Nanotechnology in Food Packaging and Food Safety

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DOI: https://doi.org/10.24321/2582.3892.202004

This review focuses to discuss several applications of nanotechnology in food packaging and food safety, nanomaterials that improve packaging, such as better barrier properties, mechanical strength, flexibility and stability, besides that developing antimicrobial activity could help control the growth of pathogenic and spoilage microorganisms, Moreover smart packaging is the use of nanosensors and nanodevices that detect freshness or contaminants in foods or monitor changes in packaging conditions or integrity. Radio Frequency Identification (RFID) tags now exist that can monitor humidity, pressure and event movement, arming users with even more data to ensure food safety and creates nano-biodegradable packaging materials which is indeed an alternative to conventional packaging with non-degradable plastic polymers that are a threat to the environment. These nanomaterials may occasionally lead to ambiguous and sometimes dangerous side-effects on food and even on human beings. Also, it reflects the urgent need for a specific legislation provides a binding framework for managing any risks associated with implementation of nanoparticles in food technology and ensure the safety of substances and products on the market.

Keywords: Nanomaterials, Food, Packaging materials, Antimicrobial, Food Safety

Introduction

Food packaging technology is able to increase the shelf life of foodstuff. In an attempt to further improve this technology, applications of nanotechnology in the field of food packaging. The appliance of this kind of technology improved quality, health benefits, shelf life and hygiene, therefore satisfying the demands expressed by shoppers and consumers.

But this technology does not stop here. Researches mentioned the fact that these nanoparticles can act as a barrier between the food and some different harmful bacteria that might infect it.

However, this technology can also be used to signal the presence of popular harmful bacteria, protecting the consumer, enabling authorities to identify spoiled or infected batches of food more easily and to deal with them safely and efficiently, thus, reducing the number of gastro-alimentary infections. Another great thing about the implementation of this technology would be the use of fewer materials as food packaging. In a period marked by high environmental damage, this comes as a very significant advantage. Furthermore, the use of nanoparticles might also bring a cost-efficient solution, helping producers to earn more and possibly reducing the overall cost of food, while making the food industry less dependent on petroleum-based products.

Nanotechnology derived food packaging materials, are
the largest category of current applications in food sector. The developed food contact materials, now incorporate nanomaterials to improve packaging properties, as a flexibility, gas barrier properties, temperature stability, nanoparticles with antimicrobial or oxygen scavenging properties, nanosensors to monitor and report the condition of the food (Singh et al., 2017; Sharma et al., 2017).

It is not yet completely clear to what extent nanoparticles embedded in food packaging can leach into food products and the toxicological nature of hazard, likelihood of exposure and risk to consumers from nanotechnology-derived food/food packaging are largely unknown.

In terms of consumer safety, several studies have shown the possibility of nanomaterial migration from packaging or containers to foodstuff and to assess their potential hazard the debate is still ongoing among researchers about the extent of migration and whether it is negligible and safe.

Nanotechnology is one of the most rapidly growing industries which is contributing to the growth of several industries; one such industry is the packaging industry. Increasing usage of nano-enabled packaging in the bakery, meat, fruit & vegetable and other processed food product are anticipated to boost demand from 2016-2024 as shown in Figure 1.

Nanotechnology comes to the rescue. Nanocomposites represent a new alternative to conventional technologies for improving polymer properties. Nanocomposites exhibit increased barrier properties, increased mechanical strength and improved heat resistance compared to their neat polymers and conventional composites (Sinha Ray and Okamoto, 2003; Sinha Ray et al., 2006; Sorrentino et al., 2007) as shown in Figures (2,3).

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The polymer composites incorporating clay nanoparticles are among the first nanocomposites to emerge on the market and limit the permeation of gases and provide substantial improvements in gas barrier properties (Kim et al., 2017).

Nanoclays can be used to improved barrier properties of the food packaging materials by incorporating and embedding inside them. The layered silicates commonly used in nanocomposites consist of two-dimensional layers, which are 1 nm thick and several microns long depending on the particular silicate.

The most promising nanoscale size filler is montmorillonite clays, it is an effective reinforcement filler, due to its high surface area and large aspect ratio (50–1000) (Uyama et al., 2003). Nano-montmorillonite clay is used in a wide range of polymers such as, polyethylene, nylon, polyvinyl chloride and starch.

The use of nanoclay in design of nanocomposite (bentonite) during manufacture of bottles and other food packaging materials provides more significant property improvement in gas barrier properties, prevent oxygen and moisture from penetration, drink destabilisation and spoilage of food.
materials. Clay nanoparticles incorporated into an ethylene-vinyl alcohol copolymer as well as polyactic acid biopolymer have been found to provide high O$_2$ barrier and excellent barrier properties to gas and water vapor. Organically-modified nanoclays have been used with polymer matrix improve mechanical and gas barrier properties.

Other benefits on the performance of a diversity of polymers as resulting from using clay nanoparticles, including a dramatic improvement in thermal degradation and in the glass transition temperature. Polymer-Clay Nanocomposite has emerged as a novel food packaging material due to its several benefits such as improved shelf life, shutter proof, light in weight and heat resistant.

Polymer nanocomposite food packaging material can be used in extrusion coating applications for fruit juices and dairy products or co-extrusion processes for the manufacture of bottles for beer and carbonated beverages. Nanocomposite layers in multilayer films can used to enhance the shelf life of a variety of foods such as processed meats, cheese, confectionery, cereals and boil-in-bag foods.

**Antimicrobial Packaging**

As well as behaving as a simple passive barrier, packaging can reduce or retard the growth of pathogenic and spoilage microorganisms in the food matrix. The incorporation of antimicrobial compounds acts as an additional hurdle to improve microbial safety and shelf-life of perishable foods.

Silver nanoparticles (AgNPs) and silver coatings based antimicrobial packaging plays an important role in extending shelf-life of foods and reducing the risk of pathogens. Silver nanoparticles, in particular, have antimicrobial, anti-fungi, anti-yeasts and anti-viral activities. Silver nanoparticles show needed action in bulk form and its ions have the ability to inhibit wide range of biological processes in bacteria (Azeredo, 2009).

Silver nanoparticles are well known for its strong toxicity to a wide range of microorganisms, they exhibit low volatility and stability at high temperatures. Silver nanoparticles increased modulus and strength of a poly (vinyl alcohol) matrix and improved its thermal properties (Mbhele et al., 2003 ) as shown in Figure 4.

A coating containing silver nanoparticles was decreasing microbial growth and increasing shelf life of asparagus.

An antimicrobial film is particularly desirable due to its acceptable structural integrity and barrier properties imparted by the nanomaterial and the antimicrobial food packaging is directed toward the reduction of surface contamination of processed, prepared foods such as sliced meats and Frankfurter sausages (hot dogs). Moreover, silver nanoparticles absorbs and decomposes ethylene (Hu and Fu, 2003), which may contribute to its effects on extending shelf life of fruits and vegetables

Other antimicrobial materials have been investigated and will most likely see increased use in packaging in the coming years. These include zinc oxide nanoparticles, which become more antibacterial as their particle size gets smaller, it can be stimulated by visible light and they are incorporated in number of polymers including polypropylene.

Titanium dioxide (TiO$_2$) has attracted a great deal of attention as a photocatalytic disinfecting material for surface coatings. TiO$_2$ is ideal candidates for food packaging due to its nontoxicity. TiO$_2$ has been used to inactivate several food-related pathogenic bacteria because it is widespread availability, broad-spectrum antibiosis and low cost. TiO$_2$ powder-coated packaging film has ability to inactivate Escherichia coli (E. coli) contamination on food surfaces, suggesting that the film could be used for fresh cut produce.

Other material that have been used as antimicrobial material is Chiston is a biopolymer derived from chitin, which is a natural substance found in the shells of crustaceans like crabs and shrimps, it recently reported antimicrobial properties additional to material for encapsulation.

Antimicrobial packaging would be highly healthy and consumer friendly products as shown in Figure 5.

**Smart/Intelligent” Packaging**

Researchers have started to explore the possibilities of “smart” packaging. In this food packaging technique the packaging material tells you, if the food inside has gone bad; it release substances to treat and purify contaminated foods.

In smart/intelligent, nanomaterials are used for sensing biochemical or microbial changes in the food, for example detecting specific pathogens developing in the food or specific gases from food spoiling (Kuswandi et al., 2011). In terms of smart packaging, nanoparticles can be applied as reactive particles in packaging materials to inform about the
state of the packaged product. The so-called nanosensors are able to respond to external stimuli change in order to communicate, inform and identify the product with the aim to assure its quality and safety.

Nanosensors are also useful to trace the external or internal conditions of food products, pellets and containers, throughout the supply chain.

This packaging system can arranged its condition according to environmental changes (like temperature and moisture) and it can be be engineered to change colour to warn the consumer about food spoilage or contamination by pathogens. To do this, electronic “noses” and “tongues” will be designed to mimic human capacities, enabling them to “taste” or “smell” scents and flavors.

There are two main mechanisms to achieve this chemical and physical. Starting with the chemical mechanism as it uses a chemical indicator which changes colour in the presence of gases given off when food oxidizes. Moving to the physical mechanism which uses nanoparticles embedded in the polymer layers which change their optical properties depending on their relative position in the lattice structure. This can be designed so that an intense colour is produced when the packaging stretches, creating an obvious indication of gas-releasing decomposition.

Usually, producers estimated the expiration date of food by considering distribution and storage conditions, especially temperature to which the food product is predicted to be exposed. However, such conditions are not always known and foods are frequently exposed to temperature abuse; this is particularly worrying for products which require a cold chain. Furthermore, self-cooling packaging has been suggested, which would use a chemical or physical process, such as evaporation of a gas, to keep the temperature inside the packaging cool.

Powered systems could also use a thin-film photovoltaic cell to power cooling using a thermoelectric material. This would reduce the need for large-scale refrigeration along the supply chain, although it is unclear whether or not there would be a cost benefit in this case as shown in Figure 6.

With intelligent packaging, the focus is on monitoring the food product during the complete supply chain, by connecting to the packaging. A well-known example is codes on the packaging, such as QR (Quick Response) codes and barcodes or even codes imbedded inside of the material. The user can read information about the product via a smartphone, tablet or other scanner. “In retail, the code can for example be linked to a website featuring product information, recipes or promotions”.

Besides providing information, intelligent packaging can also monitor the quality of a product. “For example, thermochromic ink can be applied to the packaging that change color when temperatures increase or decrease. Depending on the colour, the end-user can read when the product has reached the perfect temperature for use” as shown in Figure 7.
eliminate the need for inaccurate expiry dates and can provide real-time information about food freshness. They have also been reported that nano-biosensors already have been developed and commercialized to detect pathogens, spoilage, chemical contaminants or product tampering or to track ingredients or products through the processing chain (Nachay, 2007) as shown in Figure 8.

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**Figure 7. Intelligent Packaging with a Time Indicator**

Furthermore, it has a longer reading range, it is very strong and can work under extreme temperatures and different pressures, it can be detected at distances of more than 100m and it can read multiple RFID tags at the same time.

Radio Frequency Identification (RFID) is an alternative technology with a potential to replace traditional Universal Product Code (UPC) barcodes. Unlike a barcode, the tags don’t need to be within the line of sight of the reader, so it may be embedded in the tracked object. RFID tags can also incorporate additional data such as details of product and manufacturer and can transmit measured environmental factors such as temperature and relative humidity. RFID is a new trend in industrial technology Much as manufacturing system, product flow management in the supply chain, temperature monitoring of foods and ensuring food safety.

Nanotechnology is also enabling sensor packaging to incorporate cheap radio frequency identification tags. The nano-enabled radiofrequency identification tags are much smaller, flexible and can be printed on thin labels. This increases the tags versatility and thus enables much cheaper production (Ranjan et al., 2016) as shown in Figure 9.

RFID uses tags affixed to assets (food product, containers, pallets, etc.) to transmit accurate, real-time information to supplier and final destination.

Unique features of RFID systems presents a number of potential benefits like improvement in efficiency and speed of operations, increased accuracy of information, traceability inventory management, labour saving costs, security and promotion of quality and safety.

RFID tags now exist that can monitor humidity, pressure and event movement, arming users with even more data to ensure food safety as shown in Figures 10 and 11.

**RFID Tags**

Generally, active tags in packaging are radiofrequency identification. The tags are electronic information-based systems that use electronic transponders to track shipments and automatically capture data about the shipments and then provide real-time information about goods and shipments.

RFID (Radio Frequency Identification) tags are so widespread over the next few years and yet, they are simply treated the same way as barcodes, uniquely identifying a large number of products, but they work at a distance of up to tens of meters.
Accumulation of plastic in the environment, reduction of arable land, wear oil wells, releasing gases during incineration have prompted efforts to develop biodegradable packaging/plastics (Mohatny et al., 2015).

Biodegradable packaging is biodegradable packaging films that are applied to food products to control moisture transfer and/or gas exchange in order to improve safety and preserve the nutritional and sensory quality (Siracusa et al., 2008). Biodegradable packaging materials are extremely eco-friendly than the other conventional packaging films.

Like any kind of packaging, bio-based packaging provides a barrier between a food product and its environment, thereby protecting it against the microbial growth and spoilage, ambient relative humidity and gas conditions.

The specific characteristic that distinguishes biodegradable packaging films from other packaging solutions is that they are capable of decaying through the action of living organisms (Del Nobile et al., 2009). Biodegradable packaging type is generally perceived to be more eco-friendly as the breakdown products are all completely natural, i.e. carbon dioxide, biomass and water.

Bio-based packaging does not (or less) use fossil fuels to produce the materials, but uses renewable sources, upon disposal energy can be recovered by incineration. Commonly, biodegradable plastics that used as materials in bio-based packaging are polymeric materials in which at least one steps in the degradation process via naturally occurring organism’s metabolism.

Biomaterials (biopolymers) are polymers derived from renewable sources, like plants and animals. Their main feature is their biodegradability.

The first generation of bio-based polymers focused on deriving polymers from agricultural feedstocks such as corn, potatoes and other carbohydrate feedstock.

The focus in the biobased economy is currently shifting from food-based resources and significant breakthroughs in biotechnology. Bio-based polymers similar to conventional polymers are produced by bacterial fermentation processes by synthesizing the building blocks (monomers) from renewable resources, including lignocellulosic biomass (starch and cellulose), fatty acids and organic waste.

Natural bio-based polymers are the other class of bio-based polymers which are found naturally, such as proteins, nucleic acids and polysaccharides (collagen, chitosan, etc.). These bio-based polymers have shown enormous growth in recent years in terms of technological developments and their commercial applications (Babu et al., 2013) as shown in Figures 12 and 13.

Polymers from renewable resources are different from natural polymers because their synthesis is induced
intentionally. Conventional polymers are not biodegradable because of long chains of molecules that are too big and too well connected to each other to make them able to separate the microorganisms to break down. Unlike conventional, polymers made from natural plant materials from wheat, potato or corn starches have molecules that are easily microbiologically degradable.

The problems associated with biodegradable polymers are performance, processing and cost. This is due to “performance and processing” are common to all biodegradable polymers in spite of their origin (Trznadel, 1995; Scott, 2000).

The problem particularly, brittleness, low heat distortion temperature, high gas and vapor permeability, poor resistance to protracted processing operations have strongly limited their applications. The application of nanotechnology to these polymers could open new possibilities for improving both the properties and the cost-price-efficiency.

**Nanotechnology and food Safety**

Nanotechnology offers significant improvements to many technologies and industrial sectors: information technology, energy, environmental science, medicine, pharmacy, homeland security, transportation and food safety, among many others.

Despite the huge benefits nanotechnology has to offer in food industry, there is great public concern regarding toxicity and environmental effect.

Hundreds of reports to date are available on the bioavailability, fate, behavior, disposition and toxicity of nanoparticles in environment. Direct exposure of consumers to nanoparticles applied in food industry poses a serious problem to human health.

As long as the nanoparticles remain bound in the food packaging materials, exposure is limited or very low. However, migration of nanoparticles incorporated in food material to human is high risk. Substances that migrate from food packaging are a concern because of their potential impact on food properties and/or consumer safety.

To date, there have been very few comprehensive studies on the effects of nanomaterials upon ingestion, or the potential interaction of nanomaterial-based Food Contact Materials (FCMs) with food components.

There is need to undertake further migration and toxicological studies in order to ensure safe development of nanotechnologies in the food packaging industry.

A set of standard measurement methods suitable for nanomaterial safety assessment have been reported. However, there are currently no internationally accepted standard protocols for toxicity testing of nanomaterials in food.

Such protocols are in the development stage by organizations such as the International Alliance for Nano Environment, Human Health and Safety Harmonization (Maynard et al., 2006) and the U.S. (National Research Council).
Conclusion

The review clearly shows that nano-enhanced packaging has much to offer the food industry. The application of nanotechnology shows considerable advantages in improving the properties of packaging materials; the use of nanotechnology to fabricate food packaging can give numerous benefits in the range of advanced functional properties.

They can bring to packaging materials with enhanced processing, health and packaging functionalities, shelf-life, transportability and reduced costs. They act as barrier for exchange of gases and maintain the quality of food using nanoclays. Various antimicrobial agents as: “silver, titanium oxide, zinc oxide and other bio-nanoparticles could be incorporated into conventional food packaging systems and materials to create new antimicrobial packaging systems.

Moreover, smart packaging allows the consumers to choose right products which have good shelf life and also by indicating the nature and other characteristics of the food and where it incorporating nanosensors, could even provide consumers with information on the state of the food inside. Food packages are embedded with nanosensors that alert consumers when a product is no longer safe to eat. Moreover sensors can alarm consumers before the food goes rotten or can inform consumers the exact nutrition status contained in the contents.

The usage of RFID tags in packaging opens new avenues for greater safety, convenience and quality and it is an improvement to the previous manual tracking systems or barcodes. Furthermore, it has a longer reading range, it is very strong and can work under extreme temperatures and different pressures. Also, RFID tags can monitor humidity, pressure and event movement, arming users with even more data to ensure food safety.

Somewhere, biodegradable polymers are considered as a solution to waste-disposal problems associated with synthetic plastics. Because of their lack of biodegradability. Biodegradability, indeed, is the main reasons for the interest in biopolymers, because it answers to the need of environmental friendly disposal scenarios.

In spite of several advantages of nanomaterials as shown in Figure 15, migration possibilities and safety control of the nano-packaged foods also are crucial.

Furthermore, nanomaterials might have toxic effects in the body because of their increased surface area compared to bulk materials (Hamad et al., 2018).

For studying the effect of nanoparticles on human health, more research is needed and identification, characterization and quantification of the nanoparticles are prerequisite steps. There are some concerns which must be raised. It is not yet completely clear to what extent nanoparticles embedded in packaging films can leach into food products and what the effects of exposure to various nanomaterials on consumer health might be.

Therefore, successful and safe implementation of nanotechnology applications will require constant dialogue between the scientists and companies who invent them and the consumers who purchase them. If it succeeds, then the fruitful of incorporation of nanomaterial into food packaging may play an important role in making the world’s food supply healthier, safer, tastier, more nutritious and plentiful as well as environmental friendly.
be available increasingly to consumers worldwide in the coming years.

Acknowledgment
The author gratefully thanks Ministry of National Economy, Gaza, for Moral supporting of this work.

References
1. Azeredo HMC. Nanocomposites for food packaging applications. Food Research International 2009; 42: 1240-1253.
2. Babu RP, O’Connor K, Seeram R. Current Progress on bio-based polymers and their future trends. Prog Biomater 2013; 2: 8.
3. Chandra R, Rustgi R. Biodegradable polymers. Prog Poly Sci. 1998; 23:1273-1335.
4. Del Nobile MA, Conte A, Buonocore GG, Incoronato AL, Massaro A, Panza O. Active packaging by extrusion processing of recyclable and biodegradable polymers. J Food Eng. 2009; 93(1):1-6.
5. Hamad AF, Han JH, Kim BC, Rather IA. The intertwine of nanotechnology with the food industry. Saudi J Biol Sci 2018; 25:27-30. (https://www.azonano.com/article.aspx?ArticleID=3035).
6. (https://www.bioplasticsnews.com/2014/01/21/biobased-polymers-trends/).
7. (https://www.grandviewresearch.com/industry-analysis/nano-enabled-packaging-market).
8. (http://www.rfidtagworld.com/products/RFID-Food-Label-Tag-Sticker_1527.html).
9. (https://www.tastetomorrow.com/inspiration/the-power-of-packaging-how-smart-can-packaging-be/376/).
10. Hu AW, Fu ZH. Nanotechnology and its application in packaging and packaging machinery. Pack Eng 2003; 24: 22-24.
11. Johansson C, Bras J, Mondragon I, Nechita P et al. Renewable fibers and bio-based materials for packaging applications-A review of recent developments. Bioresources 2012; 7(2): 2506-2552.
12. Kim TY, Lee YH, Park KH et al. A study of photocatalysis of TiO$_2$ coated onto chitosan beads and activated carbon. Res Chem Interm 2005; 31(4-6): 343-358.
13. Kim TY, Song EH, Kang BH et al. Hydrolyzed hexagonal boron nitride/polymer nanocomposites for transparent gas barrier film. Nanotechnology 2017; 28: 12LT01.
14. Kuswandi B, Wicaksano Y, Abdullah JA et al. Smart packaging: sensors for monitoring of food quality and safety. Sens Inst Food Qual Safe 2011; 5: 137-146.
15. Luo PG, Stutzenberger FJ. Nanotechnology in the detection and control of microorganisms. Adv Appl Microbiol 2008; 63: 145-181.
16. Maynard AD et al. Safe Handling of Nanotechnology. Nature 2006; 444: 267-269.
17. Mbhele ZH, Salemane MG, Van Sittert CGCE et al. Fabrication and characterization of silver–polyvinyl alcohol nanocomposites. Chem Mater 2003; 15(26): 5019-5024.
18. Mohanty AK, Misra M, Drzal LT et al. Natural fibers, biopolymers and bio composites an introduction. Natural fibers, biopolymers and biocomposites. CRC, Boca Raton, 2005: 37.
19. Nachay K. Analyzing nanotechnology. Food Technol 2007; 61(1): 34-36.
20. National Research Council. Toxicity Testing in the 21st Century: A Vision and a Strategy (Washington, DC: National Academy Press, 2007).
21. Ranjan S, Dasgupta N, Lichthouse E. Nanoscience in Food and Agriculture 1: Sustainable Agriculture Reviews 20. France. Nanoscience in Food and Agriculture, 2016: 171.
22. Scott G, Bonhomme S, Cuer A et al. Environmental biodegradation of polyethylene. Polymer Degradation and Stability 2003; 81: 441-452.
23. Sharma C, Dhiman R, Rokana N, Panwar H. Nanotechnology: an untapped resource for food packaging. Front Microbiol 2017; 8: 173.
24. Singh T, Shukla S, Kumar P, Wahla V, Bajpai VK. Application of nanotechnology in food science: perception and overview. Front Microbiol 2017; 8: 1501.
25. Sinha Ray S, Eastal A, Quek SY, Chen XD. The potential use of polymer-clay nanocomposites in food packaging. Int J Food Eng 2006; 2(4): 1-11.
26. Ray SS, Okamoto M. Polymer/layered silicate nanocomposites: a review from preparation to processing. Prog Polym Sci 2003; 28(11): 1539-1641.
27. Siracusa V, Roccu P, Romani S et al. Biodegradable polymers for food packaging: a review. Trends Food Sci Technol 2008; 19: 634-643.
28. Sorrentino A, Gorrasi G, Vittoria V. Potential perspectives of bionanocomposites for food packaging applications. Trends Food Sci Technol 2007; 18(2): 84-95.
29. Trznadel M. Biodegradable polymer materials. Int Polym Sci Technol 1995; 22(12): 58-65.
30. Uyama H, Kuwabara M, Tsujimoto T, Nakano M, Usuki A, Kobayashi S. Green nanocomposite from renewable resources: plant oil-clay hybrid materials. Chem Mater 2003; 15: 2492-2494.
31. Prasad R, Bhattacharyya A, Nguyen QD. Nanotechnology in sustain
32. Prasad R, Bhattacharyya A, Nguyen QD. Nanotechnology in sustainable agriculture: recent developments, challenges and perspectives. Front Microbiol 2017; 8: 1014.
33. Wong JKL, Mohseni R, Hamidieh AA et al., MacLaren RE, Habib N, Seifalian AM. Will Nanotechnology Bring New Hope for Gene Delivery? *Trends Biotechnol* 2017; 35: 434-51

34. Kim TY, Song EH, Kang BH et al. Hydrolyzed hexagonal boron nitride/polymer nanocomposites for transparent gas

35. Kim TY, Song EH, Kang BH, Kim SJ, Lee YH, Ju BK. Hydrolyzed hexagonal boron nitride/polymer nanocomposites for transparent gas, 2017.

36. Prasad R, Bhattacharyya A, Nguyen QD et al. Nanotechnology in sustainable agriculture: recent developments, challenges and perspectives. *Front Microbiol* 2017; 8: 1014.

37. Wong JKL, Mohseni R, Hamidieh AA et al. Will Nanotechnology Bring New Hope for Gene Delivery? *Trends Biotechnol* 2017; 35: 434-451.