



Research Paper

Nanotech Based Food Packages: an innovative Approach to Reduce Food Waste

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Abstract: Food waste is a serious worldwide issue that has an impact on the environment, the economy, and society. Novel approaches to minimizing food loss and waste throughout the supply chain, from production and processing to storage and distribution, are provided by recent developments in nanotechnology. Silver, zinc oxide, and titanium dioxide nanoparticles are examples of nanomaterials with antimicrobial properties that prolong shelf life by preventing the growth of microorganisms responsible for food spoilage. Food freshness can also be preserved via nano-enabled packaging methods, such as nanocomposites and nano-coatings, which enhance barrier qualities against oxygen, moisture, and UV light. By detecting gasses, infections, or pH changes, smart packaging with nanosensors reduce premature disposal and offers real-time food quality indicators. Furthermore, nano-encapsulation technologies improve food safety and durability by stabilizing and releasing bioactive compounds, antioxidants, and preservatives in a controlled manner. These strategies aid in maximizing resource use and reducing post-harvest losses. Although nanotechnology offers intriguing answers for sustainable food systems, proper adoption requires careful consideration of the safety, legal, and environmental ramifications. The aforementioned nanotechnology-based technologies that increase food preservation, packaging performance, and allow for real-time food safety and quality monitoring are covered in this study.

Keywords: Nanotechnology, food packaging, food safety and quality monitoring

I. Introduction

Food spoilage is one of the major problems of the world and about 30-50% of food is wasted after harvesting due to poor post harvesting operations like transportation, storage etc. This food spoilage can be avoided by adopting proper handling, transportation and storage operations. Amongst many physical, chemical and biological factors, microbes are one of the main contributors towards the spoilage of food. It is revealed by World Health Organisation in 2015 that the common pathogenic microorganisms like Staphylococcus aureus, Campylobacter species, Listeria monocytogenes and Salmonella spp. etc. are responsible for 4,20,000 deaths and make 600 million people diseased in the world every year (Hoelzer et al. 2018; Bahrami et al. 2019a). The use of suitable packaging systems can contribute in a large way to prevent these incidences and can reduce the vast spoilage of food. The traditional packaging materials like metals, wood, plastic, glass, ceramics and paper are widely used for packaging of foods but most of these have many drawbacks like poor physical strength, poor barrier to oxygen and water vapours especially poor protection against microbes. These drawbacks make them ineffective to prevent the spoilage of foods in a significant way (Arora and Padua 2010; Bharathi et al. 2020). Modern food packages not only protect the food from dirt and physical injury but also provide safety from gases, microbes, moisture, and other toxic materials (Biji et al. 2015).

Amongst many developments in this field, the use of nanotechnology in food packaging systems has proved fruitful to overcome many problems. The application of nanotechnology in food packaging is the best approach focussed in recent few years due to its unique properties such as strong thermal and mechanical properties, light and fire resistance, less gas absorbance, and antimicrobial properties which increase shelf life, preserve colour and flavour, reduce the use of raw material and cost, remove extra oxygen and water vapour, easy transport and storage (Sozer and Kokini 2009; Bajpai et al. 2018; Joz Majidi et al. 2019). Nanotechnology composes the structures having size between 1nm to 100nm. The application of nanotechnology in foods has emerged at a very fast pace and has reached up to US\$125.7 billion till 2024 (Roco and Bainbridge 2001; Chen et al. 2006). It is expected that nanotechnology and nano science take hold on whole food system for tracing undesirable changes in near future. These wide range of applications of nanotechnology is due to the capability of metals to reform into nano size which impart it unique properties like high surface area to volume ratio, distinct optical behaviour, chemical and kinetic stability etc. (Benn and Westerhoff 2008; Heinlaan et al. 2008; Li et al. 2008; Wokovich et al. 2009). Nanotechnology also plays an important role in sensing of food borne

pathogens by using nanomaterial-based biosensors instead of lab testing which would take about 2 – 7 days in addition to packaging (Moraru et al. 2003).

The metal nanomaterials are synthesised by top-down and bottom-up approach. In top-down methods, large materials are broken down into small particles though high energy ball milling method etc. and in bottom-up methods, small molecules or atoms combine to form nano-sized particles though several methods like sol-gel process, precipitation, solvothermal and sonochemical methods, chemical vapour deposition and condensation methods etc. (Mendoza and Rodriguez-Lopez 2007; Raab et al. 2011; Charitidis et al. 2014; Rajput 2015). Various organic based nanomaterials have also been prepared from chitosan, cellulose, polysaccharides and starch (Beigzadeh et al. 2016; Liu et al. 2017). Nanomaterials are also classified on the basis of their dimensions i.e. zero dimensional (nanoparticles, nanoclusters, quantum dots, fullerenes), one dimensional (nanorods, nanowires, nanofilms and nanotubes), two dimensional (thin films and nanocoatings) and three dimensional (nanofibers, multilayers, nanocomposites) (Sharma et al. 2017).

Different strategies are used to find the chemical and physical properties of nanoparticles such as scanning electron microscope (SEM), transmission electron microscopy (TEM), fourier transform infrared spectroscopy (FTIR), UV-Vis spectroscopy, X-ray diffractometry (XRD), X-ray photoelectron spectroscopy (XPS) etc. (Tao et al. 2017). Improved (effective barrier), smart (controlled release) and active (antimicrobial) food packaging is also available to obtain desirable materials for food packaging (Sharma et al. 2017). The small sized food supplements in the form of nanocapsules and nanomicelle, can penetrate easily inside the body. Various supplements such as nano calcium, nano iron, nano magnesium, vitamins, minerals, omega-3 fatty acids etc. are available in the market in nano form (Noormans 2010).

Nanoparticles have lots of advantages but some drawbacks has also been observed in some researches. The research work is continued to find all the toxicological essences of these particles (Savolainen et al. 2010; Aschberger et al. 2011). These nanoparticles can enter the body of working people via inhalation and skin contact and affect their blood vessel’s linings and promote blood clot formation (Bouwmeester et al. 2009; Baltic et al. 2013; Sharma et al. 2017). It is also found from some research data that nanoparticles can enter the brain cells and affect the organs and can also interact with metabolism of foetus (Silvestre et al. 2011; Baltic et al. 2013). The toxicity level of nanoparticles depends upon various factors such as properties of nanoparticles, their route of entrance in the body, time of exposure, their concentration and also depends upon the vulnerability of the person (Maynard 2006; Aschberger et al. 2011; Silvestre et al. 2011; Baltic et al. 2013; Rim et al. 2013).

II. Existing Food Packaging Systems Versus Nano Food Packaging

The existing food packaging systems facing many challenges so, there is an urgent need to introduce advanced approaches in food packaging like nanotechnology. Amongst various materials like glass, paper, plastic and metals used in food packaging, plastics have a major share of 40% (Rhim et al. 2013). Although glass packaging is transparent, looks good to attract consumers but it is easily breakable, heavy, expensive and involve multistep manufacturing. On the other hand, metals are corrosive in nature, lack transparency and sometimes react with food and cause toxicity. Plastics including PVC, polyamide, polystyrene get easily moulded but has poor barrier properties for gas and moisture. Food packaged with paper and paperboard is cost effective but highly sensitive to moisture and temperature. Various advantages and disadvantages of existing packaging are described in Table 1. It can be concluded from the above discussion that none of the existing food packaging material possesses all desirable properties required in good food package.

The main aim of food industries is to produce food with long shelf life to meet the customer’s demand with least complaints. Nanotechnology interventions provide longer shelf life to foods by improving the properties of packaging with respect to resistance against moisture, gas and UV light exposure. The major benefits of integration of nanotechnology in food packaging are shown in Figure 1. Nanomaterials in the form of nanosensors, metal nanoparticles, nanocomposites, nanosized additives, nanoencapsulates etc. are widely used in food packaging systems due to their unique properties for keeping food safe for long time (Wesley 2014).

Table 1: Advantages and disadvantages of different packaging materials.

Type of material	Packaging	Advantages	Disadvantages
Metal	Tin	Strong, impermeable, heat stable and corrosion resistant	Food reactive, requires coating and difficult to weld
	Aluminium	Corrosion free, heat stable, moisture and gases resistant	Less Structural strength, welding free, high cost, difficult to recycle
Plastics	PVC	Chemical resistant, easily moulded and recyclable	Poor heat stability, toxic fumes are released during melting
	Polystyrene	Clear, recyclable and rigid	Less barrier capacity

Glass	Polyamide	Strong and good barrier capacity	Expensive than other plastics
	Glass	Nonreactive, transparent, reusable, moisture and gas resistant, heat stable	Heavy, easily breakable and brittle, difficult to transport
Paper and paperboard	Paper and paperboard	Low density and high strength	Light, moisture and temperature sensitive

Nanotechnology based strategies proved useful through adoption of some advanced techniques like smart packaging, which enables easy transport, tracking of storage and transport conditions and spoilage detection before expiry (Sekhon 2010). In this approach, nanomaterials are used in food packaging instead of macro materials because of many advantages. Pathogens, chemicals and toxins in the food are detected or monitored using nanotechnology based biosensors and it alerts about food spoilage and microbial action by changing the colour (Morris et al. 2011). Sensors are very useful to monitor the composition and toxicity of compounds (Nakagawa 2014).

Nanoencapsulation and nanocomposites are two widely designed terms of nanotechnology. Nanoencapsulations introduce nanoadditives, nutritional supplements, taste and color enhancer in the food packaging for better dispersion (Morris et al. 2011; Cushen et al. 2012; Duran and Marcato 2013).



Figure 1: Advantages of nanopackaging for foods.

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(Shankar and Rhim 2018) and graphene oxide (Arfat et al. 2018) are widely used inorganic nanomaterials as they form antimicrobial films over preserved foods. Silver nanoparticles are the highly used nanoparticles in foods because of their broad spectrum microbial inhibition action. These are safe to use with least toxicity (Shankar et al. 2014). Zinc oxide nanoparticles are also a material of choice in food packaging due to their low cost and less toxicity. Copper oxide and titanium oxide nanoparticles also exhibit broad antibacterial activity, so used in many food applications (Chaudhary et al. 2008; Llorens et al. 2012). Despite of all these uses and many benefits, nanotechnology is still not much accepted at wider level because of its some drawbacks as listed in Figure 2.



Figure 2: Disadvantages of nanopackaging for foods.

The composition of nanoparticles should be taken in care, as these active compounds released into the body at particular target or site depending on their nature and mechanism. Reactive oxygen species (ROS) is one of the major toxicity factor in nanoparticles because superoxide, singlet oxygen, hydroxyl radical and hydrogen peroxide damage cell organs like cell membrane and cause apoptosis of cell (Gaillet and Rouanet 2015; Wu et al. 2018). The possibility has also been seen for migration of nanoparticles (in the form of food additives) from packaging to the foodstuffs. Titanium oxide has broad spectrum antibacterial property, but it has very harmful effect when get exposed to body parts as it can induce tumor and other changes in the body (Sanders et al. 2012; Valdiglesias et al. 2013; Botelho et al. 2014). Toxicity inversely depends on the particle size of nanoparticles, as toxicity increases with decrease in the size of particles. Hence, it is very important to assess and study all these safety and health related risks associated with the use of nanoparticles in packaging system.

III. Nanotechnology in Innovative Food Packaging Systems

Main aim of food packaging is to keep the product fresh, safe and timid, to increase its shelf life, to protect food during storage and transportation and ultimately to reduce the waste generated from food. In traditional food packaging, wooden crates, cardboard boxes, glass bottles, paper bags, plastic materials etc. are used as packaging materials and all these have some advantages and disadvantages that are listed in Table 1. Hence, it can be said that no packaging material would completely satisfy the desires of the food industry by providing ideal food packaging material. However, a number of problems have been solved with the advent of nanotechnology in food packaging sector. Some of the benefits of advanced packaging systems are given in Figure 6.

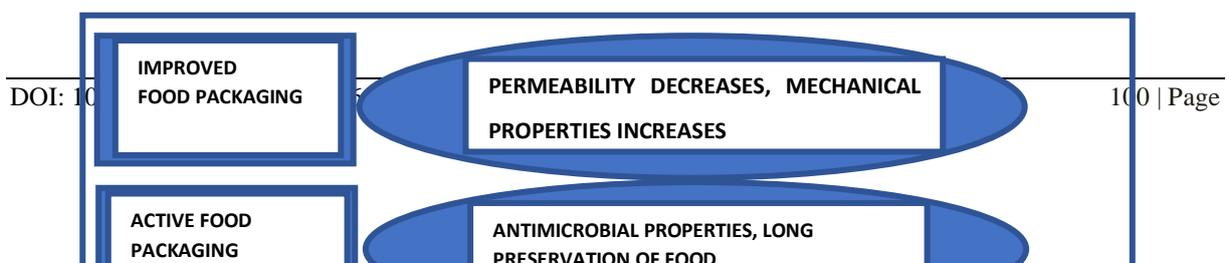


Figure 6: Types of packaging and their benefits.

3.1. Nanotechnology in active packaging: The wide production, use and misuse of antibiotics leads to the generation of multiple drug-resistant microbes which includes infectious organisms also. Nanomaterials interact with food or environment directly and protect them from bacterial contamination. Nanoparticles with antimicrobial properties play a vast role in food preservation. Among Ag₂O, CuO, ZnO, TiO₂, MgO and carbon nanotubes, silver nanoparticles are most widely used because it can destroy more than 650 pathogens in contact of just 6 minutes (Han et al. 2018). Ag₂O and TiO₂ also possess antigrowth properties against eukaryotic infectious agents in addition to prokaryotic microbes. Biopolymeric nanocarriers are used not only to kill microbes but also to preserve the food for prolonged time by incorporating preservatives, colorants, antioxidants, aromas and also suck up disagreeable odour, taste, humidity and other undesirable substances (Paseiro et al. 2011; Bahrami et al. 2019; Hosseini et al. 2019). In active food packaging, nanomaterials designing is done in such a way that it releases antimicrobials in the product matrix and in the surroundings. Packaging material forms a linkage with packaged food after releasing chemical which shows the inhibitory actions against microbes, oxidation and enhances taste, odour and shelf life of packaged food (LaCoste et al. 2005, Lopez-Rubio et al. 2006, Nachay 2007). Chemical based nanopackaging with carbon nanotubes have great specificity (Gander 2007) and prevent exchange of gases i.e. oxygen and carbon dioxide across the package. Metal based nanoparticles have a great extent of scope in future. Silver is mostly used antimicrobial material but others like nano zinc, nano chlorine, MgO, CuO and TiO₂ are also widely accepted to inhibit microbial growth (Sondi and Salopek-Sondi 2004). Very low level of silver and zinc is used as it shows small level of toxicity but are highly active due to large area to volume ratio. Biopolymers also attract great interest towards antimicrobial activity (Chandramouleeswaran et al. 2007).

To get effective antimicrobial properties, metallic ions are also incorporated into nanofillers to form nanocomposites. Silver ions embedded into inorganic complexes such as zeolites, glass and zirconium phosphate provide productive antimicrobial properties. The mechanism of nanoparticles showing antimicrobial activity has been already discussed in section . The silver and gold nanoparticles are used with zeolites to make effective antimicrobial active food packaging by slowly releasing Ag ions which kill microbes (Aryou 2011; Dallas et al. 2011; Duncan 2011; Ravishankar Rai and Jamuna Bai 2011; Silvestre et al. 2011; Lopez-Carballo et al. 2013). TiO₂ and ZnO nanoparticles are also used in packaging as these produce oxygen scavengers films which prevent food from oxidative reactions that results in undesirable smell, colour and taste, also decreased nutritional value (Xiao et al.2004; Li et al. 2011; Silvestre et al. 2011).

Nanoencapsulation also made the properties of metals or metal oxides more effective, specifically of fluid items. Nisin-loaded chitosan show most effective antibacterial properties against *Pseudomonas aeruginosa*, *Enterobacter aerogenes*, *Salmonella enterica* and *Micrococcus luteus* etc. Nanoencapsulated benzoic acid when composed with PLGA particles, used in raw and cooked chicken because it inhibits the actions of various Gram positive and Gram negative bacteria such as *Salmonella typhimurium*, *Listeria monocytogenes* and *Escherichia coli* . In a study, it is found that nanomatrix encapsulated essential oils are used to preserve the fruit juices, without affecting its quality. Lysozyme-coated with polystyrene nanoparticles alongwith specific antibodies show effective bactericidal action for the *Listeria monocytogenes*, which is commonly found pathogen in food (Yang et al. 2007).

3.2. Nanotechnology in smart and intelligent packaging: Advanced food packaging systems through various mechanisms inform us about the current status and quality of the food (Ranjan et al. 2014). Packaging materials embedded with nanosensors are also known as smart or intelligent packaging systems and these systems provide

information about physical, biological and chemical changes in food (Cheng et al. 2008; Dingman 2008; Lerner et al. 2011; Yang et al. 2011). Nanosensors are used to monitor spoilage, foul odour, taste as a result of temperature change, aqueous action and expired product packaging. Many companies achieved those technologies which can trace pathogen activity and environmental factors (Roberts 2007). These packages detect the specific microbes and gases developing during food spoiling by using nanomaterials as sensors and can also be used as tracing device (Pehanich 2006). Nanosensors equipped packaging materials are also used to detect the condition of food (spoiled or safe), humidity and moisture content by color change (Ei Amin 2006; Gander 2007). Sensor packaging is best to reduce the health problems occurred due to ingestion of spoiled food and also to prevent wastage of food.

Nanoparticles possess distinctive chemical and optical properties, which make them suitable for making nanosensors. Interaction with target molecule changes the physical and chemical properties of these nanoparticles such as conductivity, redox potentiality and surface plasmon resonance. These sensors can detect O₂, CO₂, moisture, ethylene, acetone, ethanol, gaseous amines, pathogens and toxins in food and also respond to changes like temperature, moisture and oxygen. TiO₂ and SnO₂ has been used as oxygen sensors in the presence of methylene blue and these nanoparticles behave like an indicator which changes its color when O₂ is less (Lee et al. 2005; Mills 2005; Mills and Hazafy 2008, 2009). There are time-temperature indicators, which change colour due to unsatisfactory temperature (Paseiro et al. 2011). Carbon coated copper nanoparticles are used to detect the humidity, polymer get swell up in the presence of moisture and nanoparticles get separated due to which sensors absorb distinct colors of light (Luechinger et al. 2007). SnO₂ nanoparticles and TiO₂ microrods are used to detect gaseous amine which generated due to spoilage of fish and meat, whereas, perylene-based fluorophores are used to detect even small level spoilage (Che and Zang 2009). Carbon nanotubes show effective performance in order to detect gases such as ammonia and various other gases (Abdellah et al. 2013; Su et al. 2013). Vapour organics like acetone, carbon monoxide and ethanol is detected by using nanocomposites like ZnO and SnO₂ (Comini et al. 2005; Barreca et al. 2007).

3.3. Nanotechnology for improvement in barrier properties: Barrier properties of nanocomposites are affected by many factors such as concentration, morphology and type of nanomaterials, characteristics of polymer matrix used, angle of orientation, interaction between nanomaterials and polymer used, addition of any other external agent (Souza et al. 2019). Nanoparticles are incorporated into the polymers to form nanoclay-polymer composites like bentonite has improved excellent barrier properties for gases and is cost effective (Lange and Wyser 2003; Avella et al. 2005; Smolander et al. 2010; Duncan 2011). The most important factor which provide the barrier improvement is orientation of nanoplates in polymer, so layer by layer deposition of organic and inorganic materials has been done such as anionic sodium montmorillonite clay layered with cationic polymer provide effective barrier properties (Gusev and Iusti 2001). The addition of ZnO nanoparticles into the nanocomposite of chitosan matrix results in increase of barrier properties to the moisture (Vaezi et al. 2019). The incorporation of nanoparticles also improve the other mechanical properties of packaging material such as temperature or moisture stability, longevity and pliability etc. (Hirvikorpi et al. 2010, 2011; Wu et al. 2018). Nanoclays are also used to improve the mechanical properties of wide range of polymers such as polyamide, polystyrene, polyurethane, polyimides etc. (Petersson and Oksman 2006; Hirvikorpi et al. 2010; Loryuenyong et al. 2015).

The cellulose nanocrystals are used as boosting agent and the elastic strength of polymethyl methacrylate (PMMA) electrospun was increased by 100% (Ni et al. 2019). In a study, it was observed that addition of silver coated graphene nanoplates (0.6%) into the nanocomposite matrix has been resulted in increase in its firmness (12.5%) and decrease in wear-rate (81.9%), but when the concentration of silver coated graphene nanoplates into the nanocomposite matrix has been increased above 0.6%, then, it leads to agglomeration which decreases its mechanical properties (Abu-Oqail et al. 2019). The mechanical properties of TiO₂ can be increased upto 40% by enhancing the pass numbers of friction stir processing. Carbon nanotubes when added into polymer matrix, form a nanocomposite which increase elasticity, hardness, stiffness, electrical conductivity, heat stability and chemical resistance (Shahbazi et al. 2017). Aluminium nanoparticles also provide protection from UV radiation in addition to moisture, volatiles and other gases (Camean et al. 2010).

3.4. Nanotechnology in biodegradable packaging

Various biodegradable materials are now replacing existing packaging systems to reduce a large amount of waste in environment (LeGood and Clarke 2008). Biodegradable nanomaterials like bioplastic also protects food from microbial action, humidity and other atmospheric gases so maintain the nutritious and sensory quality (Siracusa et al. 2008). The barrier properties of bioplastic materials against heat, moisture etc. can be improved while mixing with nanoclay. Other nanomaterials like nanowhiskers and nanofibers can be used with bioplastics (Sorrentino et al. 2007). Biopolymers possess nanoporous view and almost stabilises the

flammability (Robinson et al. 2010). The main advantage of this packaging is that it is completely environment friendly leaving no toxic residue. These biodegradable nanomaterials are of different types based on their formation such as polysaccharide, proteins obtained directly from biomass, biopolyester and polylactic acid synthesised by chemical method and some are produced by microbes or genetically modified bacteria like xanthan, pullulan, bacterial cellulose etc. (Sorrentino et al. 2007).

IV. Safety Aspects of Nanopackaging

Nanotechnology has developed various functionalities towards food safety and wastage reduction (Wesley et al. 2014). Physical, biological and chemical contaminations are the major concern of food industries at the time of their manufacturing and packaging. Hence, nanotechnology come with the machines with antimicrobial surfaces used in food processing industries (Nakagawa 2014). Several lethal effects can be accumulated in the body due to contact of humans with nanomaterials and food products with minimum toxicity. After many reports and tests about health aspects, nanopackaged food is approved for public use but there is no international SOPs for determination of toxicity level of nanoparticles in food products (Wesley et al. 2014). Nanoparticles inhaled by humans, get accumulated in various organs and affect hazardously after reacting with biomolecules in body. Toxicity happens either by direct chemical toxic nanoparticle inhalation or due to formation of ROS (Han et al. 2011). The cardio-toxicity in Wistar rats has been observed when rats were fed on mesoporous silica in different concentrations due to production of ROS (Hozayen et al. 2019). Toxicity level directly depends on the amount of food taken by the body, more the food taken, more the exposure to nanomaterial and hence more will be the toxicity (Jovanovi 2015). Nanoparticles of TiO₂ prove toxic to liver of human body in higher amounts and cause tissue damage (Laomettachtit et al. 2017).

Bio-based edible nanomaterial coatings are more preferred over chemical based nanomaterials due to toxicity issues (Fakhouri et al. 2014). Sometimes, a little bit amount of nanomaterials (magnesium oxide and Nanoclay) migrate into food products even get dissolved directly. It is one of the major reason of accumulating nanomaterial into body organs (Pathakoti et al. 2013; Huang et al. 2015). In view of many reported cases of nanomaterials toxicity, it becomes necessary to pass all safety tests of nanomaterials used in food both for processing and packaging before released into market (Sekhon 2010).

V. Conclusions and future prospects

Nanotechnology provide many other benefits in food sector like rapid analysis, taste, odour and quality enhancer, and it also helps in target delivery in living system. Nanotechnology provide good mechanical and physical strength to food packages in addition to its other properties like antimicrobial and antioxidant etc. The improvements in the thermal, mechanical and barrier properties (from moisture, gases and other contaminants) of food packaging materials can also be achieved with the use of nanomaterials in existing materials. Hence, nanoparticles has been used effectively for food packaging in recent years to overcome various drawbacks of existing packaging materials. Nano based food packages provide successful storage and transportation of safe and healthy food to consumers. The use of various nanoparticles like silver, copper, zinc etc. in food packages prevents food spoilage and helps to extend the shelf life of food for longer time due to their excellent antimicrobial properties. These metal nanoparticles further gave better results when used in combination with polymers by forming nanocomposites. These nanocomposites also provide many efficient types of food packaging such as improved packaging, active packaging and smart packaging. Hence, these applications of nanoparticles provide safe and healthy food to consumers and protect the consumer from the diseases caused due to spoiled food. Research work is still carried out to find the exact toxicity effects and health issues associated with the use of nanoparticles. However, for widespread use of this technology, more scientific research and development is required so that a particular procedure will be developed to identify toxicity level of nanoparticles. Overall, nanotechnology represents a transformative tool in addressing food waste, supporting global food security, and promoting sustainable development.

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