Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Nanomaterials application in greenhouse structures, crop processing machinery, packaging materials and agro-biomass conversion

M.C. Ndukwu a,⇑, C.E. Ikechukwu-Edeha a, N.R Nwakuba b, I. Okosa a, I.T. Horsefall a, F.N. Orji a

a Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umuaia, Nigeria
b Department of Agricultural and Bioresources Engineering, Federal University of Technology, Owerri, Nigeria

ABSTRACT

The discovery of nanomaterials has flagged off crucial research and innovations in science and engineering. Its unique properties and diverse applications present it as the material for the future. The aim of this study is to present the relative applications of nanomaterial in some aspects of agriculture production. The study discussed nanotechnology applicability in climate control and photosynthesis in the greenhouse farming, hydroponic systems, solar drying, fabrication of crop processing machine components, oxygen scavengers in crop packaging, and micro-organism stimulant in anaerobic digestion for agro-biomass conversion. Some highlights from the review revealed that Nanotechnology can be applied to increase water surface area to volume ratio and heat transfer in the air moving into a greenhouse farming. Water cluster can be changed when treated with nanoparticles through ultraviolet absorption spectrum and nuclear magnetic resonance (NMR) spectroscopy resulting in lower micelles to manipulate water delivery in greenhouse farming. Nano-fluids or Nano-composites can be used to recombine the reactive parts of thermal storage materials after broken at elevated temperature to recover the stored heat for drying purpose during the off-sunshine periods in solar drying of crops. Nanomaterials can be a source of electroluminescence light in hydroponic system and act as coatings and surface hardener in crop processing machinery for post-harvest machines. The reviewed work showed that nanotechnologies have good prospect in adding value in agricultural production in the aspects discussed.

Contents

1. Introduction ......................................................................................................... 691
2. Application in the design of greenhouse or crop preservation system . . . . . . . .................................................... 691
   2.1. Climate control in a greenhouse. ................................................................. 691
   2.2. Increase in speed of photosynthesis of crops in a greenhouse ................ 693
   2.3. Integration of hydroponics in a greenhouse .............................................. 694
3. Design of crop processing equipment .............................................................. 694
   3.1. Solar dryers for crops ............................................................................. 694
   3.2. Dehauling and size reduction of crops ................................................... 694
   3.3. Crop packaging ....................................................................................... 695
4. Agro-biomass conversion. ..................................................................................... 695
5. Conclusion and future perspectives ................................................................ 696
References ............................................................................................................. 696

⇑ Corresponding author.
E-mail address: ndukwumcu@ mouau.edu.ng (M.C. Ndukwu).

Peer review under responsibility of KeAi Communications Co., Ltd.

https://doi.org/10.1016/j.mset.2020.07.006
2589-2991/© 2020 The Authors. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
1. Introduction

Nanomaterials are particles in the range of 1 to 100 nm with a very large surface to the volume ratio used in manufacturing, measuring, manipulation or observing objects at a nanoscale [1,2]. According to Ejeta et al. [3], this particular property creates a new quantum mechanical effects and delivers an incredible driving force for diffusion at a high temperature. This creates a high degree of association among particles enhancing activities. Nanomaterials consist of nanoparticles made from semiconductors, metals, metallic oxides (CoFe2O4, ZnCoFe2O4, CuFe2O4, Fe2O3, FeOH etc.) or any other particles that possess high physio-chemical and electromagnetic properties [4.5.149–151]. There are also a group of nanomaterials made from allotropes of carbon (graphene) rolled into tubes and spheres or silicon tubes that possess high electromagnetic strength [3]. Nanomaterials can also generally be classified basically by their constituents make up viz: Organics, Inorganic and Hybrid system [149]. Available literatures have shown that the hybrid system of utilisation of nanoparticles can be widely adopted as an efficient technique which can be employed in advance oxidation processes (AOPs) to enable catalytic degradation of organic matters [149,150,153]. Emphasizes therefore, is on the increase in the manipulation of these particles for technological developments [6]. This involves the utilization of these materials in the design and synthesis of new structures or particles control mechanism [7], water treatment, waste treatment [150–153] etc. For example Kakavandi et al. [149], examined the use of hybrid nanoparticles in the removal of cyfluthrin from waste water. Results demonstrated that these nanomaterials exhibited efficiency rates of 88.5 and 52.4% for degradation and mineralisation of the pollutant respectively. Similarly, in another study, [150] applied a hybrid system of magnetic nanoparticles (MNP) coupled with ultrasound and ultraviolet irradiations as a possible mechanism for catalytic degradation and generation of scavengers for treatment of petrochemical wastewater. They reported over 87% pollutant removal within relatively short period. Furthermore, McIntyre [8], has observed rapid increase in the application of nanomaterials in commercial products. Maynard et al. [9] reported that in the year 2006, over 300 products on the market possess improved characteristics as a result of integrated nanomaterials; this figure has been increased four times in 2010 to 2015. The most common nanomaterial used in a commercial product is silver, followed by carbon-based materials, and oxides of metals [8]. Nanoscience has found usefulness in almost every sphere of human advancement including engineering, medicine, natural sciences and agriculture with a huge market projection of more than 1.6 trillion dollars in 2013 [10]. Although researchers have reported positive utilization of nanomaterial and nanotechnology as a promising technique but it has its drawbacks [94]. The magnetic nanoparticles acting alone, possess low surface catalytic activity, records low degradation rates, with the resultant high tendency for them to agglomerate due to lower surface/volume ratio [151]. There is the possibility of its release into consumables which might cause toxic outbreaks [94]. These metal-based oxides have been reported to elevate inter-cellular ROS that can damage the DNA [95–97]. Therefore, various countries have developed framework and policies for research, development and control of nanoscience as it has the capacities of influencing both humanitarian and military applications [11]. In Nigeria, the National Agency for Science and Engineering Infrastructure (NASENI) established the national centre for nanotechnology with the help of the Africa Institute of Technology, Federal Institute of Industrial Research, US-Africa Materials Institute and the European Union [12,13]. The major interest of the centre is to participate in the global race to exploit the benefit of nanotechnology, seeing that it has become the future technological direction. Despite the interest of the Federal Ministry of Science and Technology in nanotechnology, developments in nanomaterial and utilization are still at the infant level [13]. Therefore it can be categorized still as an emerging technology in Nigeria and most African countries.

All over the globe, research on nanomaterials utilization and nanotechnology has expanded significantly in recent years [141–143]. The recent coronavirus pandemic has highlighted, the great important role the agriculture and food sector can plays in the society [144–146]. To enhance the productivity of the agricultural and food sector, applications of the nanomaterials and nanotechnology has been adopted [23,26,147,148]. Several kinds of research have adapted nanomaterials in the area of soil bioremediation, biochar enhancement for soil enrichment, crop protection, fertilizer application, renewable energy system application in agriculture, bio-sensors, disease control, and coating of crop processing system against corrosion to achieve high processing efficiency and crop detoxification [14–19,152]. Synthesis mechanism for materials makes use of atomic, fungi, molecular, processing of particulates in vacuum or fluid medium with the fungi method the most widely used due to high cost of adopting other methods [2,20,21]. Despite all this, the real contribution of nanotechnology to agricultural production is still questioned [22].

Researchers have synthesized different kinds of nanomaterials (Fig. 1) with different research materials for agricultural development but the challenge is in the scaling up of this research to the direct benefits of farmers and agro-processors. Generally, amongst most countries, nanomaterial in agricultural productivity is less emphasized than in other areas [2]. The practice in most nanomaterial applications in agriculture is mostly on the treating agricultural product itself or purification of water delivered for irrigation either to improve vegetative growth or yield [24–26], nutritional content [27], preservation [27–31], gene expression [32] and disease control in plants and animals [33–37].

Therefore, most reviews on nanomaterials in agriculture focused on this area of seed science, precision farming, disease control in plants and animals, fertilizer application, nutrition and biosensors, feed development, the influence of polymeric nanocarriers in agricultural applications and metal-based nanoparticles interaction and transport in the soil and plants [2,20,21]. However, new areas can be exploited in agricultural product delivery using nanomaterial enhanced structures as presented in Fig. 2. Therefore, the objective of this review is to look at these new areas where nanomaterial applications could be explored in agricultural production, crop processing and biomass conversion to the benefit of farmers. These areas are discussed in the subsequent sections.

2. Application in the design of greenhouse or crop preservation system

2.1. Climate control in a greenhouse

Although greenhouse technology is a practicable route to sustainable crop production in regions with adverse climatic conditions, high summer temperatures impede the successful year crop production [46]. Similarly, greenhouse cultivation in hot climatic regions is usually characterized by the high solar thermal load which forms major problems inside the greenhouse environment and limits plant growth [47]. This is why climate control in greenhouses is currently one of the major goals of engineering in precision agriculture [48]. Table 1 presents a summary of some possible areas nanomaterials can help in climate control in greenhouse farming. Nanomaterial can help the plants in the greenhouse to adjust to a progressive climate change. Shang et al. [37] defined progressive climate change as the change in the baseline of the
weather. This can be in the form of modified temperature, water need, pH of the environment and nutrient requirements [49]. This can be achieved without upstaging the ecosystem as they adjust to environmental stress. While the focus of most research works in this area concern the direct treatment of the seed or material for planting, structure and medium for delivery can also be modified to help in climate control. The application of nanomaterial treatment can be expanded in the medium of delivery, mechanisms or systems component fabrication that can enhance the availability and choice of crops produced by farmers in a country by adapting its mechanisms to develop controlled atmospheric farming where crops will thrive. One of these areas where nature can meet nanotechnology is in the controlled atmospheric greenhouse cooling where temperate crops can be grown in a tropical climate under a controlled climate of evaporative cooling or fogging as shown in Fig. 3.

The application of evaporative cooling technology utilizes water and cooling pads (porous media) of different materials to cool the

Fig. 1. Different kinds of nanomaterials [38,39].

Fig. 2. Some areas of nanotechnology application in agriculture production process.
Summary of areas of possible application of nanotechnology in climate control in greenhouse.

| Serial no. | Applications                                      | References |
|------------|---------------------------------------------------|------------|
| 1          | Adjustment to progressive climate change          | [48,49]    |
| 2          | Modification of pH in response to environmental change | [49]       |
| 3          | Nutrient manipulation in response to environmental change | [27,49]    |
| 4          | Temperature regulation (Evaporative cooling, fogging) | [46]       |
| 5          | Modification of water need                        | [2,24–26]  |
| 6          | Modification of water delivery dynamics (misting) | [62]       |
| 7          | Increase in water surface area for delivery        | [56]       |
| 8          | Modification of air delivery dynamics             | [32]       |
| 9          | Seed treatment                                    |            |

Air [51–54] as shown in Fig. 4. The effectiveness of the evaporative cooling is a function of the condition of the porous media which serves as a water reservoir for cooling the incoming air [55]. Therefore, porous materials should be properly wetted to avoid hotspot. To rapidly move water through and uniformly wet the strands of most of the pads, water molecules need to have a large surface to volume ratio. Again, the material must be porous enough to facilitate heat transfer between the air and the fluid with air passage into the structure. Despite water delivery to the pads through the spray jets which atomize the water, hot spots can still exist in the porous medium.

Nanotechnology can be applied to increase water surface area to volume ratio and heat transfer in evaporative cooling of the air moving into the greenhouse. This is because research has shown that water cluster can be changed when treated with nanoparticles through ultraviolet absorption spectrum and nuclear magnetic resonance (NMR) spectroscopy [2]. It was reported that the O2-NMR of water half peak was narrowed, chemically shifted, and decreased resulting in higher activity with smaller micelle when treated with nano-materials [56]. This is because according to Li et al. [57] the size of half peak of water is directly proportional to the size of the molecules. Therefore, the technology can be used to manipulate water delivery to the cooling pads to drive the diffusion force through the cooling pads or water delivery during fog cooling of greenhouse or cold preservation of fruits and vegetables in evaporative coolers. This will create a high degree of association among water and cooling pads particles or contact air in the case of fogging and enhances cooling of the greenhouse. Fog cooling is simply based on the dispersion of fine water particles into the air stream to increase the rate of heat exchange between water in the air [58]. Therefore, the smaller the water particles, the greater the degree of association with air and heat transfer between them to lower the air temperature. This is important in greenhouse effectiveness because fogging and misting systems effectively lower temperatures up to 5–6 °C below the ambient temperature and also provide more uniform temperature and humidity levels inside the greenhouse when compared to the fan and pad evaporative cooling systems, as reported by Ganguly and Ghosh [59] in their report on ventilation and cooling technologies in an agricultural greenhouse application. Evaporative fogging systems have been increasingly implemented in arid and semi-arid regions to increase production cycles in very warm seasons and also to achieve near-optimum environments for all-year-round production [60]. According to Misra and Ghosh [47], a fogging system of cooling sprays water into the airstream as fine droplets in the range of 2–60 μm in diameter which direct contact with water in the air takes place. Cooling is achieved by the evaporation of the sprayed water droplets, usually with a diameter of 2–60 μm [61]. This water droplets size can be reduced more through nano treatment with increased water to air surface contact area as reported by Liu et al. [56]. Again, research has also demonstrated that heat transfer in the porous medium can be improved by a higher percentage of nanomaterial additives in the material [62]. Therefore, the quality of the cooling pad in the evaporative cooling of greenhouse or storage space can be improved with nanomaterials additives.

2.2. Increase in speed of photosynthesis of crops in a greenhouse

Another area that nanomaterial can be made useful in greenhouse farming is in the crop photosynthesis. The speed of photosynthetic activities can be improved in greenhouse cultivated crops by impregnating the greenhouse envelop with nanomaterials during fabrication [63]. It has been reported that TiO2 nanomaterial which is a photocatalyst apart from being antibacterial can hydrolyse light under ultraviolet light into protons, oxygen and electron with the proton and electron going into the reaction chain during photosynthesis at the light reaction stage to speed up the process [2,64]. Artificial photosynthesis can be induced through the use of photoexcited nanoparticles in a greenhouse.

![Fig. 3. Inside a climate-controlled greenhouse with fog cooling system and transparent envelop](50)
envelop as has been suggested [2]. Other materials like copper and silver which are antibacterial can also be used in building the structural components of a greenhouse.

2.3. Integration of hydroponics in a greenhouse

Hydroponics is the technology of growing plants in the absence of soil [65]. Many crops especially fruits and vegetables are grown with this method all over the world [66]. This is an area farmers can exploit the nanotechnology. A nano phosphor-based electroluminescence lighting device can be used as a source of light in this system [65]. Manipulation of the growth process and nutritional content of plant can be easily achieved in a regimented setting like greenhouse and hydroponics. Therefore, integration of nano research will be highly effective as a report has shown that green nanomaterials can be grown in plants in this kind of settings [67].

3. Design of crop processing equipment

Crop processing is a major challenge to farmers all over the world. Researchers are still working to improve the efficiency of all unit operations involved in crop processing ranging from moisture reduction to unit size reductions and packaging equipment [68]. According to Ndukwu et al. [69], about 32% of the crop produced globally was lost in 2009. The situation might not have changed considering the slow pace of technological development in most developing nations. The following subsections will consider possible applications of nanotechnology/materials in crop processing.

3.1. Solar dryers for crops

Drying is a major challenge in crop processing. In this era of energy optimization with less environmental impact, solar dryers have been utilized to dry agricultural products instead of fossil-based dryers [70–74]. The challenge for most solar dryers has been the intermittent nature of solar energy available for crop drying, therefore thermal storage materials have been utilized [75]. Again, collector efficiency requires improvement in the increased harnessing of available incident solar radiation. To enhance the efficiency and speed up the mechanism of the energy storage of these thermal energy storage materials, nano-fluids or nanocomposites especially phase change materials that suffer incongruent melting or supercooling is being investigated. It has been noted that the intermolecular bonding of most energy storage materials is broken at elevated temperatures to different reactive parts [76]. These reactive parts can be recombined with the help of nanomaterials to recover the stored heat for drying purpose during the off-sunshine periods in solar drying of crops [77]. Also, sorption heat storage, where the material absorbs or adsorbs hot gas or vapour for heating purpose is being investigated too [78]. Most nanomaterials in thermal energy storage can be grouped into organic and inorganic materials, whereas nanofluids comprise water-soluble or water-based fluids. These nanomaterials and other materials can be differently combined to form nanocomposites (dispersion into polymeric materials) or hybrids with improved thermal storage properties which can aid in the drying process of crops. Among nanoparticles which have found usefulness in improved energy storage efficiency include, SiO2, MgO, Al2O3, Fe2O3, and ZnO, CuO, Cu-TiO2, Fe3O4, and TiO2 nanoparticles [79–82].

The efficiency of solar crop dryers can be improved on the harnessing of the sun’s radiant energy by incorporating nanomaterials as additives to the collector [83]. Due to a large surface area to volume ratios of nanomaterials, more surface of the collector will be exposed to solar radiation [84]. However, nanofluid in solar drying is very scarce [62] and presents an exciting research prospect especially nanofluid phase change material [85] due to its characteristic high energy density.

Again drying of medicinal, aromatic plants and green vegetables are always a challenge for farmers to preserve the attractive greenish colour of the plants. Currently, the best method advocated for drying these plants is shade drying [86]. Therefore, researchers are simulating the shade drying in solar dryers by developing special glass cover for the collector. Integration of engineered nanomaterials can be a breakthrough with higher efficiency. Dehkordi and Keivani [87] reported an intelligent nano-crystalline glass produced by the method of Aero-gel. The glass changes to dark colour when subjected to intense light and brighter at reduced sunlight. With this intelligent glass, the photosynthetic reaction of dried green vegetables can be limited to retain their dry green colour pigment. Also, glasses that can reflect proportions of incident solar radiation have been reported by Vatan-dolat-xah [88]. Therefore, overheating of solar dryers and subsequent denaturing of sensory and nutritional qualities can be prevented on the drying of medicinal plants and vegetables which require lower drying temperature than other crops.

3.2. Dehauling and size reduction of crops

Another area of interest in crop processing is the contact between the processed product and the machine components during dehauling or size reduction operation. This raises safety concerns on the processed agro materials due to the oxidation of these machinery surfaces. However, engineered nanomaterial structures show unique properties for high material performances and can be used in the coating of surfaces of machinery for crop processing with high thermal performance and also utilized in the design of nano-sieves for size reduction of crops as has been suggested by researchers in the food industry [89]. These materials can create additional strength and resistance of machine surface to environmental factors and corrosion. Ceramic nanoparticles have been reported to enhance the thermal stability of coated moving parts [90]. Mica and Talc as paint have shown to reduce weight
losses of equipment and prevented the formation of a hard layer [87]. The major risk being assessed for nano-materials by an expert in agricultural processing as recommended by Codex is on the addition or direct coating of agricultural products. However, they suggested that there may be no need for expert risk assessment but protocols can be developed to measure the extent of the residue of nano-materials if the process machinery is coated with nano-materials [91].

Nano-lubricants exist and can be used to reduce wear and tear in processing machines [92]. With the improved knowledge on the interaction of sliding layered materials, their friction response has been improved [92]. The corrugation of interlayer sliding can be reduced with the application of nanomaterials like graphene [93]. Copper nanoparticles and fullerenes additive in lubricants have improved the lubrication properties of lubricants [87]. In automated systems, for a clearer view of the central display board, engineered nanomaterial can be integrated into the design. Magnetcite nanoparticles (Cationic surfactant coated silica-modified) have been used as an adsorbent for the extraction and prevention of metal reductions [98]. This can be used in coating and design of materials for fabricating agro-resources machinery. Generally, big data approach in information, risk and safety concerns of various nano-based activities have been brought together in a pool by the World Health Organisation and Food and Agricultural Organizati and is accessible through a common dashboard [99].

3.3. Crop packaging

Nanomaterials have been introduced to improve the flexibility, moisture stability, low volatility, gas barriers and temperature stability in packaging materials for fruits and vegetables [100–105]. Its application has transcended the limits of the packaging of food materials and considers monitoring of stored food material for quality retention, safety, as well as better product packaging and improvement of package biodegradability. Nanosensors (especially those from bio-chip DNA) are used to detect pathogens and contaminating agents; selection of nanoparticles with good adhesive characteristics for binding and elimination of pathogens. The merits of these nanosensors include but not limited to a high level of sensitivity, compatibility, cost-effective, and proximate real-time detection [106]. Packaging of agro-products using nanomaterials has the following notable potential benefits: improved-performance packaging with greater mechanical and barrier characteristics; packaging with antimicrobial packaging integrated nanoparticles, such as silver nanoparticles; smart-tech packaging that could avert or respond to crop spoilage (for instance applying polymer films that gives out different colour at different stages of product spoilage), dirt repulsive and water impervious packages.

However, the barrier ability of the packaging structure can be improved by introducing an oxygen scavenger into the matrix to intercept and scavenge the oxygen through chemical reactions as it passes through the walls [107–110]. Most of the metal-based nanomaterials are oxygen scavengers especially iron, coatings, extrusion additives and labels, can be used [110]. Again, lightweight packaging materials have been introduced by the integration of nanomaterials coupled with an increased storage life of crops through the production of nano-sensors that respond to environmental changes and detect pathogens [111]. Silver nanoparticles have been used in packaging horticultural crops although not yet approved by the European Food Safety Authority (EFSA) but has been approved by the United States for Food and Drug Administration (FDA) for packaging [112–116]. Nevertheless, the integration of nanoparticles into packaged material for a crop is still a danger due to the migration of this particle into products [117–120]. This has been reported by Echegoyen and Nerin [121] in the investigation of the release of nanoparticle from a container made with nano-silver. Nevertheless, research is still ongoing to produce materials that will be able to bridge this migration and douse safety concerns in nano-preservation and packaging. Accurate biological monitoring of nano-enhanced materials is very important for global food safety [122].

4. Agro-biomass conversion

Generally, one of the major concerns in Nigerian Agricultural Sector is how to dispose of a large amount of agricultural raw materials and residues (biomass) generated either in the farm, poultry houses, livestock pens, or agro-processing industries etc. However, with the increasing energy demand globally and less dependence on fossil-based energy, the emphasis is shifting to bioenergy. Therefore, this agro-biomass is now converted to bioenergy for fuel of higher energy densities [123]. Available methods adopted include hydrogenation, pyrolysis, transesterification and gasification [124]. Nanomaterials have been reported in the reforming of this biomass before processing and also in lipid extraction [125–127,154]. They can help to stimulate microorgan-
ism for anaerobic digestion. CuO and MgO nanoparticles have been used as biocatalyst during transesterification [124]. Wastes from nanomaterial-engineered crops can increase the bio-oil and biodiesel yield [127]. Therefore, technology can serve as a vehicle for biofuel of the future [128,129].

Biochar, which is a product of biomass pyrolysis is used to enhance soil nutrients or soil amendments [130]. It has a very large surface area to volume ratio with a high microstructure [131,132]. Research has shown that converting this biochar into micro-nanocomposites has improved its activities in both soil and industrial applications [133,134]. Manjunatha et al. [135] suggested other advanced techniques of exploitation and valorization of agro-wastes which include: (1) cellulose nanofibers: this is the most common biopolymer obtained from plant materials (lignocellulose), especially wood which is the most vital source of cellulose for industrial use. World production of cellulose of about 1011-1012 t/yr of cellulose has been estimated to be produced through the photosynthetic process [136]. In-plant tissues, micro and macro fibrils characterize the building units of the structural ranking of cellulose fibres (Fig. 5). Microfibrils also consist of basic fibrils (nanofibres) with a diameter range of 3–35 nm based on the cellulose derivative (Fig. 5) [137].

Recently, nanocellulose has been seen as a promising bio-based nanomaterial with outstanding fascinating optical characteristics, high strength and good specific surface area [138]. Nanocellulose can be obtained and chemically improved for different nanocomposites. Numerous crop wastes, like soy husk, wheat straw, sugar beet pulp, potato pulp and rutabaga, are potential raw materials for the production of cheap source of nanocellulose [139]. Additionally, rice husk-based silicon nano materials exists. Rice husk is the outer coat of a rice grain which guards the seed during the crop developmental phase. It contains about 72 – 85% wt. of lignocellulose and 15 – 28 wt% of silica. Silicon ranks 2nd in importance amongst all elements. Somanathan et al. [140] noted that grasses consume enormous quantities of Si and store it in phytoliths as amorphous hydrated silica (SiO2 nH2O); about 50 – 70% of silica content can be obtained from grass ashes.

5. Conclusion and future perspectives

With the expanding research and innovations in science and engineering, nanomaterials have gained growing interests in agricultural activities. Its distinctive ability to diffuse at high temperatures as well as its large surface to volume ratio has aided its projection as a cutting-edge innovation fit for technological advancements. While nanomaterials have found relevance in medicine, natural science and engineering, however, in the agriculture sector, a direct value of nanomaterials to the farmers and agro-processors is yet to be solidly established especially in growing economies like Nigeria. This review has explored the areas which the peculiar nanomaterials can be used in agricultural structures. The controlled condition has been a daunting consideration in greenhouse cultivation and nanotechnology can efficiently be employed in the atmospheric control mechanism of the greenhouse structure by increasing the surface area to volume ratio of the coolant for enhanced heat transfer in evaporative or fog cooling system of the greenhouse, thereby helping crops to adjust to a progressive environmental change. It has also been revealed that incorporating photo-catalytic nanomaterials into the material structure of greenhouse during fabrication can present the advantage of quickening photosynthetic process in greenhouse crops which results in faster and healthy crop growth. Application of nanotechnology in hydroponic farming is a viable area to be largely explored and techniques to incorporate appropriate nanomaterials into the system further developed. It can be a source of electroluminescence light in hydroponic systems. Additionally, nanotechnology has also found application in crop processing machinery for coatings and surface hardener in crop post-harvest machines and in thermal storage and collector for solar systems where nanomaterials have the potential to improve the efficiency of solar crop dryers as a result of their increased surface area to volume ratio, thereby exposing more collector surfaces to solar radiation. Also, nano-lubricant can reduce wear and tear in parts of processing machines. Nanomaterials have also been found useful in anaerobic digestion and as such can be useful in agro biomass conversion.

Overall, nanotechnology can promote and drive the next revolutions in agricultural structures but there are scarce data on the health and environmental impacts of these nanomaterial enhanced agricultural structures. In packaging, there are concerns as to the effect of the interactions of these nanomaterials with packaged foods. These health concerns need to be addressed by further research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M. Rai, A. Ingle, Role of nanotechnology in agriculture with special reference to the management of insect pests, Appl. Microbiol. Biotechnol. 94 (2012) 287–293, https://doi.org/10.1007/s00253-012-3969-4.
[2] S. Huang, Ling Wang, Liangmeng Liu, Yuxuan Hou, Lu Li, Nanotechnology in agriculture, livestock, and aquaculture in China, A review. Agron. Sustain. Dev. 2015 (35) (2015) 369–400, https://doi.org/10.1007/s13593-014-0274-x.
[3] Ejeta KO, Dolor GA, Ndubuka CI, Nkuma-Udah KI, Azeez TO, Oduwgu O, Impact of nanotechnology in Nigeria: a short survey. International Journal of Biosensors & Bioelectronics, 2(5):136-139
[4] Y.L. Hewakuruppu, L.A. Dombrovsky, C. Chen, et al., Plasmonic “Pump-probe” method to study semi-transparent nanofluids, Appl. Opt. 52 (24) (2013) 6041–6050.
[5] Robert A Taylor, Todd Otanicar, et al., Nanofluid-based optical filter optimization for PV/IT systems, Light Sci. Appl. 1 (10) (2012) 34.
[6] A. Enamifar, M. Kadivar, M. Shahedi, S. Soleimanian-Zad, Evaluation of nanocomposite packaging containing Ag and ZnO on shelf life of fresh orange juice, Innov. Food. Sci. Emerg. Technol. 11 (2010) 742–748, https://doi.org/10.1016/j.ifset.2010.06.003.
[7] Uddin, M., Chowdhury, A.R., 2001, Integration of nanotechnology into the undergraduate engineering curriculum. International Conference on Engineering Education, Session 8B2-6: 6-9.
[8] R.A. McIntyre, Common nano-materials and their use in real world applications, Sci. Prog. 95 (1) (2012) 1–22, https://doi.org/10.1148/003650112X1329471546431.
[9] A.D. Maynard, R.J. Airken, T. Butz, V. Colvin, K. Donaldson, G. Oberdorster, M.A. Philbert, J. Ryan, A. Seaton, V. Stone, S.S. Tinkle, L. Tran, N.J. Walker, D.B. Warheit, Nature 444 (2006) 267–269.
[10] A. Mohammad, C.H. Lau, A. Zahirain, M.Z. Omar. Elements of nanotechnology education in engineering curriculum worldwide. Proc.-Soc. Behav. Sci. 60 (2012) 405–412.
[11] R.K. Sastry, H.B. Rashmi, N.H. Rao, Nanotechnology for enhancing food security in India, Food Policy 36 (2011) 391–400, https://doi.org/10.1016/j.foodpol.2010.10.012.
[12] Tobin, L., Dingwall, K., 2010, Nanoscience and Nanotechnology: Nigeria: In R. Newton (Ed.), Second Annual Report on Nanoscience and Nanotechnology in Africa. Institute of Nanotechnology: Stirling, Singapore.
[13] Elegbede JA, Lateef A (2019) Green Nanotechnology in Nigeria: The Research Landscape, Challenges and Prospects. Annals of Science and Technology. DOI: 10.2478/ast-2019-0008.
[14] S.C. Eze, S.I. Umeh, C.C. Onyeke, G.I. Ameh, Preliminary investigations on the control of yam (Dioscorea rotundata Poir.) tuber rot through nanosilica, Nanotechnol. Rev. 5 (2016) 499–505.
[15] R.E. Mfon, N.I. Odiaka, A. Sarua, Interactive effect of colloidal solution of zinc oxide nanoparticles biosynthesized using Ocimum gratissimum and Vernonia amygdalina leaf extracts on the growth of Amaranthus cruentus seedlings, Afr. J. Biotechnol. 16 (2017) 1481–1489.
[16] Okeniyo, J.O., John, G.S., Oworeye, T.F., Okeniyo, E.T., Akialulun, D.K., Taiwo, O.S., Awoyeye, G.A., Ige, O.J., Obafemi, Y.D., 2017, Effects of Dialium guineense based zinc nanoparticle material on the inhibition of microbes inducing microbiologically influenced corrosion. In: Proceedings of the 3rd Pan American Materials Congress (Eds: Meyers et al.), pp. 21–31, The Minerals,
