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FUNCTIONAL NANOMATERIALS AS SMART FOOD PACKAGING: A BRIEF REVIEW

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ABSTRACT: *In order to safeguard the sustainability of world food production, it is important to explore innovative pathways to enhance crop yields, to minimize post-harvest loss and to escalate the shelf life of food. Nanotechnology has offered a new template in developing new strategies for sustainable food production. It enables the engineering of multifunctional materials through manipulating the matter at 1-100 nm where quantum effects dominate the particle properties. Among many potential materials, nanohybrids and nanocomposites have already conjured up speculation about a seismic shift, but the pace of development is modest. In the context of modern developments, smart packaging has gained a greater scientific interest due to their ability to offer much functionality other than providing the physical protection of food against environmental impacts. Here, we explore the role of engineered nanomaterials as smart packaging materials with a particular insight into recently developed strategies to curtail the post-harvest loss and to improve the shelf life. A particular emphasis will be made to discuss bio-nanocoatings, nanoclays, metal/metal oxide nanoparticles, and carbon-based nanohybrids/nanocomposites along with current challenges, safety concerns, and future prospects of these nanotechnological advancements in diminishing the post-harvest loss.*

KEYWORDS: Nanohybrids, Nanocomposites, Post-Harvest Loss, Intelligent Packaging, Smart Nanofood, Food Industry

INTRODUCTION

With the increase in world population to 6 billion, mankind has reached a critical juncture where the population versus resources is out of balance. Despite the lowering of the yield gap in developed parts of the world owing to the “green revolution”, ignorance in sustainable practices and high prices of food production has relegated closely one billion people in developing countries to chronic hunger. In order to safeguard the sustainability of world food production, it is important to explore innovative pathways for better crop management and new technologies which increase the yields, reduce wastage and thus minimize production cost.

The deterioration of the quality and/or quantity of food from its time of harvest to consumption at any stage of post-harvest system is defined as the post-harvest loss. Worldwide, one third of food produced do not reach consumer hands as they are subjected to damages/spoilage at one or several stages in the post-harvest system.(Gustavsson et al., 2011) According to a survey conducted by the Food and Agriculture Organization, it has been estimated that the current food production needs to increase by 70% in order to facilitate the world population which is increasing at an alarming rate (Kiaya, 2014). This indicates an urgent need for greater attention towards the world's food security by reducing postharvest food losses. In this scenario, everyone should pay their greater contribution to the United Nations' commitment to preventing food loss and wastage is strongly reflected through the 2030 Sustainable Development Goals.

This challenging problem which arises in this domain has been addressed by scientists by developing a number of ways to mitigate the effect while a number of novel researches are also still going on in order to find effective ways to approach this problem in various aspects. Nowadays, so many methods are being practiced to escalate the shelf life of fresh food. Conventional approaches of preservation of foods include hot water treatments (Fallik, 2004), controlled temperature and high humidity (Paull, 1999), controlled atmosphere (Taşdelen and BAYINDIRLI, 1998), silver treatment (Costa et al., 2011), gamma irradiation (Mahto and Das, 2013), edible coatings (Dhall, 2013), ethylene receptor blockers (Feng et al., 2000), application of nitric oxide (NO)(Corpas and Palma, 2018)/aminoethoxyvinylglycine (AVG)(Zhang et al., 2005)/polyamines (PA)(Valero et al., 2002)/salicylic acid (SA)(Tareen et al., 2012), oxidation of ethylene to CO_2 and water by using strong oxidizing agents like potassium permanganate ($KMnO_4$)(Álvarez-Hernández et al., 2018) and ozone (O_3)(Skog and CL Chu, 2001). Apart from these conventional methods, there is a greater tendency to use nanotechnology in food preservation and packaging in industry. Already, nanotechnology has invaded all the aspects of the food industry. Therefore, more food producers and processors use nanotechnology based applications instead of conventional methods in every scenario in order to get a better quality food experience for customers. The significant thing is that nanotechnology has been applied for every step into foods, from harvesting to consumption. In a nutshell, it means that there are nano-based implemented solutions and methodologies are being common in the food industry.

A range of nanomaterials have been modified to grasp extraordinary performances in food packaging, which could not be obtained from traditional packaging whose role was to provide a physical barrier between the environment and food items. Unlike conventional micro scale materials, the nanomaterials possess novel and unique characteristics in food and agriculture industry, such as improvement of the sensory and physical qualities of food products, improvement of the texture, color and appearance by giving fresh food experience to customers,(Yu et al., 2018), introduction of antioxidant (Bao et al., 2009) and antibacterial (Velmurugan et al., 2014, Shi et al., 2014), nanoparticles into food products, increasing of shelf life of fresh food (Ali et al., 2014), smart nano food packaging materials (Alfadul and Elneshwy, 2010) give the details about the state of the food product inside the packaging and give an improved food safety to the customers. These qualities have enabled them to find many practical applications in the food industry.

A PARADIGM SHIFT; NANOTECHNOLOGY IN FOOD CHEMISTRY

Implementation of novel nanotechnology applications in the food industry is very common in the world, and it has become indispensable nowadays. Nanoparticles are found to be more active than larger sized particles of the compounds having the same chemical composition. It is due to the greater surface area of nanoparticles per mass unit with the result of manipulation of matter at nanoscale. This significant property offers several viewpoints for nanomaterials in food applications. Nanoparticles can be used as bioactive compounds in functional foods.(Weiss et al., 2008, Yang et al., 2014) In the perspective of nanotechnology, it can be further contributed to enhance the properties of bioactive compounds, such as stability(dos Santos et al., 2016), controlled releasing properties (Luo et al., 2013), solubility inside the body (Rezaei et al., 2019), prolonged drug delivery time (Yang et al., 2014), and efficient absorption through body cells.(Liang et al., 2017). Normally, probiotics, prebiotics, vitamins, minerals, Omega 3 and omega 6 fatty acids, are used as bioactive compounds in food nanotechnology. (Watanabe et al., 2005). Apart from that, several novel applications of nanotechnologies have become prominent, including the use of nanoengineered materials, such as nanolaminates, (Sauer et al., 2013) nanoemulsions, (Silva et al., 2012) biopolymeric nanoparticles, (Joye and McClements, 2014) biodegradable nanocomposites, (Cabedo et al., 2006) carbon/clay/lipid based nanohybrids (Kamel et al., 2019) as well as the development of nanosensors (Omanović-Mikličanina and Maksimović, 2016) which are prominent in detection of pathogens and microorganisms in foods and exploration of food safety in customer perspectives (Figure 1). When considering the examples of the use of nanotechnology in food products, it contains bio nanohybrids/composites, nanoencapsulated bio active compounds (Ezhilarasi et al., 2013), foodborne pathogen detectors, (Cesarino et al., 2012) nanofood ingredients/additives (Chaudhry et al., 2008) and nano based sensors.(Li and Sheng, 2014). In the current scenario, nanotechnology-based applications in the food industry have become indispensable. Increased concern about the nanotechnology in food applications underscores the need for development and utilization of nanohybrids/nanocomposites to gain a fresh perspective on the food industry.

Figure 1: Nanomaterials and their applications in food industry

NANOFOOD PACKAGING; A SILVER BULLET IN FOOD INDUSTRY

For paving the way for a new paradigm in the expansion of new generation of functional nanohybrids for sustainable agricultural applications as implied in the United Nations 2030 sustainable development goals, it is essential to ensure the sustainability of world food production (Le Blanc, 2015). Therefore, it is important to explore the innovative pathways for better food packaging and new technologies which enhance shelf life and reduce the production cost. In this context, smart food packaging innovations and improved use efficiency play an integral role.(Robertson, 2016). Therefore, innovations in smart food packaging receive the highest scientific attention. In the quest for the exploration of efficient and biodegradable food packaging, nanotechnology has received a priority.

In the present era, a wide variety of functionalized nanomaterials have been stepped into food packaging industry with the inclusion of nanoclays (Majeed et al., 2013), metal and metal oxides based nanoparticles (nano-ZnO, nano-TiO_2 and silver nanoparticles)(Garcia et al., 2018) and carbon nanotubes (Brody et al., 2008). Based on the extra-ordinary properties in these engineered nanomaterials, they exhibit unique properties compared to the host material. Ultimately, it leads to different functional packaging applications. Nanoclays and layered silicates exhibit excellent barrier properties and sustainable release of encapsulated antioxidant/ antimicrobial agents into the matrices (de Abreu et al., 2007). Metallic nanoparticles (such as zinc and silver nanoparticles) are widely used in food packaging in the purposes of sterilization and antimicrobial properties.(Duncan, 2011). Furthermore, zinc oxide and titanium dioxide metallic nanoparticles are often used as photo catalytic agents to decay microorganisms and various organic molecules (Baruah and Dutta, 2009). When considering the photo catalytic activity of these metal oxide nanoparticles, they are capable of generating reactive oxygen species (ROS). As a result of that, cell death of microorganisms occurs by the oxidation of cellular plasma.(Sirelkhatim et al., 2015, Sun et al., 2018). Therefore, these metal oxide nanoparticles are widely utilized in smart food packaging (Figure 2). Furthermore, carbon nanotubes have also drawn attention in smart food packaging due to the strong and stiffness. It has been discovered that carbon nanotubes are stronger and durable than the Kevlar fibers (Esawi and Farag, 2007). Apart from ameliorating the properties of the polymer matrix, carbon nanotubes also possess anti pathogenic properties (Bora et al., 2013). Therefore, many scientific attempts have been devoted to developing nanotechnology based smart food packaging systems.

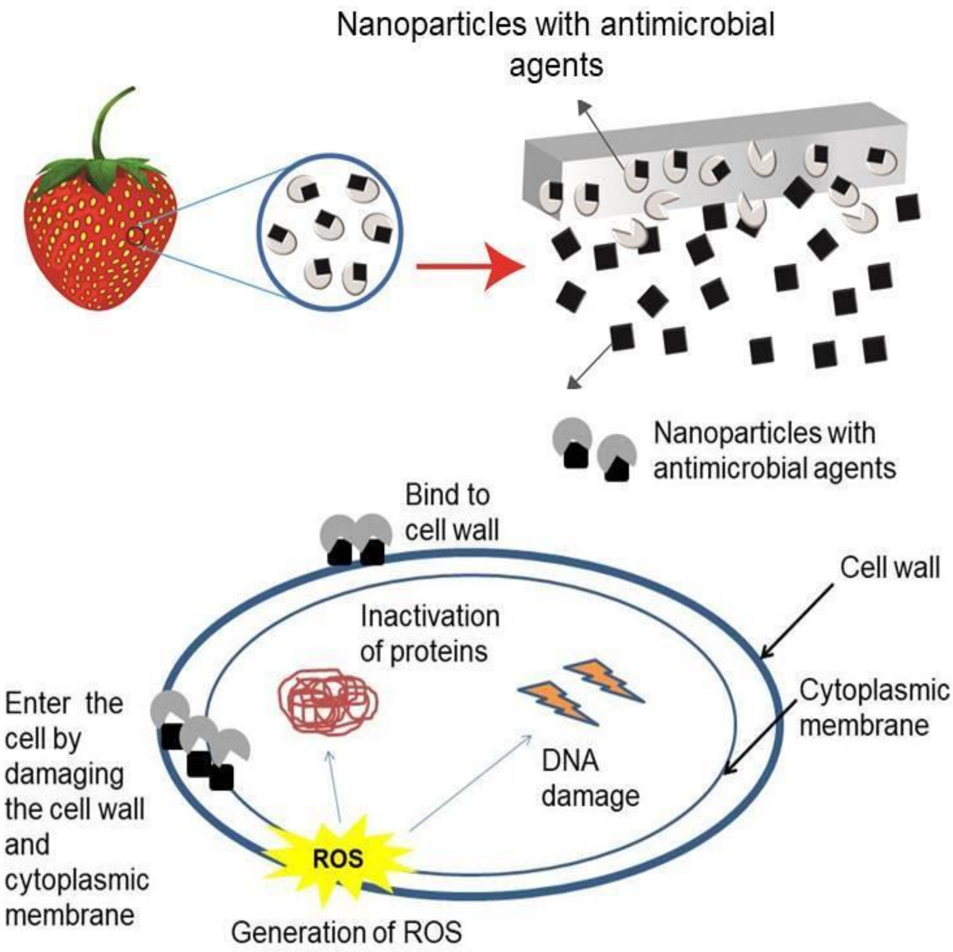

Figure 2: Schematic illustration of the mechanism of antibacterial activity of a clay based nanocoating

HOW SYNERGISTIC EFFECT IMPORTANT IN NANOFOOD PACKAGING

The combination of inorganic and organic matrices at molecular level is expected to realize the synergistic effects, while new and unexpected functional properties are emerging. Such engineered hybrid and composite materials have therefore found applications in a wide spectrum of food packaging industries. The importance of aforementioned synergistic effect in engineered hybrid/composite nanomaterials can be further extended by the following examples. Benzoate and its derivatives have antimicrobial activity (Stanojevic et al., 2009) and those are used in the food industry as a preservative.(Shahmihammadi et al., 2016). Furthermore, Zn-Al-LDHs have more intense effect on antimicrobial activity other than the Mg-Al-LDHs.(Pavel et al., 2020). Bugatti and co-workers have worked on intercalation of benzoate anions into Zn-Al-LDHs and they synthesized a nanohybrid with higher antimicrobial activity. The importance of this fact is the combination of two components which possess an antimicrobial activity. Other than those two in the matrices, the optimized results may not be obtained but benzoate anions intercalated Zn-Al-LDHs may efficiently progress in antimicrobial activity in smart food packaging.

Another promising example is chitosan incorporated nanofilms in smart food packaging. (Kumar et al., 2020). Chitosan is a biodegradable polymer (Saber et al., 2010) which owns antimicrobial properties against many microorganisms in food (Verlee et al., 2017). In order to accelerate its antimicrobial properties, it can be used with nanostructures which also possess antimicrobial properties (Kumar et al., 2020) such as silver nanoparticles (Carbone et al., 2016). Unique combinations of such antimicrobial hybrids can be discovered by incorporating those into packaging materials with the expectation of the synergistic effect. With the combination of chitosan and nanoparticle combined films, they exhibit excellent antimicrobial properties in smart food packaging. Nanofilms, as the advanced supports, synergistically promote the chitosan to exhibit superior performance, which is confirmed by experimental observations.

INNOVATIONS IN SMART FOOD PACKAGING

Clay Based Nanohybrids/Nanocomposites

Nanolayered materials have been identified as another potential nanomaterial in smart packaging applications (Madhusha et al., 2020). The presence of nano-meter thick layers in these materials leading to high aspect ratios with tunable gallery spacing, provide a unique template for modification. As a result of natural origin, they offer bio-compatible and sustainable templates.

Table 1: Clay based nanohybrids/nanocomposites and its effects on food material

Clay based nanohybrid/nanocomposite	**Effect on food**	**Reference**
Benzoate/ benzoate intercalated LDH pectin nanohybrid films	Extended shelf life, Improved elongation at break point for pectin and enhanced water vapor barrier properties.	(Zhang et al., 2014, Gorrasi et al., 2012)
Poly(ethylene terephthalate) (PET) intercalated LDH	Reduced oxygen permeability and higher thermal stability.	(Tammaro et al., 2014)
Benzoate/ 2,4-dichlorobenzoate and para- and ortho hydroxybenzoate intercalated into Zn-Al-LDH	Introduced antimicrobial activity.	(Bugatti et al., 2011, Costantino et al., 2009)
Brucite nanoplate reinforced starch	Enhanced mechanical properties and thermal stability.	(Moreira et al., 2013)
Chitosan/montmorillonite nanocomposite films	Decreased oxygen permeability.	(Kasirga et al., 2012)
Gelatin based films reinforced with MMT (Ginger oil)	Enhanced antioxidant property.	(Alexandre et al., 2016)

MMT with polyvinyl alcohol and chitosan	Increased thermal stability and antimicrobial properties.	(Butnaru et al., 2016)
Incorporation of nisin into polypropylene/montmorillonite	Enhanced the antimicrobial property.	(Meira et al., 2014)
Corn starch films with Na-MMT	Decreased permeability to water.	(Heydari et al., 2013)
Isolated Soy protein –MMT	Enhanced thermal stability, mechanical properties, and reduced water vapor Permeability.	(Kumar et al., 2010)
Whey protein isolate (WPI)/ MMT	Increased tensile strength of the WPI film and reduced swelling of the film.	(Wakai and Almenar, 2015)
Nanoclay with Gelatin/ethanolic extract from coconut husk/Cloisite Na+	Enhanced moisture barrier properties, with the extended shelf life and lower lipid oxidation products.	(Nagarajan et al., 2015)
Nanoclay developed with gelatin of Tilapia skin	Enhanced mechanical and barrier properties.	(Nagarajan et al., 2014)
Nanoclay with soluble soybean polysaccharide–halloysite	Enhanced mechanical and barrier properties.	(Alipoor Mazandarani et al., 2015)

METAL/METAL OXIDE BASED NANOHYBRIDS/NANOCOMPOSITES

Table 2: Metal/metal oxide based nanohybrids/nanocomposites and its effects on particular food material

Metal/metal oxide nanoparticle	Application on food products	Effect	Reference
Cellulose-silver absorbent pads	Beef meat	Retard the growth of lactic acid bacteria, total aerobic bacteria.	(Fernandez et al., 2010, Fernández et al., 2009)
Silver-Polyvinylpyrrolidone	Asparagus spears	Retard the growth of microorganisms.	(An et al., 2008)
Silver nanoparticle-based cellulose absorbent pads	Fresh-cut melons	Reduced antimicrobial activity and retarded the senescence rate of the fresh-cut melons and gave deteriorated appearance after 10 days of storage.	(Fernandez et al., 2010)
Sodium alginate solution containing silver nanoparticles	Carrot and pear	Antibacterial film effective against *E. coli* and *S. aureus* bacteria. Extended the shelf life of carrots and pears by reducing the weight loss and soluble proteins.	(Mohammed Fayaz et al., 2009)

Edible coating of polyvinylpyrrolidone (PVP) containing silver nanoparticle	Asparagus	Reduced weight loss, greener color, and soft textures. Retarding the growth of psychotropic microorganisms at the storage conditions of 2 °C.	(An et al., 2008)
Silver-LDPE films & ZnO-LDPE films	Orange juice	Retarded the microbial growth and increased shelf life of the product.	(Emamifar et al., 2010, Emamifar et al., 2011)
Calcium alginate film loaded with zinc oxide nanoparticles	Ready-to-eat poultry meat	Reduced microbial count of *Salmonella typhimurium* and *E. coli* at storage conditions of 8 ± 1 °C.	(Akbar and Anal, 2014)
Allyl Isothiocyanate, nisin and zinc oxide nanoparticles	Egg albumen	Inhibited the growth of *Salmonella* in liquid egg albumen (egg white).	(Jin and Gurtler, 2011)
Nano Zinc oxide–neem oil–chitosan	Carrot	Enhanced antimicrobial activity against *E.coli*.	(Sanuja et al., 2015)
Polyethylene with nano-powder (nano-Ag, kaolin, anatase TiO_2, rutile TiO_2)	Chinese jujube	Improved preservation quality and enhanced shelf life of the product.	(Li et al., 2009)
Chitosan/titanium nanoparticles/ poly(vinyl alcohol)	Soft white cheese	Antibacterial activity against Gram-positive bacteria (*Staphylococcus aureus*), Gram-negative bacteria (*Pseudomonas aeruginosa*, *Escherichia coli*) and fungi (*Candidia albicans*), and extended shelf life of the product.	(Youssef et al., 2015)
Silver oxide-PE	Apple slices	Retarded microbial growth.	(Zhou et al., 2011)

CARBON BASED NANO HYBRIDS/NANOCOMPOSITES

Graphene and carbon based nanohybrids are currently implemented in smart food packaging applications.(Lu et al., 2009, Sundramoorthy and Gunasekaran, 2014). Yu et al has synthesized poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) material which was reinforced with PHBV-grafted multi-walled carbon nanotubes. This exhibits a decrease in water uptake while reduced water vapor permeability over PHBV films. This is a prominent example for the nanocomposites with enhanced functional and structural properties in food packaging applications (Yu et al., 2014). Furthermore, Dervisevic and co-workers have synthesized poly (glycidyl methacrylate co vinylferrocene)/graphene oxide/iron oxide nanoparticle, and poly (glycidyl methacrylate-co vinylferrocene)/ MWCNT bio-nanocomposite for the detection of xanthine in fish up to the detection limit as 0.12 µM in 4 s for fish meat freshness control. (Dervisevic et al., 2015). Ye and co-workers have synthesized graphene, carbon nanotube and MnO_2 hybrid for sensing material for determination of hydrogen-peroxide in milk. (Ye et al., 2013). Furthermore, Carbon NanoTubes (CNTs) integrated on microfluidics for the analysis of selected analytes in foods such as dietary antioxidants, water-soluble vitamins, vanilla flavors, and isoflavones (Crevillén et al., 2007). Cesarino et al have proposed a biosensor based on acetylcholinesterase immobilized on a composite of polyaniline–carbon nanotubes to detect carbamate pesticides in fruit and vegetables with.(Cesarino et al., 2012) Ultrasensitive Electrochemical Immunoassay of *Staphylococcal Enterotoxin B* in Food has done by using enzyme-nanosilica-doped carbon nanotubes for signal amplification (Tang et al., 2010) and polypropylene amine dendrimers (POPAM)-Grafted multi walled carbon nanotubes (MWCNTs) hybrid materials have synthesized as a new sorbent trace determination of Gold(III) and Palladium(II) in food (Behbahani et al., 2014). Du and co-workers have synthesized Au–SnO_2/GNs-single walled carbon nanotubes (SWCNTs) nanocomposites as ultrasensitive and robust electrochemical sensor for antioxidant additives in foods (Du et al., 2014), and for the determination of bisphenol A and bisphenol F in canned food. Using a solid-phase microextraction fiber coated with single-walled carbon, nanotubes have been synthesized by Rastkari and co-workers (Rastkari et al., 2010). Furthermore, graphene wrapped-phosphotungstic acid hybrid has been used for simultaneous determination of sunset yellow and tartrazine in food (Gan et al., 2012). Antibacterial properties of graphene oxide and reduced graphene oxide have been demonstrated against *E. coli* with minimal cytotoxicity. (Hu et al., 2010). When graphene oxide was mixed with AgNPs, it exhibited stronger antibacterial activity against Gram-positive bacteria than silver nanoparticles alone (Chook et al., 2012). Also, antibody-functionalized reduced graphene oxide is proposed for selective killing of pathogenic bacteria with near-infrared (NIR) irradiation (Wang et al., 2013).

BIO-BASED NANOMATERIALS IN SMART FOOD PACKAGING

Lipid Based Nanohybrids/Nanocomposites

More commonly, lipid-based nanocomposites/nanohybrids are widely engaged in food packaging industry as nanoemulsions. (Zambrano-Zaragoza et al., 2014, Chaudhary et al., 2020)(Figure 2.) These nanohybrids are hydrophilic in nature; therefore, they exhibit low moisture barrier properties (Pérez-Gago and Rhim, 2014). Joe and co-workers have synthesized a sunflower oil-based nanoemulsion as an edible coating. It has been tested for its antimicrobial properties and exhibited significant antibacterial activity against *Staphylococcus aureus*, *Salmonella typhi*, and *L. monocytogenes*. Furthermore, these nanoemulsions exhibit antifungal activity against *Aspergillus niger*, *Rhizopus nigricans*, and *Penicillium spp*.(Joe et al., 2012). Joe and co-workers have synthesized carnauba wax nanoemulsion coating. It was developed with lemongrass oil and tested on Fuji apples. The carnauba wax coated apples exhibited lower populations of total aerobic bacterial plate count and yeasts and molds as compared to uncoated apples under the storage conditions of 1 ± 1 °C for 5 months (Jo et al., 2014). Furthermore, Surahb et al has studied the effects of nanoclay and beeswax on physicochemical properties of guar gum films to be used as nano food packaging (Saurabh et al., 2016).

Protein Based Nanohybrids/Nanocomposites

Mainly animal based proteins (collagen, casein, whey protein, egg white and fish myofibrillar protein) and plant-based proteins (zein, soybean protein, and wheat gluten) are widely utilized in the food packaging industry. When comparing with polysaccharide films, these protein films exhibit better barrier properties while lowering the water vapor permeability. (Arora and Padua, 2010). Nanocomposites with improved antimicrobial properties have been synthesized by adding TiO_2/ZnO into protein films (Zhou et al., 2009, Shi et al., 2008). These films exhibit higher oxygen barrier properties, hence used in biodegradable food packaging (Sothornvit and Krochta, 2005). Soy protein nanocomposite films exhibited lower water vapor permeability while zein is also utilized in the food industry as a coating agent (Liu et al., 2005, Yu et al., 2007). These films with the incorporation of metallic nanoparticles are used in smart food packaging with improved properties.

Carbohydrate Based Nanohybrids/Nanocomposites

Chitosan based nanohybrids/nanocomposites have drawn significant consideration nowadays in smart food packaging. These nanohybrids and nanocomposites/films and coating based on chitosan, offer considerable improvement in food packaging manufacturing. As an example, chitosan can be used to enhance shelf life of food products with incorporation of methylcellulose nanoparticles. When chitosan films were added to chitosan whiskers, then water resistance ability and tensile strength of the chitosan films were improved because of the whiskers which are significant in food packaging. Furthermore, Youssef et al have synthesized a packaging material by utilizing chitosan, carboxymethyl cellulose with the incorporation of ZnO-NPs. This bio nanocomposite displayed better mechanical properties as well as thermal properties in food packaging. Also, a chitosan/Ag/ZnO blend film has been synthesized by uniformly distributing the zinc oxide and silver nanoparticles within the chitosan polymer. These films exhibit excellent antimicrobial activities against a broad spectrum of microorganisms such as *E. coli*, *B. subtilis*, *S. aureus*, *Penicillium*, *Aspergillus* and *yeast*. Chitosan–tripolyphosphate nanoparticles have been incorporated into hydroxypropyl methylcellulose films in order to develop food packaging material. It has significantly improved mechanical and barrier properties of the films when used in food packaging. Apart from chitosan, alginate, carboxymethyl cellulose, pectin and many other carbohydrates are used with the nanocomposites for the smart food packaging.

CONCLUDING REMARKS AND PROSPECTS

This review narrates the recent advancements and applications of nanomaterials in the smart food packaging industry. Due to the higher efficiency and high aspect ratio in these nanomaterials, they exhibit an essential material for food-based applications. Foodborne pathogen detection, increasing shelf life and improvement of sensory qualities ensure to meet the growing demands for these materials (Lagaron et al., 2005, Emamifar, 2011). The biodegradability and biocompatibility are advantageous to these synthetic nanomaterials. Therefore, these functional nanomaterials have been found in intelligent/smart packaging (Tassanawat et al., 2007). These smart/intelligent packaging systems are capable of responding to changes such as temperature, color, and pH values of foods (Bratovčić et al., 2015). Utilization of functional nanomaterials to indicate toxins in foods, such as pesticides, would be beneficial compared to conventional methods. Another promising aspect is nanomaterial based detectors/biosensors, to identify the presence of food borne pathogens such as bacteria and fungi.

With the broader application of nanomaterials on food packaging systems, several toxicity issues and potential risks have been revealed, and these aspects must be addressed in a wise manner (Yang et al., 2013, Yang and Li, 2005). The effects of these nanosized particles on human beings and the environment are still unpredictable. Because the changes over time in characteristic properties of nanomaterials are not yet investigated broadly. It has been evidenced that some nanoparticles can even cross biological barriers, such as the blood–brain barrier, and enters in human body (Su and Li, 2004, Alyaudtin et al., 2001) (Figure 3). It has published a number of research articles about the cellular uptake of nanomaterial (Davda and Labhasetwar, 2002, Akerman et al., 2002) but still it is uncertain the levels of nano-exposure which could harm human health or the environment. Therefore, we should have a clear understanding about the biological behavior of these engineered nanomaterials, and the proper handling and application of nanomaterials in food must be strictly understood.

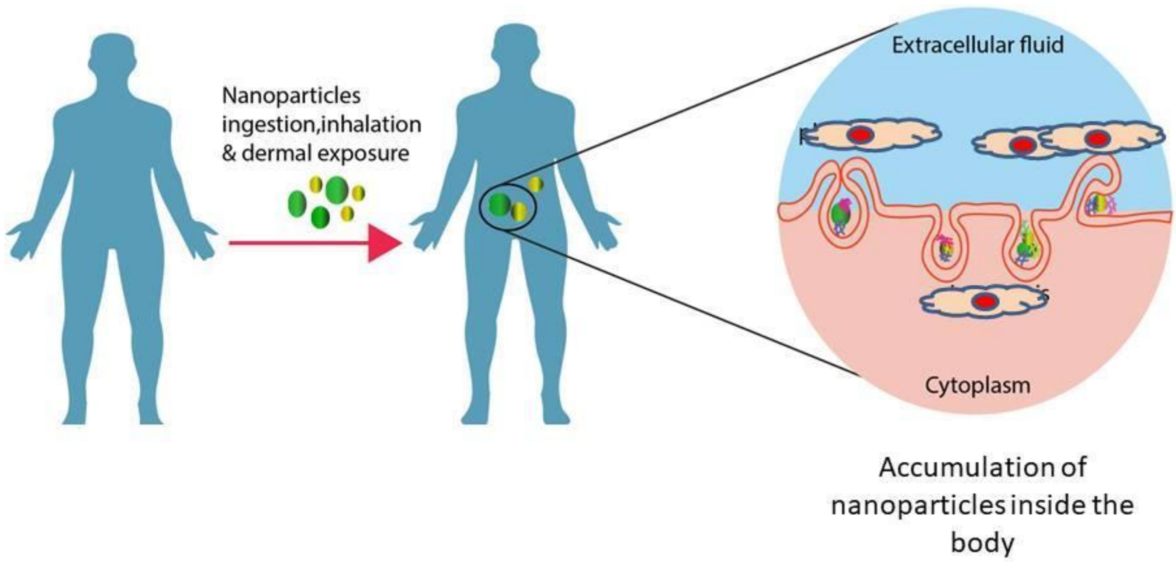

Figure 3: Schematic illustration of fate of nanoparticles inside the body

When considering the bioaccumulation of nanomaterials derived from nanohybrids/ nanocomposites and inhalation of these nanoparticles is the health issues associated with these applications (Yang et al., 2010, Jovanović, 2015, Munaweera et al., 2015b, Munaweera et al., 2015a). With the consideration of above facts, it should take necessary risk assessment procedures while processing and handling food products (Shi et al., 2013, Yu et al., 2012). Even with the prodigious applications of nanotechnology on foods and food packaging, the ultimate goal of the establishment of a healthy and sustainable food industry still remains. The significant fact that the scientific community should be followed is the educating and arranging scientific sessions regarding the human and environmental outcome/effects of nanotechnology to the public.(Munaweera et al., 2016, Munaweera et al., 2015c, Munaweera et al., 2014, Mulik et al., 2016).

In a global context, there exists many opportunities to address food packaging related issues through the lens of nanotechnology which would result in retaining and enhancing freshness of foods enabled with maximized efficacy in increasing shelf life, more importantly contributing towards minimized cost for production and reduced environmental impacts. It is important to note that the current efforts in nanotechnology innovations are basically focused on sustainable use of global resources without fully depleting their availability for the future generations.

Conflicts of Interest

The authors declare no competing financial interest.

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