial nanomaterial coatings may provide advantages for surface contamination problems in food business [170].

Moreover, when it comes to food safety, nanosensors have become a revolutionary form of nanotechnology that can be utilized for surface biocidal methods of removing biofilms as well as the quick detection of infections or other forms of contamination. For this purpose, various biosensors have been created to identify mycotoxins as well as the most prevalent foodborne pathogens connected to food contamination *viz*. *L. monocytogenes*, *E. coli* and *Salmonella* [171,172]. The findings of dangerous germs and their dangerous byproducts by nanosensors is discovered to be quicker, more accurate and succinct than conventional detecting methods, similar to antimicrobial nanoparticles. This is especially true for biosensors that bind antibodies to fluorescent dye particles on a silicon/gold nanoarray [173]. Various kinds of nanosensors have been developed recently to identify various their hazardous metabolites as well as the formation of biofilms, researchers have developed a variety of nanosensors using magnetic nanoparticles, carbon nanoparticles, metallic nanoparticles or cadmium quantum dots [154]. Table-1 summarizes the applications of nanotechnology in food industries.

Safety issues: In addition to the many benefits that nanotechnology has for the food business, there are safety concerns related to nanomaterials that must be taken into consideration. When considering safety concerns relating to nanomaterials, many studies have stressed the possibility of nanoparticles to migrate from packaging materials into food and their implications on consumer health [187,188]. Even though the material is being considered a drug that is generally recognized as safe (GRAS). Further studies must be conducted to determine the nanotechnology's risk parallels because nanostates' physicochemical characteristics are entirely distinct from those found in the macrostate. Moreover, the tiny size of nanoparticles could improve the likelihood of bioaccumulation in bodily tissues and organs [189]. For instance, silica nanoparticle exposure, which is used as an anti-caking agent, can harm human lung cells [190]. Numerous elements, such as the particle's surface shape, concentration, surface energy, aggregation and adsorption, have an impact on dissolution. To explore the migration of particles from food packaging, a model has been developed [191]. They looked into how silver and copper migrated out of nanocomposites and found that in comparison to particle size, temperature or contact duration, one of the key factors influencing migration was the amount of nanofiller in the nanocomposites. Since each nanomaterial has a unique feature, toxicity will likely be determined on a case-by-case basis [153].

TABLE-1
APPLICATIONS OF NANOTECHNOLOGY IN FOOD INDUSTRY

Types	Examples	Applications	Ref.
Nanoparticles	Ag NPs	Antibacterial agent and help in preventing microbial deterioration of food	[174]
	SiO_2	Prevent the moisture loss	[175]
	TiO_2	Serves as food colouring	[176]
Nanosensors	Au & Pt-based nanosensor	To detect any changes in the food's hue and to poisons like aflatoxin B_1 in milk	[177]
	Nano biosensor	Detection of germs and viruses	[178]
	Nano barcodes	Quality of crops for food	
	Array biosensor and Nano-test strips	Changes colour when it comes into contact with any sign of food decomposition	[179]
Nanocomposite	Nano laminates	Coating for meats, produce, dairy, cheese and bakery goods	[180]
	Nylon	Scavenges oxygen	[181]
	Polyamide	Fruit juice containers made of paperboard bringing about rigidity	[182]
	Aegis	Avoid carbon dioxide leakage from carbonated beverages	[183]
Nanofilms	Zinc oxide based films	Antibacterial and antioxidant agents	[184]
	Titanium oxide based film	Protecting fresh fruits like grapes	[185]
	Silver based film	Antibacterial agent	[186]

Outlooks for future: Currently, the development of applications in the sectors of technology, energy, health and the life sciences–all of which are actively researched remains the fundamental objective of nanotechnology research for their potential societal and economic impacts. Despite the fact that nanochemical pesticides are currently in use, other applications are still in the early stages and may take several years to become widely accessible or to be commercialized. This opens us to a wide field for the investigation of novel agricultural research areas [5]. The cytotoxicity of nanomaterials is a problem that frequently arises in scientific studies, which is understandable given that nanobiotechnology is used to build cutting-edge agricultural tools. The issues that nanotech presents for the utilization of new resources in agro-include integrating sustainable development and taking environmental effect into account [9]. Studies have revealed that the bulk of businesses providing funding for nanotechnology research concentrates on the hunt for gadgets with a high technological need and, consequently, a high financial demand. Because worries about agriculture are still not a top priority, research should be done to determine how important and profitable nanotechnology is in this industry. The ethical and societal implications of nanobiotechnology haven't yet been a major concern for many scientists working in this field. It is recommended to undertake initiatives to anticipate the ethical and social concerns that may arise with the growth of nanobiotechnoltogy in order to respond proactively and ethically to these potential social, media and political challenges [192]. Nanoparticles must meet specified requirements to be utilized in agriculture and they must also be warranted for use in this sector going forward [7,193].

Conclusion

According to the data collected, nanotechnology creates a substantial change in applying and processing almost every product in existence. Different methods and approaches have been employed to obtain nanoparticles of various sizes and shapes. The use of natural resources for synthesizing nanoparticles enhances the values of eco-friendliness, sustainability, non-hazardless and cost-effectiveness. The agricultural and food sectors generate tremendous differentiability in nanoparticle application and output. Nanotechnology-based agriculture products such as biofertilizers increase nanobio-interaction by their efficiency. Implementing nanoparticles in food technology sectors flourishes all stages of production, processing, packaging and supplements. The success of these advancements through nanotechnologies creates potential benefits in research and development. The promise of nanotechnology breakthroughs in enhancing already appalling utilization of nutrients efficiency through fertilizer nano-formulation, reducing through the use of bio-nanotechnology, monitoring and controlling pests and diseases and comprehending the mechanisms of host-parasite interactions at the creation of new-generation insecticides at the molecular level and secure transporters, food preservation and packaging and food additives, boosting natural fibre strength and removing pollutants in water and soil, enhancing the shelf-life of fruits, vegetables and flowers as well as the utilization of clay minerals as containers for nutrient ion nano-resources receptors, careful water management and soil regeneration fertility, restoration of soils damaged by salt and prevention of irrigated land acidification. A thorough understanding of nanotechnology is necessary for the fabrication and material technology, of science, in addition to understanding how food and agriculture are produced.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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