Environmental Chemistry Letters (2019) 17:277–290
https://doi.org/10.1007/s10311-018-0794-8

REVIEW

# Smart nanopackaging for the enhancement of food shelf life

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Received: 27 April 2018 / Accepted: 17 August 2018 / Published online: 5 September 2018


**Abstract**
Food spoilage is a major global concern due to the lack of proper packaging technology. Nanotechnology is expected to improve food packaging. Indeed, novel nano-based food packaging materials possess unique characteristics including antimicrobial potential, oxygen scavengers, and barriers to the gas or moisture, etc. The application of such nanomaterials in food packaging increases the shelf life of food without causing any undesirable alteration in its quality. The use of nanomaterials in food packaging is still in embryonic stage, and hence, the present review focuses on recent advances and overview of the current status in the field. Attempts have also been made to address issues related to toxicity and safety, public perceptions about nanomaterials and key areas of research in the field. The knowledge of pros and cons of this technology will therefore define their applicability as a sustainable food packaging material.

**Keywords** Nanopackaging · Nanomaterials · Active packaging · Toxicity · Public perceptions · Safety issues

## Introduction

From the last few years, the demand for "ready to use", "ready to cook" and "ready to eat" food has been increased tremendously, which has encouraged manufacturers to provide packaging of minimally processed food. The preference of the customers towards the processed food and food products has been rising. Therefore, to meet this increasing demand, the recent food packaging techniques have emerged. The development of novel food packaging material enhances the shelf life of food (Dobrucka and Cierpiszewski 2014; Carbone et al. 2016; Majid et al. 2016; Valdes et al. 2017; Shi et al. 2018).

Electrically driven packaging machinery, flexible packaging, aseptic packaging, metallic cans, aluminium foils and flexographic printing are some of the new techniques employed for food packaging. Various materials including polyester, polypropylene and ethylene vinyl alcohol are being used in the packaging purpose. It is assumed that emerging changes in food packaging materials will strengthen economy of the food industry, thereby improving food quality and safety by minimizing the loss of food products (Vanderroosta et al. 2014).

One of the most important reasons for evolution of food packaging is the outbreak of food-borne microorganisms (Pal and Mahendra 2015; Pal 2017). A major concern in food processing and food industries is the protection against food-borne pathogens and the food-borne diseases associated with them. According to the statistics of the Centre for Disease Control and Prevention (CDC), it is estimated that every year, 76 million people are sick, 325,000 are hospitalized, and 5000 people die because of food-borne diseases in the USA (Morris 2011; Carbone et al. 2015). Due to outbreak of food-borne diseases, antimicrobial packaging materials are being used, which can retain the quality of food (Appendini and Hotchtkiss 2002).

Food packaging can enhance the durability of food by providing suitable environment such as separating light, moisture and oxygen. The packaging materials not only contribute to the physical protection but also enable adequate physicochemical conditions required for extending the shelf life of food (Wesley et al. 2014; Pal 2017). The

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packaging materials should possess thermal, mechanical and optical properties. Antimicrobial property of food packaging material and barrier functions against aroma and gases play an important role at the time of nanopackaging (Rhim et al. 2013). For such applications, nanotechnology has been emerging as a boon. Nanotechnology-derived food packaging materials have the largest application in food sector (Echegoyen 2015). It is interesting to note that the use of nanomaterials has largely increased in the last decade. Nanotechnology-based food packaging has been divided into two types, i.e. improved packaging and active packaging. Improved packaging comprises the addition of nanomaterials into polymer matrix to enhance the gas barrier properties such as polymer and clay nanocomposites, whereas active packaging nanomaterials can directly interact with food or environment, which enable the proper protection of the food (Duncan 2011; Carbone et al. 2015; Pal and Mahendra 2015; Pal 2017).

In the present review, we have focused on the novel nanopackaging materials such as active, intelligent and bioactive packaging material, which enhances the shelf life of food. Moreover, the global status of nanopackaging materials has been discussed, which has greatly increased in the last two decades, because of enormous applications of nanomaterials in the packaging of minimally processed food. In addition, understanding the toxicity of nanomaterial is a prime concern. Therefore, the safety and regulatory issues concerning the application of nanomaterials in food packaging have been discussed herein.

## Diversity in nanopackaging materials

Various types of packaging materials used in food sectors include active packaging, intelligent packaging, edible coating and biodegradable polymeric film.

### Active packaging materials

Active packaging can be defined as the packaging, which provides inert barrier between food product and external environment. The packaging materials react with food product for increasing its durability (Grumezescu 2016). The nano-based active packaging involves the incorporation of nanomaterials in the packaging system, which can enhance and maintain the quality of food. Some nanomaterials are used as additive and can be incorporated directly into packaging material or introduced into separate sachets or embedded into food contact material (Restuccia et al. 2010; Echegoyen 2015; Momin and Joshi 2015; Pal 2017). Generally, nanomaterials or active substances used in packaging improve the internal environment of food by absorbing ethylene, oxygen, carbon dioxide, moisture, flavour and other gaseous compounds and thereby promote food preservation (Brody 2001; Wesley et al. 2014; Momin and Joshi 2015). Active substances are the materials, which extend shelf life of food and improve the condition of packed food. Active materials used in packaging generally absorb substances from the packed food and its surrounding (Wyser et al. 2016). The components of active packaging of food mainly include (1) nanocomposites (metal nanoparticles such as silver, copper and oxides such as titanium dioxide and magnesium oxide) (2) antimicrobial film and (3) gas scavengers (Lee et al. 2015). Hu and Fu (2003) reported that silver nanoparticles not only absorb ethylene but also decompose it, which increases the shelf life of fruits and vegetables. Oxygen is directly or indirectly responsible for the degradation of food. Oxygen scavengers-incorporated active packaging materials can be used to prevent oxidation reaction, which sustains adequate environment, thereby maintaining the quality and enhancing shelf life of food (Echegoyen 2015). An et al. (2008) reported that silver nanoparticles-containing coating can be used to decrease the microbial load and enhance the shelf life of asparagus. Nanosilica can also be used for surface coating in food packaging (Kasaai 2015). In addition, nanosilver, nanozinc oxide, nanotitanium dioxide, etc., are commercially important nanomaterials, which are used in food packaging (Echegoyen 2015).

Incorporation of oxygen scavengers in film helps in the absorption of oxygen. Nanocrystalline titanium dioxide nanoparticles can be used in packaging and processing of food due to its oxygen scavenging activity (Kuswandi 2017). Further, chitosan nanoparticles, carbon nanotubes, magnesium oxide nanoparticles, copper and copper oxide nanoparticles are used as active ingredients in nanopackaging because of their potential antimicrobial activity. Zinc oxide, quantum dots incorporated with polystyrene film or suspended in polyvinylpyrrolidone can be used as antimicrobial packaging against food spoilage microorganisms such as *Listeria monocytogenes*, *Salmonella enteritidis* and *Escherichia coli* 0157:H7 (Chaudhry et al. 2008; Jin et al. 2009; Momin and Joshi 2015).

Al-Naamani et al. (2018) studied the effect of low-density polyethylene (LDPE) packaging film coated with chitosan–zinc oxide nanocomposite on the shelf-life and quality of *Abelmoschus esculentus.* The study revealed that LDPE film helps in the preservation of okra samples by maintaining moisture content and prevents bacterial and fungal growth on the stored okra sample. It was found that nanocomposite film can inhibit the bacterial and fungal growth on okra samples for 12 days. LDPE coating with chitosan–zinc oxide nanocomposite is a promising technique, which can be used as active food packaging material. Cherpinski et al. (2018) developed oxygen scavenging film made of poly(3-hydroxybutyrate) (PHB)-containing palladium nanoparticles. The film was prepared by electrospun technique followed by annealing treatment at 160 °C. It was found that the composed film exhibited oxygen scavenging activity, and hence, it can be used as novel active packaging material for the preservation of food.

## Smart packaging material

Smart packaging materials are the substances or materials, which monitor the condition of packed food or environment surrounding the food. Smart packaging can also be defined as inexpensive labels attached to primary packaging such as pouches, trays and bottle or to the shipping container, which can help to communicate throughout the supply chain (Yam 2009). Intelligent packaging is a sort of labelling, which can give information about the physicochemical properties of food or its interior packaging environment such as temperature, pH, and chemical contaminants. Oxygen scavengers can be used in the intelligent packaging as it prevents the microbial growth, removes off flavours and off odours, prevents colour change, etc. Nanomaterials can be used for this purpose leading to the maintenance of food quality (Echegoyen 2015; Ramachandraiah et al. 2015). Martins et al. (2012) proposed that engineered platinum nanoparticles can be used to measure the changes in pH of food packaging material. The most promising use of smart packaging is the detection of oxygen and moisture content in food. Luechinger et al. (2007) reported that copper nanoparticles carbon-coated tensile film can be used as a sensor to determine moisture content. Composite film incorporated with iron oxide nanoparticles acts as humidity sensor and measure humidity (Taccola et al. 2013). It was demonstrated that titanium dioxide and silicon-di-oxide (silica) nanoparticles in combination with reactive dye (methylene blue) help in the detection of oxygen and hence are used in packaging of food (Pradhan et al. 2015). Zinc oxide nanoparticles and titanium dioxide nanoparticles are used to detect organic volatile compounds such as ethanol, gaseous amine with the help of nanofibres of perylene-based fluorophores. These volatile compounds are indicator of meat and fish spoilage. Tin oxide nanoparticles and titanium dioxide nanorods are also used to detect the release of volatile organic compounds. Tungsten oxide and titanium dioxide nanocomposite also help in the detection of ethylene gas responsible for fruits ripening (Pimtong-Ngam et al. 2007).

Application of nanoparticles-based sensor detects contaminant present in food; for instance, change in colour was observed when nanoparticles come in contact with analyte (Echegoyen 2015). Ai et al. (2009) reported that gold nanoparticles functionalized with cyanuric acid bind with melamine, which changes the colour and detect adulterants present in food.

## Edible coating

Edible coating or films can be defined as a thin layer of edible material present on the surface of food, which acts as a barrier to mass transfer. These edible coatings can provide a barrier to oxygen, moisture, gas, etc. They are prepared from edible ingredients, which can be easily eaten, and prevent pollution. Coatings can be applied on the food by two ways—either liquid solution is directly applied or molten compounds can be coated (Guilbert et al. 1997; Bourtoom 2008; Valdes et al. 2017). Nanoparticles-incorporated edible films improve physicochemical characteristics such as strength, mechanical properties and flexibility. It enhances texture, colour and flavour of food.

Nanolaminates consisted of one or more than one layer of materials, whose dimension ranges in nanometre. Layer-by-layer deposition technique is the most powerful technique in which charged surfaces are coated on the food. An advantage of layer-by-layer deposition technique is that thickness of film is very low and it is supposed to be most suitable for the coating of food products. Nanolaminate is barrier to the gas or moisture which can also be used as a carrier for antioxidants and antimicrobials (Momin and Joshi 2015). The barrier properties of film depend on the characteristics of nanomaterial used in the layers. Nano-edible coatings are prepared from lipids, proteins and polysaccharides. Lipid-based nanolaminates are poor in absorbing moisture, but it can block gases and lack adequate mechanical properties. Polysaccharide- and protein-based nanolaminate protects the food from gases and not from moisture. All the desired properties cannot be achieved by using proteins and polysaccharides as coating material (Kotov 2003; Weiss et al. 2006; Momin and Joshi 2015). There are two approaches of using nanolaminate in coating of food—dipping and spraying. Various types of adsorbing materials such as proteins, lipids and surfactants can be applied to the single layer of nanolaminated film. Colloidal suspension of nanoparticles, functional agents such as antimicrobials, antioxidants, enzymes, flavours can also be sprayed on nanolaminate film and hence can be used to enhance the shelf life of food by simple spraying or dipping method (GuhanNath et al. 2014; Ramachandraiah et al. 2015). Carbon nanotubes have been used as nanofiller in the formulation of gelatin film. The film can enhance mechanical properties by strengthening tensile strength (Ortiz-Zarama et al. 2014).

## Biodegradable packaging material

Biodegradable packaging material is gaining attention due to its eco-friendly nature. Biodegradable polymers can be easily decomposed by bacteria and other microorganisms. Biodegradable films are produced from biopolymers such as proteins, polysaccharides, lipids and their combination.

Biodegradable materials are abundant in nature, possess excellent film-forming capacity and also act as gas barrier (Cabedo et al. 2006). Nanocomposites film produced from biopolymers is known as bionanocomposites. It is combination of polymer matrix with the filling of organic and inorganic material, whose one of the dimension is less than 100 nm. Polysaccharides like starch, chitosan and galactomannans are used in edible food packaging due to their low cost and abundant supply. Guar gum can also be used in food packaging purposes owing to its high molecular weight and easy availability. Nanoparticles embedded polymeric matrix can enhance the tensile strength and desired properties of the matrix.

Biodegradable polymers can be extracted from agricultural resources polysaccharides, proteins and lipids. Biopolymers can be recovered by microbial fermentation also, e.g. pullulan and chemically synthesized as poly lactic acid (Garavand et al. 2017). On the basis of application in food packaging, there are three kinds of polymers: starch based, cellulose based and protein based (Kour et al. 2015).

In traditional approach, the food packaging is formulated in such a way that it does not interact with the food, but in a new concept the packaging interacts with food in order to obtain desirable effects as antimicrobial, providing flavour or scavenging chemicals (Cha and Chinnan 2004). Other recent approach to improving the functionality of the biopolymers in packaging is improvement of their properties by combination with additives such as plant extracts with phenolic compounds or antimicrobials to extend the shelf-life of food (Zafar et al. 2016). Van Long et al. (2016) reviewed different aspects to use antifungal compounds incorporated in packaging and emphasized the importance of pH, temperature, sodium chloride concentration and the release of antifungal compounds in efficiency of active packaging.

## Nanoantimicrobials for extending shelf life of food

The food contaminated with microorganisms leads to its deterioration and reduces shelf life. Incorporation of antimicrobial agents into food packaging materials can inhibit the microbes and extend the shelf life of the product (Ding et al. 2013; Sirelkhatim et al. 2015). Various metal and metal oxide nanoparticles are known for their antimicrobial activity and can be used in food packaging (He and Hwang 2016).

Emamifar et al. (2010) proposed the formulation of low-density polyethylene (LDPE) polymer matrix incorporated with silver nanoparticles and zinc oxide nanoparticles and evaluated antimicrobial activity of nanocomposite film against food spoilage microorganisms. The effect of nanocomposite film incorporated with nanoparticles was evaluated for the preservation of orange juice. It was found that LDPE film extends the shelf life of orange juice, and hence, it can be used in the preservation of fruit juice. Motlagh et al. (2012) and Yang et al. (2010) studied the effect of silver nanoparticles–LDPE packaging material for the preservation of barberries and strawberries. It was demonstrated that LDPE–silver nanoparticles film improved the sensory and physiological qualities of barberries and strawberries as compared to the fruits packed in normal polyethylene bags. Mahdi et al. (2012) evaluated effect of silver nanoparticles–polyvinyl chloride nanopackaging on minced beef stored at 4 °C. After 7 days, it was found that silver nanoparticles-incorporated packaging material shows inhibitory effect. The bacterial load was very less in the meat which was coated with nanopackaging material as compared to packed with common food packaging. Metak (2015) formulated polyethylene film containing silver nanoparticles and titanium dioxide nanoparticles and investigated the effect of film on fresh apple and slice of bread, carrots, fresh orange juice, etc. It was found that the film inhibited food spoilage microorganisms such as *Staphylococcus aureus*, *E. coli*, *L. monocytogenes* and coliforms. Martinez-Abad et al. (2012) prepared nanocomposite film of ethylene alcohol incorporated with silver nanoparticles and evaluated antimicrobial activity of food in contact with fresh-cut fruits, fresh juice and vegetables. Authors found that film inhibited the activity of food spoilage microorganisms, thereby enhancing the shelf life of the food products.

Toker et al. (2013) synthesized silver nanoparticles-incorporated polyurethane film and demonstrated its antibacterial activity against *E. coli* and *S. aureus.* Youssef and Abdel-Aziz (2013) developed silver nanoparticles–polystyrene matrix and characterized it by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Antimicrobial activity of the matrix was evaluated against pathogenic microorganisms such as *Bacillus subtilis*, *Enterococcus faecalis*, *E. coli* and *Salmonella typhimurium*. The matrix was found to decrease the microbial load; as a consequence, the shelf life of food was prolonged. Cellulose adsorbent pads impregnated with silver nanoparticles were assessed against *Salmonella* sp., *E. coli*, *S. aureus* and *L. monocytogenes*. It was found that these pads reduced the microbial count in beef and cut melon (Fernandez et al. 2010a, b). Khalaf et al. (2013) reported the formulation of pullulan film incorporated with nanoparticles (silver nanoparticles, zinc oxide nanoparticles) and essential oils (oregano and rosemary oil). The authors assessed antimicrobial activity of silver nanoparticles–pullulan film incorporated with both essential oils and zinc oxide nanoparticles–pullulan film integrated with two essential oils. It was found that silver nanoparticles- and oregano oil-based film was more active than zinc oxide nanoparticles- and rosemary oil-based pullulan film. Similarly, Morsy et al. (2014) evaluated activity of silver nanoparticles-incorporated pullulan film against *S. aureus* and *L. monocytogenes* on meat. Fayaz et al. (2009) synthesized sodium alginate film containing silver nanoparticles and studied the effect of film on fruits and vegetables. Titanium dioxide nanoparticles are Food and Drug Administration (FDA) approved, which can be used in food and food contact material for extending its shelf life. Titanium dioxide is known for its antimicrobial activity against *E. coli*, *Pseudomonas aeruginosa*, *Salmonella choleraesuis*, *Vibrio parahaemolyticus* and *L. monocytogenes,* which are responsible for the spoilage of food. It was reported that titanium dioxide-coated film reduced the microbial growth on the surface of solid food products (Chawengkijwanich and Hayata 2008).

Arfat et al. (2017a) developed gelatin-based nanocomposite films with bimetallic silver–copper nanoparticles and used as nanofiller. The formulated gelatin matrix was characterized for mechanical, thermal and structural properties and tested for antimicrobial activity against *L. monocytogenes* and *Salmonella enterica*. The film exhibited superior antimicrobial activity against *S. enterica* as compared to *L. monocytogenes*. Duncan (2011) reported that silver containing zeolite can be used in food contact material, which was approved by FDA. Zinc oxide nanoparticles, titanium oxide nanoparticles and silver nitrate were used as FDA-approved products, which can be used for food packaging purpose (Bumbudsanpharoke et al. 2015, He and Hwang 2016). Guar gum film containing silver–copper nanoparticles bimetallic nanoparticles was developed and characterized for their mechanical, thermal and structural properties. Guar gum/silver–copper nanoparticles film was evaluated for their antibacterial activity against *L. monocytogenes* and *S. typhimurium*. Nanocomposite film can be used in active food packaging (Arfat et al. 2017b). Arfat et al. (2017c) formulated agar film containing silver–copper nanoparticles and evaluated against *L. monocytogenes* and *S. typhimurium.* The authors suggested that agar–silver–copper nanocomposite film can be used in active food packaging to ensure food safety and also to prolong its shelf life. Further agar film can be used for wrapping of lipid sensitive food to prevent its oxidation, thereby inhibiting its spoilage. Use of the aforementioned nanoparticles in extending the shelf life of food is described in Tables 1 and 2.

Gudadhe et al. (2014) prepared agar–silver nanoparticles film and coated on the surface of *Citrus aurantifolium*. The antibacterial activity of film was also evaluated against *E. coli* and *S. aureus*. It was found that agar–silver nanoparticles film demonstrated antibacterial activity; as a result, the shelf life of fruits was enhanced up to 9 days. de Moura et al. (2012) reported the formulation of cellulose-based film containing silver nanoparticles and evaluated antibacterial activity of silver nanoparticles–cellulose film against *E. coli* and *S. aureus*. The authors reported that silver nanoparticles–cellulose film showed more activity against *S. aureus* as compared to *E. coli*. They suggested that the cellulose agar film can be utilized in active food packaging. Metallic oxide nanoparticles have attracted the attention in food packaging, due to its potential antimicrobial activity against food spoilage microorganisms. Tankhiwale and Bajpai (2012) found that zinc oxide nanoparticles-impregnated starch polyethylene film showed antibacterial activity against *E. coli*, and therefore, it can be used for prolonging shelf life of food. Several studies have reported that the combination of silver nanoparticles with either titanium dioxide nanoparticles or zinc oxide nanoparticles can enhance antimicrobial efficacy against food spoilage microbes. From the previous study, it was demonstrated that polymeric nanocomposite film embedded with nanoparticles can be used in minimizing the growth of microorganisms and extend the shelf life of food. Nanocomposite film can be used in wrapping of meat,

**Table 1** Nanoantimicrobial agents in the preservation of food

| Polymer matrix | Nanoparticles | Tested food | References |
|---|---|---|---|
| Low-density polyethylene | Silver nanoparticles | Barberry | Motlagh et al. (2012) |
| Low-density polyethylene | Silver nanoparticles and titanium dioxide nanoparticles | Strawberry | Yang et al. (2010) |
| Low-density polyethylene | Silver nanoparticles and zinc oxide nanoparticle | Orange juice | Emamifar et al. (2010) |
| Polyvinyl chloride | Silver nanoparticles | Minced beef | Mahdi et al. (2012) |
| Ethyl alcohol | Silver nanoparticles | Cheese, lettuce, apples, peels | Martinez-Abad et al. (2012) |
| Polyethylene | Silver nanoparticles and titanium dioxide nanoparticles | Fresh apples, bread, carrot juice, orange juice | Metak and Ajaal (2013) |
| Cellulose | Silver nanoparticles | Beef meat | Fernandez et al. (2010a) |
| Cellulose | Silver nanoparticles | Fresh cut melon | Fernandez et al. (2010b) |
| Pullulan | Silver nanoparticles | Meat | de Moura et al. (2012) |
| Pullulan | Zinc oxide nanoparticle | Meat | de Moura et al. (2012) |
| Pullulan + essential oil | Silver nanoparticles | Meat | Khalaf et al. (2013) |
| Pullulan + essential oil | Zinc oxide nanoparticle | Meat | Khalaf et al. (2013) |

**Table 2** Nanoantimicrobial against food spoilage microorganisms

| Polymer matrix | Nanoparticles | Test microorganisms | References |
|---|---|---|---|
| Agar | Silver nanoparticles<br>Copper nanoparticles | *Listeria monocytogenes*<br>*Salmonella typhimurium* | Arfat et al. (2017c) |
| Polylactic acid/polyethylene glycol | Zinc oxide nanoparticle<br>Silver nanoparticles<br>Copper nanoparticles | *Listeria monocytogenes*<br>*Salmonella typhimurium* | Ahmed et al. (2017) |
| Low-density polyethylene | Zinc oxide nanoparticle | *Bacillus subtilis*<br>*Enterobacter aerogenes* | Esmailzadeh et al. (2016) |
| Poly(butylene adipate co-terephthalate | Silica nanoparticles | *Escherichia coli*; *Staphylococcus aureus* | Venkatesan and Rajeswari (2016) |
| Starch/polyvinyl alcohol | Silver nanoparticles | *Listeria innocua*; *Escherichia coli*<br>*Aspergillus niger Penicillium expansum* | Cano et al. (2016) |
| Gaur gum | Silver–copper nanoparticles | *Listeria monocytogenes*<br>*Salmonella typhimurium* | Arfat et al. (2017b) |
| Fish skin gelatin | Silver–copper nanoparticles | *Listeria monocytogenes*<br>*Salmonella typhimurium* | Arfat et al. (2017a) |
| Polyethylene | Silver nanoparticles<br>Titanium dioxide nanoparticles | *Aspergillus flavus* | Li et al. (2017) |
| Poly(3-hydroxybutyrate-co-3mol%-3-hydroxyvalerate) | Silver nanoparticles | *Salmonella enterica*<br>*Listeria monocytogenes* | Castro-Mayorga et al. (2017) |

fish, poultry, cheese, fruits and vegetables (Kanmani and Rhim 2014).

## Global market of nanomaterials for packaging

From the rapid increase in the global population, it is predicted that overall population of the world will exceed 9.3 billion by 2050 and by 2100 it will be up to 10.1 billion. The tremendous increase in population also increases demand for food (Jafari 2017). The supply of food with monitoring food safety and quality as per international standards is a great challenge. In this context, smart food packaging plays an important role to increase the shelf life of food and food products. The applications of nanotechnology in the food industry are mainly focused on food packaging, which has the potential to transform the packaging materials in future (Pradhan et al. 2015). The basic aim of nanopackaging is to minimize the use of preservatives and antibiotics. Moreover, nanopackaging materials will also help to reduce the environmental pollution. Nanomaterial-based approaches can bring amazing improvement to food packaging in the form of development of nanobiosensors for the detection of pathogens, smart and active packaging, etc. (Fuertes et al. 2016). Use of nanomaterials in packaging has ability to respond to environmental conditions or repair itself or alert consumer about microbial contamination in food (Sekhon 2010). Apart from these, nanotechnology offers development of packaging materials with several benefits such as antimicrobial and barrier properties, strength, stability to heat and cold. Hence, nanopackaging is being considered as an ideal strategy for perishable food products such as fresh vegetables, fruits, fish and meat. It helps in improving the shelf life of these food items.

Many organizations performed research studies on global investments in nanopackaging market; some of these studies are discussed here. According to a report of the market study by Helmut Kaiser Consultancy in 2005, nanotechnology has been significantly increasing its impact on food and beverages packaging industry during 2002–2005. The sales of the nano-based packaging products have tremendously increased from \$150 million in 2002 to \$860 million in 2004 worldwide (Kaiser 2005). Moreover, as per the research study of Innovative Research and Products Inc., the total market value of nano-based packaging for food and beverage was about US\$ 4.13 billion in 2008, which has later grown up to US\$ 4.21 billion in 2009. Further, it attained revenues worth US\$ 6.5 billion in 2013 and increased to US\$ 7.3 billion in 2014 at a CAGR (compound annual growth rate) of 11.65%. Moreover, it was estimated that the nano-enabled packaging market will reach a value worth US\$ 15.0 billion by 2020 and about US\$ 31.2 billion by the end of 2023 (iRAP 2009).

Among the various kinds of packaging, oxygen scavenger, moisture absorbers and barrier packaging contribute more than 80% of the current market. Similarly, intelligent or smart packaging time or temperature indicators along with radio frequency identification data tags (RFIDs) also contribute a major share and it is forecasted that such packaging will have the strongest growth in future (Sari 2010;

Fuertes et al. 2016). Moreover, food products, bakery items, meat products, beverages, carbonated drinks and bottled water have attracted the most nanopackaging applications. Various nano-based food packaging materials available in the market are shown in Fig. 1. In Asia/Pacific regions, Japan is the market leader in active nano-based packaging, with contribution about 45% of the total current market. They invested approximately US$ 1.86 billion in 2008 and grown to US$ 3.43 billion in 2014, at a CAGR of about 13%. In addition to Japan, the USA and Australia successfully applied nanopackaging materials for enhanced shelf life and also to maintain nutritional quality of food (iRAP 2009; Credence Research Inc. 2016). However, in Europe, only a few of these systems have been developed and are being applied now. The main reasons for this include legislative restrictions, lack of knowledge about acceptability to European consumers, and fear about its impact on economic and environmental systems (Silvestre et al. 2011).

The active packaging and intelligent packaging are the important global nano-enabled packaging approaches in food and beverages market. It is forecasted that active packaging segment will be dominant in next few years. Similarly, the intelligent packaging segment is foreseen to be the fastest growing one, accounting for substantially increased revenues by the end of 2020.

## Toxicity of nanomaterials: a major concern

Although the quality and safety of food are key criteria to be considered while developing a nanotechnology-based strategy, the assessment of safety issues is also equally important before it reaches the consumers. This is because theoretically humans can be exposed to nanoparticles via food packaging coated with nanomaterials. Therefore, many research groups have focused their studies on migration of nanoparticles from the packaging materials to food whereby it will show the negative impact on them, leading to toxicity effect to the consumers (Bradley et al. 2011; Golja et al. 2017).

Nanoparticles exposure to humans and animals is via inhalation, injection and ingestion (Gupta et al. 2012). However, as far as the toxicity of nanoparticles used in


**Fig. 1** Various nano-based food packaging materials available in the market, where **a** nanosilica-coated high oxygen barrier nylon films, **b** titanium dioxide nanoparticle-coated UV absorbent transparent film, **c** nanoclay beer bottles having excellent barrier properties, **d** nanoaluminium films for high barrier properties for gases, **e** silver nanoparticles-based plastic bags, **f** nanosilver-coated plastic food storage container for long-term storage of food items, **g** double handle nanosilver baby bottle to inhibit pathogens, **h** nanosilver-coated plastics materials having antimicrobial properties and **i** intelligent nanosensor-based labels for food packaging materials that change colour to indicate the ripeness of fruit

food packaging is concerned, it will pose risk via getting delivered into the gastrointestinal tract through packaged food into the nanomaterials-containing coating. However, inhaled nanoparticles may be trapped into the respiratory system and can also be translocated into the gastrointestinal tract. In the context of human gastrointestinal tract, during the food digestion in stomach, which lasts there for 3–4 h, they may be processed by acids and enzymes of the stomach in lower pH (Wang et al. 2008). Thus, during this period, nanomaterials get enough time for breaking down, which can possibly produce toxic compounds. Epithelial cell lining of the small intestine forms a barrier keeping the intestinal lumen away from the systemic blood circulation. Subsequently, this avoids the uptake of toxic compounds and microorganisms in the gastrointestinal tract. But ingested nanoparticles showing toxicity, may damage intestinal epithelial linings, thereby interfering their protection role (Sansonetti et al. 1999; Fleckenstein and Kopecko 2001). The possible ways of toxicity of nanomaterials in gastrointestinal tract are depicted in Fig. 2.

As nanomaterials can cross the intestinal epithelial lining, they can translocate to the blood circulation. They are mostly translocated via the M cell layer of Peyer's patches (Powell et al. 2010). Via blood circulation, they can reach to organs such as liver (Choi et al. 2017; Yin et al. 2017), kidney (Kononenko et al. 2017), brain (Yin et al. 2017) and cause harmful effects. The mice liver orally exposed to silver nanoparticles induced inflammation and lymphocyte infiltration leading to apoptosis (Cha et al. 2008). $Cd^{2+}$ ions generated by dissolution of quantum dots in gastrointestinal tract, after translocation, were reported to bind to sulfhydryl groups of mitochondrial proteins, generate reactive oxygen species (ROS), causing the liver toxicity (Rikans and Yamano 2000). After packaging fresh-cut melon and fresh beef by material containing cellulose and silver nanoparticles, there was direct contact between silver nanoparticles and food matrix, wherein the silver ions were reported to leach into the meat and melon exudates (Fernandez et al. 2010a, b). However, there is a pressing need to study the effect of environmental conditions such as temperature, pressure, pH of food and nanoparticle size and shape, storage time, and composition of packaging material on the food–nanoparticle interaction.

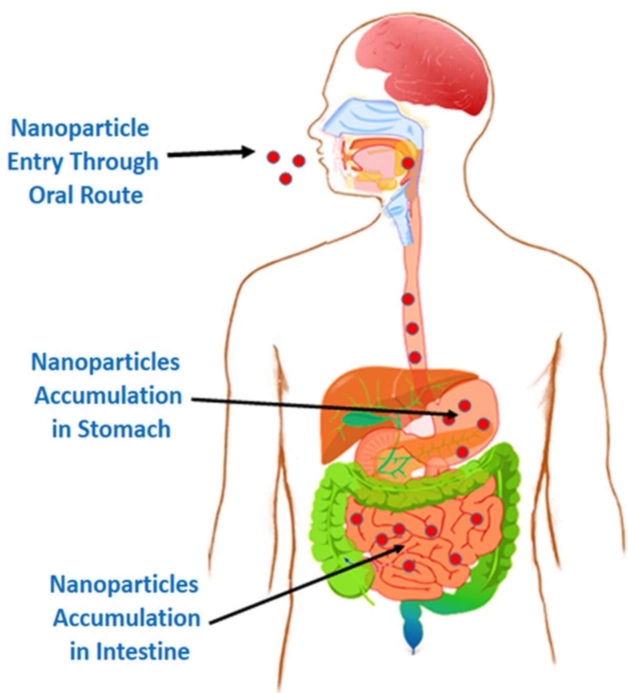


**Fig. 2** Toxicity of nanomaterials to gastrointestinal tract: nanomaterials used for food packaging enter gastrointestinal tract through the oral route. In the stomach, nanomaterials get enough time and environment to get broken down, producing the toxic compounds. They cause damage to gastrointestinal linings, consequently interfering their protective function

## Safety and regulatory issues

It is essential to design and apply best practices while making use of nanomaterials owing to the uncertainties of their safety. Even though the field of nanomaterial-based food packaging is rapidly growing, the consumer safety and regulatory issues associated with them require attention. Still, there is no specific regulation regarding nanotechnology applications in food industry. Advertising Standards Authority (ASA), a UK Food Standards Agency, a competent authority for drafting the regulatory guidelines, has published a draft on regulatory implications and risk associated with the use of nanomaterials in food. The agency recommended the mandatory pre-market approval for all novel systems. The recommendation of the agency is mandatory to European Union (EU) member countries.

EU has considered engineered nanomaterials as novel, and therefore, they are being covered by novel food regulations. For their safety assessment and authorization as food, particular provisions will be applied from 2018 onwards. As per EU regulation, No. 1169/2011 nanomaterials in food must be indicated in the list of ingredients (EU Regulation 228, 2015). Additionally, nanomaterials used in food contact materials must be approved [Commission Regulation (EU) No. 10/2011] and potential risk associated with them is also essential [EU Regulation 228, 2015, Commission Regulation (EU) No. 10/20119]. Advisory Committee on Novel Foods and Processes (ACNFP) is authorized for in-depth safety evaluation based on data of toxicological study, allergenicity, nutrition, consumer safety and ethical issues. The approval is granted through voting at EC Standing Committee on the Food Chain and Animal Health. The nanotechnology applications in food and food packaging will be bound to prior approval before use by such agency (Chaudhry et al. 2007).

The FDA is responsible for regulating many products including those prepared from materials in the nanoscale range (Thomas et al. 2006; Weiss et al. 2006). According to the Institute of Food Science and Technology (IFST), while labelling nano-based products as food additives, the subscript "n" should be used with the conventional E-numbering system (Weiss et al. 2006). All of these regulatory authorities are continuously keeping a close watch on the current development of nanotechnology in food packaging. But for making decision or establishing regulations, still there is a need of in-depth analysis and thorough international discussion regarding the regulatory needs of nanomaterials, execution of proper product labelling and development of more safety testing and risk assessment methods.

In order to deliver food safely to consumer, it is very important to get the knowledge of risk associated with the use of nanomaterials in food packaging. The effect of such nanomaterial exposure to the cells present in the routes of alimentary canal needs to be studied. Some questions such as, whether nanomaterials are translocated in intact form or in the dissolved state in the form of ions, should be addressed. Silver nanoparticles were reported to exert adverse effect on human skin/carcinoma cells and fibroblasts (Chun et al. 2010). They were reported to be safe up to the concentration of 6.25 µg/mL (Duncan 2011). Exposure beyond the safe level has been shown to cause dose-dependent mitochondrial damage, ROS production, DNA damage and anti-proliferative activity. However, the ions were generated after dissolution of nanoparticles reported to play the major role in hazardous effect (AshaRani et al. 2009; Khosravi-Katuli et al. 2018).

Although much emphasis has been laid on the toxic effect of nanomaterials, still there is paucity of the literature on the cumulative effect of size and shape on cellular metabolism. Therefore, there is an urgent need to perform such studies. However, future research is also required to study potential contamination of food products which are packaged by the nanomaterials. In addition, attention should be paid to translocation studies of nanomaterials that generated ions due to their dissolution in acidic environment of stomach, to placenta, breast milk, and blood–brain barrier, etc.

## Public perceptions

Public perception plays a crucial role in commercial success of any product. Public response to nanotechnology in food production and packaging is partially attributed to consumers' views towards applications of nanotechnology (Gaskell et al. 2005). A large number of people are unfamiliar with this new technology. US survey found that over 60% of participants among 1500 people had never heard of nanotechnology (Waldron et al. 2006). It is, therefore, important to consider consumers' viewpoint towards nanotechnology applications in food for the development and commercialization of food products.

The consumers are ready to buy low-cost products with more benefits, but their unwillingness was also seen to use nanotechnology in food (Siegrist et al. 2007). A study by Bieberstein et al. (2013) showed different views of German and French consumers towards nanofood and nanopackaging. Both German and French consumers were unwilling to accept nanopackaging in their foods. Another study by Siegrist et al. (2008) in Switzerland showed that consumers found nanopackaging less problematic. Comparatively, it is observed that awareness of nanotechnology has been slightly increased in Europe and US consumers (Erdem 2015). Public acceptance of nanotechnology in food study was carried out in Canada and USA, and it was found that lay people have insufficient knowledge but have positive expectations with regard to new technologies (Cobb and Macoubrie 2004).

Understanding of risk and benefits, social norms and personal level of satisfaction are main influencing factors for the public to accept application of nanotechnology in food (Stampfli et al. 2010). The commercialization and development of nanotechnology in food depends on positive or negative responses of the public. Moreover, public trust not only significantly related to knowledge about nanotechnology but also associated with the understanding of potential risk and benefits (Rossi et al. 2017).

Overall, trust and knowledge are key factors for making nanotechnology successful. In addition, there is a greater need to popularize nanomaterial-based products so that each and every person can be aware of it. Currently, nanotechnology-based products are more expensive, but after popularization, the production demand will increase, which may help to reduce market price of nanoproducts.

## Key areas of research

Nowadays, the use of nanotechnology in food packaging is a major focus in the food industry. Nanopackaging involves incorporation of various nanomaterials, which make it "smart", having the ability to respond to environmental conditions or repair itself or alert a consumer about contaminations and/or the presence of pathogens. Considering these benefits of nanopackaging, its application in detection of pathogens, contaminant and allergens, protection from ultraviolet rays, antimicrobials, high gas barrier plastics, etc., are important areas of research (Duncan 2011). The use of nanotechnology in plastic food packaging is one of the most important areas of research as it makes the packaging stronger, lighter and also increases its performance. Apart from these, nanomaterials having strong antimicrobial properties such as silver or titanium dioxide can be used in food packaging to prevent spoilage of food (Chau et al. 2007). In addition, the application of clay nanoparticles in food packaging helps to restrict the entry of oxygen, carbon dioxide and moisture towards food material, thereby preventing the food spoilage.

Presently, more research has been focused on the development of nanosensors, which are being added in plastic packaging to identify gases released from spoiled food. In the situation of food spoilage, the packaging material will alert by changing its colour. Furthermore, plastic films embedded with silicate nanoparticles are being developed to keep food fresh for a longer time. Here, the nanoparticles play an important role in reducing the flow of oxygen into the package. Moreover, it helps to prevent the moisture leaking out from the package. Several studies are also ongoing to find out the bacterial contamination of food such as *Salmonella* sp. on the surface of the food. Nanoparticle-based sensors will detect the contaminating bacteria, which will help to analyse the food package more frequently with great efficiency and at a cheaper rate (Inbaraj and Chen 2016).

## Conclusions

The promising results obtained from previous studies clearly confirm that nanotechnology is becoming increasingly important and recently being used in the food sector. There are tremendous opportunities offered by nanotechnology for innovative developments in food packaging that can benefit both consumers and industry. It is well known that nanoparticles have demonstrated broad-spectrum antimicrobial activity, and therefore, they can be used with food packaging material to prevent the growth of common food contaminating microorganisms, which will help to increase the shelf life of food. Nanoparticles are also being used as gas barriers in order to maintain the original taste and flavour of packaged food materials. Moreover, with the help of nanosensors, there is a huge possibility of detecting the lowest amount of food contaminating bacteria and chemicals.

The use of nanotechnology in food packaging considerably improves the property of normal packaging materials, but the toxicological aspects of nanomaterials involved in the packaging cannot be ignored, and hence, there is a pressing need to perform extensive studies for better understanding of advantages and disadvantages of nanomaterials used in packaging. Such studies will help to weigh applications against the toxicity of nanomaterials. Although nanopackaging materials have demonstrated encouraging results, still there is hesitation in public to accept the technology. This concern is obvious in consumers while accepting a new technology. Therefore, there is a need to develop awareness and attitude among the public for the use of nanotechnology. In our opinion, this technology is relatively young and has exciting future, and therefore, rigorous attempts are needed to make it successful so as to provide fresh and safe quality food to consumers of every corner of the world.

**Acknowledgements** MKR gratefully acknowledges University Grants Commission, New Delhi, for providing Basic Science Research Faculty Fellowship Grant No. F 18-1/2011 (BSR); 30/12/2016. RP acknowledges Department of Science and Technology, New Delhi, for providing DST-INSPIRE fellowship Grant No. (IF150452) for pursuing her research work. API is highly thankful to Research Council of the State of Sao Paulo (Fundação de Amparo à Pesquisa do Estado de São Paulo, FAPESP) (Process No. 2016/22086-2) for financial support in the form of Post-Doctoral Research Fellowship.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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