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Applications of Nanotechnology in Agriculture

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ABSTRACT: Research has shown nanoparticles to be a groundbreaking tool for tackling many arising global issues, the agricultural industry being no exception. In general, a nanoparticle is defined as any particle where one characteristic dimension is 100nm or less.^[1] Because of their unique size, these particles begin to exhibit properties that their larger counterparts may not. Due to their scale, quantum mechanical interactions become more important than classic mechanical forces, allowing for the prevalence of unique physical and chemical properties due to their extremely high surface-to-body ratio. Properties such as cation exchange capacity, enhanced diffusion, ion adsorption, and complexation are enhanced when operating at nanoscale

KEYWORDS: nanoparticles, agriculture, quantum, mechanical, ion adsorption, nanoscale, body ratio, complexation, soil

I.INTRODUCTION

This is primarily the consequence of a high proportion of atoms being present on the surface, with an increased proportion of sites operating at higher reactivities with respect to processes such as adsorption processes and electrochemical interactions. Nanoparticles are promising candidates for implementation in agriculture.¹ Because many organic functions such as ion exchange and plant gene expression operate on small scales, nanomaterials offer a toolset that works at just the right scale to provide efficient, targeted delivery to living cells.^[3] Current areas of focus of nanotechnology development in the agricultural industry include development of environmentally conscious nano fertilizers to provide efficient ion, and nutrient delivery into plant cells, and plant gene transformations to produce plants with desirable genes such as drought resistance and accelerated growth cycles.^[4] With the global population on the rise, it is necessary to make advancements in sustainable farming methods that generate higher yields in order to meet the rising food demand. However, it must be done without generating long-term consequences such as depletion of arable land or water sources, toxic runoff, or bioaccumulative toxicity. In order to meet these demands, research is being done into the incorporation of nanotechnology agriculture.²

One area of active research in this field is the use of nanofertilizers. Because of the aforementioned special properties of nanoparticles, nanofertilizers can be tuned to have specialized delivery to plants. Conventional fertilizers can be dangerous to the environment because of the sheer amount of runoff that stems from their use.^[5] Having a detrimental effect on everything from water quality to air particulate matter,³ being able to negate runoff from agriculture is extremely important for improving quality of life around the world for millions. For example, runoff from sugar plantations in Florida has spawned the infamous algae bloom called "red tide" in water tributaries across the state, creating respiratory issues in humans and killing vital ecosystems for years.^[6]

Studies have shown that, in most cases, greater than 50% of the amount of fertilizer applied to soil is lost to the environment, in some cases up to 90%.^[7] As mentioned before, this poses extremely negative environmental implications, while also demonstrating the high waste associated with conventional fertilizers. On the other hand, nanofertilizers are able to amend this issue because of their high absorption efficiency into the targeted plant- which is owed to their remarkably high surface area to volume ratios. In a study done on the use of phosphorus nano-fertilizers, absorption efficiencies of up to 90.6% were achieved, making them a highly desirable fertilizer material.^[8] Another beneficial aspect of using nanofertilizers is the ability to provide slow release of nutrients into the plant over a 40-50 day

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time period, rather than the 4-10 day period of conventional fertilizers.^[9] This again proves to be beneficial economically, requiring less resources to be devoted to fertilizer transport, and less amount of total fertilizer needed.⁴

As expected with greater ability for nutrient uptake, crops have been found to exhibit greater health when using nanofertilizers over conventional ones. One study analyzed the effect of a potato-specific nano fertilizer composed of a variety of elements including K, P, N, and Mg, in comparison to a control group using their conventional counterparts. The study found that the potato crop which used the nano-fertilizer had an increased crop yield in comparison to the control, as well as more efficient water use and agronomic efficiency, defined as units of yield increased per unit of nutrient applied. In addition, the study found that the nano fertilized potatoes had a higher nutrient content, such as increased starch and ascorbic acid content.^[10] Another study analyzed the use of iron-based nanofertilizers in black eyed peas, and determined that root stability increased dramatically in the use of nano fertilizer, as well as chlorophyll content in leaves, thus improving photosynthesis.^[11] A different study found that zinc nanofertilizers enhanced photosynthesis rate in maize crops, measured through soluble carbohydrate concentration, likely as a result of the role of zinc in the photosynthesis process.^[12]

Much work needs to be done in the future to make nanofertilizers a consistent, viable alternative to conventional fertilizers.⁵ Effective legislation needs to be drafted regulating the use of nanofertilizers, drafting standards for consistent quality and targeted release of nutrients.^[13] Further, more studies need to be done to understand the full benefits and potential downsides of nanofertilizers, to gain the full picture in approach of using nanotechnology to benefit agriculture in an ever-changing world.⁶

II.DISCUSSION

Nanotechnology has played a pivotal role in the field of genetic engineering and plant transformations, making it a desirable candidate in the optimization and manipulation of cultivated plants. In the past, most genetic modifications to plants have been done with *Agrobacterium*, or utilising tools such as the gene gun (biolistics); however, these older methods of gene implementation face roadblocks due to low species compatibility lack of versatility/compatibility with Chloroplastial/Mitochondrial gene transformations, and potential for cell or organelle damage (due to impact of biolistics).⁷ While biolistics and *Agrobacterium* are useful in specific species of plants- more refined approaches are being explored through the utilisation of nanomaterials- allowing for a less invasive and forced delivery approach. These methods utilise Carbon Nanotube (CNT) and various porous nanoparticle (NP) enabled delivery methods, which may allow for higher-throughput plant transformation- while also circumventing legal GMO restrictions.^[14] The research of non-incorporative/DNA-Free genetic modifications has become a very important field of study,⁸ since traditional methods of plant transformation (*agrobacterium* and biolistics) risk DNA incorporation in the plant genome, thus making them transgenic and qualifying them as a GMO.^[15]

A novel strategy utilizes highly-tailorable diffusion based nanocarriers for the delivery of genetic material, allowing for non-transgenic, non-destructive plant transformation. The method specificity is highly dependent on the properties of the material utilized, with key factors including size, polarity, and surface chemistry. Some approaches to diffusion based delivery have used Nano-Structured-DNA,^[16] carbon nanotubes,^[17] and other nanoparticles^[18] as vesicles for the delivery of genetic information. . These methods typically rely on functionalization of the surface or manipulation of porosity of a nanocarrier in order to optimize the loading and delivery of genetic information. DNA nanostructures have been shown to be a highly programmable modality in terms of delivery of small interfering RNA (siRNA), exploring the optimal design parameters necessary for plant cell internalization.^[19] A recent study utilizing DNA loaded CNTs was able to successfully express desired traits in various mature model plant systems- and even isolated *Eruca sativa* protoplasts while managing to protect and maintain the fidelity of the transferred genetic material.^[20] Lastly, porous nanoparticles have been shown to be an effective DNA delivering agent for plant transformations- with efficiency depending on pore size and strand length.^[21] All in all, these diffusion based gene transformation methodologies offer a cheaper mode of plant gene transformation with lower impact to plant tissue, lower transformation efficiencies, and little to no risk of DNA incorporation.⁹

Biolistics is the primary approach to plant transformation. The biolistic process involves launching microprojectiles (usually gold microparticles) carrying genetic information through the cell walls and membranes of cells to impart

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genetic transformation.^[22] As previously mentioned, biolistics may result in damaging the targeted cells or organelles- thus in order to minimize potential cell damage, nano-biolytic methods have been developed. Due to the significantly reduced size of the particle being launched into the cell,¹⁰ the impact can be minimized, while offering a similar efficiency of genetic transformation as traditional biolistics. However, most studies utilizing nanoscale biolytic approaches are done with animal cells, so implementation in plant transformation is still fairly novel and may encounter roadblocks unseen in animal cell studies.^[23]

Overall, nanotechnology provides a novel and competitive approach to genetic transformation of plants. Going forward, future research into the applications of these approaches will span a greater variety of crops, aim to utilize cheaper, more scalable methods, and explore potential environmental effects. Ultimately, once these design criteria will determine whether nanomaterial plant transformations will become a widespread practice in the future of agriculture.¹¹

III.RESULTS

In recent years, as applications of nanotechnology have exhibited promise in many fields of study, an increasing number of government, scientific, and independent institutional bodies have seen the potential of nanotechnology in making significant contributions to alleviating the burden of the global food supply. Current public views on nanotechnology development in the agricultural industry are mixed.^[24] With consideration of the potential hazards in conjunction with the potential benefits, the current public opinion appears to be relatively neutral as critics see the technology as less risky,¹² and more beneficial than a number of other technologies such as pesticides and chemical disinfectants; however, it is perceived as riskier and less beneficial than solar technologies and vaccinations.^[25]

Among the general public, there still exists negative connotations related to fertilizers and genetic modification of living organisms. Concerns that despite the benefit of higher yields and shorter growing cycles, fertilizers are associated with toxic runoff that contaminate sources of water and can lead to the generation of acid rain.^[26] Additionally, there exists the unfounded fear that consumption of genetically modified foods is 'unnatural' and dangerous, which has led to numerous legislative efforts- limiting the field to non-transgenic transformations.^[27] While the majority of public fears and concerns are unfounded, it is more the result of poor communication and lack of public awareness related to the issue of introducing novel technology to a traditional industry such as agriculture.¹³ Ultimately the production of clean and healthy food is considered by many to be of high importance, simply due to the high frequency of consumption and intimate relation people have with the food they consume. Hydrogels, nanoclays, and nanozeolites have been reported to enhance the water-holding capacity of soil, hence acting as a slow release source of water, reducing the hydric shortage periods during crop season. Applications of such systems are favorable for both agricultural purposes and reforestation of degraded areas.¹⁴ Organic e.g., such as polymer and carbon nanotubes and inorganic e.g., such as nano metals and metal oxides nanomaterials have also been used to absorb environmental contaminants, increasing soil remediation capacity and reducing times and costs of the treatments. Nanotechnology can find applications also in the development of analytical devices dedicated to the control of quality, bio/security, and safety not only in agriculture, but also along the food supply chain¹⁵. In this context, nanosensors represent a powerful tool with advanced and improved features, compared to existing analytical sensors and biosensors. Nanosensors are defined as analytical devices having at least one sensing dimension no greater than 100 nm, fabricated for monitoring physico-chemical properties in places otherwise difficult to reach. Nanotubes, nanowires, nanoparticles, or nanocrystals are often used to optimize the signal transduction deriving by sensing elements in response to exposure to biological and chemical analytes having similar size. They have unique surface chemistry, distinct thermal, electrical and optical properties, useful to enhance sensitivities, reduce response times, and improve detection limits, and can be used in multiplexed systems. Considering the huge amount of research in this area, real applications of nanosensors for field analysis are unexpectedly scarce, implying the potential for a new market. In this perspective, nanotechnologies could enhance biosensor performance to allow real applications in agrifood. Indeed, thanks to important progresses in nanofabrication,¹⁶ laboratory analytical techniques, such as surface plasmon resonance, mass spectrometry, chromatography, or electrophoresis chips, can support the development of viable sensor components. However, the real need of the market is the realization of automated embedded systems, which integrate biosensing components with micro/nanofluidics, data management hardware, and remote control by wireless networks. This is a key issue for nanotechnology, which can provide the decisive approaches as well as novel nanomaterials for the realization of biosensing devices. Indeed, "Nanosensors help farmers in maintaining farm with

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precise control and report timely needs of plants.” Thus, it will be mandatory to address research efforts to the development of nanosensors to aid decision-making in crop monitoring, accurate analysis of nutrients and pesticides in soil, or for maximizing the efficiency of water use for a smart agriculture.¹⁷

In this context, nanosensors could demonstrate their potential in managing all the phases of the food supply chain, from crop cultivation and harvesting to food processing, transportation, packaging, and distribution. Among them, nanosensors for dynamic measurement of soil parameters (pH and nutrients, residual pesticides in crop and soil, and soil humidity) detection of pathogens and prediction of nitrogen uptake are only few examples to foster a sustainable farming. Specifically, nanosensor systems can be developed to monitor the presence of pests, pathogens or pesticides in order to better tune the amount of insecticides to be employed for crop productivity management, since they show higher sensitivity and specificity compared to the “traditional” sensors. For example, controlled release mechanisms via nanoscale carriers monitored by nanosensors integrated in platforms employing wireless signals, will avoid overdose of agricultural chemicals and minimize inputs of fertilizers and pesticides during the course of cultivations, improving productivity, and reducing waste. Networks of nanosensors located throughout cultivated fields will assure a real time and comprehensive monitoring of the crop growth, furnishing effective high quality data for best management practices¹⁸.

Nanotechnology can increase agricultural production, and the following are included in its applications:

1. Postharvest management
2. Poultry production, animal breeding, animal health.
3. Plant disease diagnostics.
4. Nanodevices for the plants’ genetic engineering.
5. Nanosensors’ application in crop protection to identify the diseases and residues of the agrochemicals.
6. The nanoformulations of the agrochemicals to apply fertilizers and pesticides to improve crops.¹⁹

Crop yields are also improved by precision farming techniques without damaging water and soil. Moreover, there can be less loss of nitrogen because of emissions, leaching, and soil microorganisms. The nanotechnology applications include the DNA transfer or nanoparticle-mediated gene in the plants to develop insect-resistant varieties, food storage and processing, and improved product shelf life. The development of biomass-to-fuel production can be increased by nanotechnology. According to the experts, there needs to be a balance of nanotechnology’s potential benefits for aquaculture, fisheries, food, and agriculture, against the concerns for the workers’ occupational health, environment, water, and soil. Currently, there are ongoing researches and tests on the usage of nanotechnology, and in some cases, they have already been implemented in food technology.²⁰ There have been considerations of the nanomaterials with particular mechanical, physical, and chemical characteristics. Recently, a huge amount of interest has been gained by the agricultural waste products as the source of renewable raw materials for being processed as an alternative to various applications and also the raw material for the production of nanomaterial. Right now, the most perfect example of the evolution in an ecological time scale is Insecticide resistance. There is a need of studying insecticide resistance as it results in understanding the mechanisms that are functioning in real-time and due to its economic significance.²¹ It is now a huge problem in insects for public health and agriculture.

Agricultural Practices of Nanotechnology

A broad amount of selective regimes can be included in agricultural practices. There have been tests of nanotechnology applications in agriculture and food technology. In agriculture, the nanomaterials’ applications main purpose is the reduction of spraying of plant protection products and increasing plant yields. Nanotechnology means nanoparticles and nanocapsules are examples of their usages to treat and detect diseases. There has been an exploration of nanotechnology-derived devices in the plant breeding and genetic transformation field. Nanotechnology’s potential is large in agriculture, whereas there needs to be addressing of some issues like risk assessment.²²

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Nanoparticles' Derivatives

There is a derivation of some of the nanoparticle attractants from the biopolymers like carbohydrates and proteins with less effect on the health of the environment and human beings. There are many usages of nanotechnology in all the stages of agricultural product production, processing, storing, packaging, and transport. The food industry and agriculture can be revolutionized by nanotechnology in farming techniques, improving the plant's capability of absorbing nutrients, detecting diseases, and controlling pests.

Nanotechnology in The Fertilizers and Pesticides

There is a need for Sustainable agriculture these days. Presenting the ecosystem's good approach for the long run might now be understood. Practices causing long-term soil damage include soil's excessive tilling resulting in irrigation and erosion with no need for drainage, leading to salinization. This is for satisfying the food of animals and human beings and the fiber needs.

Long-Term Experiments

There is a need for long-term experiments for demonstrating the impact of the different practices on the characteristics of the soil that are important for sustainability and for giving significant information on this objective. In the US, Nano chemicals development has become a promising pest control and plant growth agent. There is a requirement for fertilizers in the growth of plants. Nanomaterials function as fertilizers that may have the characteristics like crop enhancement and less eco-toxicity. A major way can be given by plants for their bioaccumulation into the food chain. For the chemicals to be safely and effectively used for plants, the latest developments in agriculture cover nanoparticle applications.²³

Effects

Several workers reported the effects of the different nanoparticles on phytotoxicity and plant growth including plant growth, magnetite (Fe_3O_4) nanoparticles, zinc, alumina, and zinc oxide on the seed germination and root growth of the five higher plant species; cucumber, corn, lettuce, rape, and radish, zinc oxide in mungbean, sulfur nanoparticles on tomato, silver nanoparticles and seedling growth in wheat, nanoparticles of ZnO , NiO , MnO , FeO , CuO , and AlO . Wheat Yield and growth can be stimulated by the silver nanoparticles. There are highly favorable growth-promoting effects of the soil-applied 25 ppm SNPs on the wheat yield and growth.

Zinc's Usage

Zinc is an important micronutrient for various metabolic activities in the plants however it is needed in very little amounts in plants. According to the findings, a significant role is played by zinc in the management of the reactive oxygen species and protection of the plant cells against oxidative stresses. There are important purposes for zinc in synthesizing indoleacetic acid (IAA) or auxin from tryptophan and in the biochemical reactions that are needed to form carbohydrates and chlorophyll. Zn's deficiency can affect the crop yield and produced can's quality. There has been an increasing problem with the development of insecticide resistance in the pest insects for public health and agriculture.²⁴

Magnesium Oxide

MgO (magnesium oxide) is a significant inorganic material with various usages like photo electronic materials, toxic waste remediation, advanced ceramics, fire retardants, and adsorbents. Thus, there have been reports of the numerous

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routes and techniques to synthesize MgONPs. Green methods were used to synthesize the MgOH by utilizing the Citrus limon leaves extract, nontoxic neem leaves extract, and acacia gum.

Control of Plant Pests

In various countries, fusarium wilt is lettuce and tomato's destructive disease because of its extreme production loss, fungus' prolonged survival in the soil, and resistant races' generation. There can be a reduction of the disease to some extent with the utilization of resistant chemicals and cultivars. Although, the continuing complication is the development and occurrence of the latest pathogenic races, and the chemicals used are not always effective but always expensive. Nanomaterials usage has been an alternative solution for controlling plant pathogens in recent years. Magnesium oxide's (MgO) nanoparticles have been made by Ghidan et al. He also tested different concentrations' effects on the GPA (green peach aphid) under greenhouse conditions.²⁵

Nanomaterials' Synthesis

There has been a successful synthesis of the nanomaterials of magnesium oxide (MgO), magnesium hydroxide (MgOH), zinc oxide (ZnO), and copper oxide (CuO), by utilizing the aqueous extracts of *Chamaemelum Nobile* flowers, *Olea europaea* leaves, and *Punica granatum* peels. According to the synthesized bio-nano particles screening, these nanoparticles were effective in increasing the green peach aphid's mortality percent. There was an analysis of the metal oxide nanoparticle accumulations in the green sweet pepper's leaves and fruits after the glasshouse experiments. According to the results, no plant fruits had any kind of metal accumulation.²⁶

The Eco-friendly Nanomaterials

Green methods and eco-friendly prepare the nanomaterials that may increase the agriculture potential to enhance pesticides, plant growth, and the process of fertilization. The amount of dangerous chemicals that are polluting the environment is also minimized by this technology. The key pest on a peach is considered to be the green peach aphid and is also considered a globally important pest of a wide range of horticultural and arable crops, like Jordan. In the world, the most significant agricultural pest is the pest. This devastating pest overproduces the insecticide-degrading carboxyl esterases to combat the organophosphorus and carbamate insecticides. Also, it is now extremely difficult to control such a pest, as there is more production of resistance for the aphid individuals when utilizing chemical insecticides like pyrethroids, organophosphates, and carbamates.²⁷

Chemical and Physical Methods

Different chemical and physical methods were used to synthesize the nanomaterials like magnesium oxide (MgONPs), magnesium hydroxide (MgOHONPs), zinc oxide (ZnONPs), and copper oxide (CuONPs). With the growing need to minimize the use of environmental-risk substances, like insecticides, nanoparticles biosynthesis has gained increasing interest as a rising highlight of biotechnology and nanotechnology. In comparison to the microorganisms, the metal ions rate of reduction using the plants has been way faster, and there are reports of the stable production of the nanoparticles.

Antimicrobial Activity

In food packaging, various nanomaterials are utilized as antimicrobial agents in which there is a great interest possessed by the silver nanoparticles, and all of this is because of its prolonged usage. Silver, gold, magnesium oxide (MgO), silicon oxide (SiO₂), zinc oxide (ZnO), and titanium dioxide (TiO₂) are some other nanoparticles that are currently being utilized. Particular functions and properties are possessed by all of them, for instance, antifungal and antimicrobial activity is shown by the zinc nanocrystal. Russian Space Station and NASA used silver as a sterilizing agent and

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disinfectant for silver, silver zeolite, and water. Good antimicrobial and antifungal effects, low volatility, and high-temperature stability are possessed by gold against 159 different kinds of bacteria. In 2009, FDA approved silver's direct usage in commercial water as a disinfectant as there were effective and efficient results shown against the microorganisms.²²

Antifungal Activities

Similar results were provided by the nanosilver particles coated with cellulose acetate phthalate, *Staphylococcus aureus*, *L. monocytogenes*, and *E. coli*'s antimicrobial effect. Antifungal activity is shown by some of the nanoparticles. Yeast, *Aspergillus Niger*, and *Candida albicans* are included in these fungi. AgNPs are also effective against the methicillin-resistant *Staphylococcus aureus*. Antimicrobial properties like titanium oxide (TiO₂) are also possessed by nanoparticles other than silver. It has an obvious antimicrobial activity in UV light. Antimicrobial activity is possessed by the Zinc oxide in packaging material.

Applications of Nanotechnology as Nanofungicides

Recently, there have been studies on the nanosilver's usage against phytopathogen *Colletotrichum gloeosporioides*. There have also been reports of the other nanoparticles (carbon nanotubes, Al₂O₃, CeO₂, TiO₂, ZnO, Zn, Al, Si, Cu, and Fe) having some bad effects on plant growth other than the antimicrobial characteristics. An effect is possessed by the nanoparticles at times on the growth of the beneficial soil bacteria, like *Pseudomonas putida* KT2440. The focus of several research groups was on the utilization of eco-friendly pesticides. There has been an exploration of the herbicides and nanoparticle-based pesticides like chemical pesticides for the application of antimicrobial agents for protecting the crops from numerous diseases.¹¹

Nanoparticle-based pesticides can be formulated with the help of the nanoparticles' antifungal characteristics. Various researchers have broadly studied silver among the different inorganic nanoparticle-based antimicrobial agents, due to its various advantages over other nanoparticles like TiO₂, Al₂O₃, ZnO, gold, zinc, and copper.

Inhibitory Effect

Nickel nanoparticles possess the same inhibitory effects in a liquid medium and solid media. The mycelial growth and surface areas acting on the *Fusarium*'s mycelia can be majorly increased by utilizing the Ni nanoparticle solution.

Nanotechnology for Controlling Plant Virus

The naturally occurring nanomaterials in plant viruses are the spherical virus in particular. Satellite tobacco necrosis viruses are yet the smallest plant viruses that are known and they are only 18 nanometers in diameter. Double or single-stranded DNA/RNA as genome encapsulated by a protein coat, makes up the plant viruses. Their capability of infecting, and delivering the nucleic acid genome in the host cell to a particular site, replicating, and packaging the nucleic acid, and coming out of the host cell in a precise and orderly manner, makes it compulsory for them to be utilized in the nanotechnology. Young et al. recently did a review on using plant viruses as the bio templates for the nanomaterials and their usages.²³

Nanotechnology in Food Packaging

There is a lead taken by the food industries in making good nutritive value food. For instance, they utilize high impermeable packaging nanomaterials to protect food from UV radiations and offer more strength for maintaining the protected food from the environment, thus improving and prolonging their shelf lives. Nanosensors are utilized to detect

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pathogens, gases, and chemicals, in food. Such type of packaging is often known as smart packaging in modern terminology. According to some of the studies, it is because of some of the risk factors that nanoparticles' direct involvement in food is not accepted by people. Thus, some safety measures should be provided for lessening human safety and risk.¹⁸

IV.CONCLUSIONS

Nanotechnology has made a lot of advancements over the past decades and fairly in the field of agriculture. They have initiated new concepts of how our fields, crops, plants, and fruits can be protected and their growth can be maximized at a greater level. The research carried out in this regard has massively proved beneficial against the agenda that it began for which was bringing advancements in the field of agriculture.²⁷

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