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Are Green Technology and Plant-Derived Nanomaterials the Way Forward to Halal-Certified Food Products?

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Abstract

The wide utilization of intricate and innovative nanotechnology products with a size less than 100 nm is still uncertain due to its potential long-term health risk and environmental hazards. One of the main factors that contributes to its slow commercialization progress is nanotoxicity, that is associated to the nanomaterials synthesis and methodology used in their production. This paper provides an overview on nanotechnology, nanotoxicity, and nanofabrication techniques using green chemistry. Information regarding halal food guidelines and regulations are included. The question of whether the production of safer bio-based nanomaterials is able to meet halal compliance is addressed. This paper also highlights some of the challenges and limitation faced by the industry in adopting the green and eco-friendly nanotechnology that will support the United Nations Sustainable Development Goals. Although many studies had proven that green synthesis methodology produces safer nanomaterials but insufficient data on toxicological studies and life cycle assessments have delayed the establishment of legislation on nanomaterials application, as a consequence, hinders the development of halal regulations and guidelines for nano-based or nano-ingredients in the halal food industry.

Keywords: *Green technology; Halal; Nanomaterials; Nanotechnology; Nanotoxicity*

Introduction

The halal industry is one of the fastest-growing trade sectors and the demand to feed Muslim population is ever-increasing. Based on the report of the global Islamic economy (Dinar Standard, 2022), the Muslim consumers worldwide expenditure on food and beverages increased by 6.9% in 2021, from US$1.19 trillion to US$1.27 trillion and is expected to reach US$1.67 trillion (7.0%) in 2025. The State of the Global Islamic Economy (SGIE) also reported that the 57 countries of the Organization of Islamic Cooperation (OIC) imported US$200 billion in halal food and beverages in 2020 and forecasted to increase to US$236 billion by 2025 (Dinar Standard, 2022). The awareness in obtaining halal products is not limited to Muslim consumers and not constrained to Muslim countries only. There is also a growing demand from non-Muslims, in which the highest halal food expenditure per capita is in European and North American Muslim minority countries (ITC, 2015).

According to Islamic Jurisprudence (*fiqh)*, the term 'halal' means a choice that is permissible by the *Shariah* law. The permissible sources of food for Muslim consumption must be nutritious, hygienically prepared, of high quality and safe also does not pose any health risk. This is in line with the *Maqasid As-Shariah*, which is for the attainment of *maslahah* (benefits) and the rejection of *mafsadah* (evil). The goal of the *Shariah* encompasses the protection and preservation of religion, life, intellect, lineage, and property that secure the benefits and safeguarding the people's interest in this world and the next. This is in alignment with the *Qaidah Al-fiqh* or Islamic Legal Maxim (*Al-Darar Yuzal*), which stresses on the elimination of harms. In Surah Al-Baqarah, verse 195, Allah says, "And spend of your substance in the cause of Allah and make not your own hands contribute to your destruction but do good, for Allah loves those who do good" (Al Qur'an, 2: 195). This verse shows that the safety and well-being of Muslims is not only confined to the consumption of foods, but also covers their conduct in the present, which impacts the future to come. In accordance with this, manufacturing of halal food must not stop at safeguarding against non-halal ingredients contamination and ensuring the halal ingredients are safe with no adverse health effects, but the by-products and wastewater discharge from the manufacturing facility must also be inspected and confirmed to be safe, and not harmful to the environment or to other living beings. Unfortunately, these further processing or waste treatments were not considered as potential halal threat and therefore not identified as halal control point (HCP) in the halal risk management plan.

The term 'nano' refers to the atomic size with the scale of 1 - 100 nanometer (1 nm = 10^{-9} meter). Nanotechnology refers to the technology used in the development and use of particles, structures, devices, and systems with novel properties and functions that are related to their nano size (Aishah et al., 2020). There are various potential benefits of nanotechnology, which leads to the improvements in performance, efficiency, and optimization of food manufacturing methods, environment and water purification systems, renewable energy systems, health through nanomedicine, and nutrition absorption in human body among others (Aishah et al., 2020; Aithal & Aithal, 2021a). However, the potential disadvantages of the technology are currently being investigated, which include the environmental pollution, health risks to human, animals, plants, social life, and economy if it is not being handled or managed properly (Aithal & Aithal, 2021b).

In 2015, the United Nations (UN), a multi-country membership organization, had announced 17 Sustainable Development Goals (SDGs) with a slogan of action to end poverty, to protect the planet, and to ensure peace and prosperity by the year 2030. The nanotechnology involvements in realizing the SDGs are tremendous. As much as 13 of the SDGs can be achieved with the applications of the universal nanotechnology (Aithal & Aithal, 2021a). The advancements and enormous coverage of nanotechnology in many areas of scientific fields include nanomedicine, nanobiotechnology, nanomaterials design and fabrication technologies, nanoelectronics, nano sensors, and nano mechanics among others. The technology is expected to solve certain problems in health and medicine, agriculture and food industry, drinking water systems, efficient automobiles, renewable energy systems, high speed optical computers, low cost and durable buildings, embedded intelligence as well as space vehicles (Aithal & Aithal, 2016; 2018a, b). However, the downside of the technology is its potential risks of nanotoxicity. One of the factors associated with the risk is contributed by the sources and methods used in the fabrication of the atomic scale materials.

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This paper focuses on the halal aspects pertaining to nano-sized ingredients and nanomaterials involves in the food industry. An overview of the various nanotechnology applications in the food product and some information on the toxicological impacts and health risks of this nano-sized ingredients are explained. In this paper, the green technology related to the sources of nanoparticle food ingredients, extraction methods, and processing techniques used are elaborated. It is hoped that the risk of nanotoxicity can be minimizes and the commercialization progress of the eco-friendly nanotechnology can be widened, hence the UN mission in realizing the SDGs is attainable.

Halal Food Guidelines and Regulations

Among the different Islamic countries around the world, different halal regulatory frameworks or standard based on their designated halal certification bodies or organizations have been established. Besides the geographical perspectives, the difference in the school of Islamic thoughts (*mazhab*), namely, Hanafi, Shafie, Maliki, and Hanbali within the Islamic jurisprudence also contributes to the different halal standards. Several attempts have been made to harmonize the halal standards, but currently, no consensus on a single unified halal standard is able to be established (Abdallah et al., 2021).

Aithal and Aithal (2021a) had identified and divided some of the major halal international standards based on the geographical areas as shown in Figure 1. The halal standard of Gulf Standards Organization GSO 993: 2015 was issued by the Gulf Cooperation Council (GCC) Standardization Organization has the national departments for standards and specifications of the Arab Gulf states (Saudi Arabia, Qatar, Kuwait, Oman, Bahrain, and United Arab Emirates) (GSO, 2015). The OIC/SMIIC 1:2019 standard (SMIIC, 2019) was issued by the Organization of Islamic Cooperation (OIC) and the Standards and Metrology Institute for the Islamic Countries (SMIIC). The OIC is an alliance of 56 countries spread over four continents, primarily in North Africa, Middle East, and Central Asia, including Malaysia and Indonesia. SMIIC is the designated organization for the development of standards under the OIC countries. The OIC/SMIIC provides a unified and similar framework of standards and methodologies for certification, accreditation, and laboratory services, therefore, facilitate the commercial exchanges among its members (Halim & Mahyeddin, 2012). Although Malaysia and Indonesia are the OIC members, both countries have their own halal standards. The halal standard authority of Indonesia is *Lembaga Pengkajian Pangan Obat-obatan dan Makanan, under the Majelis Ulama Indonesia* (LLPOM MUI). They issued several halal assurance systems (HAS) such as HAS 23103: 2012 Guidelines of halal assurance system criteria on slaughterhouses; HAS 23201: 2012 Requirements of halal food materials; and HAS 23000-1: 2021 Requirements for halal certification, (LLPOM MUI, 2012a; 2012b; 2021). The halal standard of Malaysia, MS 1500: 2019 Halal food - General requirements was issued by the Department of Standard Malaysia with the involvement of various halal stakeholders such as Department of Islamic Development Malaysia (JAKIM), industries and academia (DSM, 2019a). The Malaysian standards have been considered as a model for halal certification by the Codex Alimentarius Commission and have been used as the basis of halal standards in many other countries (Al-Tienaz et al., 2020).

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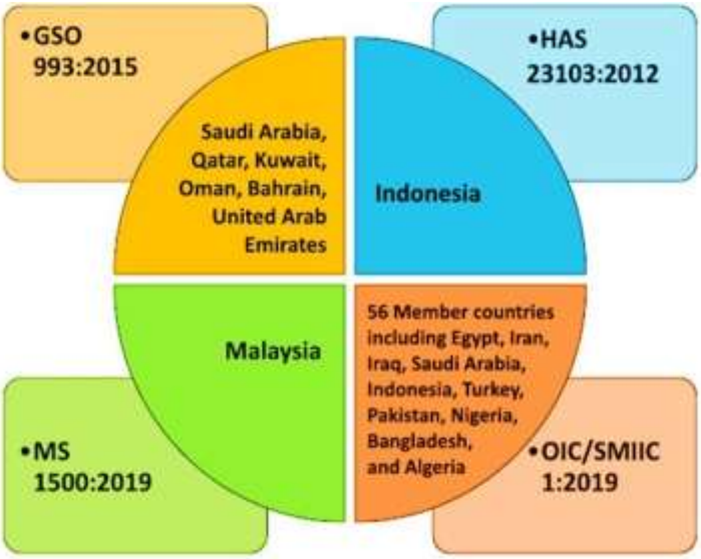

Figure 1: The major halal international standards in Islamic countries (Source: Aithal & Aithal, 2021a).

The stringent requirements of halal products certification can be generally divided into *Shariah* and *Tayyib* compliance. The *Shariah* aspects involve the sources or origin of the food and slaughtering procedures, while the *Tayyib* aspects deal with the product processing, handling and distribution, product storage, display and servings, hygiene, sanitation, and food safety, as well as packaging and labelling.

Shariah Compliance

The *Shariah* law is the communication from Allah concerning the conduct of the *mukallaf* (accountable person who are required to comply with the rulings of *Shariah*), which consists of a demand (commandments and prohibitions) and option or an enactment. Under the law, all sources of food from animal and plant origins are lawful except from the following sources, including their products and derivatives. The non-halal food sources are elaborated in MS 1500: 2019 which are (a) pigs and boars, (b) dogs, snakes and monkeys, (c) carnivorous animals with claws and fangs, such as lions, tigers, bears and other similar animals, (d) birds of prey with claws, such as eagles, vultures, and other similar birds, (e) pests, such as rats, centipedes, scorpions and other similar animals, (f) animals forbidden to be killed in Islam, such as ants, bees, and woodpecker birds, (g) animals, which are considered generally repulsive, such as lice, flies, maggots, and other similar animals, (h) animals that live both on land and in water, such as frogs, crocodiles, and other similar animals, (i) mules and domestic donkeys, (j) all poisonous and hazardous aquatic animals, (k) any other animals not slaughtered according to the Islamic Law, (l) blood, and (m) intoxicating and hazardous plants except where the toxin or hazard can be eliminated during processing (DSM, 2019a).

Alcoholic drinks whether derived through fermentation or distilled alcoholic drinks, which alter the consciousness, including all forms of intoxicating and hazardous drinks are forbidden. However, some halal standards allow the alcohol or ethanol content with a concentration of less than 0.1 % in the finished product. According to the *Muzakarah* of Fatwa Committee of the National Council for Islamic Religious Affairs Malaysia, food or drinks that naturally contain alcohol, for example, fruits, nuts or grains and its extract, or if the alcohol is produced as a by-product of the food or drink-making process is permissible to be consumed. Similarly, foods or drinks that contain added flavor or coloring that contains alcohol as a stabilizer is permissible if it is not produced from the process of making liquor and the alcohol percentage content in the final product is not more than 0.5 % (Umar Mukhtar, 2019).

The Islamic *Shariah* defines the specific conditions for the prescribed method of ritual slaughtering of halal animals. To meet the halal requirements, Allah ordains that animal species must be slaughtered by a Muslim who is knowledgeable of the Islamic slaughtering procedures. The animal to be slaughtered should be alive at the time of slaughtering. The invocation of the *Bismillah* phrase should be recited before the slaughter. The knife or slaughtering device used must be sharp and should not be lifted off the animal during the slaughtering act. The cut of the animal neck should sever the trachea, esophagus, and main arteries and veins. Prior to slaughtering, the animal's welfare with humane treatments must be practiced (JAKIM, 2008).

Tayyib Compliance

Besides abiding to the *Shariah* law, the quality and safety of the food produced must be ascertain. *Tayyib* reflects a quality standard to ensure the halal food is safe for human consumption, non-poisonous, and non-hazardous to human health. In food production generally, there are various food safety standards or quality assurance systems (QAS) that are utilized. Among the common QAS used are the Good Manufacturing Practices (GMP), Good Hygiene Practices (GHP), Hazard Analysis Critical Control Points (HACCP), Codex Alimentarius and many more (Ahmad et al., 2018). The halal certification system has the same requirement as the other existing QAS as it provides a way to ensure the safety, health level as well as the quality of the products.

The Malaysia Halal Management System (MHMS, 2020) is an integrated management system that is developed, implemented, and maintained by an organization or company to manage the products and services and to guarantee the halal status. For a large and medium industry, a Halal Assurance System (HAS) is used while for micro and small industry, Internal Halal Control System (IHCS) is to be set up. HAS and IHCS is a tool of halal manufacturing quality assurance, which can assist to ensure and preserve halal integrity of the halal industry manufacturing activities. The system is intended to be used from the beginning of the process until the end of the production line. HAS consists of seven importance principles, which are: Identification of halal potential contaminant and/or precursor, determination of control measures, determination of Halal Control Point (HCP), determination of monitoring system for HCP, determination of corrective actions for HCP, determination of verification procedures and documentation system and management of records (DSM, 2019b). A comprehensive HCP analysis is used to make halal decision based on the HCP risk ranking matrix of likelihood (likely, moderate, unlikely) and severity or impact (critical, moderate, insignificant) of the halal potential contaminant and/or precursor. Therefore, the halal auditor assigned for halal inspection at a certain industry must be knowledgeable with scientific and technical competence on the processing method and procedure used by the industry. This is to ensure that the quality and safety aspects are scrutinized thoroughly.

Another factor of quality assurance observed in the halal food industry is related to ethical issues, which include environmental pollutions from processing by-products or waste, animal cruelty, and intentional food contamination with hazardous substances (Ahmad Jamil et al. (2021).

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Nanotechnology in Food Products

The implementation of nanotechnology in agriculture, food processing, and preservation sector is tremendous. The functional properties of the nanotechnology are utilized to enhance food quality, shelf-life extension, safety from pathogenic microbes, physical and mechanical properties enhancement of food packaging materials, and food security by product tracking throughout the supply chain among many others. Smart food, smart packaging, nano-capsules, and nano-robot food production are the various ways, in which nanotechnology are implemented by the food companies (Jagtiani, 2021; Lugani et al., 2021a; Prasad et al., 2022; Pusparaj et al., 2022). Specific applications of engineered nanomaterials, such as nano-tubes, nanofibers, and metal/metal oxide nanoparticles are found in food processing and preservation, food packaging, detection of pathogens in food samples, and production and controlled delivery of nutraceuticals, while nano-devices, nano-switches, electronic nose, nano-chips, and biosensor are used in the smart sensing and unique delivery system (Lugani et al., 2021b).

Food ingredients in nano-sized are normally intentionally added directly into food, while nanoparticles or nano-sensors are embedded in the food packaging material. Examples of nanoproducts available in the food market are shown in Table 1. The various applications of nanotechnology in the food industries are illustrated schematically by Lugani et al. (2021b) as shown in Figure 2. There is also a possibility of an unintentional present of nanomaterials, such as from contamination or through migration from food contact materials, such as processing machinery, utensils, and devices or from nano-engineered pesticides used in agricultural activities (Couch et al., 2016).

Table 1: Nano products from food industry available in the market (Source: Lugani et al., 2021a)

Nanomaterial	Improved product functionality	Manufacturer	Trademark/Commercial name of product
Silver nanoparticles (Ag NPs)	Enhanced antibacterial properties	Baby dream	Nano silver baby mug
Ag NPs	Possesses antibacterial property which keeps food fresher for longer time	New life Co., Ltd.	Everin Food Containers Nanosilver Airtight
Ag NPs	Prevents food from dirt, remove foul smell, and inhibits germ growth	Dai Dong Tien Co.	Sina Antibacterial Food Storages
Silica-mineral hydride complex	Increased potency and bioavailability, and acts as powerful antioxidant	RBC Lifesciences	Mycrohydrin powder
Silver-base zeolite	Antimicrobial (bacterial, yeasts, and molds) property	Sinanen Zeomic Co., Ltd.	Zeomic
Iron oxide NPs	Increased reactivity and bioavailability	Toddle health	Oat chocolate Nutritional drink mix
Nanoclay	Cost effective material with easy processing, and maintaining barrier properties	Mitsubishi gas Chemical Company, Inc.	Imperm Nylon Nanocomposite
Silica NPs in polymer-based nanocomposites	Enhance shelf-life of product by preventing the penetration of oxygen	Bayer	Durethan KU 2-2601 plastic wrapping

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Figure 2: Nanotechnology application in food sector (Source: Lugani et al., 2021b)

Nanotechnology has many applications and is considered as a multidisciplinary frontier technology; however, its commercialization process is hindered by its nanotoxicity risks. Some of the adverse effects associated to a prolonged use of nanoparticles are environmental poisoning, toxicity in various human organs, altered cell morphology, allergic reactions, hypersensitivity reactions, and carcinogenic effects (Bumbudsanpharoke & Ko, 2015).

Nanotoxicity

Nanotoxicology is the scientific field dealing with nanomaterial concentrations that cause unintended effects of toxicity to non-target cells, organs, or organisms proven through clinical investigations (Bondarenko et al., 2021). Nanotoxicological mechanisms begin with the overproduction of reactive oxidative species (ROS) in the affected organisms as the main cause for a cellular damage and death (He et al., 2014a). The presence of excessive ROS and the subsequent accumulation of ROS lead to oxidative stress, autophagy (Khan et al., 2012), neuron damage (Long et al., 2007), severe damage to DNA (He et al., 2014b; Singh et al., 2009), and potentially mutagenesis, carcinogenesis, and aging-related diseases in humans. Due to their small size, nanomaterials are capable of overcoming the blood brain barrier, which gives them an easy access to most organs (Bai et al., 2018). Besides ROS, metal ions released from nanomaterials may pose adverse effects of allergic reactions (He et al., 2016).

It was initially believed that the size of nanomaterial is the cause of toxicity since an inert element, such as gold can become highly reactive at the nanometer dimension. However, contradicting results were obtained in investigations on the toxicity of nano-sized materials (Bondarenko et al., 2021). Some studies prove that smaller nanoparticles possess higher toxicity

(Ariano et al., 2011; Bhattaachatjee & Chakraborti, 2012), while other investigations have shown otherwise (Carlson et al., 2008; Pinto et al., 2016).

Other than size, other properties of nanomaterials that influence toxicity include chemical composition, shape, surface area, surface structure, surface charges, aggregation and solubility, presence or absence of functional groups of other chemicals, pH of the medium, metal ions released from nano metals/nano metal oxides, UV light activation, and also mode of interaction with cells (Aithal & Aithal, 2021a, Donaldson & Poland, 2013; Stone et al., 2007). The nanoparticles ingested through food and drink may lead to toxicity to the human body and cause several associated diseases, such as stomach and colon cancer, Crohn's disease, arrhythmia, asthma, lung cancer, autoimmune diseases, and neurological disease. The factory workers at the nanomaterials production facility may also be exposed to the nanomaterials through inhalation and skin absorption. In the case of inhalation, the nanoparticles may enter through the lungs, and subsequently, enter the bloodstream, and consequently cause heart related problems (Aithal & Aithal, 2021a).

The environmental related risks of nanomaterials may come from the unused nanoparticles or waste nanomaterials during synthesis. For example, unused silver nanoparticles if mishandled may contaminate sewage sludge and affect the microorganisms in the soil of agricultural fields or affects the marine animals in the river and ocean. At high concentration, these particles may agglomerate to form into a larger particles or longer chain, thus having an altered physical, chemical, and biological properties than the initial nano-sized particles (Aithal & Aithal, 2021a). The possibility of nano-agglomeration in the environment may exist and the impact of its altered states is unknown.

Nanomaterials are classified into two main categories, (1) organic (from natural sources, such as vitamins, fatty acids, lipoproteins, minerals) and (2) inorganic (from metal and metal oxides, such as silver, titanium dioxide, zinc dioxide, silicon dioxide, and iron oxide). There are also nanomaterials with a combination of both organic and inorganic, for example, clay. The sources of organic nanomaterials derived from nature, such as mineral oxide was initially regarded as biologically inactive and physiologically inert and was, therefore, deemed as harmless to humans and animals (Kang et al., 2008). However, further studies have reported that the use of nanoparticles TiO_2 causes pulmonary inflammation, fibrosis, epithelial hyperplasia, and tumorigenesis observed in animals and a lung burden due to a sufficiently high dose and/or duration of exposure of substantial TiO_2 nanoparticles (ILSI, 2000; NIOSH, 2011). These findings lead to the reassessment of nanoparticles TiO_2 as "possibly carcinogenic to humans" on the basis of the sufficient evidence of carcinogenicity in experimental animals and inadequate evidence in humans (IARC, 2010).

The increase in the surface area to volume ratio of nanomaterial is another factor associated to nanotoxicity. For example, the usage of nano-emulsion as food processing aid provides greater reactivity through an increase in absorption rates, however, it also increases the risk of overdosing and toxicity (Livney, 2009; Llorens et al., 2012). Exposure through inhalation of silica nanoparticle used as an anti-caking agent in powdered food products was found to be cytotoxic in human lung cells (Athinarayanan et al., 2014). The small size of engineered nanomaterials increases the risk for bioaccumulation within body organs and tissues, thus increase its severity at long-term interactions and higher exposure concentration (Chen et al., 2013). An inorganic source of non-toxic nanoparticle polystyrene was found able to be disrupted by an iron transport, and a chronic exposure causing changes in intestinal villi, therefore, affects the absorption of other nutrients (Mahler et al., 2012). Nanoclay is listed as generally recognized as safe (GRAS) and a widely used nanomaterial in packaging, since it possesses better mechanical, thermal, corrosion resistance, and barrier properties as well as economical (He et al., 2019). Nonetheless, several studies have shown the potential migration risks of nano-clay into food (Echegoyen et al., 2016; Huang et al., 2015).

Another factor determining toxicity is the synthesis approach and methodology used to produce nanomaterials. In this case, the source of toxicity could be the harsh production environment, noxious reducing agents, toxic solvents, lethal intermediates, or harmful by-products (Bai et al., 2018). For this matter, the principles of green chemistry of the nanomaterials synthesis approaches may be introduced to deliver safer nanomaterials.

Malaysia Halal Regulatory Approaches to Nanotechnology

In Malaysia, JAKIM together with the Islamic Religious Departments (JAIN) or the State Islamic Religious Councils (MAIN) are entrusted to examine and certify foods and non-food products for consumption of Muslim consumers and to issue the Halal certification. JAKIM/JAIN/MAIN are responsible to carry out a halal audit and halal monitoring across the country. However, their ability to exert a full control in the cases of halal violation, such as abuse of Halal certificates, is limited. They cannot be involved in the enforcement activities without the presence of the officials from the Ministry of Domestic, Trade and Consumer Affairs. The governance of legal controls over halal products is assigned to the Ministry under the general provisions of the Trade Description Act 2011. Supplementary to the law is the subsidiary legislations relating to the Halal enforcement: The Trade Description (Definition of Halal) Order 2011 and Trade Description (Certification and Marking of Halal) Order 2011 (Awang & Zakaria, 2019).

The basic principle of halal regulation is similar whether nanotechnology-derived ingredients or additives was used in the food itself, used to facilitate in processing or used to enhance quality and shelf-life of the food products. This means that the halal product must still remain safe, nutritious with the desired quality, and safe with no potential risk to the health of consumers (*Tayyib*).

In Malaysia, the safety governance for food products is under the jurisdiction of the Food Safety and Quality Division, Ministry of Health (MOH). The safety of food products from preparation to production is captured in Section 13 of the Food Act 1983. For imported food products, Regulation 3A of the Food Regulation 1985 applies (Food Act 1983 & Food Regulation) which requires the import, preparation or advertisement for sale or selling of food products obtained through a modern technology to acquire the written approval of MOH. In terms of the safety standard or specification to nano-incorporated food products, the challenge for MOH is to decide on the acceptable level of risk. In the case of food additives, the determination of what is safe lies in the types of the additives. The criteria inform the limits by the reference to quantity. There is no denotation regarding its particle size or characteristics of particulate materials. Currently, there are no maximum residue limits (MRLs) specified for nano-based food products or foodstuffs. In most cases regarding food regulatory, MOH will seek information from other countries if the nanotechnology application and nano-incorporated food products are to be regulated (Awang & Zakaria, 2019).

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Safety Regulation on the Use of Nanomaterials

In the other parts of the world, the safety regulation on the use of nanomaterials lies on the major regulatory bodies, which are the European Food and Safety Authority (EFSA), National Institute for Occupational Safety and Health (NIOSH), Environmental Protection Agency (EPA), Food and Drug Administration (FDA) US Patent and Trademark Office (USPTO), Consumer Product Safety Commission (CPSC), US Department of Agriculture (USDA), and Occupational Safety and Health Administration (OSHA) (Qi et al., 2004). For European Union (EU) regulations for food and food packaging, EFSA has recommended that nano-foods should meet the recommended specific risk assessment and safety standards, of which this means that nanofoods must undergo a safety assessment before being authorized for use and introduced to the market (Halliday, 2007; Cubadda et al., 2013). It is also stated in the Framework 1935/2004 regulations set by EFSA that there shall be no change in inherent and organoleptic properties of food by substances incorporated in foods. Additionally, the EFSA regulations state that the heavy metals and mycotoxins free approach needs to be incorporated for designing nanomaterials (nanoparticles/quantum dots/nano-tubes/nano-wires/nano-clay) before their use in the food industry (EU Commission Regulation, 2011; Silva et al., 2012).

Green Nanotechnology

Green nanotechnology involves utilising the green chemistry concepts in nanotechnology for the sustainable, safe, economical, and eco-friendly production of nanomaterials (Bai et al., 2018). The green chemistry is defined by 12 major principles developed by Anastas & Warner (1998) as presented in Table 2. According to Aithal & Aithal (2021a), green nanotechnology deals with processes of preparation, large-scale manufacturing, and industrial use of nanomaterials by minimising environmental degradation and potential risks of health hazards. The ultimate goal of green nanotechnology is to minimize the hazardous effects of nanomaterials by introducing green principles in the synthesis, handling, and application of nanomaterials and, therefore, produces safer, nontoxic, natural and bio-compatible materials. Similarly, Nazrolzadeh et al. (2019) state that the use of plant-derived nanoparticles can decrease their toxicity besides improving the dissolution and bioavailability of the medicinal therapeutic compounds. Table 3 shows the green chemistry principles of green nanomaterials design and practice in the food industry and environmental applications.

Table 2: Twelve major principles of green chemistry (Source: Anastas & Warner, 1998)

No.	Principle	Remarks
1	Prevention	Better to prevent generating waste than to clean up
2	Atom economy	Synthetic methods should maximize the incorporation of all materials used in the process into the final product
3	Less hazardous chemical syntheses	Alternative synthetic methods should be devised to generate substances with little or no toxicity to health or the environment
4	Designing safer chemicals	Chemical products should be designed to achieve their functions with minimized toxicity
5	Safer solvents and auxiliaries	When possible, auxiliary substances should substitute from harsh solvents, separation agents, etc.
6	Design for energy efficiency	Experiments should be designed to be conducted at ambient temperature and pressure to minimized energy use and environment impact
7	Renewable feedstocks	Renewable. Raw materials/feedstocks should be used, when technically and economically feasible

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8	Reduce derivatives	Needless derivatizations (physical/chemical processes) should be avoided to prevent the use of additional reagents and generation of waste
9	Catalysis	Catalytic reagents are superior to stoichiometric reagents and should be used
10	Design for degradation	Chemical products should be designed to innocuously degrade at the end of their function with minimal environmental impact
11	Real-time analysis for pollution prevention	Analytical methodologies should be developed real-time, in-process monitoring and control prior to the formation of hazardous substances
12	Inherently safer chemistry for accident prevention	Substances that are used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires

Table 3: Green chemistry in the design of green nanomaterials (Source: Bai et al., 2018)

Design	Green chemistry principle
Safer nanomaterials	Evaluating the biological properties of nanomaterials (size, structure, and surface functionality), focusing on the desired characteristics, and using safe raw materials.
Reduce environmental impact	Analyzing the degradation properties of nanomaterials, the toxicity of the degraded subunits, and the use of biosynthesis approaches.
Prevent waste	Eliminating the use of solvents for purification, developing alternative purification methods (nanofiltration), and limiting the generation of unwanted derivatives or by-products.
Ensure process safety and efficiency	Using benign reagents and renewable feedstocks as well as replacing toxic reagents and solvents. Optimizing process parameters at ambient conditions and real time monitoring options to reduce time and other resources during the reaction.
Enhance materials efficiency	Utilizing novel synthesis approaches, optimizing novel benign raw materials/solvents, and real time monitoring of nanomaterial synthesis.

The health implications of green chemistry in nanomaterial fabrication encompass a range of factors starting with solvent selection, using a renewable, biocompatible, and eco-friendly solvent in the nanofabrication process. Many of the serious concerns related to nanotoxicology could be addressed through the green nanotechnology. This could be obtained through design modifications of material synthesis to greatly improve nanomaterials safety level. The green chemical approaches could indirectly minimize the cost of production, reduce energy and amount of raw materials, eliminate the use of harsh chemicals, prevent waste formation, and minimize unnecessary intermediates, of which will increase the process efficiency. The utilization of biomass to prepare nanomaterials could also become a feasible solution for waste management along with the utilization of resources with the recycle or reuse provisions (Ibrahim et al., 2015; Jagtap & Bapat, 2013; Paul et al., 2015). The adoption of biogenic synthesis approaches has increasingly raised product quality to a safer level.

Research on Green Nanomaterials Synthesis and Application

There are many green synthesis protocols using the green chemistry principles for the preparations of nanoparticles have been researched with successful outcome. Several studies have shown that nanomaterial produced using the green nanotechnology processes are more biocompatible, can be safely consumed and absorbed in the body and serve better therapeutic functional purposes (Gopi et al., 2016). A systematic review of the recent studies of green nanotechnology was

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published by Aithal & Aithal (2021a) as shown in Table 4. The area of the research work includes green production of nanomaterials, nanomaterials for agriculture and food industries, also nanomaterials for potable water and clean environment industries. Looking at the initiatives and efforts on applying the green synthesis methods, it is therefore possible to produce a safer nanomaterial for living beings and the environment. In this case, a halal nano-ingredients that complies to the halal requirements for the halal food industry is also possible.

Table 4: The scholarly publications related to green nanotechnology in the year 2015 – 2020

Area of research work	Issue and Outcome	Publication author
Green production of nanomaterials	Green production of carbon nanomaterials	Rezaei & Kamali (2018)
	Green nanotechnology of Au particles from plant extracts	Geraldes et al. (2016)
	Green manufacturing of ultrapure engineered nanomaterials	Ortiz de Zárate et al. (2020)
	Green synthesis of iron nanoparticles	Saif et al. (2016)
	Green approach for the production of zinc oxide nanoparticles	Al-Dhabi & Valan Arasu (2018)
Nanomaterials for Agriculture and Food industries	Nanomaterials in food and agriculture: Safety Concerns and regulatory issues	Jain et al. (2018)
	Nanosensors applications in agriculture and food industry	Omanović-Mikličanina et al. (2016)
	Frameworks and tools for risk assessment of manufactured nanomaterials	Hristozov et al. (2016)
	Nanomaterials in plant protection	Mazzaglia et al. (2017)
	Nanomaterials for food packaging	Huang et al. (2018)
	Nanotechnology in precision agriculture	Duhan et al. (2017)
Nanomaterials for potable water and Clean Environment Industries	Ideal water purifier system using nanotechnology	Aithal & Aithal (2018b)
	Nanotechnology for water treatment - a green approach	Patanjali et al. (2019)
	Synthesis and applications of biogenic nanomaterials in drinking and wastewater treatment	Gautam et al. (2019)
	Remediation of water and wastewater by using engineered nanomaterials	Bishoge et al. (2018)
	Nanotechnology applicability in industrial wastewater treatment	Kamali et al. (2019)
	New generation nanomaterials for water desalination	Teow & Mohammad (2019)
	Engineered nanomaterials for water treatment and remediation	Adeleye et al. (2016)
	Sustainable development of environment using green nanomaterials	Sivaraj et al. (2016)
	Environmental risk assessment of nano- TiO_2, nano-Ag, nano-ZnO, carbon nanotube, and fullerenes	Coll et. al. (2016)

Challenges and limitations of Green Nanotechnology

There are a few challenges in adopting green chemistry to fabricate a green nanomaterial for commercialization. The foremost challenge is the practical application of the green chemistry principles (Wardencki et al., 2005). A clear guideline must be designed together with

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the specific requirements for the development and production of green nanomaterials (Bai et al., 2018). Prior to generating a regulatory guideline, an experimental protocol should be established for each specific nanomaterial on its application in agriculture, food and environment thus ensure the safer usage of nanoparticles in the industry (Jain et al., 2018). The assessment of risks, benefits and ethical issues depend on several factors, not only related with the composition and nanomaterials synthesis, but also with the specific area of application, methods of deployment, and final goals. According to Fajardo et al. (2022), no standard regulatory laws related to the use of nanotechnology in food and agricultural sector have been implemented which is the major limitation in the implementation of nanotechnology. The actual legislation remains at the initial stage of development, covering only general approaches related to nanomaterials and nanotechnology.

Another concern is the efficiency of recycling and reusing the green inputs used in synthesis approaches (Wong & Karn, 2012). Similar to the production of nanomaterials, the guideline and legislation for the management of nano-waste does not exist (Karlaganis et al., 2019). Another issue faced in the green nanotechnology is the broad definition of sustainability, which strains the economic feasibility of the approach. Not limited to the conventional synthesis, a comprehensive assessment of green synthesis of nanomaterials also must be conducted to find possibilities of negative impacts hence proves their no risks or very minimal risks on health and environment. A life cycle assessment needs to be performed rigorously for all types of industry while for a food industry, the green nano-incorporated product shelf-life assessment. One of the green chemistry principles is to decrease energy requirements and minimize energy wastage, which will pose a great challenge when implementing the green nano-production methodologies.

Other challenges that may hinder the execution of green nanotechnology or the use of novel green benign technologies is the acceptance by the industry itself. The adaptation of the technology will involve renovation in process design and equipment, implementation of new regulatory as well as economic constraints (Lu & Ozcan, 2015).

Conclusion

The progress in nanotechnology coupled with the green chemistry methodologies will enable the production of a safer food product containing nanomaterials and a sustainable future environment is achievable. In the case of halal certification, the proof of green synthesis of the nano-sized food ingredients or processing aids must be validated. As long as all the resources used in the fabrication of the nanomaterials are *Shariah* compliance then the halal threat is eliminated. However, a comprehensive risk assessment must be conducted to ascertain the safety or health hazards implication of the nanomaterial in order to be *Tayyib* compliance. If both *Shariah* and *Tayyib* compliance are met, then the halal inspection of nano-products can be carried out similar to other conventional halal foods. Generally, an effective policies and guidelines are needed for the safer usage of nanoparticles in the industry. However, the applications of nanomaterials are hindered by the lack and inconclusive toxicological data to prove the nanotoxicity impacts on humans as well as the environment. Therefore, the regulatory authority body must work closely with the scientific community to expedite the nanotoxicity assessment and solve the environment and other living being's ethical issues before a policy, rules, or guidelines could be established.

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