Nanotechnology Applications in Crop Production and Food Systems

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Global food insecurities, climate change, and population increments exert enormous pressure on the existing agro-food systems. The aforementioned constraints call for the adoption of novel and result-oriented scientific innovations. Nanotechnology is an emerging and promising innovation with a great potential to significantly and sustainably promote enhanced agricultural productivity and proliferate the efficiency of food systems. Nanotechnology is the manipulation of matter at atomic and molecular levels in the production of specialized microscale-based products or devices. The application of nanotechnology in agriculture encompasses; nutrition management, insect pest and disease control, precision farming, plant breeding, and waste management. On the other hand, nanotechnology is also being applied in all facets of food systems including; production, processing, transportation, and packaging. Despite the wide applicability of nanotechnologies, elevating concerns on their potential health and environmental risks continue to sway among consumers and policymakers. Furthermore, the absence of a defined and complete global regulatory standard and framework for nanotechnology utilization derail its wide adoption and acceptability. The main thrust of this review is to present in summary the numerous nanotechnological applications in agriculture and food industries paying particular attention to the current technological trends, potential benefits, associated risks, and the future outlook.

Keywords: Nanotechnology, Agro-food Systems, Food Insecurities, Climate Change, Scientific Innovations

INTRODUCTION

Nanotechnology is the scientific study, creation, design, manipulation, synthesis, and application of devices, functional materials, and systems through controlling matter at a nanometer scale (1–100 nm), and exploiting its properties and novel phenomena at that scale (Salamanca-Buentello et al., 2005). Nanotechnology integrates a different range of applied sciences such as chemistry, physics, biology, medicine and engineering to produce materials possessing unique properties such as high surface area, target site of action and slow release of particular elements (Ghidan and Antary, 2019;Huang et al., 2015;Joshi et al., 2019;Kalpana Sastry et al., 2012;Khan and Rizvi, 2014;Nikalje, 2015). Research studies are currently taking heed of the multifaceted attributes of nanotechnologies and exploiting them for enhancing crop production and improving food systems.

The agricultural industry is always changing thereby creating both opportunities and challenges for the present and future generations (Sabourin and Ayande, 2015). At the present moment, climate change is negatively affecting crop productivity across the world as evidenced by the negative slopping trend in crop yields. The application of nanotechnologies in agriculture can promote the realization of food security in light of the projected increments in the global population. Meetoo (2011) asserted that, nanotechnology provides a sustainable solution to agricultural production constraints in natural

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resource depleted communities. Sabourin and Ayande (2015) stated that, the adoption of nanotechnology can promote development and transformation in the food sector, enhance agricultural productivity, and industrial economic growth by a 30% margin (Average: US$0.9 trillion). The high potential nature of nanotechnology render it more suitable for less-developed countries and economies (Rashidi and Khosravi-Darani, 2011). Furthermore, the adoption of nanotechnology can increase the competitiveness of the agricultural industry and boost its annual growth rate (Sabourin and Ayande, 2015). The main thrust of nanotechnologies in agriculture is to minimize the use of pesticides and fertilizers; to reduce nutrient losses during fertilization and; to increase overall yield margins of cultivated crops through optimal nutrient management (Chung et al., 2018; Abobatta, 2018). Prominent industry players such as Syngenta, BASF, Monsanto, Cargill, and Bayer Crop Science are currently undertaking research and commercialization of nano-derived agrochemicals and seeds (Lyons, 2010).

However, the future impacts of nanotechnology to agriculture, health and safety is of prime interest and debate among the concerned stakeholders especially upon mirroring on similar issues and concerns raised on some previously implemented emerging technologies (Chung et al., 2017; Roco et al., 2011). The potential risk to human health, animals and the environment should be assessed and prioritized (Dimitrijevic et al., 2015). Meetoo (2011) asserted that, no regulatory or statutory standards have been put in place on the global market to ensure proper labeling of all food products containing nanoparticles. Despite the concerns on the potential risk of some nanomaterials, nanotechnology remains a sustainable and a significant alternative in bringing change and increasing the efficiency of agricultural and food systems (Elemike et al., 2019).

**Objectives of this Review**

a) To outline the applications of nanotechnologies in the agricultural and food industries, and;

b) To assess the adoption implications and future potential of nanotechnology in agricultural and food systems.

**Application of Nanotechnology in Agriculture**

Agricultural applications of nanotechnology have been widely reported via numerous platforms over the years. Joshi et al. (2019) highlighted that, the main purpose of nanotechnology in agriculture is to minimize the volume of spread chemicals, reduce nutrient losses during fertilization, and increase the crop yield through nutrient and pest management. Additionally, nanotechnology enhances the performance and acceptability of agricultural technologies by increasing their effectiveness and safety in use (Iavicoli et al., 2017; Rawat et al., 2018; Srlatha, 2011).

**Nutrient Management**

Nanotechnology is utilized for nutrient management in cropping systems through nanotechnological applications such as nanofertilizers, nanocoating, nanoclays, zeolites, growth regulators and zerovalent particles. Mikkelsen (2018) underscored that, nanofertilizers are classified into three main classes namely: (a) nanoscale fertilizers (nanomaterials containing nutrients); (b) nanoscale coating (nanoparticles coated or loaded on traditional fertilizers i.e. nanocoating) and; (c) nanoscale additives (nanoscale additives mixed with traditional fertilizers). Nanofertilizers have a high surface area and high supply at an active site which increase their absorption rates by plants and ultimately help in minimizing environmental pollution (El-Ghamry et al., 2018; Joshi et al., 2019). Nanofertilizers (e.g., zeolites and nanoclays) slowly release nutrients throughout the life cycle of the crop thereby reducing the risks of leaching, adsorption, surface runoff and decomposition (Joshi et al., 2019). Zeolites are naturally occurring minerals that have a honeycomb-like layered crystal structure which can be loaded with macronutrients and essential micronutrients needed for plant growth (Joshi et al., 2019). The slow mineral release nature of zeolites enhances the nutrient use efficiency rates of crops. Essential micronutrients may also be foliar applied through nanotechnology.

Cieschi et al. (2019) conducted an iron availability experiment with three iron-humic nanofertilizers ($^{57}$Fe-NFs) on a calcareous soil pot trial under growth chamber conditions. The research compared the iron nutrition contribution of the three hybrid nanomaterials in iron-deficient soybean plants. The nanofertilizers allowed continuous iron uptake and exhibited high shoot fresh weight. Jannmohammadi et al. (2017) also carried out an experiment to compare the effects of nanostructured fertilizers (Mn, Zn, Fe) and farmyard manure (Zero (M), 20 (M$_2$) t/ha) on agronomical attributes and yield of common sunflower (Helianthus annuus L.). The study exhibited the best performance levels from the nanochelated Zn and manure combination treatments.
Furthermore, Fe and Zn application increased achene yield, oil concentration and the harvest index of sunflower. Furthermore, Kale and Gawade (2016) evaluated the effect of combining N (15%): P (15%): K (15%) and ZnO nanoparticles (ZnO NP) on brinjal (Solanum melongena L) growth attributes. The research concluded that, the combination increased yield and biomass of brinjal by 38% and 21% respectively.

**Nanocoating** is one of the most common strategies utilized in nano-nutrient supplementation. In this procedure, traditional fertilizers are coated with nanoparticles to enhance their stability in the soil and absorption coefficients by plants. Nanocoated fertilizers have low dissolution rates in the soil (Duhan et al., 2017) which increases their soil lifespan and availability for plant uptake. A good example of a nanocoated fertilizer is the Slow-soluble Released fertilizers (SRFs). SRFs are made by coating the traditional fertilizer granules with nanomaterials which promote the slow release of nutrients for plant uptake (Fawzy et al., 2018). Nanocoating nitrogen and phosphate fertilizers will be beneficial in meeting the crop and soil demands (Duhan et al., 2017). The release of nutrients as per crop requirements can also be regulated through the use of **nanotubes** (Fawzy et al., 2018). Nanotubes are organic or inorganic atomic sheets arranged in a tube structure which can be loaded with plant nutrients.

**Nanoencapsulation** is the technology of loading liquid, solid or gas nanoparticles in a secondary matrix to form nanocapsules. Nanoencapsulation plays a pivotal role in protecting the environment by reducing evaporation and leaching of harmful substances (Duhan et al., 2017). Nanoencapsulated fertilizers are characterized by their slow release of nutrients for plant uptake properties (as shown in Fig 1 and 3). Chitosan and Carrageenan are secondary nano-materials that are normally used in encapsulating fertilizers, pesticides or herbicides. Duhan et al. (2017) highlighted that, the addition of nitrogen, phosphorus and potassium was found to increase the stability of the chitosan-polymethacrylic acid (CS-PMAA) colloidal suspension.

Nanoencapsulation can be utilized for ensuring the availability of ions in plant utilisable forms and at rates suitable for plant growth (Mukhopadhyay, 2014). Mukhopadhyay (2014) explained that, the ion adsorption, surface area, cation exchange capacity (CEC), and complexation functions of clays might be multiplied further when brought to a nanoscale. The ability of soils to hold on to nutrients is enhanced by the increase in CEC. Furthermore, the application of **zerovalent particles** of iron with high adsorption affinity for organic compounds can also be harnessed for soil remediation in pesticides contaminated arable lands (Mukhopadhyay, 2014). Furthermore, compounds of Titanium and Silicon nanoparticles have been found to enhance the nitrate reductase action and the absorption capacity to water and fertilizer in soybean plants (Ali et al., 2018).

**Plant regulators** such as nano-5 and Nano-Gro are also being produced to enhance the hormonal effects in plants (Joshi et al., 2019). Syngenta has been selling a nanofORMULATED plant growth regulator under the trade name Primo MAXX for several years (Miller and Senjen, 2008). Plant hormones are directly involved in all development processes and play a role in the ability of plants to absorb nutrients from the soil. However, the absorption efficiency and overall effects of nanomaterials on the metabolic functions and growth vary among plants (Duhan et al., 2017).

Figure 1: A Schematic Illustration of the Nutrient/Pesticide/ Herbicide Controlled Release Mechanism.
Adapted from: Duhan et al. (2017)

**Precision Agriculture**

Precision agriculture or farming is the development and utilization of wireless networking and miniaturization of sensors for assessing, monitoring, and controlling agricultural practices (Shang et al., 2019). It utilizes computers, GPS and remote sensing devices in measuring highly-localized environmental conditions and aid in determining crop growth efficiency and existing problems (Duhan et al., 2017). Precision farming decreases agricultural wastes thereby participating in minimizing environmental pollution (Anjum and Pradhan, 2018; Gul et al., 2014). Joshi et al. (2019) asserted that, precision agriculture will continue to benefit immensely from nanotechnology through enhanced nutrient absorption by plants, efficient and targeted utilization of inputs and disease detection. The application of nanomaterials in precision agriculture enhances the effectiveness of operations. Nanomaterials positively influence the level of crop productivity by enhancing the efficiency of agri-inputs utilization through site-targeted and controlled nutrient delivery facilitation (Shang et al., 2019). Joshi et al. (2019) stressed that; the integration of nanomaterials, remote sensing and the global positioning system (GPS) could hasten the detection of insect pest infestations or drought and nutrient deficiency stress incidences based on spectral images. Furthermore, the use of nanosensors in precision agriculture and...
Nanomaterials for site-specific water and soil conservation (e.g. Nano and Geohumus) helps in the efficient utilization of natural resources (Joshi et al., 2019).

Nanonetworks are also being used in advanced precision farming projects for monitoring and detection of various field-based profiles (Fig 2). A nanonetwork is a group of inter-connected nanomachines assembled to perform computing, sensing, data storage, and actuation. Nanonetworks gives automatic alerts on the input status or profile for efficient usage of fertilizers, pesticides, and water (Marchiol, 2018). The alerts provide a significant base for timely and accurate decision-making in sustainable crop production (Marchiol, 2018). Furthermore, wireless nanosensors are also being utilized to monitor crop disease incidences and growth rates, nutrient use efficiency, and field environmental conditions (He et al., 2019).

Fig 2: Nano-network System for Plant Monitoring Operations. Source: Marchiol (2018)

Pest and Disease Management

Nanotechnologies have been incorporated in pest (i.e. insects and weeds) and plant disease management research schemes targeting the timely detection and control in major crops. Nanomaterials of different forms have been shown to be efficient in pest and disease management (Anand and Bhagat, 2019). Nanotechnology in crop pest and disease management is applied via two mechanisms namely: (a) nanoparticles used as the main control agent (complete pesticides or part formulations), or (b) nanoparticles used as carriers of traditional pesticides (Worrall et al., 2018). Nanopesticides may be encapsulated in nanoparticles (Fig 3) to ensure the controlled release and, nano-emulsions for good control of pests (for example the Allosperse Delivery System), adjuvant and Nano revolution-2 (Joshi et al., 2019).

Fig 3: (a) Nanocapsule Model with macro/microelements. (b) Deposition after leaf-spray treatment. Source: Marchiol (2018)

Nanomaterials have been reported to control several diseases including powdery mildew in major crops such as pumpkin. Research experiments have also shown that fungal hyphae growth and conidial germination are inhibited significantly by nanomaterials especially silver and copper nanoparticles (Gul et al., 2014). Chitosan nanoparticles are a special product of nanotechnology.

Nanomaterials such as silver ions, polymeric nanoparticles, iron oxide and gold nanoparticles are currently used as pesticides (Ali et al., 2018). Silver nanoparticles (AgNPs) serves a dual purpose of plant disease management and plant growth enhancement (Anand and Bhagat, 2019). Nanosilver has a strong bactericidal and a broad-spectrum antimicrobial properties and controls spore-producing fungal pathogens (Agrawal and Rathore, 2014).

Nanopesticides have high permeability implying that less volume is required per application which ultimately translates to reduced costs (Fawzy et al., 2018). Nanopesticides also increase the wettability and dispersion of pesticide formulations thereby decreasing chemical runoff and unwanted pesticide movement (Handford et al., 2014). Microencapsulation (Fig 1) has been employed as a reliable tool for hydrophobic pesticides since it increases their dispersion in aqueous mediums and induces a controlled-release profile of the active compounds (He et al., 2019; Sekhon, 2014). The insecticide ethiprole contains Polylactic acid and polycaprolactone nanospheres as encapsulation agents (Sekhon, 2014). Bioefficacy studies of nanoescapsulated Imidacropid (1-(6 chloro-3-pyridinylmethyl)-N-nitro imidazolidin-2-ylideneamine) was conducted on whitefly (Bemisia tabaci Gennadius) and stem fly (Melanagromyza sojae Zehntmer) and exhibited better pest control in soybean (Sekhon, 2014). On the other hand, research has also reported that, herbicide penetration through tissues and cuticles can be enhanced through the use of nanocapsules which allow the slow and constant release of the active compounds (Sekhon, 2014).
which is being used for seed treatment and as a
biopesticide for fungal infections (Duhan et al., 2017). Furthermore, nano-coating seeds with elemental forms of Mn, Zn, Pt, Pa, Ag, and Au protect seeds from pathogen infestations (Agrawal and Rathore, 2014). Studies have also reported that, small-sized particles of sulfur nanoparticles (35 nm) have a high efficacy in preventing fungal growth in tomato, potato, grape and apple from different diseases in organic farming (Joshi et al., 2019). Furthermore, the use of capric oxide in controlling tomato diseases achieved 95% efficiency with very low concentrations as shown in experiments documented by Fawzy et al. (2018). Studies conducted on maize showed that, the application of nanosilica (20–40 nm) improved resistance against *Fusarium oxysporum* and *Aspergillus niger* (Duhan et al., 2017).

Spraying nanosilica has a positive influence on the feeding preference of *Spodoptera littoralis* on tomato plants thereby enhancing the resistance levels of plants (Gul et al., 2014). The spray affects the reproduction potential of insect females thereby promoting insect population density reductions (Gul et al., 2014). The effect of nano-glycerin has also been shown to be superior to that of normal glycerol in controlling pests over a short period of time in numerous crops (Fawzy et al., 2018). Nanoherbicides are currently being developed to offer a significant remedy to the problems in the management of perennial weeds and weed seed banks (Joshi et al., 2019). An example of a commercialized herbicide product developed through nanotechnology is Karate® ZEON which is a quick-release microencapsulated product composed of an active ingredient called lambda-cyhalothrin (Agrawal and Rathore, 2014).

Nanomaterials can be used in identifying pest and disease infestation in plants even before farmer identification (Chakraborty et al., 2015). Nano-based virus diagnostics such as the multiplexed diagnostic kit can detect exact strains of a virus and other pathogens (Joshi et al., 2019). The use of nanosensors which can detect pathogen levels as low as parts-per-billion (Joshi et al., 2019) has improved the efficiency of plant-disease detection experiments. Specifically, silver nanoparticles have recently been used effectively for detecting phytopathogens on seed and soil surfaces (Joshi et al., 2019). This timely detection and identification of phytopathogens is of greater importance in the control of plant diseases.

**Agronomy and Environmental Sensitivity**

Nanotechnology is also opening new avenues with a greater potential for enhancing agricultural productivity and promoting environmental sensitivity. Several research studies have presented the possibility of employing nanotechnologies in hydroponics production systems of vegetables and fruits (Ali et al., 2018). Hydroponics is a production system which encompasses the cultivation of plants in a soil-less media composed of nutrient-water solutions. The applications of nanoparticles in nutrient delivery, pest and disease control shape-up success and enhances the efficiency of a hydroponics system.

Researchers have also carried experiments on increasing seed germination through imbibing seeds in nano-encapsulations containing specific bacterial strains of *Pseudomonas* spp (Joshi et al., 2019). The experiments led to the development of Smart Seed varieties which are programmed to detect when the right conditions are available for germination (Joshi et al., 2019). Furthermore, the application of titanium dioxide (TiO2) on major food crops has been shown to promote plant growth, minimize disease severity and increase yield by a 30% margin (Agrawal and Rathore, 2014). Recent studies have begun exploring the utilization of nanoparticles in photosynthesis as synthetic probes in augmenting how plants use light (Swift et al., 2019).

Nanomaterials are also being used extensively in agricultural waste recycling initiatives across the globe. The Central Research Institute of Cotton in India developed a technology for the production of nanocellulose from agricultural residues. Scaling-up recycling initiatives should be on the frontline in the fight against environmental degradation and pollution. Nanotechnology is also promoting environmental remediation through the use of magnetic nanoparticles and nanofibers. Magnetic nanoparticles facilitate the removal of soil contaminants such as Hg, Zn and Pb (Joshi et al., 2019). Nanofibers are utilized in encapsulating chemical pesticides, for preventing the scattering of chemical components in the environment and ultimately reduce water and soil pollution (Mousavi and Rezaei, 2011). Moreover, nano-filtration and nano-particles are being utilized in providing a high possibility of refining and eliminating microbial contaminants in water with great speed and accuracy (Mousavi and Rezaei, 2011).

**Genetic Manipulation of Crops**

Nano-biotechnology provide a set of tools and technological platforms for improving agricultural productivity through genetic modification of plants and transportation of gene and drug molecules to specific locations at a cellular level (Ali et al., 2018). The incorporation of nanogenomics-based methods in plant breeding has enhanced precision in trait selection and gene transfer, and reduced the overall breeding time requirements (Abd-Elsalam and Alghuthaymi, 2014). Nanosensors have also been used in reducing the levels of pollen contamination on wind-pollinated plant species (Agrawal and Rathore, 2014). Nanogenetic manipulation through the use of nanoparticles, nanocapsules and nanofibers (Agrawal and Rathore, 2014) is providing a sustainable approach to crop improvement initiatives.

Nanotechnology in plant breeding, is being utilized for plant DNA transfer in breeding for insect-pest resistance
schemes (Duhan et al., 2017). Nanoparticles provide a source of protection to the DNA from enzymatic attack during its transfer into and within plant cells (Joldersma and Liu, 2018). Experiments exhibited that the plasmid DNA can be successfully transferred using the gene gun method with gold-capped nanoparticles in maize and tobacco tissues (Agrawal and Rathore, 2014). Mesoporous silica nanoparticles (MSNs)/DNA complexes have been shown to have enhanced transfection efficiency (Mustafa and Zaied, 2019). Furthermore, MSNs can be used in delivering foreign genetic material (transformation) and in carrying effectors (estradiol) which induces gene expression (Mustafa and Zaied, 2019). Additionally, nanobarcode are utilized as identification tags in the multiplexed analysis of gene expression for environmental stress resistance (Duhan et al., 2017). Nanobarcode particles are developed through semi-automated electroplating of inert metals (e.g., gold and silver) (Duhan et al., 2017).

Application of Nanotechnology in Food Industries

The application of nanotechnology in agro-food systems possess tremendous benefits to the society (Meetoo, 2011). Singh et al. (2017) asserted that, the applications of nanotechnologies in food industry encompasses two main facets namely; food nanostructured ingredients (i.e. food processing, nutrient enhancement, and packaging) and food nanosensing (i.e. pathogen and freshness detection). The application of nanotechnology in food systems include nanosensors, nano based-food additives, nanocapsules, nanopackaging and nanobased smart delivery systems (Rashidi and Khosravi-Darani, 2011). Nanotechnology enables researchers to manipulate the existing food industry in ensuring product safety thereby creating a culture of healthy and nutritional food consumption (Rashidi and Khosravi-Darani, 2011).

Food Packaging

Oxygen is one of the major problematic factors in food packaging, since it can promote or facilitate spoilage and discoloration of food products (Joshi et al., 2019; Mousavi and Rezaei, 2011). The inherent impermeability of polymers to gases render polymer silicate nano-composites more ideal substitutes for packaging (Rashidi and Khosravi-Darani, 2011). Nanoparticles have been used to develop a new plastic-type that prevents the penetration of oxygen (Joshi et al., 2019). These plastics contain nanoparticles arranged in a zigzag film (Fig 4) which prohibits the penetration of oxygen (Mousavi and Rezaei, 2011). This approach provides a smart food packaging alternative for shelf-life optimization and reduction of losses arising from spoilages. The technology is also offering cost-effective methodologies for storage and distribution of agricultural products (Rashidi and Khosravi-Darani, 2011). Moreover, the utilization of nanoparticles in these plastics enhances the heat resistance and mechanical properties in food packaging thereby increasing the shelf life through its gas or water vapor permeability influences (Rashidi and Khosravi-Darani, 2011).

![Fig 4: The effect of nano-plates in packaging material. Source: Wyser et al. (2016)](image)

The first nano-composite was produced by interacting an organic substance such as a protein, lipid or peptide with an inorganic substance (for instance calcium carbonate) and form a toughened material (Rashidi and Khosravi-Darani, 2011). Nanoclay is widely used for the packaging of food due to its thermal and mechanical barrier properties, and cost-effectiveness (He et al., 2019). Research has shown that, the addition of montmorillonite (3-5%) into the production of nano-composites make plastics lighter and stronger with increased thermal stability (Rashidi and Khosravi-Darani, 2011). It also increases barrier properties against carbon dioxide (CO2), oxygen (O2), moisture, and volatiles (Rashidi and Khosravi-Darani, 2011). Bayer Polymers Company has developed and commercialized the Durethan (KU2-2601) packaging film which prevents drying and protects against oxygen and moisture build-up in food products (Pradhan et al., 2017).

Food Processing and Safety

Nanotechnology enables food and beverage industries to alter and manipulate their products for more effective nutrient delivery so as to specifically target the enhancement of nutritional and health statuses of consumers (Handford et al., 2014). Bajpai et al. (2018) highlighted that, Nanotechnology enhances the functionality of food either by increasing nano-sized nutritional supplements or by the elimination of chemical toxicants. However, some food products are known to naturally contain nanomaterials. For instance, the natural nano-selenium content in green tea has numerous health benefits (Bajpai et al., 2018). On the other hand, nanomaterials can be developed to act as colour or flavour additives, preservatives, or food supplement carriers (i.e. nanoemulsion and nanoencapsulation) (He et al., 2019). Nanomaterials are also used for the edible coating to protect against cosmetic, nutritional quality and post-harvest losses (He et al., 2019). Nanolaminates are employed in the preparation of edible films and coatings for the food industry including vegetables, fruits, meats,
candies, chocolate, bakery products, and French fries (Rashidi and Khosravi-Darani, 2011). Nanolaminates consist of two or more physically or chemically bonded nanomaterials layers are also utilized in the food industry (Rashidi and Khosravi-Darani, 2011).

Some signs depicted on frozen food products to give the consumer an insight on the freshness level of the product are developed using nanotechnology. In frozen poultry, three signs are used namely green (fresh product and safe for consumption), orange (safe for consumption) and red (not safe for consumption) (Fawzy et al., 2018). Suresh Neethirajan (University of Manitoba, Winnipeg) developed sensors for early detection of storage grain spoilage using microelectronics and nanotechnology (Mousavi and Rezaei, 2011). Nanosensors used in plastic packaging detects gases produced during food spoilage allowing the packaging material to change its color as an alert to the consumer (Pal, 2017). Nanotechnology has also seen the development of sensors that can detect *Escherichia coli* contamination in food packages (Pal, 2017). Nanosensors are also utilized in the detection of gases, toxins (including pesticide residues) or pathogens in packaged foods (Rashidi and Khosravi-Darani, 2011). Additionally, nanomaterials have been documented to increase the shelf-life of fruits. Nano-kutuzan is sprayed on strawberries to increase the shelf-life by 20-28 days without mold development (Fawzy et al., 2018).

Nano-encapsulated active ingredients such as vitamins and fatty acids are presently being sold commercially for utilization in processing and preservation of meats, cheese, beverages and other foods (Miller and Senjen, 2008). Silver nanomaterials have also been reported to have antimicrobial properties in the food production and processing systems (Joshi et al., 2019). Nanotechnology may be utilized for rapid identification of nutrient deficiencies and food pathogen levels (Rashidi and Khosravi-Darani, 2011). Oxonica Inc (a United States of America registered company) developed nano-barcodes visible only with a microscope as an anti-counterfeiting measure on their products (Alfadul and Elneshwy, 2010). This initiative provides a reliable approach in ensuring consumer awareness on company products and also acts as a safety and control measure against counterfeiting.

**FUTURE OUTLOOK: NANOTECHNOLOGY ADOPTION**

**Opportunities and Potential of Nanotechnologies**

Nanotechnology has a great potential in revolutionizing the 21st agricultural (Joseph and Morrison, 2006) and food industries (Hosseini et al., 2010; Spandana, 2016). The transformative potential of nanotechnology may be heightened further through increased media coverage alongside other scientific technologies such as biotechnology, physics, and chemistry (Rashidi and Khosravi-Darani, 2011). The beneficial sides of consuming food products derived from nanotechnology need to be fully explained to the ultimate consumers or beneficiaries (Meetoo, 2011). Awareness of the benefits of such products will increase their global adoption rates and market shares. The absence of established special regulations on nanotechnology utilization in food production and processing (Rashidi and Khosravi-Darani, 2011) is a limiting factor to its acceptability by the general populace. In the United States of America, the Food and Drug Administration (FDA) traditionally regulates many products composed of particulate materials (Rashidi and Khosravi-Darani, 2011). However, at the present moment no policy frameworks and enforcing institutions have been established to oversee the production and marketing of nanotechnologies. The establishment of a specific regulation framework on nanotechnology will boost its consumer adoption levels. Dimitrijevic et al. (2015) alluded that, the implementation of a regulatory framework and good governance will further promote the acceptability and functionality of nanotechnology.
Roco et al. (2011) underscored that, nanotechnology-enabled products are impacting the overall marketplace landscape as exhibited by its estimated economic value of $254 billion worldwide. It is, therefore, rightly placed to positively impact the agricultural industry through enhanced business resource possibilities in the next decade (Sabourin and Ayande, 2015). Nanotechnology is participating in enhancing food security (Muller et al., 2017), nutrient absorption by plants, pathogen detection, flavour and nutrition (Rashidi and Khosravi-Darani, 2011). Researchers in Iran achieved a remarkable milestone fostering environmental sustainability by developing a nano-organic iron-chelated fertilizer (Sekhon, 2014). It also has future potential applications which include nanodelivery of veterinary products in fish food, antibacterial surfaces fish food and nanosensors for water pathogens detection (Sabourin and Ayande, 2015).

**Risks Associated with Nanotechnology Adoption**

The increased application and utilization of nanotechnology in agriculture and food systems over the course of the past decades has attracted public attention and generated elevating concerns (He et al., 2019). The general public continues to raise questions pertaining to the safety of such technologies on their well-being and that of the environment. Environmental health concerns arising are directly hinged on the interaction of nanoparticles used as nano-pesticides, nanoherbicides, nano-fertilizer, and the immobilized nanosensors (He et al., 2019). The potential risks associated with direct exposure to nanoparticles are not well established and fully understood (Berekaa, 2015; Meetoo, 2011). The elevating concerns regarding their fate, bioavailability, transport, and nanomaterials limits the inclination to adopt and accept such technologies (Mishra et al., 2017). The environmental fate and behavior of nanomaterials are largely dependent on their physicochemical properties (He et al., 2019). Predicting the behavior and fate of these nanomaterials is limited by the complexity and dynamism of environmental conditions (He et al., 2019). Researchers are therefore presented with a mammoth task of providing clarity on the subject matter.

![Fig 6: Benefits Vs Potential Risks of Adopting Nanotechnology. Source: Handford et al. (2014)](image-url)
CONFLICT OF INTEREST
The authors of this article declare no conflict of interest.

AUTHOR’S CONTRIBUTIONS
Authors conceived the study and equally participated in designing and drafting of the manuscript. The authors proof-read and approved the final draft of the manuscript.

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A wide research gap exists on the potential health risks associated with the consumption of food products containing nanoparticles (Meetoo, 2011). Handford et al. (2014) outlined potential risks associated with nano-food consumption in a schematic illustration shown in Fig 6. It is therefore imperative to establish research schemes targeting the toxicity and health risks associated with the consumption of nanofoods. Toxicity studies on the effects of nanoparticles on the environment and health safety can significantly influence consumer acceptability levels (Ziarati et al., 2018). Furthermore, the continued development of new research protocols and the implementation of different analytical techniques (for instance microscopy, fluorescence spectroscopy, and magnetic resonance imaging) can considerably contribute to understanding the plant-nanomaterial interactions (Fraceto et al., 2016). Future studies should, therefore, focus on filling the research gap on the toxicity of nanomaterial (to mammal cells, tissues or organs) and the migration of nanoparticles to food; environmental or degradation fate; nanomaterials bioaccumulation and their impact on ecosystems (He et al., 2019). Moreover, developers should collaborate with regulators, risk assessors and researchers in all processes of product development to ensure safety procedures are observed (Dimitrijevic et al., 2015).

CONCLUSION

The application of nanotechnology in agriculture and food systems can contribute immensely to livelihood sustainability and food security. The major contribution of nanotechnology in agriculture is realized in nutrient management, precision farming, insect pest and disease management, agronomy and crop improvement schemes. Interestingly, nanotechnology is utilized across the whole operating systems of the food industry. However, at the present moment, development and advancement of nanotechnologies are mainly focusing on its beneficial effects with little attention being placed on nano-toxicology (Ziarati et al., 2018). Furthermore, no regulatory standards have been established to govern the use of nanomaterials. This is currently acting as a barrier to the outright adoption and acceptance of nanotechnology by the general public. Conclusively, the establishment of a regulatory framework encompassing particle size, measurement, and range, physicochemical and processing property specifications, safety and risks can help in bridging the knowledge gap and bringing closure to the consumers.

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