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REVIEW

How helpful is nanotechnology in agriculture?

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Abstract
Nanotechnology has great potential, as it can enhance the quality of life through its applications in various fields like agriculture and the food system. Around the world it has become the future of any nation. But we must be very careful with any new technology to be introduced regarding its possible unforeseen related risks that may come through its positive potential. However, it is also critical for the future of a nation to produce a trained future workforce in nanotechnology. In this process, to inform the public at large about its advantages is the first step; it will result in a tremendous increase in interest and new applications in all the domains will be discovered. With this idea, the present review has been written. There is great potential in nanoscience and technology in the provision of state-of-the-art solutions for various challenges faced by agriculture and society today and in the future. Climate change, urbanization, sustainable use of natural resources and environmental issues like runoff and accumulation of pesticides and fertilizers are the hot issues for today's agriculture. This paper reviews some of the potential applications of nanotechnology in the field of agriculture and recommends many strategies for the advancement of scientific and technological knowledge currently being examined.

Keywords: nanotechnology, agriculture, applications, nanoscience

Classification numbers: 1.00, 2.03, 2.04

1. Introduction

Currently, the major challenges faced by world agriculture include changing climate, urbanization, sustainable use of natural resources and environmental issues like runoff and accumulation of pesticides and fertilizers. These problems are further intensified by an alarming increase in food demand that will be needed to feed an estimated population of 6–9 billion by 2050 [1]. Furthermore, the world's petroleum resources are decreasing; there will be an additional demand on agricultural production as agricultural products and materials will soon be viewed as the foundation of commerce and manufacturing. At one fell swoop, there are new opportunities emerging, e.g. generation of energy and electricity from agricultural waste but pending workable economics and encouraging policy [1]. This above-mentioned scenario of a rapidly developing and complex agricultural system is existing and greater challenges will be posed to the developing countries as, in the developing countries, agriculture is the backbone of the national economy. They face many critical issues such as lack of new arable soil, reduction of the current agricultural land due to competing economic development activities, commodity dependence, poverty and malnutrition, which need to be solved on a sustainable basis. Profound structural changes in the agricultural sector have occurred due to the fast development of technological innovations, but these also pose challenges such as sustainable production considering food security, poverty reduction and public health improvement. For developing countries, advancement in science and technology can offer potential solutions for discovering value addition in their current production systems.

Many technologies have been developed that have the potential to increase farm productivity and also reduce the

Table 1. Size of different organisms and biomolecules on the micro- and nanometric scale.

No.	Nature of organisms and different biosubjects	Size range (μm)	Size on nanometric scale (nm)
1	Plant, animal cell	10–100	10 000–10 0000
2	Bacteria	$\leqslant$ 1–10	$\leqslant$ 1000–100
3	Virus	0.03–0.1	30–100
4	Simple molecules (proteins, DNA turns)	0.001–0.01	1–10
5	Atoms (DNA 'base')	0.0001–0.001	0.1–1

environmental and resource costs related with agricultural production. These technologies have the ability to conserve land and water by increasing yields through the application of the same or fewer inputs, ultimately conserving the environment. However, it will be very critical to support them, as these may not be commercially profitable and may also result in increase in the disparity between developing and developed countries. So their social and ethical implications should be considered. However, the need of the hour is to consider their efficiency in some fields, while these may not provide a solution to the existing problems associated with food production and its distribution round the world. Therefore, the developing countries should actively participate in research and development of these technologies while considering their ability to utilize these new technologies.

2. What is nanotechnology?

Nanotechnology, this vast field of the 21st century, is making a very significant impact on the world's economy, industry and people's lives [2,3]. It deals with the physical, chemical and biological properties of matter considered at nanoscale (1–100 nm) and their implications for the welfare of human beings [4]. The sizes of organisms and different biosubjects are given in table 1. According to the US EPA (US Environmental Protection Agency), nanomaterial is an ingredient containing particles with at least one dimension that approximately measures 1–100 nm. It has the ability to control and/or manufacture matter at this scale which results in the development of innovative and novel properties that can be utilized to address numerous technical and societal issues. Research work on nanotechnology-based delivery of agricultural chemicals has been quickly done by developing countries like China and their field applications are expected in the next 5–10 years. However, their success depends on many factors like market demand, profit margin, environmental benefits, risk assessment and management policies in the background of other competitive technologies.

In the following section, some potential applications of nanotechnology for agriculture and food production and related issues are discussed. There are a number of applications in this field, but these are mostly at the bench-top exploration stage. However, it is very likely that in the near future, agriculture and the food sector will see large-scale applications. Some recent advances are discussed in the following section.

3. Overview of nanotechnology applications in agriculture

Applications of nanotechnology in materials science and biomass conversion technologies applied in agriculture are the basis of providing food, feed, fiber, fire and fuels. In the future, demand for food will increase tremendously while natural resources such as land, water and soil fertility are limited. The cost of production inputs like chemical fertilizers and pesticides is expected to increase at an alarming rate due to limited reserves of fuel such as natural gas and petroleum. In order to overcome these constraints, precision farming is a better option to reduce production costs and to maximize output, i.e. agricultural production. Through advancement in nanotechnology, a number of state-of-the-art techniques are available for the improvement of precision farming practices that will allow precise control at nanometer scale.

3.1. Nanoscale carriers

Nanoscale carriers can be utilized for the efficient delivery of fertilizers, pesticides, herbicides, plant growth regulators, etc. The mechanisms involved in the efficient delivery, better storage and controlled release include: encapsulation and entrapment, polymers and dendrimers, surface ionic and weak bond attachments among others. These mechanisms help improve stability against degradation in the environment and ultimately reduce the amount to be applied, which reduces chemical runoff and alleviates environmental problems. These carriers can be designed in such a way that they can anchor the plant roots to the surrounding soil structure and organic matter. This can only be possible through the understanding of molecular and conformational mechanisms between the delivery nanoscale structure and targeted structures and matter in soil [5]. These advances will help in slowing the uptake of active ingredients, thereby reducing the amount of inputs to be used and also the waste produced.

3.2. Microfabricated xylem vessels

We are able to study the physico-chemical and biological interactions between plant cell bodies and various disease-causing organisms, i.e. pathogens, through the advancement in nanofabrication and characterization tools. These tools have helped us in understanding the mechanisms involved and ultimately improved the strategies for the treatment of these diseases [6]. For example in the past, to study xylem-inhabiting bacteria, changes in bacterial populations were monitored through destructive sampling techniques at different distances from inoculation sites but

Table 2. Relationship between cluster size (nm) and surface area (%).

No.	Cluster size (nm)	% increase in surface area
1	20	10
2	10	20
3	5	40
4	2	80
5	1	100

this does not provide information about colonization, film development, and subsequent movement and re-colonization at new areas because the same sample site cannot be followed temporarily. It has only been through the discovery of micro-fabricated xylem vessels with nano-sized features that we are able to study the above mechanisms which otherwise was not possible through traditional methods [7].

3.3. Nanolignocellulosic materials

Recently, nanosized lignocellulosic materials have been obtained from crops and trees which had opened a new market for innovative and value-added nano-sized materials and products, e.g. nano-sized cellulosic crystals have been used as lightweight reinforcement in polymeric matrix [8, 9]. These can be applied in food and other packaging, construction, and transportation vehicle body structures. Cellulosic nano-whisker production technology from wheat straw has been developed by Michigan Biotechnology Incorporate (MBI) International, and is expected to make biocomposites that could substitute for fiberglass and plastics in many applications, including automotive parts [10]. For the commercialization of this technology, North Dakota State University (NDSU) is currently engaged in a project.

3.4. Clay nanotubes

Clay nanotubes (Halloysite) have been developed as carriers of pesticides for low cost, extended release and better contact with plants, and they will reduce the amount of pesticides by 70–80%, hence reducing the cost of pesticide and also the impact on water streams [11].

3.5. Photocatalysis

One of the processes using nanoparticles is photocatalysis [12]. It is a combination of two words 'photo' means 'light' and 'catalysis' means 'reaction caused by a catalyst'. So, it involves the reaction of catalyst (nanoparticles) with chemical compounds in the presence of light. The mechanism of this reaction is that when nanoparticles of specific compounds are subjected to UV light, the electrons in the outermost shell (valence electrons) are excited resulting in the formation of electron hole pairs, i.e. negative electrons and positive holes. These are excellent oxidizing agents and include metal oxides like TiO_2 [13], ZnO [14], SnO_2 [15], etc., as well as sulfides like ZnS [16]. Due to their large surface-to-volume ratio, these have very efficient rates of degradation and disinfection (see table 2). As the size of particles decrease, surface atoms are increased, which results in tremendous increase in chemical reactivity and other physico-chemical properties related to some specific conditions such as photocatalysis, photoluminescence, etc. So this process can be used for the decomposition of many toxic compounds such as pesticides, which take a long time to degrade under normal conditions [17], e.g. pathogens, etc.

3.5.1. Bioremediation of resistant pesticides. Nanoparticles can be used for the bioremediation of resistant or slowly degradable compounds like pesticides. These harmful compounds tend to join the positive holes, are degraded and converted into non-toxic compounds. Otherwise these harmful compounds enter the food chain and result in serious problems for the body. So nanoparticles can be used for environmental safety [18].

3.5.2. Disinfectants. The electron hole pair, especially the negative electrons resulting from the excitation of nanoparticles, can also be used as a disinfectant of bacteria, as when bacteria make contact with nanoparticles, the excited electrons are injected into their bodies, which results in the bacterial removal from the object concerned, as in fruit packaging and food engineering [19].

3.5.3. Wastewater treatment. In modern environmental science, the removal of wastewater is an emerging issue due to its effects on living organisms [20, 21]. Many strategies have been applied for wastewater treatment, and of course the role of nanotechnology is also there. Photocatalysis can be used for purification, decontamination and deodorization of air. It has been found that semiconductor sensitized photosynthetic and photocatalytic processes can be used for the removal of organics, destruction of cancer cells, bacteria and viruses. Application of photocatalytic degradation has gained popularity in the area of wastewater treatment [19].

3.6. Nanobarcode technology

In our daily life, identification tags have been applied in wholesale agriculture and livestock products. Due to their small size, nanoparticles have been applied in many fields ranging from advanced biotechnology to agricultural encoding. Nanobarcodes (>1 million) have been applied in multiplexed bioassays and general encoding because of their possibility of formation of a large number of combinations that make them attractive for this purpose. The UV lamp and optical microscope are used for the identification of micrometer-sized glass barcodes which are formed by doping with rare earth containing a specific type of pattern of different fluorescent materials [9].

The particles to be utilized in nanobarcodes should be easily encodeable, machine-readable, durable, sub-micron-sized taggant particles. For the manufacture of these nano-barcode particles, the process is semi-automated and highly scalable, involving the electroplating of inert metals (gold, silver, etc.) into templates defining particle diameter, and then the resulting striped nanorods from the templates are released. These nanobarcodes have the following applications.

3.6.1. Biological applications of nanobarcodes. Nanobarcodes have been used as ID tags for multiplexed analysis of gene expression and intracellular histopathology. Improvement in the plant resistance against various environmental stresses such as drought, salinity, diseases and others have only been possible through advancement in the field of biotechnology at the nanoscale. In the near future, more effective identification and utilization of plant gene trait resources is expected to introduce rapid and cost effective capability through advances in nanotechnology-based gene sequencing [22].

3.6.2. Non-biological applications of nanobarcodes. Nanobarcodes serve as uniquely identifiable nanoscale tags and have been applied for non-biological applications such as for authentication or tracking in agricultural food and husbandry products.

This nanobarcode technology will enable us to develop new auto-ID technologies for the tagging of items previously not practical to tag with conventional barcodes.

3.7. Quantum dots (QDs) for staining bacteria

Bacteria, the most primitive life forms present almost everywhere, are useful as well as harmful for life. There are numerous bacteria which are responsible for many diseases in humans like tetanus, typhoid fever, diphtheria, syphilis, cholera, food-borne illness, leprosy and tuberculosis caused by different species. As a remedial process, we need to detect bacteria and for this, dye staining method is used. To stain bacteria, the most commonly used biolabels are organic dyes, but these are expensive and their fluorescence degrades with time. So the need of the hour is to find durable and economical alternatives.

Fluorescent labeling by quantum dots (QDs) with bio-recognition molecules has been discovered through the recent developments in the field of luminescent nanocrystals. QDs are better than conventional organic fluorophores (dyes) due to their more efficient luminescence compared to the organic dyes, narrow emission spectra, excellent photostability, symmetry and tunability according to the particle sizes and material composition. By a single excitation light source, they can be excited to all colors of the QDs due to their broad absorption spectra [23]. Bio-labeled bacillus bacteria with nanoparticle consisting of ZnS and Mn^{2+} capped with bio compatible 'chitosan' gave an orange glow when viewed under a fluorescence microscope.

For the detection of *E. coli* O157:H7, QDs were used as a fluorescence marker coupled with immune magnetic separation [24]. For this purpose, magnetic beads were coated with anti-*E. coli* O157 antibodies to selectively attach target bacteria, and biotin-conjugated anti-*E. coli* antibodies to form sandwich immune complexes. QDs were labeled with the immune complexes via biotin-streptavidin conjugation after magnetic separation.

3.8. Biosensors

A variety of characteristic volatile compounds are produced by microorganisms that are useful as well as harmful to human beings, e.g. fermentation makes use of yeasts while alcohol is produced as a by-product when bacteria eat sugar. For rapid growth of a wide range of microorganisms, dairy products, bakery products and other food products represent ideal media. The most common causal organisms of food rotting are bacteria. Foul odor is a clear indication of food rotting. The human nose can detect and distinguish a large number of odors, but sometimes it may be impractical and a further cause for poisoning. Therefore, it is more sensible to use an instrument like rapid detection biosensors for the detection of these odors.

3.8.1. Rapid detection biosensors. These instruments are able to reduce the time required for lengthy microbial testing and immunoassays. Applications of these instruments include detection of contaminants in different bodies such as water supplies, raw food materials and food products.

3.8.2. Enzymatic biosensors. Enzymes can act as a sensing element as these are very specific in attachment to certain biomolecules. According to [25], enzymatic biosensors on the basis of immobilization surface are classified into four groups (i) controlled-pore glass beads with optical transducer element, (ii) polyurethane foam with photo-thermal transducer element, (iii) ion-selective membrane with either potentiometric or amperometric transducer element and (iv) screen-printed electrode with amperometric transducer element.

3.8.3. Electronic nose (E-nose). It is a device based on the operation of the human nose and is used to identify different types of odors; it uses a pattern of response across an array of gas sensors. It can identify the odorant, estimate the concentration of the odorant and find characteristic properties of the odor in the same way as might be perceived by the human nose. It mainly consists of gas sensors which are composed of nanoparticles e.g. ZnO nanowires [26,27]. Their resistance changes with the passage of a certain gas and generates a change in electrical signal that forms the fingerprint pattern for gas detection. This pattern is used to determine the type, quality and quantity of the odor being detected. There is also an improved surface area which helps in better absorption of the gas.

3.9. Gold nanoparticles

Man has been fascinated by gold for a long time. It is one of the most widely studied and abundantly used nanoparticles like bulk gold. Due to several qualities, it has remained valuable both as a medium of exchange and for decorative use as jewelry throughout history. The gold nanoparticles, commercially used as rapid testing arrays for pregnancy tests and biomolecule detectors, are based on the fact that the color of these colloids depends on the particle size, shape, refractive index of the surrounding media and separation between the nanoparticles. A quantifiable shift in the surface plasmon response (SPR) absorption peak results due to a small change in any of these parameters.

We can make these nanoparticles attach to specific molecules by carefully choosing the capping agent for stabilizing gold nanoparticles. These specific molecules get adsorbed on the surface of these nanoparticles and change the effective refractive index (RI) of the immediate surroundings of the nanoparticles [28]. A few nanoparticles will be adsorbed if the detecting molecules (bio-macromolecules) are larger than the gold nanoparticles and result in the formation of lumps after agglomeration. Ultimately, color of gold nanoparticles is changed due to shift in SPR that results from the reduction of particle spacing.

3.10. Smart dust

We can use the 'smart dust' technology for monitoring various parameters like temperature, humidity, and perhaps insect and disease infestation to create distributed intelligence in vineyards and orchards.

3.11. ZigBee a mesh networking standard

ZigBee is a wireless mesh networking standard with low-cost and utilizes low-power. It has given the concept of 'Smart Fields' and 'SoilNet'. It consists of one or more sensors for environmental data (temperature, humidity, etc.), a signal conditioning block, a microprocessor/microcontroller with an external memory chip and a radio module for wireless communication between the sensor nodes and/or a base station. It can be used for the identification and monitoring of pests, drought or increased moisture levels in order to counterbalance their adverse effects on crop production [29]. Through this wireless sensor technology with nanoscale sensitivity, we can control plant viruses and level of soil nutrients, as the plant surfaces can be changed at nanoscale with specific proteins. This technology is important in realizing the vision of smart fields in particular. Wireless network sensor technology can also be used for monitoring the optimal conditions for mobile plants biotechnology.

4. Nanotechnologies in animal production and health care

Livestock, poultry and aquaculture are related with agriculture, and have an important role and will continue to play an important role in human nutrition. There are a large number of constraints in animal production such as production efficiency, animal health, feed nutritional efficiency, diseases including zoonoses, product quality and value, by-products and waste, and environmental footprints. Nanotechnology can provide state-of-the-art remedies for these challenges [30].

4.1. Improving feeding efficiency and nutrition

The main challenge in sustainable agriculture is to minimize the inputs and to maximize the output. Feedstock is the most important input in animal production. Feeding efficiency is inversely related with demand of feed, discharges of waste, environmental burden, production cost and competing with other uses of the grains, biomass and other feed materials. Nanotechnology has the potential to improve the profile of nutrients and their efficiency. In developing countries, animal feeds are mostly suboptimal in nutrient composition. To supplement them with nutrients is an efficient way of elevating the efficiency of protein synthesis and utilization of minor nutrients in animals. Similarly, cellulosic enzymes can help in better utilization of the energy in plant-derived materials. Moreover, micronutrients and bioactives can help improve the overall health of animals, ultimately achieving and maintaining optimal physiological state. For efficient supply of nutrients, a large number of nanoscale delivery systems like micelles, liposomes, nano-emulsions, biopolymeric nanoparticles, protein-carbohydrate nanoscale complexes, solid nano lipid particles, dendrimers and others have been developed. These systems not only have better adaptability against environmental stresses and processing impacts but also have high absorption and bioavailability, better solubility and disperse-ability in aqueous-based systems, i.e. food and feed, and controlled release kinetics [31]. Sustainability can be achieved through the utilization of self-assembled and thermodynamically stable structures. So less energy is needed to process these structures. In addition, efficient veterinary drug delivery can be achieved through these systems which protect the drug in gastrointestinal tract and provide optimal rate and location for optimal action. These systems have helped in improved utilization efficiency of nutrients and product quality, as well as reducing the amount and financial burden of the producers, and ultimately production yield. Similarly to food applications, it is the requirement of the system to be effective in its intended use and against adverse effects or unintended uses. There should be an accurate risk assessment of the nanoscale particles to be used in order to ensure safe and sound development and deployment in the products.

4.2. Zoonotic diseases

Substantial losses in animal production are caused by diseases such as bovine mastitis, tuberculosis, respiratory disease complex, Johne's disease, avian influenza, and porcine reproductive and respiratory syndrome (PRRS). According to an estimate of the World Health Organization (WHO), 1/5 of animal production costs in the developed world and 1/3 in the developing world are represented by animal diseases. During the last thirty years, infectious diseases have emerged and 75% of them are zoonotic [32], which not only cause economic loss but also serious danger to human health, e.g. Variant Creutzfeldt–Jakob disease (vCJD). The zoonotic diseases include mad cow disease, avian influenza, H1N1 influenza, Ebola virus and Nipah virus. For integrated animal disease management, detection and intervention are two important tools in order to reduce and/or to eradicate the disease. Nanotechnology has the potential to provide these strategies and has enabled revolutionary changes in this field, and new state-of-the-art strategies are expected to be developed in the near future [33, 34]. Numerous detection and diagnostic techniques have been offered by nanotechnology which are highly specific and sensitive, can detect multiple samples at a time, are time saving, robust, have on-board signal processing, communication, automation, and are convenient to use and economical. These help in quick, simple and inexpensive treatment strategies that can be taken to remedy the situation. For agricultural field applications, portable, implantable devices have been developed. Drugs and vaccines developed through nanotechnology are relatively more effective and cheaper than those manufactured through previous technologies. This has enabled precise delivery and controlled release of drugs, resulting in a small footprint in animal waste and the environment, which would otherwise result in antibiotic resistance. So it has reduced environmental concerns associated with the use of antibiotics and enabled new drug administrations that are easy, quick, non-intrusive to animals and most importantly, economical. Through advancement in nanotechnology, theragnostics has been developed in which both diagnostics and therapy are performed in a single step. But before deploying this innovative technology, pharmacokinetic and pharmacodynamic studies should be conducted under *in vivo* conditions in order to establish a relationship between dose, drug concentration at the site of action and drug response [35]. Moreover, there should be collaboration between human and veterinary medical communities in the research and development for dealing with zoonotic diseases.

4.3. Animal reproduction and fertility

Animal reproduction is an important challenge for both developing and developed countries, as low fertility causes low production rate, increases in financial input and reduced efficiency of livestock operations [36]. To improve animal reproduction, many technologies have been developed, but microfluidic technology has ruled over the last two decades and many nanoscale processing and monitoring technologies have been integrated, which include food and water quality, animal health and environmental contaminations. These have enabled us to produce an automated and large number of embryos *in vitro*, and this has improved genetics and selection of livestock for human food and fiber production. In Brazil, fixed-time artificial insemination (FTAI) technology has been used to increase the cattle reproduction rate for many years, but its efficiency depends on the regulation of progesterone. Inefficient and irregular dispersion of hormone, disposal issues, being labor intensive, and requiring multiple animal handlings for each attempt are the drawbacks of this technology. Nanotechnology-based delivery systems help to improve bioavailability and release kinetics, reduce labor intensity, and minimize waste and discharge to the environment [33, 36]. An implanted nanotechnology-enabled sensing device with wireless transmission ability is another strategy that can be used to control animal hormone level, thus providing information about the optimal available fertility period. This information is helpful for the livestock operators in decision making for reproduction [37].

4.4. Animal product quality, value and safety

Modification of animal feed not only improves the animal production but also product value and quality, which is helpful in producing animal-derived foods or products consistent with health recommendations and consumer perceptions, e.g. milk fatty acids, cis-9, trans-11 conjugated linoleic acid (CLA) and vaccenic acid (VA). These products help in the prevention of chronic human diseases such as cancer and atherogenesis [38]. Nanotechnology based delivery of nutrients is helpful in efficiently controlling the biosynthesis and concentration of CLA and VA in the milk fat of lactating ruminants. It also helps in examining the biological benefits of functional foods with high CLA/VA contents and their relationship with human chronic diseases using biomarkers and biomarker triggered release mechanisms. Moreover, it has played an important role in economical sequencing of the mammalian genome within 24 h [22]. In the next decade, if this technology is available, advances in biotechnology research and development will be substantially accelerated.

4.5. Nanotechnology and animal waste management

In the animal production industry, animal waste is a serious concern and its irresponsible discharge can only be prevented through strict environmental policies. It is also responsible for the production of unpleasant odors that adversely affect quality of air and, in turn, living conditions and the real estate value of the adjacent area. Animal waste could be used for the production of high-quality organic fertilizer when value is added, and for improving environmental quality. Its bioconversion into energy and electricity can result in new revenue, renewable energy in the form of natural gas [39]. In efficient and cost effective bioconversion, nanotechnology based catalysts will play a critical role in electricity production and its storage which will be very helpful in the development of distributed energy supplies, especially in rural communities where infrastructure is lacking [40,41]. Such an approach could eliminate the need for a system of wide electricity grids, accelerate rural development and improve productivity.

5. Nanotechnologies for water quality and availability

Currently, provision of clean and abundant fresh water is one of the most important challenges faced by the world for human use and industrial applications such as agriculture [42]. According to a survey, more than one billion people in the world are deprived of clean water and the situation is getting worse. In the near future, it has been estimated that average water supply per person will drop by a factor of one third, which will result in the avoidable premature death of millions of people [43]. A large amount of fresh water is required in agriculture, but in turn, it contributes to groundwater pollution through the use of pesticides, fertilizers and other agricultural chemicals. To combat this problem, novel, sustainable and cost effective technologies will be required for the treatment of this large amount of waste water produced. During the treatment of wastewater, critical issues like water quality and quantity, treatment and reuse, safety due to chemical and biological hazards, monitoring and sensors should be considered. Research and development in nanotechnology has enabled us to find novel and economically feasible solutions for remediation and purification of this wastewater.

Accessible water resources are mostly contaminated with water-borne pathogenic microorganisms like cryptosporidium, coliform bacteria, virus, etc., various salts and metals (Cu, Pb, As, etc.), runoff agricultural chemicals, tens of thousands of compounds considered as pharmaceuticals and personal care products (PPCP), and endocrine disrupting compounds (EDC) and radioactive contaminants, either naturally occurring or as the result of oil and gas production as well as mining activities due to natural leaching and anthropogenic activities. For improving water quality, nanotechnology has provided novel solutions which are discussed below.

5.1. Nanooligodynamic metallic particles

Physico-chemical microbial disinfection systems like chlorine dioxide, ozone and ultraviolet are being commonly used in developed countries, but most of the developing countries are lacking these systems due to the requirement of large infrastructure which makes them costly. The need of the hour is to search and develop alternative cost-effective technologies. Nanotechnology based oligodynamic metallic particles have the ability to serve this function. Among these nanomaterials, silver is the most promising one as it is both bactericidal and viricidal due to the production of reactive oxygen species (ROS) that cleaves DNA and can be utilized for a wide range of applications. Other properties include low toxicity, ease of use, its charge capacity, high surface-to-volume ratios, crystallographic structure and adaptability to various substrates [44].

5.2. Photocatalysis

Visible light photocatalysis of transition metal oxides, another nanoscale technological development, produces nanoparticles, nanoporous fibers and nanoporous foams that can be used for microbial disinfection [45] and for the removal of organic contaminants like PPCPs and EDCs. Moreover, tubular nanostructures, embedded into microbial cell wall, can disrupt its cell structure resulting in the leakage of intracellular compounds, and ultimately cell death.

5.3. Desalination

Due to limited resources of fresh water, it is likely that in the near future, desalination of sea water will become a major source of fresh water. Conventional desalination technologies like reverse osmosis (RO) membranes are being used but these are costly due to the large amount of energy required. Nanotechnology has played a very important role in developing a number of low-energy alternatives, among which three are most promising. (i) protein-polymer biomimetic membranes, (ii) aligned-carbon nanotube membranes and (iii) thin film nanocomposite membranes [46]. These technologies have shown up to 1000 times better desalination efficiencies than RO, as these have high water permeability due to the presence of carbon nanotube membranes in their structure. Some of these membranes are involved in the integration of other processes like disinfection, deodorizing, de-fouling and self-cleaning. Some of these technologies may be introduced in the market place in the near future but scale-up fabrication, practical desalination effectiveness and long-term stability are the most critical challenges to be considered before their successful commercialization.

5.4. Removal of heavy metals

Ligand based nanocoating can be utilized for effective removal of heavy metals as these have high absorption tendency. It becomes cost effective as it can be regenerated *in situ* by treatment with bifunctional self-assembling ligand of the previously used nanocoating media. Multiple layers of metal can be bonded to the same substrate using crystal clear technologies [47] and this technology is expected to be available in near future. According to [48], another strategy for the removal of heavy metals is the use of dendrimer enhanced filtration (DEF) and it can bind cations and anions according to acidity.

5.5. Wireless nanosensors

Crop growth and field conditions like moisture level, soil fertility, temperature, crop nutrient status, insects, plant diseases, weeds, etc. can be monitored through advancement in nanotechnology. This real-time monitoring is done by employing networks of wireless nanosensors across cultivated fields, providing essential data for agronomic intelligence processes like optimal time of planting and harvesting the crops. It is also helpful for monitoring the time and level of water, fertilizers, pesticides, herbicides and other treatments. These processes are needed to be administered given specific plant physiology, pathology and environmental conditions and ultimately reduce the resource inputs and maximize yield [3].

Scientists and engineers are working from dawn to dusk in developing the strategies which can increase the water use efficiency in agricultural productions, e.g. drip irrigation. This has moved precision agriculture to a much higher level of control in water usage, ultimately towards the conservation of water. More precise water delivery systems are likely to be developed in the near future. These factors critical for their development include water storage, *in situ* water holding capacity, water distribution near roots, water absorption efficiency of plants, encapsulated water released on demand, and interaction with field intelligence through distributed nano-sensor systems [43].

5.6. Detection of pollutants and impurities

Sensing and detection of various contaminants in water at nanoscale under laboratory and field conditions has remained a hot issue over the last decade. In the near future, state-of-the-art nanotechnology-based techniques will help in developing many new technologies that will have better detection and sensing ability [1].

6. Nanotechnology and shelf life of agricultural and food products

Most of the agricultural commodities (fresh vegetables, fruits, meats, egg, milk and dairy products, many processed foods, nutraceuticals and pharmaceuticals) are either perishable or semi-perishable. Research and development in nanotechnology can help to preserve the freshness, quality and safety.

7. Green nanotechnology

For sustainable development around the world, finding an inexpensive, safe and renewable source of energy is the need of the hour. Green nanotechnology has been developed for a flexible and efficient source of energy in the form of solar cells which have long been an ambition for tropical countries. However, the use of glass photovoltaic panels is delicate and too expensive. A high priority of research in most industrialized countries has been given to the development of photovoltaic panels, energy storage and other nanotechnology-enhanced solar-thermal energy conversion systems. Economic feasibility is the critical factor for developing these photocatalysts and energy materials and if we address this factor properly, we will be able to develop more and more 'out-of-box' ideas. A substantial technical breakthrough has been made by Jennings and Cliffel at Vanderbilt University who have explored the use of photosynthesis protein units derived from leafy vegetables and plants for direct conversion of solar energy to electricity [49], and has remained functional for about one year. A glass microscope slide that serves as the cell base is the most expensive component of this system. Capturing solar energy will be a great achievement that will serve humanity and is likely be persistent and intensified in the years ahead.

Nanotechnology is also helpful for the conversion of biomass into fuels, chemical intermediates, specialty chemicals and products including catalysts in order to reduce production cost while being economically feasible. These nanostructured catalysts have large surface area per unit volume and are capable of having precisely controlled composition, structure functionalization and other important properties of catalysts [40].

8. The role of good governance and policies for effective nanotechnology development

For about the last decade, nanotechnology has been actively pursued worldwide. Of course, it has made many advances in various fields but the results are inconsistent across different scientific areas and geographic regions as these developments are at bench-top scale. Research on methodology, identification and characterization of nanomaterials, testing priorities and regulatory guidance on nanoparticle safety are still in their infancy, hence great efforts for their commercialization are required. In order to make advancement in the field, more research in potential risk assessment for responsible development by all the stakeholders will be required. There will also be the requirement of private–public partnership for getting substantial contributions and advancements in nanotechnology. However, engagement of the public to ensure a transparent and constructive discussion of the various issues will be mandatory.

There should be fruitful discussion to establish good governance of nanotechnology-based applications in agriculture and food systems for sustainable financial investment, and these aspects include: research and development, transfer models, intellectual property and efforts to understand and facilitate technology adoption and sharing among industrialized and technologically disadvantage countries. For proper consideration of the above-mentioned issues for development and innovation in nanotechnology, we need to enhance the role played by developing countries, encourage the development of innovative products addressing the current issues and make these products safe, appropriate, easily accessible and on a sustainable basis. For this purpose, a policy briefing published by the International Food Policy Research Institute should also be consulted.

Partnerships and collaborations can play a key role in sustainable agriculture development. Nanotechnology is a multidisciplinary (engineering and the natural sciences, including such disciplines as physics, chemistry, biology, materials sciences, instrumentation, metrology and others) approach requiring a high degree of cross-sector collaboration among academic researchers, industry and government. Progress in a number of tools for visualization, characterization and fabrication, as well as methods for reproducing and controlling properties, scalability, and cost will be required for the advancement of nanotechnology.

Most developing countries continue to work on filling critical gaps in research infrastructure through contact and access to international research and development networks, despite the strong research capacity building efforts that have been made by these countries. So, an evaluation of possible collaboration and partnership mechanisms either between public and private or between developed and developing countries in order to meet global demands and expectations should be performed. Many developing countries, particularly Brazil, China, India and South Africa have already started significant investments in strategically conducting research in nanotechnology and its applications for agriculture and food systems. These investments are particularly made for research related to national interests like energy, health, water treatment, agriculture and the environment. So in conclusion, there is a dire need for collaboration between public and private sector partnerships, and between developed and developing countries.

9. Conclusion and perspectives

Nanotechnology has great potential as it can enhance the quality of life through its applications in various fields like agriculture and the food system. Around the world it has become the future of any nation. But we must be very careful with any new technology to be introduced about its possible unforeseen related risks that may come through its positive potential. However, it is also critical for the future of a nation to produce a trained future workforce in nanotechnology. In this process, to inform the public at large about its advantages is the first step, which will result in tremendous increase in the interest and discovery of new applications in all the domains. With this idea in mind, this review has been written.

The theme of the paper is based on the provision of basic knowledge about the applications of nanotechnology in agriculture and their prospects in the near future with reference to the current situation around the world. In this review, some of the potential applications of nanotechnology in agriculture for the welfare of humans and for sustainable environment, challenges and opportunities for developing countries have been identified. Finally, for their solution, collaboration among developed and developing countries, public and private sectors and between research institutions and international organizations have been identified and suggested.

The future of nanotechnology is uncertain due to many reasons, such as negative reaction of the public towards genetically modified crops, lack of many of the requisite skills in public agricultural research organizations for this type of research and ill-equipped and somewhat hesitant regulatory structures to deal with these new technologies. There is a dire need to tear down the sharp boundary present between the social and natural sciences and if we succeed in discarding this boundary, we may be able to develop a more desirable and more democratic sociotechnical future.

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