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POSITIVE ASPECTS OF NANOTECHNOLOGY ON AGRICULTURAL SUSTAINABLE DEVELOPMENT: APPLICATION OF NANOPARTICLES AND FIBERS FOR INCREASING AGRICULTURAL YIELD

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ABSTRACT

Recently, nanotechnology is widely used in agriculture with the aim of achieving high agricultural yields. Due to the unique surface and physicochemical properties, nanomaterials can be used to deliver nutrients to plants via nanoparticles, for the synthesis of nanopesticides, nanofungicides, and to design nanosensors for the detection of very low concentrations of pesticides and other contaminants. Excessive use of pesticides and fertilizers causes the loss of soil biodiversity and the development of resistance to pathogens. Nenoencapsulation of fertilizers, pesticides and herbicides is used for slow and specific dosed release of nutrients as well as agrochemicals. This paper discusses the applications of nanotechnology and their positive effect in agriculture in relation to the common methods used so far.

Keywords: Nanotechnology, Agriculture, Nanofertlizers, Nanofibers

1. INTRODUCTION

By 2050, the population is projected to reach 9.7 billion, leading to an increase in food use and an increase in global biomass production of up to 60% compared to 2005 levels [1-2]. Agriculture is considered the backbone economy for most developing countries as a vital role in progress and development. The rising population in the world results in high demand for more food supply, and scientists and engineers are now practicing new methods to increase agricultural production [3]. According to the most recent reports, as much as 7.5 million tons of agrochemicals, including fertilizers, pesticides, herbicides, fungicides, and hormones, were used globally in the year 2015 [4]. However, >90% of these chemicals go nontarget. This not only leads to wastage of capital but also causes serious environmental hazard, affecting both land and water ecosystems. The development of a sustainable and productive agricultural system is essential for the existence and health of humanity, which is unimaginable without innovative technology and advanced techniques, such as nanotechnology. Developed and emerging countries like Germany, the United States of America (USA), Brazil, China, India, France, and Korea show increased curiosity for using nanomaterials for agriculture uses as revealed via a more producing high number of publications and patents [5]. The world is exposed to innumerable and unprecedented challenges due to increasing climate change, land constraints, increasing population, industrialization, low productivity, and high postharvest losses [6].Over the past few years, the interest of material scientists for metal nanoparticles has been booming because of its unique physicochemical characteristics such as a high specific surface area and a high fraction of surface atoms [7]. Nanotechnology is necessarily a multidisciplinary field which encompasses and draws from the knowledge of several diverse scientific fields of study including chemistry [8-9], physics, molecular biology, material science [10], medicine, pharmacy [11-12] and agriculture [13-14]. Nanotechnology is a promising tool of precise farming techniques has the potential to improve global food production and food quality through increased plant protection, detection of diseases, monitoring plant growth, and reduced waste for strengthening agriculture sustainability [15]. Nanomaterials in the agriculture and agroindustry are used as nano-fertilizers, nano-pesticides, and more recently as compounds to improve harvest yields and also as disease plant protection [16]. Metal oxides as nanomaterials heterogenized with the nanofibers of biopolymers can act as excellent carriers and even soil enhancers [17]. Nanotechnology means the "synthesis, designing, characterizing, and utilization of assemblies, tools, and systems via directing the morphology and size variation at nanometer level from 1 - 100 nm" [18]. For your reference, one nanometer-scale means one-billionth (10^{-9}) of part of one meter which implies the application of the technology at this size. A graphic exhibition of substances falling in "nano" (<100 nm) and "micro" (>100 nm) size scales is shown in Figure 1.

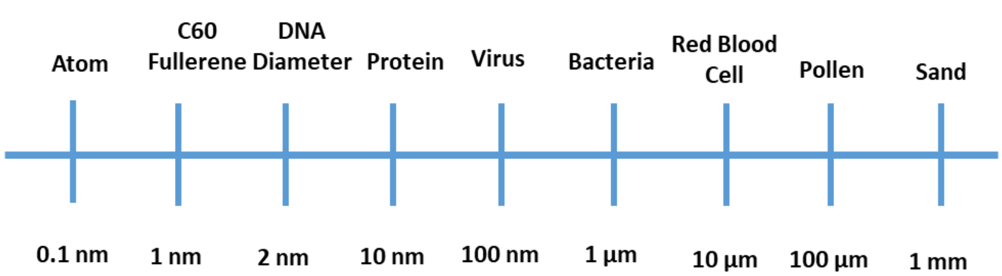

Figure 1: A pictorial exhibition of things in the "nano" (<100 nm) and "micro" (>100 nm) size ranges.

A wide range of materials are used to make nanoparticles like metal oxides, ceramics, magnetic materials, semiconductor [19], quantum dots, lipids, polymers (synthetic or natural), dendrimers

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and emulsions [20]. Nanoparticles have been found to solve many of the agricultural-related obstacles with significant improvement observed in plant growth of plants, nutrient uptake, or plant disease control as compared to conventional systems. Chitosan nanoparticles are being used in agriculture in seed treatment and as biopesticide which helps the plants to fight off fungal infections. Nanoparticles affect germination process and growth of the plant.

Elicitors are external stimuli intended to mimic biochemical or physiological responses to pathogen defense or stress response inducing the accumulation of target metabolites. Both, biotic (where plants respond to pathogen attacks) and abiotic elicitor types (originate from nonliving sources - hormonal, chemical, and physical elicitors) enhance the production of terrestrial plant defense-related metabolites from almost all chemical classes, such as sesquiterpene lactones, anthocyanins, flavonoids, alkaloids, tannins, resins, etc. [21]. The most studied oxide nanoparticles are: titanium dioxide (TiO_2), silicon dioxide (SiO_2), zinc oxide (ZnO), Iron oxides (Fe_3O_4, Fe_2O_3), cerium dioxide (CeO_2) and other metal oxides NPs. Silica nanoparticles (SiO_2 NPs) are recently used as nanocarriers to achieve the controllable delivery and release of chemicals, nuecleotides, and proteins with precise dosage in plants, which can significantly enhance the efficiency of agricultural inputs. Additionally, SiO_2 NPs have been applied to reduce cadmium (Cd) uptake and arsenic (As) accumulation in both pot and field experiments, alleviating heavy metal element-induced oxidative stress in crops [22]. Furthermore, SiO_2 NPs can directly be served as nanopesticides, nanoherbicides, and nanofertilizers to inhibit plant pathogens, promote crops production, and remove unwanted weeds and insects with less cost and energy, possessing great potential for agricultural sustainability [23].

Research carried out by El-Shetehy et al. [24] demonstrated that amorphous SiO_2 NPs could serve as a traceless, degradable, cost-effective, and highly efficient treatment to protect plants against pathogen through the controlled triggering of acquired immune response without inducing obviously adverse consequences on crop yield or non-target organisms. The well-dispersed amorphous SiO_2 NPs with an average hydrodynamic diameter of 76.7 nm and the polydispersity index of 0.07 were synthesized. The SiO_2 NPs suspensions were sprayed on a widely studied model plant Arabidopsis thaliana and infected with bacterial pathogen *Pseudomonas syringae*, another popular model organism. The results revealed that SiO_2 NPs activated the immune response of plants to protect plants against pathogen attacks via stimulating the secretion of a defence-related plant hormone salicylic acid. Due to population growth, the need for larger quantities of food has increased. However, the whole world is facing low yields of agricultural food production due to climate change that accompanies too long droughts, but also floods and frequent fires. In addition, the problem is about twenty-two thousand detected various plant pathogens (fungi and bacteria) that cause losses in the range of twenty to forty percent of crop production [25-26].

In Fig. 2 is possible to see that nanoparticles and nanofibers are the most studied nanomaterials in Agricultural field. In the last five years, naopesticides and nanofertilizer are being to be explored.

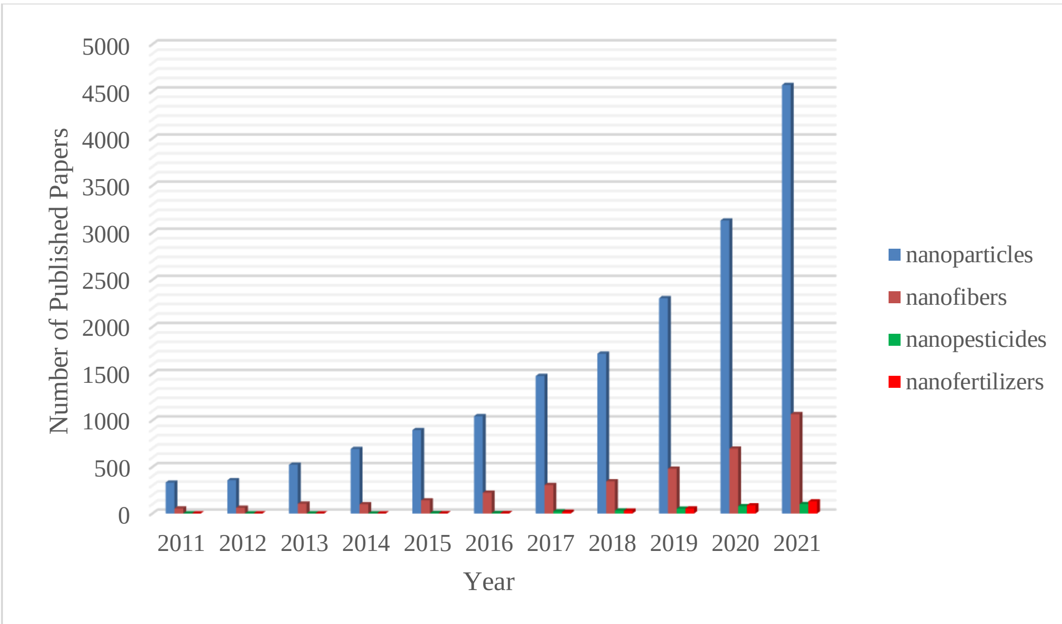

Figure 2: Number of publications for searched term "X" for Increasing Agricultural Yield on Science Direct.

Nanotechnology can also reduce post-farming losses by increasing the shelf life with the aid of nanoparticles. However, further investigation is required to solve the safety and health risks associated with the technology [27].

1.1 Application of nanofibers

Nanofibers can be obtained from natural and synthetic polymers, as well as metals and metal oxide. They can appear as natural or synthetic, organic, or inorganic, carbon and/or composites, solid, porous, nonporous, and hollow. Nanofibers has some advantages over nanoparticles, such as nanofibers do not induce cell lysis, unlike nanoparticles below <100nm which can penetrate cells humans and generate damage to cellular components causing cell death [28].At the agricultural level, nanofibers have several applications at the preharvest level, nanofibers have been used mainly as vehicles for fertilizers, pesticides, and herbicides, as well as biosensors, while at the postharvest level they are used for the generation of coatings to provide some advantages such as antioxidant characteristics and/or antimicrobial, and also induce added value increasing the shelf life of the product [29]. Biodegradable biopolymers such as cellulose

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derivatives, poly (lactic acid) (PLA), zein, chitosan, alginate, gelatin, DNA, polycaprolactone (PCL), as well as poly (ethylene oxide) (PEO), and poly (vinyl alcohol) (PVA) are excellent raw materials for development and production of nanofibers from agro-industrial waste. The main applications of nanofibers are as an encapsulant. The objective of encapsulation is to regulate its release to reduce the uptake of pesticides.

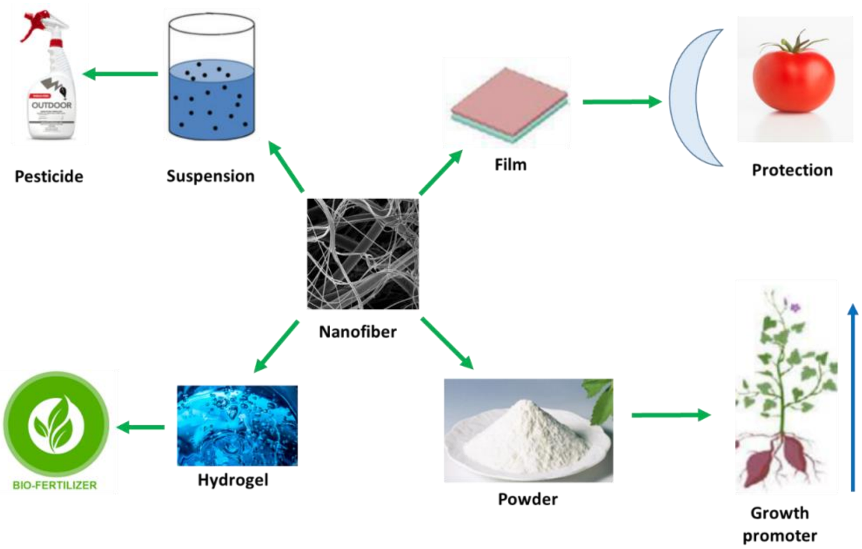

Figure 3: Employment of nanofibers in the agricultural industry.

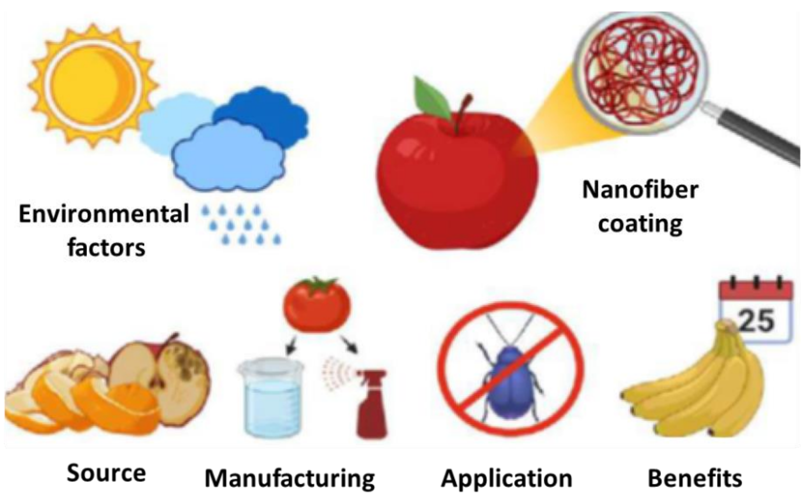

Figure 4: General aspects of nanofibers used in agriculture. Sources, manufacturing, applications, and benefits.

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Nano-emulsions enable the encapsulation of nonpolar bioactive components since they can be solubilized within the hydrophobic interior of the lipid used droplets [30]. Nanoemulsions increase the bioavailability of certain types of lipophilic substances encapsulated within them which may be useful for increasing the bioactivity of agrochemicals [31]. Nano-lipid carriers are a newer generation of lipid-based nanocarriers which have been claimed to have higher advantages over classical nanoemulsions due to lower leakage of entrapped bioactive ingredients and a better control of the size and release process [32]. Wani et al. in 2019 [33] discussed an insight of nanotechnology in the application of fertilizers, pesticides, fungicides, and herbicides, in agriculture, the production of nanodelivery systems usinglipid- based (emulsions and liposomes) and other novel strategies (niosomes and dendrimers).

2. NANOFERTILIZERS – NANOTECHNOLOGY TO IMPROVE QUALITY OF SOIL AND FERTILIZER DISTRIBUTION

Nanotechnology for the management of crops is used as an essential technology for enhancing crop productivity. In evaluation of the quality of soil and fertilizer distribution in agriculture research as biosensors are used carbon nanotubes, nanofibers, and quantum dots. The purpose of nanoparticles is to reduce the chemicals and nutrient loss during fertilization, as well as to increase the quality and yield with proper nutrient [34]. The development and use of vermiculite, nanoclay, and zeolite could improve fertilizer efficacy and crop production [35]. Amending sandy loam soils with inorganic amendments reduce NH_4–N passage and increasing the yield of N fertilizer in ecological agriculture systems [36]. Most of the productivity of agricultural practices is heavily dependent on fertilizer use. Studies show that crop production is linearly determined by exhaustive application of fertilizers to increase soil fertility [37]. The use of nanofertilizer is crucial to enhance crop production. Nanofertilizer improves the delivery of nutrients to plants and managed their gradually release into the soil in a highly controlled way, hence stopping eutrophication and contamination of water [38]. Some researchers have encapsulated different types of fertilizers for higher efficiency and delayed release. Nano-fertilizer could improve nutrient efficiency through: (a) nutrient encapsulation within nanoporous structures, (b) coating of thin polymeric film, or (c) delivery in the form of particle or suspensions with nanoscale sizes. Nanoscale fertilizers may allow nutrients access to plant surfaces and transport channels [39]. Nano-fertilizer based on banana peels were used in the growth of tomatoes, peppers, or flowers [35]. Nano fertilizers were used for the growth and improvement of different crops, for instance, nanoparticles of ZnO for chickpea, silicon dioxide and iron slag powder for maize, colloidal silica and NPK for tomato, TiO_2 for spinach, gold and sulphur fertilizers were used for the growth of grapes [35].Fertilizer usage with nanoscale transporters may be subjected in a way so that they anchor the roots of the plant with the surrounding soil contents and organic material hence decreasing chemical loss and lessening environmental issues [40]. Nanoscale fertilizers can decrease the toxicity of soil by slowly releasing the nutrients and extending the time of fertilizer impact [41]. TiO_2 nanoparticles have shown a major effect on the growth of maize crop; moreover, SiO_2 plus TiO_2 nanoparticles elevated the action of nitrate and increased plant absorption potential, by controlled use of water and fertilizer with the efficient outcome [42-43].

2.1 Application of nanotechnology in delivery fertilizers

Enormous amounts of nitrogen-containing fertilizer (ammonium salts, urea, and nitrate) or phosphate compounds have increased food production considerably, but they have many harmful effects on the beneficial soil microflora. Due to run-off, most of the fertilizers are not available to plants and cause pollution [44]. Fertilizers coated in nanomaterials can solve this problem. Nanomaterials have potential contributions to the slow release of fertilizers as nanoparticles hold the material more strongly from the plant due to the higher surface tension of nanoparticles than conventional surfaces. Moreover, nanocoatings provide surface protection for larger particles [45-46]. A schematic representation of the delivery of pesticides/fungicides/nutrients from nanocoating is shown in Fig. 5.

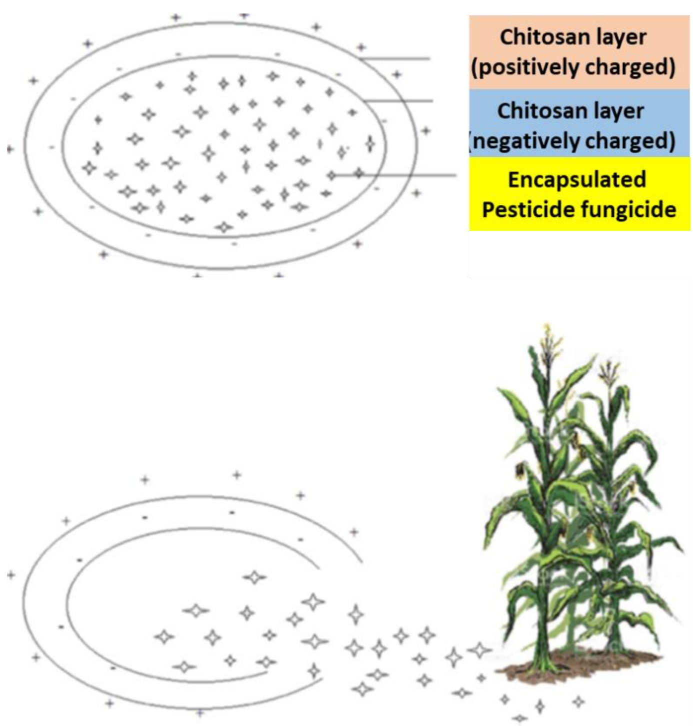

Figure 5: Controlled release of pesticides/fungicides/nutrients from nanocoating [47].

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Excessive use of nitrogen fertilizers leads to an increase in N_2O in the atmosphere by about 80% which causes increased atmospheric temperature and thus contributes to global warming [48]. It is estimated that about 40–70% of nitrogen, 80–90% of phosphorus, and 50–70% of potassium of the applied fertilizers (urea, diammonium phosphate (DAP) and single superphosphate (SSP)) is lost to the environment as run-off or volatilized and can't be absorbed by plant [49-50]. In order to overcome this problem, nanocoating is the solution because it allows slow, sustained release of coated fertilizer and is more efficiently absorbed by plant roots. In this way, the fertilizer consumption is kept to a minimum and consequently, there is a minimum impact on the environment. Many natural and synthetic polymers have been used for this sustained release of fertilizers. Biodegradable polymeric chitosan nanoparticles (~78 nm) showed good results for the slow release behavior of NPK fertilizer [51]. Kaolin and polymeric biocompatible nanoparticles also have potential application in the slow release behavior of fertilizers [52].

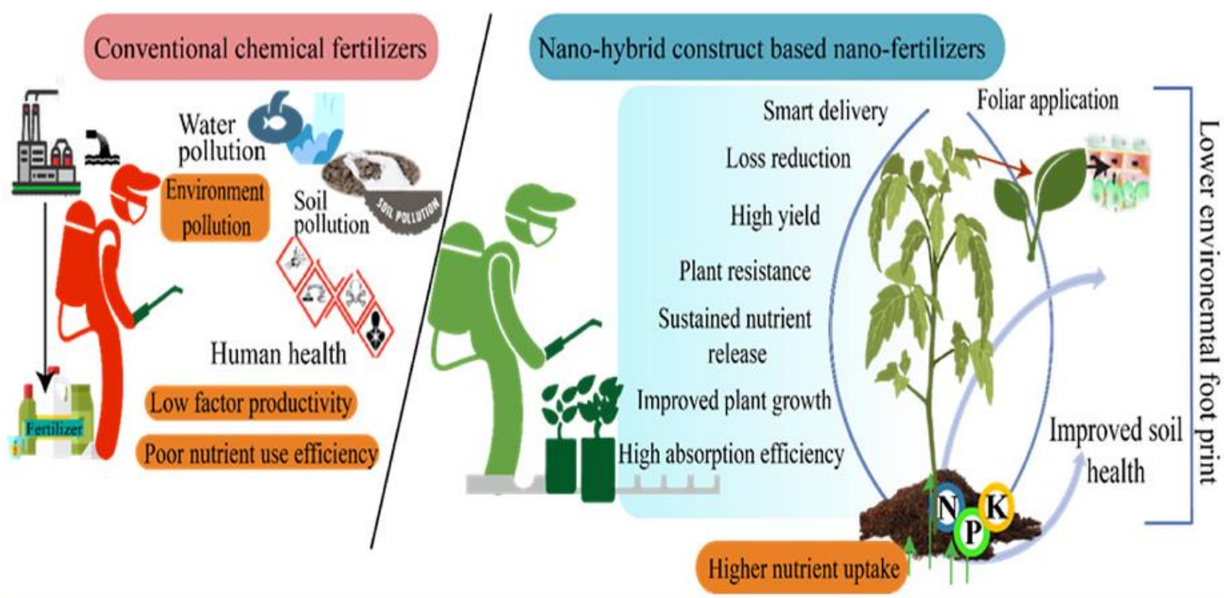

Figure 6: Advantages of nano-fertilizers vs. conventional chemical fertilizers.

Nanofertilizers (NFs) provide smart nutrient delivery to the plants and proves their efficacy in terms of crop productivity and environmental sustainability over bulky chemical fertilizers. NFs are also called smart fertilizers [53]. Plants can absorb NFs by foliage or roots depending upon the application methods and properties of the particles. NFs enhance the biotic and abiotic stresses tolerance in plants. The extensive release of NFs into the environment and food chain may pose a risk to human health, hence, need careful assessment. Chemical fertilizers accounted for ~50–55% crop yield increment in developing countries. However, the use efficiency of applied nutrients through fertilizers remain very low (nitrogen (N) 30–40%, phosphorus (P): 15–20%, potassium (K): 50–55%, and micronutrients: 2–5%) [54]. Small particle dimensions (<100 nm) enable NFs to enter plant systems when used as foliar spray or basal [55]. Owing to ultra-small size, nanomaterials like NFs have a high surface area and surface area to volume ratio [56], which increase the absorption and retention capacity of NFs as compared to conventional bulky chemical fertilizers.

Foliar application of NFs reportedly increases 10-25% yield of cereals, 20-30% in oilseeds, and 13-15% in pulses as compared to the conventional fertilizers in different agro-climatic and management conditions [57]. Similarly, the application of phosphorus-based NFs has the potential to increase the seed yield of soybean by ~20% over conventional synthetic fertilizers [58]. However, the overuse of NFs may have a harmful effect on crop growth and the environment [59]. Cost-effectiveness, non-toxicity, recyclability, biodegradability, and the potential for recovery after use are some other major challenges for NFs manufacturers [60].

Common basic materials that can be nanostructured and utilized as NFs include zeolites, silver (Ag), copper (Cu), aluminum (Al), carbon (C), zinc (Zn), potassium (K), nitrogen (N), silica (Si), iron (Fe), magnesium (Mg), sodium (Na), calcium (Ca), and manganese (Mn). Grape plant substrates [61], and other plant-based materials are also being used for NFs preparation. Natural zeolite (composed of >50 minerals) has recently been transformed into NFs.

There are three different ways for preparation of NFs: 1. Developing nanoparticles that contain nutrients. 2. Nanoscale additives in traditional fertilizers. 3. Nanoparticles coating in traditional fertilizers. The most prevalent method of producing NFs with nanomaterials is nutrient encapsulation. Based on the type of nutrients content, NFs can be generally categorized into three groups: (i) macronutrient-based (ii) micronutrient-based, and (iii) biofertilizer-based NFs [62].

3. NANOPESTICIDES – NANOTECHNOLOGY TO CONTROL PLANT DISEASES

About 20–40% of crops are lost due to plant pests and pathogens each year worldwide [63]. The development of cost-effective high-efficiency pesticides is key to reducing the environmental pollution. **Nanopesticides** can reduce toxicity, improve shelf life and increase the solubility of poorly water-soluble pesticides, all of which could have positive effects on the environment [64]. Nano-based conventional herbicides and pesticides assist in the slow and continued supply of nutrients and agricultural chemicals in a controlled amount to the plants.

In general, the use of nanoparticles to protect plants can occur via two different mechanisms: (a) nanoparticles themselves providing crop protection, or (b) nanoparticles as carriers for existing

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pesticides and can be applied by spray [65]. However, the use of nanomaterials in plant protection and production of food is under-explored.

Sharma et al. (2017) [66] used reduced graphene oxide decorated with copper selenide for controlled and targeted delivery of a chalcogenic pesticide (Cu_2–xSe) and achieved >35% larval mortality. As compared to graphene oxide, reduced graphene oxide has tremendous pesticide loading efficiency of almost 400% that is released in larval gut conditions.

3.1 Nanoherbicides

Pereira et al. (2014) [67] encapsulated atrazine in poly (epsilon–caprolactone) for evaluating its herbicidal activity and genotoxicity. Showing reduced mobility in the soil and genotoxicity (*Allium cepa* chromosome assay), the nanoparticles of atrazine effectively controlled the targeted *Brassica* sp. against *Zea mays*.

3.2 Nanofungicides

Fungi are involved in the spoilage and infection of food and agricultural products and result in heavy losses in both the production and marketing of the agricultural produce.

Globally, plant pathogenic fungi contribute to approximately $45 billion in crop losses yearly. They are able to infect any tissue at any stage of plant growth [68].

The harm caused by fungi in five of the world's most important crops (rice, wheat, maize, potato, and soybean) has an estimated annual cost of more than $60 billion.

Nanoparticles of metals and metal oxides attracted remarkable scientific interest in plant disease control, and were promising against recalcitrant plant pathogens responsible for huge financial losses in the agricultural sector [69].

Various types of nanoparticles and their derivatives have attracted considerable attention for their potential antimicrobial activity. Metal nanoparticles such as silver (Ag), silver oxide (Ag_2O), titanium dioxide (TiO_2), silicon (Si), copper oxide (CuO), zinc oxide (ZnO), gold (Au), calcium oxide (CaO), and magnesium oxide (MgO) have been shown to have robust antifungal activity Abd-Elsalam et al. in 2019 [70] consider the antifungal applications of metal nanoparticles (NPs), and metal oxide nanoparticles (ZnO, MgO, CuO, Cu_2O, Al_2O_3, and TiO_2) in combination with natural products as well as hybrid NPs made from biodegradable materials such as chitosans loaded with other antifungal agents against plant pathogenic fungi, as a new alternative for synthetic fungicides. The application of NPs in plant disease control has two major considerations to look for, that is, direct impact of NPs on plant pathogens and impact of nanomaterials in regulating biopesticides as nanoproducts. There is a need to discover options to

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conventional fungicides with new hybrid nanofungicides that are more eco-friendly. New green and/or hybrid nanofungicides can be produced with suitable dispersion, a synergistic approach, proven recyclability in soil and surrounding water, targeted toxicity, well understood toxicodynamics, and broad spectrum applications in plant health.

Sulfur nanoparticles (SNPs) also have significant potential as fungicides. The modification of the surface of SNPs has provided fungicidal products against *A. niger*and *Fusarium oxysporum*. Green nanofungicides are fabricated from biodegradable materials, including enzymes, nutrients, polysaccharides, plant extracts, biodegradable polymers, and microorganisms. Microorganisms such as bacteria, algae, yeasts, fungi, actinomycetes, and viruses are being used in the biomediated synthesis of nanometals.

Nanobiofungicdes can offer a cheap, efficient, and ecofriendly strategy for pest control in agriculture. Nanoformulation of fungicides absolutely protects the untimely degradation of the environment and delivers a high impact on target species. Less environmental contamination and safe handling are the advantages of nanofungicides (Fig. 7).

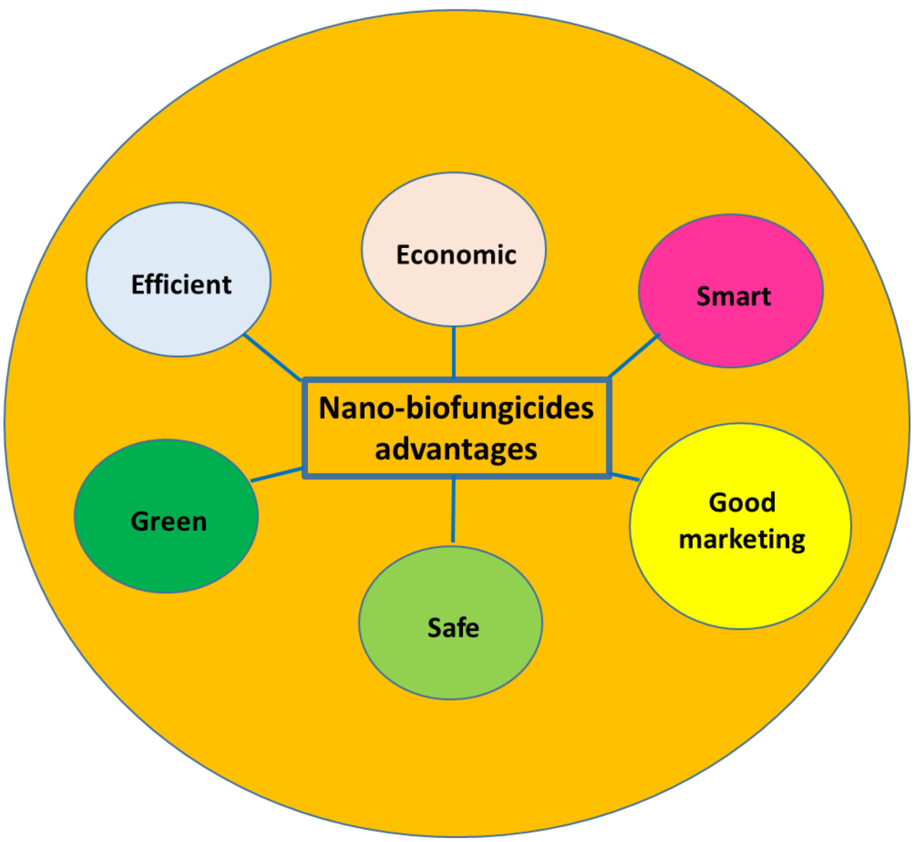

Figure 7: Advantages of hybrid nanobiofungicides.

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Neodymium (III) doped zinc oxide nanophosphor has been developed by Yadav et al. (2018) [71] using *Aloe vera*gel as surfactant. The nanoparticles controlled the growth of *Alternaria alternata* and *Fusarium oxysporum*. According to the authors, ZnO:Nd^{3+} induces a decrease in the potential energy at the bacterial membrane and the leakage of electrolytes of fungal spores which causes local damage to the cell membrane and cell breakdown.

Copper nanoparticle plays an important role as a novel antimicrobial. Hydroxyapatite has been reported to be an innovative nanodelivery system for Cu (II) ions that was successfully applied in *Vitisvinifera* L. leaves for controlling the pathogen, *Plasmopara viticola* [72]. Kanhed et al. (2014) [73] reported antifungal activity of copper nanoparticles against crop plant pathogenic fungi, *Phoma destructiva, Curvularia lunata, Alternaria alternate* and *Fusarium oxysporum*, owing the activity of copper nanoparticles to their large surface area to volume ratio.

4. FUTURE PROSPECTS IN AGRICULTURE

Production of nanoagrochemicals work with the basic principles of nanotechnology involving encapsulation of the active ingredient in a suitable carrier material for controlled release and targeted delivery of the nanoscale active ingredients. Most recently, nanotechnology-based (bio)sensors have been introduced to support farmers in delivering fast, accurate, cost-effective, and in-field analyses of soil humidity, water and soil nutrients/pesticides, and plant pathogens (Antonacci et al., 2018) [74]. However, nanotechnology in agriculture is still in its developing stage and there is a huge scope for the development of precise nanoagrochemicals with respect to their containment in suitable carrier materials, techniques of fabrication, mode of application and above all the assessment of safety and toxicological implications of the nanoproducts on the plant body and the final agricultural produce.

5. CONCLUSION

In general, the abuse of farm chemicals, including fertilizers and pesticides, is one of the greatest issues and challenges facing modern agriculture. With a growing number of chemical substances

and additives prohibited or regarded harmful to human and environment, the need for alternative is extremely urgent. Nanotechnology is still in its infancy in cases of agricultural applications. As such, the possible mechanism of action and overall implications of nanotechnology in agriculture including safety, toxicity, and interaction with other compounds within the plant system, are yet to be established.

Nanofertilizers not only have a great impact on agricultural and environmental sustainability but also overcomes the detrimental effect of traditional fertilizers. Besides NFs offer optimum nutrients to plants in a controlled fashion as per the crop need and reduces plant stress.

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Undoubtedly the NFs are an eco-friendly and amicable alternative to chemical fertilizers but optimum dose, quality, and methods of application must be taken into consideration since repeated and excessive use may have some detrimental effect on the food chain. Uncertainty about the interaction of nanofertilizers with the environment and potential effects on human health must be objectively studied before their popularisation on a commercial scale. Future studies should focus on generating database and information in these under-explored areas for wider application of this novel frontier in sustainable agriculture. Hence, studies on the toxicity of different nanoparticles used for nanofertilizers production and application safety must be a priority.

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