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Nanotechnology for agricultural transformation: A review

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ABSTRACT

Agribusiness has been confronted with a wide array of complications encompassing; stagnant crop yields, climatic variation, water inaccessibility, agrochemicals buildup, less supplement use proficiency, reduced soil organic matter which has subsequently influenced the worldwide food demand. For the eradication of those aforesaid concerns, there is a prerequisite of a pioneer innovation, such as 'Nanotechnology' to be incorporated in the plant breeding sector, which can alleviate those snags alongside securing environmental parameters. Basically, Nanotechnology is a new breakthrough that operates at the subatomic level, particle by iota for fabricating a structure, apparatuses, or gadgets forced with a new sub-atomic collection that can sustain and improve the current status of plant breeding. The application of nanotechnology in plant breeding comprehends; disease and vermin control, seed technology, plant genetic modification, monitoring of plant growth stages, incitement of hormonal impacts, and precise farming. Other than this wide relevance of nanotechnology, a few investigations show that nanotechnology imparts phytotoxicity effects, which can be a restrictive risk for the environment, beings, and natural boundaries. However, if we can eliminate the potential risks and outcomes of this innovation, it could potentially reform the entire agricultural cosmos. Furthermore, this paper summarizes several nanotechnological approaches in plant breeding, recompensing specific consideration to its current utilization, and moreover, scans the opportunities, potential advantages, associative risks, deterrents, and conceivable prospective changes.

Keywords: Agriculture, breeding, materials, nanotechnology

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1 Introduction

The present population of the world is 7.77 billion, approximately 59% of which lives in Asia, and the forecasted global population might reach about 9.6 billion by 2050. This directly suggests that the immense increase in the population necessitates the need for more food (Ali et al., 2018). To meet the increasing global food demand, we have been using and exploring different fields of science and technology for the past few decades (Chhipa and Joshi, 2016). So, taking into consideration all these problems, nanotechnology has emerged as a powerful and promising tool to explore the darkest avenues of science and technology research (Nikunj et al., 2014). 'Nanotechnology' was first termed by Taniguchi introduced in the 1960s by Dr. Richard Feynman (Bhau et al., 2016; Reddy et al., 2017). Nanotechnology is referred to as the scientific study, formation, modeling, controlling, and utilization of functional materials, devices, and systems at a nano-scale. 'Nano' usually falls between 1nm to 100 nm (Ndlovu et al., 2020; Sinha et al., 2017; Elizabath et al., 2019). On the other hand, nanotechnology is an innovative approach that encompasses the application of nano-sized materials and equipment that can manipulate physiological properties at a molecular level (Yogranjan et al., 2017). This technology is associated with multi-disciplinary subjects including chemistry, biology, and other integrative areas (Elizabath et al., 2019; Kumari et al., 2018). The important feature of nanomaterials is not only their size but also their capacity to manipulate and control the physical, chemical, mechanical, and biological properties that operate at this scale, including enhanced conductivity, optical properties, and reactivity (Pramanik and Pramanik, 2016). It is one of the most promising tools that can enhance agricultural potential through higher yields in an ecofriendly way that too in a challenging environment (Mishra et al., 2017). Nanotechnology plays a crucial role in the development of genetically improved crops through the study of nanomaterials (Servin et al., 2015). Today, nanotechnology has been working as an imperative tool to solve the challenges related to food security and agriculture. The integration of nanotechnology with genome editing tools like CRISPR/Cas is being widely used as a delivery tool for proteins and template DNA. Moreover, this also helps in increasing food production effectively and economically (Ghouri et al., 2020). Similarly, another useful branch of nanotechnology that can bring a drastic change in plant breeding is DNA nanotechnology. Using this technology, plant breeders can have the opportunity to maximize their knowledge of the complementary base pairing property of nucleic acid so that artificial nucleic acids with the desired target structure can be manufactured (Sah et al., 2014). In addition, deficiencies in macro and micronutrient content, increasing population, industrialization, depletion of water resources, differences in soil nutrient levels, and topsoil erosion cause direct and indirect effects on plants and animals. Therefore, developing nano-based fertilizer with proper application in the field helps to overcome these problems by improving nutrient use efficiency and spraying accessibility even in aquatic conditions (Manjunatha et al., 2016). Similarly, the thousands of nano capsules mixed with flavored and colored helps to add the nutritional elements such as vitamins, proteins, etc. during food processing. Strong barrier properties, antimicrobial properties, and heat and cold stability are developed by using nanocomposite material to improve food packaging characteristics (Bhagat et al., 2015). Nanotechnology is a propitious part of associative research that can transform agriculture and related disciplines. It can emerge as a suitable tool for comprehensive knowledge of various biological and physiological processes such as cellular processes, regulation of traits, and development of genotypes tolerant to biotic and abiotic factors to increase crop productivity (Ali et al., 2018). Even though Nepal has a large number of active agricultural researchers, studies in the field of nanotechnology are restricted and lagging. As a result, this article can serve as a beacon of hope for those researchers and academicians working to advance their studies and expertise in order to revolutionize traditional agricultural technology in Nepal.

2 Nanotechnology in agriculture

Nanotechnology combines many scientific disciplines, including engineering, medical, biological, physical, and chemical Fig. 1. If this technology is precisely introduced in the agricultural and plant breeding sectors, there might be a massive escalation in food, productivity, and economic zones, which directly raises the shattered food security in different nations (Ndlovu et al., 2020). Nanotechnology has emerged as one of the most imperative tools in the recent agriculture sector (Acharya & Kumar, 2020). In this modern era of science and technology, there are no such fields left untouched by nanotechnology. Agriculture is no exception. This technology has broad applications in the agriculture and food sectors, telecommunication, the food industry, cosmetics, etc. Through nanobiotechnology, we can understand the biology of different crops, which will eventually help enhance the yield and nutritional value of those crops through breeding (Sah et al., 2014). The need for nanotechnology in the agriculture sector is felt to improve crops, diagnose plant diseases, and monitor plant health and soil quality. These will ultimately contribute to enhanced plant performance, which is the main focus of every breeding program (Sertova, 2015).

2.1 Hormonal effects in plants

Numerous plant regulators are being manufactured and utilized throughout the world to amplify the hormonal effects, including nano-5 and nano-gro. A leading agricultural company, i.e., Syngenta has been fabricating Primo MAXX, a plant growth regulator, for the past couple of years (Ndlovu et al., 2020).

2.2 Genetic manipulation and crop improvement

Nanotechnology can be used to reform the genetic constituents of plants and can act as a defensive shield for pathogens, therefore helping in crop improvement (Elizabath et al., 2019; Ndlovu et al., 2020). With this technology, breeders can develop potentially enhanced plants that improve resistance to various environmental stresses such as drought, cold, disease, salinity, etc. For example, zinc nanoparticles are widely used to enhance the productivity of *Pennisetum americanum*. The use of TiO_2 NMs increases the productivity of mung beans (Manjunatha et al., 2019). The advancement in nanotechnology empowered by

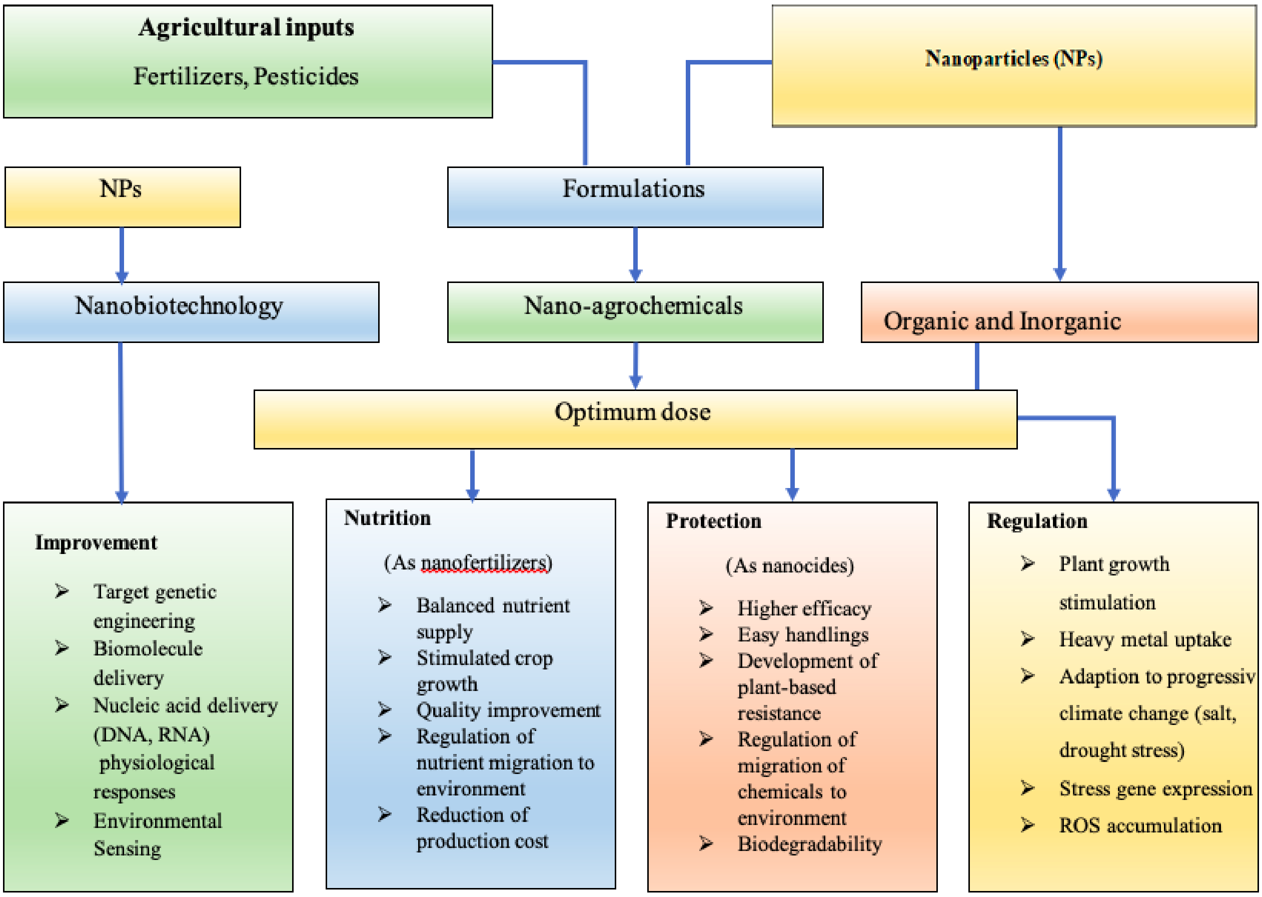

Figure 1. Application of nanotechnology in agriculture. Modified from Shang et al. (2019)

gene sequencing is used to effectively identify and utilize plant genetic resources (Sangeetha et al., 2017). The application of nano-genomics based technology in plant breeding can be used to deploy nanomaterials as transporters of DNA or RNA in plant cells that divert the genes to the target location at a cellular level for gene expression (Ndlovu et al., 2020; Omanovic-miklicanin and Science, 2017; Wani and Kothari, 2018). The use of nano-fertilizers improves crop yield and quality with higher nutrient efficiency while simultaneously reducing spillage in the environment and the cost of production, thus contributing to sustainable agriculture. For example, the application of phosphatic nano-fertilizers has been found to increase the growth rate by (32%) and seed yield by (20%) of soybean (*Glycine max*) as compared to those treated with conventional fertilizers. Also, carbon nanoparticle nanotubes of Au, SiO_2, ZnO, and TiO_2 ameliorate the development of plants by enhancing elemental uptake and use of nutrients (Fraceto et al., 2016). A recent study on different crops has also shown increased germination, seedling growth, physiological activity like photosynthetic activity and nitrogen metabolism, m-RNA expression, and some positive changes in gene expression, fostering their potential use in crop improvement (Pramanik and Pramanik, 2016). Nutrient deficiency in crops can be managed by the use of nanocarriers that help in fulfilling the nutrient requirements of plants. Nanotechnology can also be used to recognize superior genes to improve crops for disease resistance or higher productivity (Kerry et al., 2017). Just as genetically modified agriculture has given rise to a new level along the food chain, likewise, nanotechnology deployed from seeds to stomach, genome to gluten, will strengthen the grasp of agribusiness over global food farming at every stage (Bhau et al., 2016).

2.3 Resistance against abiotic stress

Nano-barcode particles are usually manufactured through semi-automatic lamination of inactive metals such as Au, Ag, or Pt. Those nano-barcodes are applied in the analysis of gene expression to develop resistance against ecological stresses and to induce resistance against corrosiveness and ultraviolet rays' effects on the chloroplast (Ndlovu et al., 2020). The use of various nanoparticles, GPS (Global Positioning System), and remote sensing technologies by farm managers helps widely detect multiple crop pests or evidence of different environmental stresses such as drought, pollution, nutrient deficiency, etc. This helps to make a plan and protect our crops accordingly (Joshi et al., 2019).

2.4 Seed science

To improve the germination of the rainfed crop, researchers are working on metal oxide nanoparticles and carbon nanotubes. It is also found that carbon nanotubes can enhance the germination of tomato seeds through the better conveyance of moisture. The data shows that carbon nanotubes (CNTs) acts as a new pore and facilitate the passage of water by penetrating the seed coat and acting as a way to channelize the water from the substrate into the seeds. Hence, it can enhance germination in the rainfed agricultural system (Reddy et al., 2017). It was found that Ti NPs at 20 g/L concentration significantly increased the ear mass, seed number, biomass, stem elongation, flowering, yield, starch, and gluten content in wheat. Similarly, carbon nanotubes (CNTs) were reported to enhance the germination percentage of tomato seeds by penetrating their hard outer coat. Moreover, the germination percentage of other crops, like soybean, barley, corn, etc., was also increased when sprayed or encapsulated with multiwall carbon nanotubes (MWCNTs) (Acharya and Pal, 2020). The use of nanoparticles (manganese, molybdenum) and multiwalled carbon nanotubes (MWCNTs) has increased the germination percentage of Brassica juncea, Phaseolus mungo, etc. Silver nanoparticles are also used for seed dressing and surface sterilization of seed crops (Chhipa, 2019). Germination rate, bud length, diameter, fresh bud weight, etc. were found to be higher in the seeds of cowpea, cabbage, and cucumber treated for 2h, 4h, and 12h respectively with nano-863 than soaked in pure water. When soaked in nano-863 treated water, garlic produced about 5cm longer heights of bolts after about 20 days of treatment than the ones in the control group (Huang et al., 2014).

2.5 Seed storage

Stored seeds emit several volatile aldehydes, which decide the degree of aging. These emitted gases affect other seeds too. So, to detect these volatile aldehydes and seeds showing signs of degradation, biosensors can be used, and they can be separated from the healthy ones before they come into use (Reddy et al., 2017). In a like manner, the nano-sensors can be used to identify the presence of insects or fungus precisely inside the stored grains in storage houses (Sekhon, 2014).

2.6 Disease and pest control

In 2011, a statement was fortified by Pimentel and Burgess that almost 545 million kg of pesticides is utilized on plants in the United States each year, but <0.15% of this reaches the preferred target and eliminates the pests (Vega-Vásquez et al., 2020). This statement reflects the overuse and uncontrolled application of pesticides and unsuccessful measures of pest control. Generally, plant diseases are generated by pathogenic microorganisms such as bacteria, fungi, nematodes, and viruses, which promptly reduce the crop quality and yield. Many practices are carried out to control diseases and pests, including cultural, physical, chemical, legislative, genetics, breeding, and integrated disease and pest management approaches. However, they can't control them (Kumar et al., 2018). The issue might lie in recognizing economic threshold levels outside of which they can't be controlled (Elizabath et al., 2019). Nano-based diagnostics can identify diseases and agrochemical residues by measuring differential protein in diseased and healthy crops, which leads to the identification of specific microorganism species and the stage of therapeutic drug application to prevent and stop disease (Chung et al., 2017; Elizabath et al., 2019) (Tables 1 and 2). Moreover, nanotech applies to nanoparticle-mediated gene transfer in crops to create efficacious pest-resistant and tolerant lines (Chung et al., 2017). The utilization of biomarkers unequivocally indicates disease stage (Dhewa, 2015; Sertova, 2015), and nano silica-silver composite Silicon (Si) is known to be absorbed into plants to expand disease obstruction and stress resistance (Bhagat et al., 2015). Nanostructured frameworks have a broad scope of use in determining and treating diseases in plants, giving better management of insects and diseases (Dhewa, 2015; de Oliveira et al., 2014; Sah et al., 2014). Allowing their lower portions to be used, which will also ensure environmental protection (Bhan et al., 2018; Grover et al., 2012; Jha et al., 2011). Utilizing nano-sensors and carbon nanotubes further develops monitoring and protection of plants from plant diseases through prompting plant infection obstruction (Cicek and Nadaroglu, 2015; B, 2011).

2.7 Monitoring of plant growth stages

Nano-sensors are immobilized bio-receptor probes that are designed for earlier response to alteration in the environment. Ultimately, it can be linked with GIS, and monitoring is possible to vast crop cultivation areas. With the help of nano-sensors, all possible growth stages of the plant, including the sensitive stages such as photosynthesis and seed germination, can be precisely monitored for obtaining higher and maximal yields (Ghasemnezhad et al., 2019; Kumari et al., 2018). Their application can also detect the composite content in the plants and soil, including urea, pesticides, metabolites, and glucose, along with the detection of pathogens. Applied nano-sensors can improve the ability to recognize crop health, microbial

Table 1. List of encapsulated and non-encapsulated nano pesticides used against insect pest

Ingredients	Target organisms	References
Avermectin	*Martianus dermestoides*	Bhan et al. (2018)
Nanopermethrin	*Aedes aegypti*	Bhan et al. (2018)
Artemisia arborescens	*Bemisia tabaci*	Bhan et al. (2018)
Azadirachta indica	*Bemisia tabaci*	Bhan et al. (2018)
Nanoalumina	*Sitophilus oryzae*	Bhan et al. (2018)
Nanosilica	*An. stephensi*, *Cx. quinquefasciatus*, *Aedes aegypti*	Bhan et al. (2018)
Aloe vera	*Anopheles stephensi*	Bhan et al. (2018)
Emblica officinalis	*Culex quinquefasciatus*	Bhan et al. (2018)
Rhizopus	*Anopheles stephensi*	Bhan et al. (2018)
Nelumbo nucifera	*Culex quinquefasciatus*	Bhan et al. (2018)
Nano-silica	*Sitophilus oryzae*	Jatav and Nirmal (2013)
Imidacloprid	*Melanagromyza sojae*, *Bemisia tabaci*	Sekhon (2014)
Carbofuran + Imidacloprid	*Aphis gossypii*, *Amrasca biguttula*	Sekhon (2014)
Aqueous leaf extract of *Tinospora cordifolia*	*Anopheles subpictus*, *Culex-quinque fasciatus*	Sekhon (2014)
Garlic essential oil	*Tribolium castaneum*	Sekhon (2014)
DNA-tagged gold nanoparticles	*Spodoptera litura*	Sekhon (2014)

Table 2. List of nano based products used in agricultural sector

Products	Application	References
Super combined fertilizer and pesticides	Release active ingredients slowly	Bhan et al. (2018)
PRIMO MAXX	Control of insect pests of rice peanuts and cotton	Bhan et al. (2018)
Subdue MAXX	Control *Pythium* and *Phytopthera* blight	Bhan et al. (2018)
Nano green	Induce rice yields by 25%	Bhan et al. (2018)
Nanopesticide	For crop protection 10-150 nm	Bhan et al. (2018)
Nanoemulsion	Insect pest control 10-400 nm	Bhan et al. (2018)
Herbicide	Prevent weed growth	Bhan et al. (2018)
Teprosyn-Zn	Corrects Zn deficiencies in wheat, maize, sunflower, groundnut and soybean	Jatav and Nirmal (2013)
Chitosan-coated NPK	Controlled release of nutrients and water-retention abilities	Cicek and Nadaroglu (2015)
Sulfur coated fertilizer	Slow release of sulfur contents	Jatav and Nirmal (2013)

contamination, and harvest time (Singh et al., 2020). The sensors work as outside observing gadgets for on-location checking of ecological conditions, plant development, and protection (Bhagat et al., 2015; Jatav and Nirmal, 2013; Jha et al., 2011). Nanoparticles of TiO_2 improve spinach development by improving nitrogen digestion and light assimilation limit (Ali et al., 2014).

2.8 Secondary metabolites exploitation

Secondary metabolites (alkaloids, phenolics, and terpenoids) emitted by the plant as self-safeguarding tools of nature provide protective and defensive capacity against insects (Cicek and Nadaroglu, 2015). The nanostructures can be used to discover precious metabolites; for instance, nano-convectors can detect terpenoids, anthocyanins, and other beneficial secondary metabolites in therapeutic herbs and shrubs. Furthermore, the nano-polymers can augment plant cell catalytic activity, thus producing more protein (Ghasemnezhad et al., 2019). Mycotoxins are harmful auxiliary metabolites produced by fungi that are fatal to living beings. So, the pores of nanostructured polymer layers could be utilized as receptors to acknowledge comparable poisonous metabolites (Huang et al., 2014; Sertova, 2015).

2.9 Smart delivery of agrochemicals

The nanobiosensors that use carbon nanotubes or nano-cantilevers are very small enough to trap and deliver even the smallest molecules and other individual proteins (Abd-Elrahman and Mostafa, 2015). Smart sensors and smart delivery systems assist the horticultural business with combatting infections and other harvest microbes. The nano-based impetuses improve the effectiveness of pesticides and herbicides, permitting lower portions to be utilized (Rai and Ingle, 2012; Sertova, 2015). For example, nano encapsulated pesticides increase the solubility of poorly soluble active ingredients and release them slowly. This activity of nano-encapsulated agrochemicals allows for slow and effective release to a specific host, reducing toxicity to non-targeted organisms. Such controlled nanoparticulate delivery systems will require a designated conveyance approach centered on utilizing the information on the life-cycle and the conduct of the microbe or irritation (Jatav and Nirmal, 2013). As per the research carried out by various workers, it has been found that nanoparticles of different metals are also cost-effective and the most reliable alternative for controlling insects, and pests. In this way, this technology has helped in the smart delivery of agrochemicals and is thus gaining popularity these days (Kumar, 2020).

2.10 Nano fertilizers

One of the significant commitments of nanotechnology in agribusiness is the detailing of nano-based composts, i.e., nano fertilizers (Ali et al., 2018). Nutrients can either be encased within nanomaterials like nanotubes or nanoporous materials laminated with thin protective polymer film or rendered as particles or emulsions of nanoscale dimension (Ranjan et al., 2016). Nano fertilizers have interesting attributes like super high assimilation, an enormous surface region, pore-volume, and exceptionally requested pores. These properties enable slow delivery and advanced, proficient supplement take-up by harvests, making them more powerful than the majority of the most recent polymeric-sorted ordinary composts that have essentially been performed over the previous decades (Ali et al., 2018; Elemike et al., 2019; Kumar et al., 2018; Singh et al., 2020). The primary delegates are nitrogen composts, potash manures, nanoporous zeolite, zinc nano fertilizers, zeolites, and nano clays that discharge supplements gradually for the duration of the existing pattern of the crops, thereby lessening the dangers of filtering, adsorption, surface spillover, and deterioration (Ndlovu et al., 2020; Omanovic-miklicanin and Science, 2017). Unlike traditional fertilizers, nano fertilizers can be made to release nutrients in a controlled way in a gradual manner into the soil, which may help prevent putrification and contamination of bodies and the environment. Similarly, foliar application of nanofertilizer has been reported to increase crop yields significantly (Singh et al., 2016).

3 Opportunities

The utilization of nanotechnology and other fundamental science disciplines can produce optimized beneficiaries that can rectify the various challenges of agriculture, industry, health, communication, energy, and the environment (Krishnan, 2018). The world has now realized that nanoscale science and nanotechnologies can revolutionize the agriculture and food system and have given birth to 'agro-nanotechnology'. Although the first green revolution promised food to everyone, agriculture production is now facing a plateau, compelling the second green revolution, and this nanotechnology can grab this opportunity. Considering the current scenario, the most incredible opportunity of nanotechnology is 'crop improvement'. This technology helps develop resistant and improved plant genotypes through plant breeding or genetic engineering (Nikunj et al., 2014). Nanotech-derived devices (nano-sensors, nanoparticles) are widely used in plant breeding and genetic transformation to develop improved crops (Kumar, 2020). Nano-biosensors possess unique physio-chemical properties such as being independent of pH, temperature, stirring, stability under normal storage conditions, etc. In addition to this, they are very tiny, cheap, portable, non-toxic, and non-antigenic, and hence can be operated easily. There is a vast opportunity in tissue culture, molecular breeding, genetic engineering, transgenic approach, and so on, through various approaches that include the following principles: using nanomaterial coated 'smart seeds', targeted delivery of agrochemicals and drugs, monitoring soil and plant health using bio-sensors, and decreasing losses through appropriate disease management practices.

Besides all these opportunities, nanomaterials also have a chance to functionalize membranes and eliminate and or recover nutrients from a source of contaminated water and a waste stream (Lowry et al., 2019). It opens a broad range of opportunities in technical and mechanical fields, and its application in those fields can indeed bring prodigious positive changes in the coming decades (Elizabath et al., 2019). Due to the uncontrolled and unmanaged administration of chemicals on crops, adverse effects are visible in the ecosystem. These resistant and tardily degrading compounds like pesticides, insecticides, weedicides, and rodenticides enter the food chain of organisms and show detrimental effects. Thus, nanoparticles can play a nurturing role in the bioremediation of those contaminants by assisting microbial action and degrading them into innocuous (Kumar et al., 2018; Singh et al., 2020). Furthermore, the powerful nanoparticles can be combined with botanical sides that are harmless to plants and the environment (Ghasemnezhad et al., 2019). As well, nanotechnology can be permitted in agricultural research and applied zones for its advancement. Through nanotech, plant diseases can be prevented, early stresses can be detected and minimized, and diversified lines can be produced that are uninfluenced by harsh environmental fluctuations. Additionally, the amplification of nanotech in plant breeding can lead us to make our agricultural systems futuristic and quick-witted. Various advancing engineered tools can be accoutered with nanodevices that have the potential to supplant many cellular levels of machinery (Singh et al., 2020). With the furtherance of nanotech, there could be immense advances in gene drives, delivery systems, homology-directed repair, and editing specificity that can improve gene editing in synthetic biology (Chen et al., 2019). Besides this, it can be applied to nurse wastewater to induce crop quality and production, acquire clean energy, and minimize resource utilization, thus aiding environmental and ecological fields (Kumar et al., 2018). From nanotechnology, the food industry can also benefit since it can be used to modify the flavours and nutrients according to individual preferences and can be used for active and safe packaging (Krishnan, 2018). Furthermore, the application of this technology in genetic engineering can aid in the transduction of desired traits in medicinal plants for increasing metabolite production, as well as the precise delivery of drugs in animals and humans (Ghasemnezhad et al., 2019; Kumar et al., 2018). And the environment can be monitored at different matrices levels to ensure effective pollution control and to support and sustain soil life (Elemike et al., 2019).

4 Potential

Nanotechnology has come forward as a futuristic weapon to mitigate those challenges (Elmer and White, 2018). The entrance of nanotechnology into plant breeding can bring colossal and drastic changes that will directly enhance the world economy. This technology shows great potential in embracing today's technologies despite competing with them. The versatile capacity of this tech will seize and uplift the growth of several fields, including agriculture, that will help to achieve the UN millennium goal by influencing food security and food safety in upcoming years (Ghasemnezhad et al., 2019; Krishnan, 2018; Kumar et al., 2018). The applications of nano-fertilizers and nano-pesticides enhance agricultural productivity with low cost and energy input without deteriorating functional bodies like soil, water, turf, and other vegetation (Mishra et al., 2017; Singh et al., 2020). Nanotechnology can further participate in the monitoring of water quality, crop disease incidences, growth rates, nutrient use efficiency, and pesticides through nanonetworks and wireless nanosensors for their efficient usage in field conditions to attain high-tech agriculture farming and sustainable development in agriculture (Ndlovu et al., 2020; Singh et al., 2020).

In the last two decades, along with technological advancement, nanotechnology has emerged as a crucial and promising tool to revolutionize the agriculture and food system. The unique physicochemical property of this technology has huge potential in almost every sector, including agriculture, particularly in the crop improvement system (Shashidara et al., 2015). Nanotechnology can bring about the next agri-tech revolution, transforming agriculture to be more effective and sustainable. And this technology in agriculture will continue to advance along with development in nanotechnology and understanding of nanomaterial-plant interaction (Lowry et al., 2019). The integration of nano-based materials like nano biosensors, nanotubes, and nano encapsulated agrochemicals can potentially enhance the yield and nutritive value of a crop by helping us to understand their biology (Yashveer et al., 2014). Likewise, nanotechnology has considerable potential in a crop protection system, which can be achieved through the controlled release of encapsulated pesticides, fertilizers, and other agrochemicals against targeted pathogens and pests. This potential of nanotechnology directly helps in the development of efficient and potential approaches for disease management.

Similarly, nano-sensors are widely used for the early detection of plant diseases and pollutants, including residues, thereby decreasing their toxicity to humans and other living organisms. Nanotechnology has substantial potential in the agricultural sector. However, a few issues are still to be addressed, like risk assessment issues, sufficient study on nanotoxicity, increasing the production scale, and lowering the cos (Kumar, 2020). Another essential potential of nanotechnology is the development of an insect, pest, and disease-resistant varieties through appropriate breeding programs that encompass nano-based materials. This can be achieved by incorporating nanoparticle-mediated genes or DNA of our interest into a targeted plant (Prasad et al., 2017). Another essential potential of nanotechnology is the development of genetically modified (GM) crops with improved performance and increased yield, which is the most urgent need to meet the increasing demand for produce. And this can be achieved through various principles of nanobiotechnology, such as transgenic breeding, induced or natural mutation, etc. (Adlak et al., 2019). Current agriculture is facing a broad spectrum of local as well as global challenges, which has led to various problems, including decreased production, environmental issues, etc. So, now is the time to integrate this beautiful and yet powerful technology into agriculture as it has the potential to transform agriculture (Acharya and Pal, 2020). Nanotechnology has the phenomenal potential to facilitate and frame the next stage of the precision farming technique. Nevertheless, the primary focus of nanotechnology has always been placed on crop genomes to develop potentially enhanced plant varieties that are more tolerant to various biotic and abiotic stresses (Prasad et al., 2017). Therefore, the latest and most revolutionary technology is nanotech, under nanoparticles, which acquires pioneering and unique properties that can revive and aggravate the world's agricultural and plant breeding sectors, among many more (Prasad et al., 2017).

5 Challenges

Despite these potential advantages, the agricultural sector is still comparably marginal and has not yet been able to make progress in the market to any greater extent relative to other fields of nanotech application (Kumar, 2020). Nanotechnology has successfully been implemented in the sectors of genetics and plant breeding. However, nanotechnology remains insignificant and has not yet taken the market because of its poor cargo loading capacity (Vega-Vásquez et al., 2020). Despite those aforesaid opportunities and potentials of nanotechnology, some studies indicate the negative effects of nanoparticles on the human body, which might be trapped by the imputation of nanotechnology in the agricultural field. The inhalation of even low concentrations of nanosized titanium dioxide in rats induces microvascular dysfunction. Nanoparticles smaller than 1 m have the ability to pierce the healthy human skin and may affect the vascularized organs, including the brain and blood vessels (Wani and Kothari, 2018). Different governmental and non-governmental organizations and scientific authorities, as well as environmental, health, and safety councils, are giving their suggestions, opinions, and guidance for minimizing the risk of nanotechnology to human health, the environment, animals, and plants (Huang et al., 2014). The major challenge in adopting this technology on a large scale is overcoming the risk issue. And as we know that 'technology-yes but safety-must', before the adoption of this technology, it is very important to assess the possible risks and consequences of using nanoparticles (Acharya and Pal, 2020).

6 Positive aspects

Nanotechnology intends to be an innovative technology that is implanted in plant breeding to develop precision and meet the intense demand for food in the world through its criterion (Elemike et al., 2019). The miniature materials manufactured through the utilization of nanotech, i.e., nanomaterials, ameliorate the efficacy of microorganisms to degenerate noxious and unwanted materials. The breakdown of those harmful substances in agricultural factors, including soil water and soil, subsequently induces safety by potentially suppressing toxic residue deposition (Prasad et al., 2017). Furthermore, green nanomaterials, based on environmentally friendly concepts, are employed in the present agricultural system to enhance yield, input use efficiency, and reduce fertilization costs. These convenient materials play an outstanding role in repressing greenhouse gas emissions. In particular, the agricultural field minimizes the production of significant amounts of nitrous oxide, methane, and carbon dioxide (Omanovic-miklicanin and Science, 2017). Furthermore, the use of nanotechnology in plant breeding reduces chemical hazards, nutrient losses, pest outbreaks, and crop yields, while also helping to stabilize changing climatic conditions and levels of food security (Elemike et al., 2019; Omanovic-miklicanin and Science, 2017). Nanotechnology helps in minimizing crop loss to a greater extent. Typically, the remediation process for stress caused by biotic and abiotic factors, disease, and insect-pest infestation starts only after the development of symptoms. Since this technology operates at the same nanoscale as that of viruses or diseases, it potentially helps in their early detection and eradication (Sah et al., 2014). This technology will provide plants with augmented functions, helping them endure various biotic and abiotic stresses in a rapidly changing climate. Also, treating plants with low doses of antimicrobial micronutrients coated with nanoparticles increases the plant's ability to manage biotic stress from fungal root infection (Lowry et al., 2019). According to Prasad et al. (2017), nanomaterials synthesized from biopolymers (cellulose and starch) are safe for humans and have gained popularity around the world because they are non-toxic to humans and are generally regarded as safe.

7 Negative aspects

Besides these ample benefits, nanotechnology also comes up with several negative impacts. Similar to that of all chemical processes, it may also have an unwanted and undesirable effect on non-targeted plants and plant-associated organisms. Therefore, for the large-scale adoption of this technology, there must be a clear understanding of its agro-ecological ramifications, potential, and nanotoxicity (Bindraban et al., 2015). As a thumb rule, anything that has some benefits may also have some limitations, and so is the case with nanotechnology. The accumulation of nanomaterials in food products may give rise to various human health concerns and environmental issues (Ghouri et al., 2020). In recent days, the use of nanotechnology in plant breeding and other prospective agricultural fields has prompted concerned authorities, including breeders, agriculturists, environmentalists, researchers, and even the general public, to express concerns about the initial and long-term safety of beings, the environment, and environmental parameters (Ndlovu et al., 2020). Many studies have also reported the negative impact of using metal oxide nanoparticles on plant growth and seed germination, hence causing phytotoxicity, cytotoxicity, and genotoxicity (Prasad et al., 2017). Improper use of this technology can pose a greater threat to living organisms. The negative impact of nanomaterials on plants and soil microbes has been broadly identified. The phytotoxicity effects of five different types of nanomaterials (multiwalled carbon nanotubes, aluminum, alumina, zinc, and zinc oxide) have been reported on seed germination and development. Likewise, the negative effect of nano-TiO_2 is observed on the photochemical reactions of chloroplasts (Rana et al., 2020). From the current studies, it is clear that engineered nanoparticles can be a prohibitive risk for humans, animals, and the ecosystem (Singh et al., 2020). To a certain extent, nanotechnologies have been found to impact the growth, enzyme activity, chlorophyll, and protein content of algae, though the effect is more dependent on the type of algae and the character of nanomaterials (Huang et al., 2014). The use of nanotechnology has been banned in "organic food production in Canada", where an amendment was added to its national organic rules banning nanotechnology as a 'Prohibited Substance or Method' (Pramanik and Pramanik, 2016). An International Federation of Organic Agriculture Movements Position Paper on the Use of Nanotechnologies and Nanomaterials in Organic Agriculture rejected the use of nanotechnology in organic agriculture, indicating that nanoparticles behave in an unpredictable manner, which may be harmful to life. A major concern while using nanomaterials is that they may be taken up by cells and cell nuclei of individuals where they may cause cell death or DNA mutation (Pramanik and Pramanik, 2016). Though carbon nanotubes facilitated better root elongation in onions and cucumbers, it was found that they significantly decreased the root length in tomatoes (Mishra et al., 2017). An international policy debate has now emerged in the last 5 years concerning an appropriate mechanism for the regulation and governance of nanotechnology (Read et al., 2015). The nanoparticles incorporated into plants as nanopesticides, nano-herbicides, or nano-fertilizers may block the vascular bundle in plants and prevent the transference of nutrients, minerals, water, and products of photosynthesis. They may also reduce pollination by creating physical obstruction between pollen and stigma (Elizabath et al., 2019; Ndlovu et al., 2020). According to the researchers, air-borne nanoparticles pose an extreme level of threat to human and animal health. Those miniature particles might enter the respiratory and circulatory systems and enhance the chances of emphysema, protein fibrillation, asthma, genotoxicity, and chronic pulmonary diseases (Elizabath et al., 2019). Because of these mentioned risks, the application of nanotechnology in significant fields like agriculture and plant science should be attended to with supreme attentiveness. However, there has been limited research on nanotechnology-based on its risky elements and toxicity. Further integrations of studies are being carried out to expand the criteria of nanotechnology's application (Elizabath et al., 2019; Mishra et al., 2017). Therefore, considerable attempts should be made to analyze the interactions and nature of nanoparticles in the environment to ensure a viable and secure future (Kumar et al., 2018; Mishra et al., 2017).

8 Conclusion

Agricultural activities can be sustained directly by nanotechnology, by reducing the effects on crops, plants, animals, and human health. There has been significant progress in nanotechnology in various fields of agriculture, like crop improvement, disease diagnosis, insect-pest management, monitoring soil health, etc. Nano-derived devices (nano-sensors, nanoparticles) are widely used in plant breeding and genetic transformation of crops to develop improved varieties through appropriate breeding programs. This technology has the potential to revolutionize the agriculture and food system because of its substantial and diversified applications. Even though this technology has brought out a significant change in agriculture, such advancements have also raised challenges and safety concerns about the practical use of nanotechnology. Nanotechnology provides a pool of research opportunities in plant breeding and medicine, healthcare, energy, materials, and manufacturing. The areas of nanotechnology can be applied in all aspects of the food chain to improve food safety and quality control and to novel food ingredients or additives.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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