NANOTECHNOLOGY IN HALAL FOOD: A TECHNOLOGICAL BENEFITS AND ETHICAL DILEMMAS ASSESSMENT

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ABSTRACT

Nanotechnology has transformed food production and packaging by enhancing food quality, safety, and sustainability. However, concerns exist regarding the alignment of nanotechnology with Islamic beliefs, especially with health hazards, possible contamination, and transparency in labelling. Therefore, this review article examines the incorporation of nanotechnology in the halal food sector, evaluating its technological benefits and ethical issues. This article utilises a qualitative research method conducted by doing a thorough literature analysis of current studies about the significance of nanotechnology in food science, focusing specifically on halal food production. This article further assesses the advantages of nanotechnology in food processing and packaging by analysing current developments and innovations while addressing ethical issues through Islamic law perspectives on halal certification and nanotoxicology research. It also underscores the necessity for precise requirements to guarantee adherence to halal standards and examines alternative materials that may offer feasible solutions.

Keywords: *Food processing, Food industry, Halal food, Health hazard, Packaging*

1. Introduction

Nanotechnology has massively revolutionised industries around the world with remarkable applications in various sectors, including the food industry. The concept of nanotechnology comes from the Greek word "nano", which means dwarf (Momin & Joshi, 2015). The late Norio Taniguchi introduced "Nanotechnology" in 1974, while Richard Feynman provided the principles in 1959. Nanotechnology deals with particles of size ranging from 1 – 100 nanometres in diameter (Patel et al., 2021). In comparison, nanoparticles are about 1/1000th the diameter of human hair.

The utilisation of nanotechnology in the food industry has recently garnered considerable attention due to its ability to address numerous difficulties. Nanotechnology has invaded the food industry, demonstrating significant food processing, packaging, and safety possibilities. For instance, in food processing, nanotechnology mainly aims to enhance food quality (flavour, colour, and texture), improve food stability using nanoemulsions, nanoencapsulation for controlled release of additives and nutrients, and enzyme immobilisation for more efficient food processing (Mohammad et al., 2022). Additionally, nanotechnology is extensively employed in food packaging for antimicrobial purposes and to create enhanced, active, and smart packaging (Gupta et al., 2024). Nanotechnology is also used in food safety to detect pathogens and poisons in food products and improve barrier properties (Mohammad et al., 2022).

Nanotechnology undoubtedly offers substantial technological advantages. Nevertheless, as the global halal food market expands, the prospective incorporation of nanotechnology prompts significant enquiries. Ethical problems exist about its alignment with Islamic beliefs, as nanoparticles may pose a possible toxicity risk to human health. Extensive studies have been conducted to examine the potential dangers and health problems associated with nanotechnology; nevertheless, the halal dimension has received comparatively little attention. Therefore, this review article aims to evaluate the applications and benefits of nanotechnology in food processing and packaging while confronting the ethical issues associated with its utilisation. This article will further examine the alignment of nanotechnology with halal principles and offer possible alternative materials that can be utilised in food processing and packaging.

2. Application of Nanotechnology in Food Processing and Packaging

Food processing is transforming food into a consumable state by preserving it with the aid of technologies and procedures (Dera & Teseme, 2020). Compared to fresh food, processed food lasts longer and does not degrade as rapidly. They are more appropriate for long-distance transit from the production site to the retail destination. Nanotechnology in food processing includes incorporating nutraceuticals, gelation and viscosifying agents, nutrient delivery, mineral and vitamin fortification, and nanoencapsulation of flavours (Lamba & Garg, 2018). These methods have been developed to maintain the flavour and quality of food while protecting it from microbial infestations that lead to degradation (Dera & Teseme, 2020).

Nanotechnology has advanced food processing procedures by enhancing physicochemical properties and augmenting nutrient stability and bioavailability (Patra et al., 2018). Nanoencapsulation is one prominent technique where bioactive ingredients such as flavours, antioxidants, and essential oils are encapsulated to protect them and improve their controlled release in food products. This not only enhances taste but also ensures consistency and stability during storage. For instance, nanoencapsulation of omega-3 fatty acids has been employed to enhance the flavour stability of functional foods such as bread (Gökmen et al., 2011).

Additionally, nanoemulsions can be utilised to modify the texture of processed foods or improve their stability, making them smoother and more consistent (Primozic et al., 2017). These nanoemulsions can boost both the solubility and bioavailability of flavour components, increasing food flavour and whole sensory enjoyment (Silva et al., 2012). Nanoparticles like zinc oxide and titanium dioxide also contribute to maintaining food quality, impacting texture and flavour over time during storage. As stated by Ariyarathna et al. (2017) and Omerović et al. (2021), the mesoscopic properties of nanoparticles include a large surface area, high reactivity, small particle measurement, significant durability, quantum effects, and flexibility. These properties explain why nanoparticles are used in processed foods.

Due to their characteristics, nanoparticles exhibit more biological activity than larger particles of identical chemical composition, facilitating their application in functional food (Pateiro et al., 2021). Transport properties, solubility, residence time in the gastrointestinal tract, and effective absorption can be improved by reducing particle size (Martínez-Ballesta et al., 2018). Additionally, nanoparticles are utilised to improve the aesthetic and colouration of processed food. Nanotechnology facilitates the creation of nanoscale pigments and colourants that yield more vivid and stable hues, especially in foods sensitive to environmental factors like heat and light.

Food packaging can enhance its properties through the use of nanotechnology. The primary aim of packaging is to reduce spoilage and contamination while providing physical protection to food from temperature variations, external impacts, vibrations, and microbial infections by acting as a barrier to prevent the intrusion of oxygen and other gases that cause spoilage (Mohammad et al., 2022). Nanotechnology applications, such as nanoparticles and polymer-based composites in food packaging, demonstrated optimal efficacy in this area. Biodegradable materials are mostly preferred for food packaging production and construction to reduce environmental harm.

Food packaging continually advances because of material science and technology developments and customers' evolving lifestyles. Food and consumer product packaging plays an essential role in today's global economy, both in distribution and preservation and in improving end-user convenience and connection with consumers. As a result of these massive undertakings, packaging has become the world's third-largest industry, accounting for around 2% of the Gross National Product (GNP) in developed countries (Mihindukulasuriya & Lim, 2014).

3. Benefits of Nanotechnology in Food Processing and Packaging

Significant benefits arise from nanotechnology in the food industry including food processing, packaging, and safety. Khare & Vasisht (2014) assert that the primary advantages of nanotechnology in food processing include: (1) Increased surface area, which may improve the absorption of flavours and food components; this is especially important for flavour molecules with low solubility and low thresholds of identification for flavour and odour; (2) Improvement of solubility for poorly soluble in water compounds: For example, the solubilisation of omega-3 fish oil employs a micelle-based approach; (3) Visually clear (essential in beverage applications): Nanoemulsions with oil droplet diameters below 100 nm demonstrate optical transparency; (4) Improved ingredient preservation during processing (decreased volatile organic carbon) in spray drying; (5) Achieving an authentic molecular solution (uniformity in system attributes, such as density): Molecular inclusion complexes formed from amylose and cyclodextrins and; (6) Enhanced activity levels of encapsulated substances, such as antimicrobials in nanoemulsion forms.

In food packaging, nanomaterials offer numerous advantages, including enhanced mechanical barriers, the ability to detect microbial contamination, and the possibility for increased bioavailability of nutrients. This is likely the most conventional application of nanotechnology in the food and related industries (Singh et al., 2023). Nanotechnology in food packaging has also resulted in enhanced, active, and intelligent packaging solutions. These innovations help maintain food quality and allow for better traceability all the way through the supply chain (Ashfaq et al., 2022). Nanoparticles enhance the mechanical and physical qualities of food packaging, and these properties include strength, biodegradability, thermal stability, UV absorption, and impermeability to water vapour and oxygen. By incorporating these nanoparticles, food packaging can be made to last longer and keep food quality intact. For instance, nanoclays serve as reinforcing agents in food packaging films and coatings, enhancing the barrier against oxygen and moisture, which is especially beneficial for packing perishable items (Nath et al., 2022).

One major use of nanomaterials is active packaging, which enhances packaged foods' safety and longevity by interacting with the product and the environment (Chinsirikul et al., 2021). Nanoparticles in active packaging may absorb unwanted substances, such as oxygen and ethylene, or release beneficial substances, such as antioxidants and antimicrobials. Zinc nanoparticles have shown remarkable effectiveness in significantly postponing ripening by reducing weight and moisture loss while maintaining fruit firmness (Odetayo et al., 2022).

Intelligent food packaging comprises nanotechnology-based sensors that monitor the condition of the food and its surrounding environment, as well as their interactions, delivering information on food quality and safety through various signals (Azeredo & Correa, 2021). The temperature of the food, as well as its freshness and expiration date, can be shown using an intelligent packaging system (Ghaani et al., 2016). These sensors may change colour or signal if there is spoilage or a change in environmental conditions. For instance, carbon nanotubes detect changes in gas composition inside the packaging, indicating food spoilage (Nguyen et al., 2013).

4. Problems related to Nanotechnology

Contemporary food issues are frequently controversial due to advances in technology and the tendency of people towards innovation (Onyeaka et al., 2022). Recent research indicates that incorporating nanotechnology has advantages, such as producing substantial amounts of more nutritious, high-quality, durable, and cost-effective food (Aishah et al., 2023). It has impacted various facets of food, including processing, formulations, safety, and packaging (Onyeaka et al., 2022). Nevertheless, enquiries frequently emerge regarding the authenticity of these food products as halal and the potential presence of prohibited components (Omar et al., 2024).

Public concerns over food packaging usually arise from incorporating nanomaterials, which may result in exposure to these particles from intake through the mouth (Hammed, 2018). Ingestion of nanomaterials via food and beverages may result in damage to the human body and contribute to several ailments, including stomach and colon cancer, arrhythmia, asthma, lung cancer, immunological disorders, and neurological diseases (Aishah et al., 2023). The presence of nanostructures in living organisms can disturb normal functions, potentially resulting in malfunctions and illnesses. Furthermore, nanomaterials can readily permeate biological membranes, circulate through the bloodstream, accumulate in many organs of the body, and influence cell survival (Hammed, 2018).

The use of nanoparticles raises safety concerns for industrial workers in production environments, as health risks from exposure, inhalation, and dermal absorption may significantly exceed those encountered by food consumers (Bujang et al., 2020). The toxicity of nanomaterials is typically affected by size, chemistry, structure, surface structure, charge on the surface, the ability to dissolve, accumulation, and other chemical properties (Hammed, 2018). According to Aishah et al. (2023), nanotoxicology is the scientific discipline that examines the quantities of nanomaterials that induce unintended toxic effects on non-target cells, organs, or creatures, as demonstrated by clinical studies. Adding on, the elevated surface-to-volume ratio of nano-emulsions enhances reactivity, which automatically heightens the potential for overdose and toxicity. Moreover, the undesirable effects of prolonged nanomaterials include environmental contamination, organ toxicity, altered cell shape, allergic reactions, hypersensitivity, and carcinogenic effects (Aishah et al., 2023).

In Islamic jurisprudence, Muslims underscore the importance of the permissibility of food sources for ingestion. This is due to the fact that food consumption promotes the improvement of human health and behaviour. Therefore, the increasing availability of food in the market has heightened concerns regarding the validity of halal food among Muslim customers globally, and Muslims necessitate certain safeguards to guarantee the accuracy of information on food labels and other sources about halal food matters (Fadzlillah et al., 2011). In the area of nanotechnology, it is imperative to assess the health hazards posed by these nanomaterials to human health when ascertaining their halal status, which corresponds with the *Maqasid Shariah* focused on achieving *maslahah* (benefits) (Bujang et al., 2020).

For example, silver nanoparticles from food packaging were demonstrated to migrate into food matrices when subjected to elevated temperatures, prolonged storage durations, and compromised polymer matrices. It enhances the oral exposure of nanoparticles throughout the gastrointestinal tract, hence elevating safety and health issues. The distinctive characteristics of nanoparticles, including rapid movement and diminutive size, enable them to penetrate deeper into the human body and access sensitive regions, potentially resulting in numerous health difficulties (Bujang et al., 2020).

Also, silica exhibits cytotoxicity in human lung cells when used as an anti-caking ingredient in food. Acute exposure to non-toxic polystyrene nanoparticles decreased iron transport, whereas chronic exposure resulted in the remodelling of intestinal villi, suggesting that even non-toxic nanomaterials might affect nutritional absorption (Aishah et al., 2023). Furthermore, nanomaterials can penetrate further into the cell nucleus, causing DNA damage that may result in breaks or mutations associated with cancer (Onyeaka et al., 2022).

In Brunei Darussalam, Halal Food Standard PBD24:2007 stipulates that in order for nanomaterial to be deemed halal, it must adhere to specific requirements (Deuraseh, 2020):

a) the food or its ingredients that do not contain any parts or products of animals that are non-halal to Muslims according to *hukum syarak* or products of animals which are not slaughtered according to *hukum syarak*;
b) the food does not contain any ingredients that are *najs* according to *hukum syarak*;
c) the food that is safe and not harmful;
d) the food that is not prepared, processed or manufactured using equipment that is contaminated with things that are *najs* according to *hukum syarak*;
e) the food or its ingredients do not contain any human parts or its derivatives that are not permitted by *hukum syarak*;
f) during its preparation, processing, packaging, storage or transportation, the food is physically separated from any other food that does not meet the requirements stated in items (a), (b), (c), (d) or (e) or any other things that have been decreed as *najs* by *hukum syarak*.

Furthermore, PBD24:2007 sets out certain additional basic principles requiring that the packaging must be produced and meet the following supplementary conditions (Deuraseh, 2020):

a) the packaging materials shall not be made from raw materials that are decreed as *najs* by *hukum syarak*;
b) the packaging material is not prepared, processed or manufactured using equipment that is contaminated with things that are *najs* as decreed by *hukum syarak*;
c) during the preparation, processing, storage or transportation of the packaging material, it shall be physically separated from any other packaging material that does not meet the requirements stated in item a) or b) or any other things that have been decreed as *najs* by *hukum syarak*;
d) the packaging material does not contain raw materials considered hazardous to human health.
e) The packing process shall be done cleanly, hygienically, and in sound sanitary conditions.

Additionally, the halal food industry has lagged in integrating nanotechnology for food processing and packaging, leading to an absence of religious rules concerning the content and technology of food packaging systems. Nevertheless, numerous ways can be derived from established dietary laws, and it is proposed that forthcoming religious dietary regulations for food packaging should encompass the following areas (Hammed, 2018):

a) the origin of nanomaterials must be halal, and their safety will be crucial to exclude the potential of contamination and safety concerns.
b) food packaging materials must be evaluated according to their protective efficacy. The materials must be protected against physical, chemical, and biological harm.
c) the utilisation of dangerous nanoparticles in food packaging ought to be deemed illegal, given that the production, sale, distribution, and consumption of hazardous products are strictly prohibited.
d) statement of composition should be compulsory to ensure transparency. The food packaging system must give out essential information to enhance customer comprehension.
e) the packaging must be certified as halal to ensure a complete, trustworthy product. This indicates that the entire supply chain of food products is thoroughly checked (Ab Talib & Mohd Johan, 2012).

5. Alternative Materials other than Nanotechnology

5.1 Gelatin

Gelatin is a widely recognised bio-based polymer commonly utilised in the food and pharmaceutical sectors due to its palatability, solubility, flexibility, and affordability (Mohd Hatta et al., 2023). Fish and bovine bones are currently extensively utilised as the primary source for halal gelatin. Bovine products are usually permissible, provided that the slaughtering process adheres to the required Islamic method. Nonetheless, challenges such as Bovine Spongiform Encephalopathy (BSE), widely called mad cow disease, present substantial issues, amplifying the demand for non-mammalian collagen and gelatin (Nirwandar, 2020). Conversely, fish skin is abundant in collagen, making the extraction of collagen and gelatin from this byproduct a prospective option for value improvement, and this makes fish-derived sources possess the ability to fulfil halal standards for Muslims (Nurilmala et al., 2022).

5.2 Exopolysaccharides

Dextran, xanthan, and pullulan are bio-based polymers synthesised by fungi and bacteria. Before the 1950s, dextran had been studied as a nutritional supplement, and it is typically utilised in numerous food products for gel formation, viscosity enhancement, texture modification, and emulsification. The US FDA (United States Food and Drug Administration), as stated by Suryawanshi et al. (2022), has recently classified dextran as a safe food ingredient. As for xanthan, it is inherently non-toxic and does not inhibit growth. It has also undergone extensive evaluation on its toxicity and safety for food and medicinal applications, and it has been proven to possess a non-sensitizing characteristic (Suryawanshi et al., 2022). Pullulan is characterised by its distinctive properties and beneficial attributes, particularly its ability to prolong food shelf life by minimising the risk of spoiling. Pullulan also has the potential for application in the packaging industry due to its excellent film formability, enabling the creation of flexible, delicate layers with targeted antibacterial properties (Mohd Hatta et al., 2023).

5.3 Polysaccharides

Natural polymers, particularly those sourced from polysaccharides, have exceptional biological compatibility, availability, stability, low toxicity, cost-efficiency, and biodegradable properties (Benalaya et al., 2024). Since plants have pigments such as chlorophyll, carotenoids, anthocyanins, and betalains, bioactive chemicals derived from plants, particularly those found in plants, are being proposed as substitutions. In a study conducted by Mohd Hatta et al. (2023), it was found that natural pigments may be extracted from various fruits and vegetable waste products, including seeds, peels, skins, and leaves. These natural pigments consist of several bioactive chemicals with physiological attributes, including antioxidants and antimicrobial agents, which safeguard tissues as well as cells from damage caused by harmful free radicals and singlet oxygen; they also have the ability to prolong the longevity of either freshly prepared or processed food.

Additionally, halal biomaterials appropriate for food packaging include bioplastics sourced from starch, cellulose-based materials, chitosan extracted from prawn and crab shells, and bamboo fibres. These materials offer sustainable and environmentally friendly alternatives to traditional food packaging since they are renewable, biodegradable, and recyclable. Thus, it is also crucial that halal biomaterial packaging not only complies with Islamic law but also represents an environmentally sustainable option for the packaging sector (Mohd Hatta et al., 2023).

Cellulose is known for its superior biocompatibility, non-toxicity, flexibility, and renewability (Zainul Armir et al., 2021). Additionally, bamboo fibres are one of the sustainable projects, characterised by their biocompatibility and biodegradability, which is utilised in numerous applications, including controlled and gradual material release and water retention. Moreover, the supply of raw materials for producing bamboo fibres is cost-effective and plentiful and has emerged as the optimal substitute for traditional synthetic fibres (Zainul Armir et al., 2021). Other than that, pectin and other polysaccharides are being explored as alternatives to animal gelatin for halal food products. It is found that pectin serves as a protective barrier for food ingredients and is utilised for the encapsulation of bioactive chemicals and materials sensitive to adverse environmental conditions (Zahra Khoshdouni Farahani, 2021).

6. Conclusion

This review article comprehensively analyses the technological advantages and ethical challenges associated with the implementation of nanotechnology in the halal food industry. Methods like nanoencapsulation are proven to enhance flavour, nutrition delivery, and texture, whilst nano-based packaging solutions prolong shelf life and offer intelligent packaging that assesses food freshness. Nonetheless, the integration presents significant ethical dilemmas, especially concerning its alignment with Islamic teachings. The primary concerns pertain to the possible health hazards linked to nanotechnology, including toxicity, pollution, and the incorporation of non-halal compounds, which may erode the confidence of Muslim customers.

This article underscores that although the advantages of nanotechnology are indisputable, a more thorough evaluation of its conformity with halal principles is necessary. It indicates that establishing explicit standards and restrictions for utilising nanomaterials in halal food is crucial to maintaining consumer confidence. The article also emphasises alternative materials that may provide feasible and ethically responsible food processing and packaging choices. These innovations possess considerable potential to satisfy the increasing demands of the worldwide halal food market, enhancing the quality and sustainability of food items.

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