Revolutionizing Agriculture with Nanotechnology: The Emergence of Nano-Fertilizers and Nano-Pesticides as a New Horizon of Hope

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Abstract: The agricultural sector is at a crossroads, facing challenges from rapid population growth, climate change, and environmental degradation. This paper explores the pivotal role of sustainable agricultural practices, emphasizing the integration of nanotechnology to overcome traditional farming limitations. Nanotechnology offers revolutionary tools such as nanofertilizers and nanopesticides that optimize resource utilization, enhance crop yields, and mitigate ecological impacts. Nano-enhancements in fertilizers improve nutrient delivery and minimize wastage, while nanopesticides enable precision targeting of pests with reduced toxicity. Additionally, innovations like nanosensors enhance real-time monitoring of soil and plant health, enabling smarter resource management. Case studies highlight the efficiency of nanomaterials like silver nanoparticles in pest control and biochar nanoparticles in improving soil fertility. While the potential benefits are vast, challenges such as high initial costs, regulatory gaps, and safety concerns hinder widespread adoption. This study advocates for collaborative efforts in research, policy, and education to realize nanotechnology's potential in creating a resilient, sustainable agricultural future.

Keywords: *Nanofertilizers, Nanopesticides, Nanotechnology, Nanoinsecticides, Agriculture*.

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I. INTRODUCTION

Agriculture and responsible for bringing surfeit of benefits it cost both economical and developmental benefits the modern way of agriculture is rising approach that includes using of high quality seeds fertiliser pesticide, the use of plastic in micro irrigation and during the various process of crop production which leads to the adverse effect and due to these safety of foods are declining and people are facing different kinds of health hazards is the population and rising the demand for food are also increasing and there is rising demand of food which bound the people to follow different alternative ways over the conventional method for meeting up the needs and those methods now causing harm to the environment leading to many harsh effect and this adverse effect ultimately destroyed the changes of chances of sustainable environment in the near future. Sustainable development is defined as the use of resources for developing human race in such a way that it can meet the present need along with the future need. It aims to form a society that make proper utilization without destroying the mother nature [1]. The world population are expanding at a high rate according to the latest estimate given by various organization the population are likely to expand to more than 8.4 billion within a few year which attract the scientist to find a better way to save the environment and for utilization of the present resources in an effective way and there comes the concept of sustainable agriculture which involves different techniques and practices which give solution in such a way that the current resources are used in a way that makes them sustain along with maximum production it can be defined as a sum of sample of production from both plant and animal that have a target specific application over a prolonged period of time that will persuade the need of human and maximise the quality of environment and proper use of natural resources on which the agriculture economy stands[2] . It also makes proper and maximum use of non-renewable resources that maximise the quality of life the society. The idea of

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sustainability in agriculture can be picturized by many alternative ways among them one is ecocentric way and another one is technocentric way. Technocentric way is also known as anthropocentric way. Ecocentric way mainly are pivot on organic and biologically dynamic farming practices with a view of changing consumption patterns, allocation of resources and use rather than no or low growth level of human evolution. On the other hand the techno centric way are the way where the modern technology proper planning and lifestyle are considered as a vital components of a holistic approach to the analysing the sustainable development in general and sustainability of the present environment in particular conventional .One factor based approach to sustainability issue are considered as total risk way as it misrepresents the existent fundamental image which are required to form as the pillar for creating development plans and policies and it cause hamper to the distinctive techniques[3].

By merging all the elements an interdisciplinary and effective way to sustainable development has been opted. From the idea that different changes in industrial system like agricultural system based on conservation should be kept into place to the asseration that a biotechnological way is the most significant means of meeting the evolving demand for food. The techno centric way claims that sustainability can be achieved by a wide range of scenarios in addition to these perspectives it gives a wide range of differentiation among the ecocentric and techno centric approaches. The previous one is separated into two categories techno centric of abundance and techno centric of accommodation and they are described in this manner as they depend on technological innovation to address the various issues which are related to the shortage of food. The latter asks to develop a proper balance with the environment in a coexisting manner among the social structure and the ecosystem which is more distinctly further divided into communitarian ecocentric and radial ecocentric subtypes [4]. The security of food that covers the availability of food or the proper quantity of food production access to food and the capability for purchasing food and sufficient amount of nutrition which include energy, micro nutrients and protein, safety and the financial stability which is connected to the sustainable agriculture to improve the problem of long-term security of foods. New and productive agriculture techniques and methods must be hold and use at all scale of agriculture production under the ages of sustainable method of farming. Various ways are approached in agriculture. Agricultural sustainability largely pivots on conceding and evaluating different tried and true way which are applied specially to evolve a more sustainable agriculture. The maximum of which give a prominent focus on the ecosystem, this tells that the maximum of this strategies had well defined tenets as well as social and financial objectives regarding environment. They either evolved as strategies that are methodological like agro ecology or sustainable intensification or at the top of the policy agenda from the initial like carbon farming. These methods to agriculture sustainability generally take into account the whole form of the system in their design or they can be altered to a span of condition of production and methods. They generally have experts and sometime a level on market that are existing connect with them [5]

A. Challenges in Modern Agriculture

A significant part of income of small-scale producers and landless households proportionally depend on agriculture and they are occupied in different agriculture-based activities and the other small owners indirectly depend on agriculture as they supply machinery, storage, seeds, fertilizers. A wide range of people are starving in poor countries and they depend only on the agriculture for their living but for a large period of time their input is not significant according to their output that create an issue in the overall production. Less investment minimises the ability of farmers to cope up with the situation of price changes and other external factors like changes related to weather and the economy. Change in climate are affecting the farmers livelihood and the security of food across the world [6].

The production of the necessary amount of food to feed the world's exponential growing population has create the vital and rapidly growing challenge that are facing by the people around the world. New creation of institutions, regulations and technology will make agriculture to overcome the hurdles distinct regions have distinct problems, and the proportion of agriculture in overall production and employment is decreasing at varying rates. Although the technology are advancing and agricultural investment are rising but production are stalled which is a concerning situation. Main objective of maximising the production can be done by reducing grain loss and the output of agriculture. Another challenge is destruction of natural resources the biodiversity loss in the spreading of various plant and animal disease and pest have minimise the required force for productivity growth and many plants are resistant to the market and antimicrobial agent and fencing the productivity and profitability of the small scale farmer deeply linked in maximising the management of natural resources in developing nations as they are creating a content set of technologies incentives and policies for motivating small scale farmers to place a maximum value on long term management of resources in developing nation. Agro ecology, agroforestry, climate, intelligent agriculture and protective agriculture at the holistic process of transformation that are grounded in conventional knowledge. The development of the innovative technology must amalgate with the drastic outbreak in the scope of economy and the agricultural fossil fuel are used to solve the issue of climate change and the escalation of the natural disaster which impact all the ecosystem and facets of the human life [7]. The cooperation and exchanges from the outside the country are needed to strengthen for minimising the different cross border agricultural threats and other threats like pest and disease threat and other significant challenge that are faced by the modern agriculture is draw which affect different region of the world and leads to prominent obstacle in the agriculture manufacturing and commerce areas. The main reason of drought is due to the climate change and it becomes severe when the climate change occurs drastically drought has a more impact on the semi-arid region where the population is high and has more economical and social activity.

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B. Emergence of Nanotechnology as a Game Changer

One area of current research that is both attractive and budding rapidly is nanotechnology. For the first time Richard Feynman coined the term "miniaturization" which refers to the optimal technical solution. He explained how this evolving technology will impact the era. Nanomaterials which are particles having single dimension with a vary size range between 1 to 100 nanometre that act diversely from the established form due to its quantum properties. In the agricultural sector there still exist sustainable competitions, although the nanotechnology is evolving exponentially. In the current situation the field of agriculture is a manifestation of the need for supplying enough nutrition for the world's budding population annually. It has been estimated that 1/3 of the world's total crop production are destroyed every year by wide range of factors like microbial disease, pest infestation and natural disaster that minimise soil fertility. Various technological ways are applied but most of them possess disadvantages.

To minimise this nanotechnology was introduced in agriculture system. In the current times what most important is improving the rational design and the new ways are highly necessary. Nano agro particles are the particles of nanosized that are formulated to reduce the drawbacks of the conventional system in agriculture. These nanoparticles can act as a fungicidal, insecticidal agent and also plays a vital role as a growth enhancer of plant. Chemical synthesis of nanoparticle cause harm to the environment therefore biogenic source for synthesis are employed. Nanoagro particles are sustainably escalate the recently developed new prototype in agricultural field and reduce the existing disadvantages. Silver, Gold, Copper, Zinc, Aluminium, Graphene nanoparticles are some commonly used nanoparticles. One of the necessary requirements for effective agricultural activities is the successful and proper utilization of the nanoagro particles. They must have reasonable design like specificity, solubility, non-self-decomposition and controlled component release which are significant in agriculture.

Most of the time nano agro particles are conjugated with molecules that act as a carrier and result in the formulation of product based on hydrogel, liposome, polymerization and emulsion. They possess various advantages like cost minimization biocompatible and require less maintenance with maximum activity. Fungal disease in a plant is a serious concern nowadays. The species like rice, wheat, barley cotton are more susceptible to have fungal attack so in order to restrain this fungal disease fungicides are used which cause adverse effect on all forms of life present in the ecosystem and also target nonspecific living form. Therefore, use of chemical fungicide become lessen and scientists develop combined nanoparticle complex which contains minimum one molecule in active form. Silver nanoparticle can be used as an alternative for isoprothiolene and azoxystrobin which are used against rice blast disease that are caused by Magnaporthe grisea. Copper nanoparticles also play a significant role in minimizing the exponential growth of wide range of phytopathogens. Moreover, they are able to suppress the growth of fungus Alternaria alternata.

Sulphur nanoparticles show fungicidal activity against phytopathogens that are responsible for causing apple scab disease and the causative organism of the disease wilt of tomato can be inhibited by using silver nanoparticle that are formulated from *Aspergillus terrous*. The production of micro toxins is suppressed by ZnO nanoparticles. Nanoagro particles can act as a potential bacteriocide in a scientific study it has been shown that the substantial activity of the nanoparticles against extensive range of harmful bacteria showing their bacteriocidal characteristics. The protein capped silver nanoparticles which are made from *Macrophomina phaseolina* shows prominent antibacterial activity. Spherical silver nanoparticles ranging in size from 5 to 40 nanometer have notable efficiency against both normal and multi drug resistance strain of bacteria Agrobacterium tumefaciens. Silver nanoparticle obtained from extracts of leaves and stems of Piper nigrum shows antibacterial efficacy against phytopathogenic bacteria like *Citrobacter freundi* and *Erwinia cacticida* [8]. The power of photosynthesized silver nanoparticles for fighting against phytopathogenic bacteria utilising an aqueous extract of *helicopus tuberosus.* The silver nanoparticles show prominent minimization of growth of bacteria. Bio-nano hybrid agro particles are a sophisticated nano system which rely on the bioconjugation chemistry for profound action, bioconjugation offers a significant deal of biological curiosity. Though a lot of compounds can be used to customise the biomolecule conjugating with the nanoparticles has recently occupied importance as a technique. The selection of bioconjugation technique depends on the physiochemical and biological characteristics of the nanomaterial and the bioactive molecule. The basic for the interaction between nanoparticles and the biomolecules are the electrostatic force and functional moiety result in the reversible production of the functionalised nanoparticle and the covalent bond with hydrophobic interactions are formed by the functional moieties holding promises for the creation of bio nanohybrid compounds that can effectively show prominent action against drug resistance pathogen. When pathogens are resistant to different antimicrobial agent than nanomaterials played a significant role in combating the problem and getting rid of unwanted chemical is one of the major risks of farming for this many chemicals herbicides are used to inhibit the growth of these weeds though even in low amounts, large portion of this chemical-based pesticides have shown to have lifelong toxicity. Nano herbicides are therefore a safer option to get out of this predicament. Nanoherbicides exhibit soil absorption, photo decomposition, viability, solubility and chemical stability. Polyepsilon caprolactam nanoparticle are used as a carrier in the formulation of various nanoparticles that contain active ingredient like atrazine which maximise the hard residual activity by decreasing the genotoxicity and minimising the herbicide mobility in soil.

In addition to this chitosan and sodium triphosphate nanoparticles were successfully formulated that minimise toxicity in comparison to the active ingredient alone and reduce the environment risk in recent time. Chitosan particles were cross linked by using diuron disulfide bonds for regulating the release of herbicide in respect to glutathione levels. The results successfully maximise the growth of plant and decrease the toxicity. The systemic control release of

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herbicides can be done by creating hybrid polymeric polycaprolactone nano capsule that contain the 3 herbicides which are called triazine and triazine contain ametryn, atrazine and simazine [9]

II. UNDERSTANDING NANOTECHNOLOGY IN AGRICULTURE

Around 59% of the world's current population of 7.77 billion people reside in Asia, and by 2050, it is predicted that there will be roughly 9.6 billion people on the global. Mitigating the effects of climate change on the agriculture industry is currently one of the biggest difficulties. Conventional agriculture contributes to climate change through increased greenhouse gas emissions, groundwater pollution, decreased supplement use proficiency, and decreased soil organic matter. These factors include the extensive use of herbicides and pesticides to control weeds and pests, as well as the inappropriate use of mineral fertilizers that direct impact on the global food demand. To solve these issues, more cutting-edge technologies like nanotechnology must be employed which integrates numerous scientific fields like engineering, medicine, biology, physics, and chemistry [10]. The manipulation of matter at the atomic and molecular level to create specialized microscale-based goods or equipment is known as nanotechnology. Precision farming, plant breeding, waste management, disease control, and nutrition management are all areas in which nanotechnology is being used in agriculture. Nanotechnology is also being used in every aspect of food systems, such as packaging, processing, transportation, and production.

A. Basics of Nanotechnology

Over the years, several platforms have reported on the widespread use of nanotechnology in agriculture. Nanotechnology's primary goals in agriculture are to boost crop output through nutrient and pest management, decrease fertilizer losses, and reduce the amount of broadcast chemicals used. Furthermore, by making agricultural technologies more efficient and safer to employ, nanotechnology improves their performance and acceptance [11]. According to the material matrix, nanomaterials can be divided into several categories, including semiconductor nanomaterials, metal-based nanomaterials, carbon-based nanomaterials, and nanocomposites [12].

B. Role of Nanotechnology in Enhancing Agricultural Practices

A wave of revolutionary developments in agriculture, including nutrient management, pest and disease control, crop genetic manipulation, the use of nanotechnology in the food industry, agronomy, and environmental sensitivity, have been brought about by nanotechnology in the last decade [11]. The development of agricultural information technology has been accelerated by nanotechnology such as to monitor soil quality, plant conditions, and weather patterns in real time with the help of nano-sensors monitoring equipment. Precision agriculture's goals are embodied by this scientific management technique, which not only increases agricultural production efficiency but also decreases resource waste. The successful used of nanotechnology in agriculture, it offers strong assistance for increasing food production, improving agricultural sustainability, and reducing environmental effects [12]. The most common methods for producing nanomaterials are "top-down" or "bottom-up" approaches, which are also referred to as physical and chemical methods, microbial-mediated synthesis, and green synthesis. Compared to the same material in another form, nanoparticles (NPs) can enter and interact with plant cells and tissues because of their small size (range of 1 to 100 nm) and special surfaces and characteristics [12][13].

➢ *Nutrient Management*

The two main issues with conventional fertilizers based on phosphorus and nitrogen is their low nutrient uptake efficiency and quick conversion into chemical forms that cannot be used by plants. These issues have a detrimental effect on the soil and environment, increasing the emissions of harmful greenhouse gases and causing eutrophication. Thus, the adoption of cutting-edge technologies like nano-fertilizers, which release nutrients gradually, plays a major role in sustaining soil fertility and increasing agricultural yields while also helping to dramatically reduce nutrient loss while maintaining environmental safety. They may alter their bio effectiveness and crop absorption mechanism. Root uptake and foliar uptake are the two primary channels involved in the mechanism of nanoparticle transport in plants. There are several varieties of nano-fertilizer, including nano-potassium, nano-phosphate, and nano-nitrogen fertilizers [13][12].

- *Nano-Potassium Fertilizer:*

More effective potassium nutrient delivery is made possible by nanoparticles' enhanced ability to penetrate the plant root system. Potassium nano-fertilizers strengthen the plant's resistance to harsh climatic conditions (such as infections, drought, and salt) by increasing its physiological activity and nutrient balance, which eventually improves crop survival and output. Under various climatic conditions, the impacts of nano-potash fertilizers are more noticeable than those of standard potash fertilizers.

- *Nano Phosphate Fertilizer*

When it comes to increasing the effectiveness of phosphorus in the soil, nano phosphorus fertilizers show unique results. Because of their large specific surface area, the nanoscale particles make it easy to combine soil particles and nano-phosphorus fertilizer to create a more stable compound. This technique increases the efficacy of phosphorus by delaying its movement and leaching in the soil. Furthermore, the nano-size characteristic enhances the connection between the plant root system and the nano-phosphorus fertilizer, promoting the plant's effective uptake of phosphorus.

- *Nano-Nitrogen Fertilizer*

There are significant benefits to using nano-nitrogen fertilizers to increase nitrogen use efficiency. Nano-nitrogen fertilizers have improved binding to soil particles because of their small particle size, which extends the amount of time that nitrogen remains in the soil. It helps to reduce nitrogen leaching and volatilization. Nitrogen waste is reduced because of the precise and targeted release mechanism linked to nano-nitrogen fertilizers, which helps plants absorb nitrogen more effectively throughout crucial growth stages [12, 9].

- *Nanoparticles in food preservation*

Food production and conservation are among the many issues that food factories due to climate change. As a result of global warming many diseases, including fungus proliferation and producing toxins that endanger food production. Nanoparticles known as nano-emulsions (NEs) can be used in the food industry to address issues related to food quality and packaging, as well as to serve as carriers that allow the incorporation of beneficial substances into the final product. The shelf-life of products can be increased by using nano-emulsions in food packaging with coatings and films. They can also be used separately as edible envelopes that include antioxidants, flavourings, colourings, and helpful enzymes. A type of storage called a desiccant air-conditioning (DAC) system can address issues like increased transpiration and respiration after harvest that are caused by climate change. DAC is divided into two stages. In the first, known as dehumidification, nanoparticles are used as a silica gel to absorb moisture from the air. Regeneration, the second stage, returns things to as they were before. Furthermore, it's critical to understand that toxicity depends on the dose, exposure duration, surface coating properties, and most importantly, nanoparticle size [13].

- *Nanoparticles Used in Agriculture to Cope with Climate Change*

The application of nanotechnology is essential to tackling today's pressing environmental sustainability concerns in the fight against climate change. The application of nanoparticles, in particular, seems to be of recent interest in addressing a number of issues pertaining to climate change and conventional agriculture [13]. Ag-NPs, or silver nanoparticles showed antifungal and antibacterial qualities were comparatively good, which helped them control many plant diseases and increase plant yield. Gold nanoparticles, or Au-NPs, aid in the growth of plants and make photosynthesis easier. In agronomy, iron oxide nanoparticles (Fe3O4-NPs) are becoming more and more effective at managing drought. These nanoparticles are very beneficial and helpful for soil and plant safety. Cu-NPs, or copper nanoparticles, have drawn interest due to their possible application in agricultural stress management that serve as a buffer against harsh climatic factors such atmospheric dryness. Zinc Oxide nanoparticles (ZnO-NPs) have attracted interest because of their novel function in supporting plant growth and their ability to withstand harsh environmental circumstances. Because of its beneficial effects on plant development, growth, and stress tolerance [14].

- *Improved Seed Germination and Plant Growth*

A higher seed germination rate or percentage is required in order to meet the demand for increasing crop yield. On the other hand, a number of abiotic stress and environmental contaminants negatively impact seed germination and seedling health. In an effort to boost the germination rate, the impact of manomaterial on seed germination has been closely examined in recent years. TiO2NPs improved spinach germination, dry weight, and chlorophyll content in one research. Titanium dioxide nanoparticles (TiO2-NPs) have shown promise as useful and promising instruments in the agricultural field. Healthy and nourishing foods are approved by the US Food and Drug Administration to promote long and healthy lives. Fertilizers are consequently necessary for fortifying such soils. Excess micronutrients get washed off with rain into local water bodies [15][14].

- *Pest and Disease Management*

In sustainable crop production, plant infection is a serious and concerning issue that accounts for 20–30% of the overall yearly loss. The majority of plant insects are susceptible to the many impacts of silver nano-insecticides. Microcapsule-based pesticide formulations highlight the potential of nano-pesticide technology, which might result in reduced insecticide use and targeted delivery to lessen environmental impacts, resulting in low toxicity. Furthermore, these materials usually have a longer shelf life than chemical insecticides. Numerous compositions of nanoparticles were created to combat insect pests and phytopathogens. For instance, Ag–Zn NPs were advantageous against Aphis nerii, whereas ZnO–TiO2-Ag NPs were effective against Frankliniella occidentalis Pergande. Nanosilica has special insecticidal properties. Insects are killed when nanosilica absorbs their cuticular lipids. Conventional pesticides, which are long-lasting, require little maintenance, and have a higher rate of pest death, are being replaced with nanopesticides. Herbicides are important for controlling weeds and protecting crops. However, its widespread use has led to both economic and environmental problems. To encourage crop development, farmers often apply herbicides in higher doses than advised. Herbicide-resistant weeds are encouraged to emerge by these methods [16].

One of the major challenges in managing plant diseases is identifying the disease at the appropriate stage. Since many plant diseases are first discovered at later stages, controlling them becomes a challenging task. In order to safeguard plants, insecticides and fungicides are typically applied immediately after symptoms start to show. These result in substantial crop loss rather than plant protection. For site-focused and extended pesticide use with minimal ecological risks, ranchers would greatly benefit from appropriate identification frameworks that could detect and evaluate diseases in specific areas of the field. In this case, once deployed in the field, nano-biosensors could detect infections with remarkable affectability and particularity. Such nano-based diagnostic kits would lead to improved detection power and be able to identify the pathogen and disease more quickly [17].

- *Nanobiosensors for detection of plant diseases and biological components*

In order to detect biological entities, biological components like enzymes, antibodies, chemical compounds like phenols, benzene, and insecticides in an analyte, a biosensor employs a transducer. It is a nanofabricated device

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designed to identify harmful compounds and disease particles. A nanosensor is now frequently used to evaluate substances utilizing nanoparticles due to its unique properties. Gold nanoparticles, carbon nanotubes, and quantum dots are among the NPs that have been used in nano biosensors up to this point. Notable examples include the use of CNTs for the electrochemical detection of pesticides, AuNPs for the amperometric detection of Salmo nella typhi bacteria, and bio-conjugated dye-doped SiNPs for the detection of E. coli. Additional biosensors include single-walled carbon nanotubes (SWCNTs), fluorescence resonance energy transfer (FRET)-based nanosensors in combination with polystyrene nanoparticles, and sensors based on methyl parathion gold nanoparticles and carbon nanotubes [16, 17].

- *Nanotechnology in wood-based industry*

There are two ways that nanotechnology can be used in the wood-based industry: extracting nanomaterials from forests and using them to make wood-based products. In the wood-based industries, nanotechnology Paper, pulp, lumber, and cellulose are examples of forest products that would benefit from the application of nanotechnology since it would increase their value and durability while also fostering sustainability. A wood coating made of nano zinc oxide falls under the latter category, while nanocellulose made from lignocellulosic forest materials falls under the former. Different chemicals can be obtained depending on the method used. Preservative systems and wood modification are the two techniques used in conventional wood preservation. To protect wood from fungi and insects, wood preservative systems apply pressure treatment or chemical treatments. Nanotubes, nanosized metals, and polymeric nanocarriers are all employed in nanotechnology. The two nanosized metal systems that are currently in widespread usage are micronized copper azole (MCA) and micronized copper quaternary (MCQ). The technique known as nanofiltration (NF) finds application in wastewater treatment, biotechnology, pharmaceuticals, and refining operations. Surface water and groundwater systems are purified using NF membranes composed of alumina fibers and carbon nanotubes (CNTs), which filter microscopic particles such as bacteria, parasites, and other substances. Additionally, NF membranes are effective at desalinating brackish water for use in irrigation [18].

III. DEFINITION AND MECHANISM OF NANOFERTILIZER

Nanofertilizer defined as the synthetic form or advanced form of traditional fertiliser bulk fertilizer material or extracts obtained from the wide range of botanical microbial or animal origin that are formulated by variety of methods like chemical, physical, mechanical or biological method by incorporating the concept of nanotechnology. This nanoparticles can formulated from bulk traditional fertilizer at the level of nanoscale the physical and chemical properties of the fertiliser that are formulated by nanotechnology had dynamic properties which differ from the counterpart. The nano fertilizers have maximum ability and absorption as they have higher ratio of surface area to volume size. The size of the particle of nanofertilizer are less than 1 to100 nanometre in one dimension that aid maximum uptake from soil or leaves that result in maximum photosynthesis and biomass which are necessary for healthy crop. Nanofertilizer possess maximum benefits like they delayed the release process, transportation process and with this the cost of application are also minimised. Depending on the size, surface charge and other chemical and physical properties of nanoparticle foliar and root treatment which result in the proper uptake by the plant. Larger nano fertilizer travel by the stomatal conducts of leaves and smaller nanoparticle travel through channel of waxy cuticle based on their hydrophobicity. Nanoparticles and able to translocated by the root with the help of charge-based absorption and are followed by migration which are apoplastic and endocytosis. The size of the nano fertilizer effects their chances to penetrate circulatory tissue. By recent transcriptomic, protemic and metabolomics investigation, nano fertiliser governed the taking process and minimise the extra nutrient toxicity by controlling the expression level of the gene. The transport nutrient have a large control on the cell division, photosynthesis, nitrogen and metabolism of carbohydrate and the signaling of phytohormone dependent pathway which are responsible in developing the stress response and the defence of the plant that cause nano fertiliser to elevate growth. For enhancing development and the stress tolerance nano fertiliser reduce calcium that are responsible for initiating second messengers and related proteins in the cascade of signal that ultimately reach the transcription factors and aid in synchronising the expression of gene investigating molecular interaction with the plants which is necessary to create the significant nanoparticle encapsulated fertilizer in the future that reduce toxicity and have better efficacy. The behaviour, bioavailability and the absorption of nano fertilizers in plant are regulated by their ability to be penetrate through the route and the leaves in number of studies it has been found that nano fertilizers efficacy is better than the conventional fertilizer. When nano fertilizers of macronutrients are used in place of traditional fertilizer the development of the plant are enhanced to a great extent in comparison to conventional fertilizer. Nano fertilizers of micronutrient are efficacious by 18%. While nano fertilizer of carrier for the macronutrient maximise growth to a large extent. The sugar content and the wheat quality are maximised by the nano fertilizers. In a study it has been found that silver nanoparticles are able to enhance the growth of wheat by enhancing the length of shoot and roots, leaves area and the quantity of proteins, carbohydrates and chlorophyll. A delayed release of nutrients also occur to great extent [19].

A. Advantages Over Conventional Fertilizer

In compared to conventional fertilizer nano fertilizer causes a large number of benefits like maximum efficiency as the supply significant nutrients to plant directly and have less adverse effect to the environment as they use fewer chemical substances for maximising the production. Nano fertilizer play vital role as compared to the conventional one some advantages are like nutrient concentration, solubility. Solubility defines a large amount of chemical that are dissolved in a specific solvent at a require temperature and pressure. As the nano fertilizer size range in the nanoscale therefore the surface area are huge which provides more solubility and they are more readily soluble and the solution of soil as nano fertilizers are more dissolved rapidly in a number of solvents that include water also. Therefore, insoluble nutrients are more easily soluble and more easily available to the organism present in the environment. In comparison to the conventional phosphorous fertilizer, the phosphorus-based nanoparticle like nano hydroxy apatite shows maximum solubility. Bulk zinc oxide, nano zinc oxide and zinc-based nanoparticle possess high solubility. The encapsulation capability of the fertilizer in nanoparticle is an important parameter that makes them a preferable alternative as a result of encapsulation crop absorb large amount of nutrition. One way for encapsulation of utilizer is polymer based encapsulation that involves the use of interfacial and emulsion polymerization for developing a matrix around the fertilizer. The use of inorganic elements like calcium carbonate or silica develops shell around the fertilizer by Sol gel technique. Another way is layer by layer construction that develop a shell which is multilayer on the surface of the fertiliser by the position of the charged polymer nanoparticle or different other compound. Fertilizer are nano encapsulated by zeolite-based nanoparticle which encapsulate various nutrients in the porous structure of the zeolite that act as a nano scale transporter. Nano fertilizer that are based on zeolite are able to hold the nutrients in the soil specially ammonia which inhibit loss of nutrient by process called denitrification, volatilization and leaching. Simple penetration of the fertiliser and controlled release nano fertilizers significantly facilitate the uptake of fertilizer and usage by plant aiding fertilizer penetration into the plant tissue for maximum penetration. Nanoparticles having high surface area to volume ratio are used for manufacturing nanoparticle. The cell wall and membrane of the plant permit this small particle to diffuse through rapidly, therefore small amount of fertilizer is needed and therefore there is minimum loss and run off happens that aid in inhibiting different problem. Maximum crop yields higher nutritional quality, and the overall agricultural sustainability are all aided by the proper penetration of the nano fertilizers into the tissue of the plant and because of their maximum penetration nanoparticles plays a significant role in enhancing the plants nutritional profile which results in healthy seedling.

In compared to zinc sulphate in bulk nano-ZnO show more peanut seed germination and root development. High efficiency of absorption of nano fertiliser decreases the use of conventional fertiliser by enhancing the ratio of soil nutrient absorption. The loss of fertiliser due to the leaching are inhibited by nano fertiliser. The application of the nanoparticles prominently maximises the zinc uptake, root length and shoot dry weight of the plants. Proper nutrient release and duration are also an important parameter as the sustainability and the productivity of the agricultural are prominently hampered by the proper duration of release of nutrient in nano fertilizer. It guarantees that in the time of growth cycle plant get the proper nutrient they need. In addition to this the nitrogen that are regulated release minimum nutrient loss that reduce the demand for repeated fertiliser treatment and minimise pollution in environment. The working of bulk fertilizer is limited to a short period after application. Nano fertiliser may lengthen the release time profile of nutrient, the proper timing of the release of nutrient in nanofertiliser based chitosan and are able to release nutrients for more than a month. The nanofertiliser that are polymer coated release nutrient for more than two months [20]

B. Case Studies

1)Abdel-Aziz and colleagues looked into the potential impacts on French bean plants of using two engineered nanomaterials as fertilizers: carbon nanotubes (CNTs) or nano chitosan (Cs), either by themselves or loaded with NPK. They discovered that foliar spray outperforms seed priming in terms of plant growth, yield, antioxidant system, and biochemical content of produced seeds. Furthermore, compared to control and seed priming treatments (110 days), foliar treatment reduced the days to harvest by 37.5% (80 days) without lowering yield. Interestingly, Cs nanoparticles seemed to enhance growth and yield metrics more than CNTs when applied topically. Their recommendation is to use nano fertilizers topically [21].

2)In a work by Gao et al, cyantraniliprole (CNAP) was nanocarried by an adhesive hollow mesoporous silica hybrid with a distinct spherical form to create an adhesive nanopesticide (CNAP-HMS-PDAAM). According to the results, CNAP-HMS-PDAAM demonstrated long-term control efficacies against *Cnaphalocrocis medinalis* (Guenee) and *Chilo Suppressalis* (Walker), mostly because of its potent adhesive and prolonged releasing qualities on rice leaves. All four doses of CNAP-HMS-PDAAM were substantially more effective than Benevia (cyantraniliprole 10% EOD) twenty-eight days after spraying. Furthermore, the nanocarriers demonstrated strong biocompatibility and had no discernible impact on rice growth [22].

IV. DEFINITION AND MECHANISM OF NANO-PESTICIDES

To enhance delivery efficiency, pesticide active ingredients are encapsulated, trapped, or adsorbed in nanocarriers, referred to as nanopesticides. Examples include metal-based nanoparticles, polymeric nanoparticles, nano-clays, and nanoscale emulsions. These formulations aim to increase the bioavailability of active components while reducing risks to environmental and public health, thereby maximizing pesticide effectiveness [23]. Moreover, the deployment of nanopesticides enables controlled release mechanisms, thereby ensuring that active ingredients are delivered over an extended period. This sustained release not only minimizes the frequency of pesticide applications but also helps in reducing the overall dosage required, which subsequently lessens the ecological footprint associated with traditional pesticide use [24]. Through innovative design, nanopesticides can be engineered to respond to environmental triggers, such as changes in pH or temperature, further enhancing their targeted activity. In addition to improving the efficiency of pesticide delivery, these advanced formulations can also be tailored to specific pest populations or growth stages, allowing for more precise interventions. This specificity not only preserves beneficial insect species but also contributes to the development of integrated pest management strategies [25]. As a result,

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farmers may experience increased crop yields while simultaneously promoting sustainable agricultural practices. Research continues to investigate the potential of integrating nanopesticides with other technologies, such as precision agriculture and real-time monitoring systems. These interdisciplinary approaches can lead to the creation of smart farming solutions that optimize input use while maintaining high productivity levels. The future of pest management thus lies in harnessing the power of nanotechnology to create safer and more effective agricultural tools that align with the principles of environmental stewardship and public safety [26].

A. Mechanism of Action of Nanopesticides

Nanopesticides utilize specially designed nanoparticles to enhance the release, bioavailability, and effectiveness of agrochemicals against pests and diseases, while minimizing environmental impact. The Mechanism of action is as follows

- *Encapsulation and Controlled Release:*

Active ingredients (AIs) are often encapsulated in nanopesticides using nanocarriers such as liposomes, polymers, micelles, silica nanoparticles, or carbon-based structures. This encapsulation protects AIs from environmental factors like moisture, temperature, and UV radiation that can cause premature degradation. Nanocarriers enable controlled or sustained release, allowing pesticides to be gradually delivered to targeted areas for prolonged effectiveness. Stimuli-responsive systems can release AIs in response to specific environmental triggers such as changes in pH, humidity, or light intensity [25].

- *Enhanced Penetration and Targeting:*

Nanoparticles, with sizes ranging from 1 to 200 nm and a large surface area, are more effective than traditional insecticides in penetrating plant tissues and pest organisms. This enhanced efficiency leads to increased toxicity toward target species by improving contact with pests' membranes, enzymes, and metabolic pathways.

- *In Plants System:*

Nanopesticides improve cuticular penetration and leaf adherence, allowing more active ingredients to reach pests' interiors without washout from wind or rain.

- *In Pests and Pathogens:*

Nanoparticles can disrupt cellular integrity, interfere with enzyme systems, or generate reactive oxygen species (ROS), leading to oxidative stress and damage to the pest's cells [27].

- *Mechanical Disruption:*

Abrasive nanoparticles like silica damage insect cuticles, leading to desiccation. Additionally, toxic nanoparticles such as copper and silver generate reactive oxygen species (ROS) in pathogens and insects, disrupting DNA replication, protein synthesis, and cellular respiration.

- *Targeted Action:*

Ligands or chemicals that target specific pest receptors are sometimes functionalized into nanocarriers for precise delivery while safeguarding beneficial species. These nanocarriers, often engineered to enhance stability and bioavailability, can encapsulate active ingredients, allowing for controlled release in targeted environments. By optimizing the size and surface properties of these carriers, researchers can ensure that they navigate through various ecological niches, minimizing off-target effects and preserving the integrity of non-target organisms.

- *Improved Solubility and Stability:*

Nanosuspensions and nanoemulsions enhance the solubility, stability, and transport of poorly soluble active chemicals in plant and pest systems, improving their overall bioactivity and uptake efficiency. These advanced formulations not only facilitate the effective delivery of active ingredients but also enable targeted application strategies, minimizing waste and enhancing environmental safety. By harnessing the unique properties of nanoscaled materials, they can permeate biological membranes more efficiently, allowing for faster and more uniform distribution within plant tissues or pest organisms [28].

- *Reduction of Environmental Impact:*

Nanopesticides reduce the environmental chemical burden by utilizing lower concentrations of active ingredients due to their enhanced effectiveness. Controlled release minimizes leaching and runoff, thereby preventing pollution. The targeted application of nanopesticides further enhances their ecological profile. By precisely delivering the active ingredients to specific pests, these formulations limit unintended harm to beneficial organisms, promoting biodiversity in agricultural ecosystems. Moreover, the reduced volume of chemicals used minimizes the risk of soil and water contamination, supporting healthier ecosystems.

Nanopesticides offer a multi-faceted mechanism of action: This invention enables sustainable farming by enhancing insect management through prolonged release, improved targeting, and effective administration, while reducing environmental hazards and harmful effects from physical disruption or reactive oxygen species (ROS).This innovative approach not only mitigates the risks associated with traditional pest control methods but also promotes ecological balance by fostering beneficial insect populations. By utilizing advanced biocompatible materials, the system ensures that the active ingredients remain effective over extended periods, minimizing the frequency of applications and thereby reducing resource consumption. The mechanism of nanopesticide is demonstrated in Figure 1.

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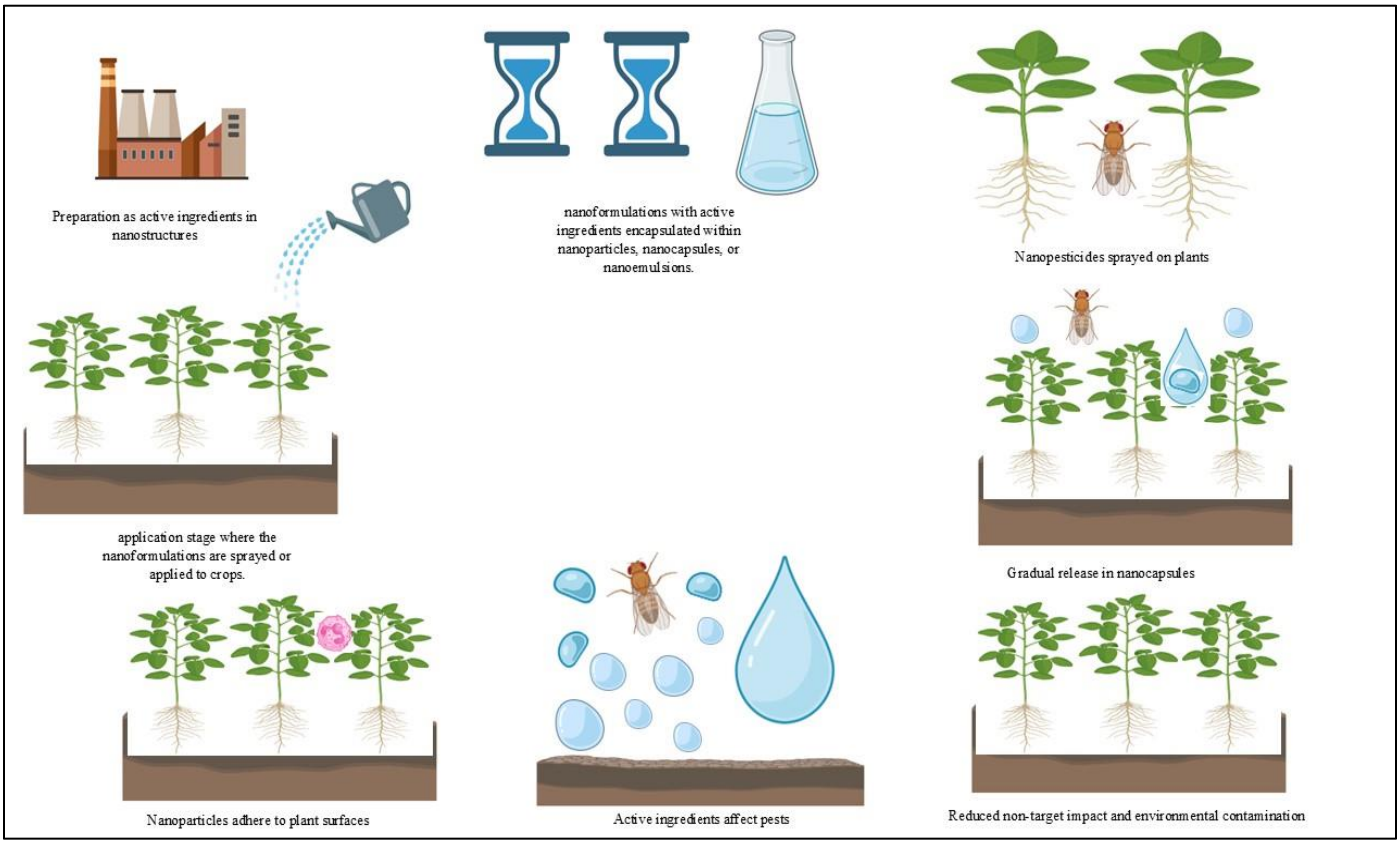

Figure 1. Mechanism of Nanopesticides

B. Benefits Over Traditional Pesticides

Nanopesticides offer several key advantages over conventional pesticides, enhancing the efficiency, safety, and sustainability of pest management in agriculture. Nanoagriculture is currently advancing towards targeted farming techniques that utilize nanosized particles with unique properties to enhance crop production [29]. Traditional agricultural practices such as seed germination, plant growth promotion, and crop improvement are increasingly being supplemented, or even replaced, by the use of carbon nanotubes, which act as regulators for seed germination and plant growth [30]. Similarly, nanosized bacteriophages have emerged as effective biological alternatives to conventional copper-based bactericides.

The small size and high surface-to-volume ratio of nanoparticles render them more efficient compared to their bulk counterparts. Engineered nanoparticles can penetrate plant tissues via the apoplastic pathway, entering the intercellular spaces. Through the apoplast (cell walls), these particles may proceed into epidermal and cortical cells, ultimately reaching the endodermis, where they can accumulate either uniformly or as aggregates [31]. Alternatively, Rico et al. (2011) [32]. suggested that the symplastic pathway, which involves movement through the cytoplasm, provides a more organized and regulated route for engineered nanoparticles within plants. They proposed that the binding of nanoparticles to carrier proteins facilitates cellular internalization, enabling them to traverse ion channels, aquaporins, and endocytosis pathways with ease.

➢ *Improved Efficiency and Targeted Delivery:*

Nanopesticides utilize nanoformulations such as nanocapsules, nanogels, and nanoemulsions to encapsulate active ingredients. This enhances their solubility, stability, and controlled release. The nanoparticle carriers ensure precise delivery to specific pests or plant tissues, reducing wastage and enhancing bioavailability of the active compound, even at low dosages. This also minimizes off-target effects and environmental contamination.

➢ *2. Reduced Environmental Impact:*

Nanopesticides require significantly fewer chemical inputs than conventional pesticides due to their controlled and sustained release properties. They reduce groundwater pollution and harm to non-target organisms, including beneficial insects, aquatic life, and soil microorganisms, by decreasing leaching into soil and water bodies. The utilization of nanopesticides enables more efficient target delivery, thereby minimizing the overall quantity needed for effective pest control. This precision not only conserves resources but also promotes ecological balance by reducing the likelihood of pest resistance development, a common concern with traditional chemical applications. As a result, integrated pest management strategies can be enhanced, allowing for a more sustainable approach to agriculture that prioritizes the health of both crops and the surrounding ecosystem.

➢ *Enhanced Stability and Longevity:*

Nanoparticles protect active chemicals in pesticides from UV radiation, heat, and microbial activity, enhancing the shelf life and effectiveness of insecticides and reducing the need for repeated applications. Nanoparticles can improve

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the targeted delivery of these active ingredients, allowing for more precise application directly to the pests. This specificity minimizes the environmental impact by reducing the number of pesticides needed and lowering the risk of non-target organism exposure. The incorporation of nanoparticles can facilitate the slow-release of active compounds, ensuring that the insecticides remain effective over a longer period and providing sustained protection against pest populations. By optimizing the formulation and stability of these chemicals, nanoparticles play a crucial role in modern pest management strategies, contributing to agricultural sustainability and promoting safer farming practices.

- *Lower Toxicity Risks:*

Nanopesticides reduce harmful chemical exposure to non-target species, including humans, animals, and plants, through efficient delivery. This decreases food residue and enhances agricultural worker safety. Nanopesticides promote targeted pest control, minimizing the necessity for broad-spectrum chemicals that indiscriminately affect beneficial organisms. By utilizing innovative formulations, these advanced solutions can effectively concentrate on specific pests while preserving the vital ecological balance. This selective approach not only sustains biodiversity but also facilitates more sustainable farming practices, allowing for the preservation of pollinators and natural pest predators.

- *Reduced Pest Resistance:*

Long-term use of traditional insecticides often leads to pest resistance. In contrast, nanopesticides, with their smart release mechanisms, help prevent this resistance. Furthermore, innovative nanocarriers enable the distribution of multiple active substances, enhancing effectiveness against resistant pest species. Nanopesticides exhibit a targeted action that minimizes the impact on non-target organisms, promoting a healthier ecosystem. This specificity not only reduces the collateral damage often associated with conventional pesticides but also supports beneficial insect populations that are crucial for pollination and natural pest management.

- *Economic Benefits:*

Nanopesticides offer farmers significant financial benefits by reducing the amount of active chemicals needed and boosting overall crop yields. Although nanoformulations may have higher initial costs, their long-term advantages, such as fewer applications, result in lower operating expenses.

- *Enhanced Crop Productivity:*

Nanopesticides enhance pest control, leading to higher agricultural yields and healthier plants. Certain nanoparticles also boost nutrient absorption, promoting increased resistance and overall growth. Moreover, the targeted delivery systems enabled by nanopesticides reduce the reliance on traditional chemical treatments, mitigating the environmental impact associated with pesticide runoff. This precision not only protects beneficial organisms but also fosters a more balanced ecosystem, allowing for natural pest predators to thrive [33].

Nanopesticides offer a sustainable solution for modern agriculture by balancing enhanced pest control with reduced environmental and health impacts. However, further research on their long-term safety and environmental effects is needed for widespread acceptance. Additionally, the integration of nanopesticides into existing agricultural practices necessitates a comprehensive understanding of their interactions with various ecosystems. This includes studying their effects on non-target organisms, soil health, and the potential development of resistance among pests. Collaborative efforts between researchers, policymakers, and farmers will be crucial in establishing guidelines for the responsible use of these advanced formulations. The primary challenge associated with conventional agroherbicides and pesticides lies in their typically low solubility [34]. This poor solubility necessitates the use of substantial quantities of organic solvents to dissolve these compounds for effective application in the field. However, the reliance on organic solvents escalates costs, introduces environmental pollutants, and increases user exposure risks [35]. For practical application, it is often essential to disperse the active ingredients (a.i.'s) of pesticides in a liquid medium, as it enables ease of spraying. Water, being cost-effective, widely available, and environmentally compatible, is the most suitable liquid for pesticide application [36].

Nevertheless, many pesticides exhibit poor or no solubility in water due to two key reasons:

- *Lipophilicity:*

These pesticides are highly nonpolar, making their mixing with water thermodynamically unfavorable. Increasing the contact area between the two incompatible phases elevates interfacial free energy.

- *High Lattice Energy:*

Some pesticides possess strong intermolecular bonding and high lattice energy in their solid state, often characterized by melting points exceeding 200°C [37]. As a result, such pesticides tend to separate from water through processes like coalescence, flocculation, sedimentation, and creaming unless subjected to continuous agitation. This separation complicates uniform application, necessitating the use of larger quantities to achieve the desired pest control. This practice not only increases costs but also amplifies environmental and health-related concerns. Nanotechnology offers a solution by reducing pesticide particle sizes to the nano or colloidal scale, which enhances water solubility, dissolution rate, and uniform dispersion. Moreover, nanosized particles tend to exhibit partially or fully amorphous structures, which are more soluble than their crystalline counterparts [38]. A common approach to address solubility issues in commercial formulations is the inclusion of surfactants. Surfactants, which have both polar and nonpolar components, reduce the unfavorable interaction between water and pesticides. The polar component interacts with water, while the nonpolar component faces the pesticide, lowering the interfacial surface energy. This promotes the dispersion of pesticides into small particles. Liquid pesticide formulations using surfactants are termed emulsifiable concentrates, while solid pesticides are referred to as wettable powders. The particle sizes in these formulations typically range from 1–20 µm in diameter. Despite their enhanced stability, such formulations still require constant agitation to prevent separation over time. Recent advancements focus on dispersing the active ingredients in water as a colloid. In these colloids, pesticides are present as nanosized droplets or particles (<250 nm in diameter) stabilized by surfactants [39]. This approach provides several benefits:

- *Prevention of Sedimentation and Creaming:*

Particles smaller than 200 nm remain suspended due to Brownian motion, counteracting gravitational and buoyancy forces.

- *Resistance to Flocculation and Coalescence:*

Surfactants create a strong repulsive force, such as electrostatic or steric hindrance, establishing an energy barrier that prevents these processes

In some cases, cosurfactants like aliphatic alcohols are added to act as spacers between surfactant molecules, optimizing the surfactant density at the particle interface and enhancing stability. Nonionic surfactants are preferred for their inertness, compatibility with pesticides, and resistance to issues arising from water hardness [40]. Depending on the nature of the active ingredients, colloids are categorized as nanoemulsions for liquid a.i.'s (or those dissolved in minimal organic solvents) and as nanodispersions for solid particles. The latter consists of solid pesticides or liquid pesticides incorporated into an inert nonpolar matrix [41]. This innovative approach to pesticide formulation enhances stability, uniformity, and efficacy, addressing the limitations of traditional pesticide applications.

C. Current Applications and Success Stories

A significant advancement in agriculture is the application of nanotechnology in pest management, specifically nanopesticides. These innovative formulations aim to enhance the safety, efficacy, and environmental sustainability of traditional pesticides by manipulating materials at the nanoscale. This comprehensive review emphasizes the transformative potential of nanopesticides in modern agriculture by examining current applications, success stories, and future prospects.

D. Current Applications of Nano pesticides

Nanopesticides are being integrated into various agricultural practices to address the limitations of traditional pesticides. Their nanoscale size allows for improved solubility, targeted distribution, and controlled release of active ingredients, enhancing pest control effectiveness while reducing environmental impact. For instance, biopolymeric nanopesticides have been developed as eco-friendly alternatives, demonstrating strong antifungal properties and promoting plant growth in crops like chickpeas [42].

Similarly, "all-organic" nanoinsecticides have shown promise in effectively targeting pests while minimizing adverse effects on non-target organisms [43]. Nanotechnology has many uses in agriculture than only controlling pests. For instance, nanofertilizers have been developed to increase agricultural yields, decrease environmental runoff, and improve nutrient absorption efficiency. According to studies, traditional fertilizers are much outperformed by nanofertilizers, which may attain absorption efficiencies of up to 90.6%. This dual application of nanotechnology in both pest management and fertilization underscores its potential to revolutionize agricultural practices.

E. Success Stories in Nanopesticide Implementation

Numerous success stories demonstrate the effectiveness of nanopesticides in agriculture. Research on copper-based nanopesticides in the US indicates their high efficiency against fungi and pests, potentially reducing pesticide use and minimizing environmental impact. These findings suggest that nanopesticides can offer cost-effective and environmentally friendly solutions for pest management. Nanopesticides derived from chitosan show significant potential in India for managing plant diseases. Research indicates that chitosan nanoformulations can inhibit the mycelial growth of pathogens affecting chili plants, thereby reducing illness incidence and enhancing agricultural productivity [42].

These success stories highlight the versatility and effectiveness of nanopesticides across different agricultural contexts.

V. FUTURE PERSPECTIVES OF NANOPESTICIDES

Continuous research and technological breakthroughs are expected to drive significant advancements in nanopesticides. One promising approach is the development of biodegradable nanoparticles, aimed at minimizing environmental impact by preventing nanopesticide residues from lingering in ecosystems [44]. Combining nanopesticides with precision farming techniques may enhance pest management efficiency, optimize resource use, and minimize harm to non-target species. Several obstacles hinder the widespread use of nanopesticides. To ensure their safe and effective application, regulatory frameworks must address potential environmental and health hazards. Additionally, transparent communication about the benefits and risks of nanotechnology in agriculture is vital for public perception and acceptance. Economic considerations and the scalability of production are also key factors influencing global farmer adoption of nanopesticides. In summary, nanopesticides offer enhanced efficacy, safety, and environmental compatibility compared to traditional pesticides, representing a significant advancement in agricultural pest control. Although future developments suggest a move towards more precise and sustainable pest management, current applications demonstrate their effectiveness in addressing urgent agricultural issues. To fully harness the potential of nanopesticides in global agriculture, further research and supportive regulatory and commercial frameworks are essential. Following is a table showing advancement in nanopesticide development: different types of nanoformulations of conventional pesticides demonstrated in Table 1.

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Table 1 Advancement in Nanopesticide Development: Different Types of Nanoformulations of Conventional Pesticides
(A) Nanoformulation

Pesticide	Crop Disease	Pathogen	Impact	References
Cellulose/silica nanocomposites	Leaf senescence and decay	Rust and moulds	50% improvement in release rate	Mattos and Magalhaes (2016) [45]
Porous hollow silica	Validamycin	–	Loading capacity improved up to 36%	Liu et al. (2006) [46]
Calcium carbonate	Validamycin	Rhizoctonia solani	Controlled release up to 2 weeks	Qian et al. (2011) [47]
TiO2 with Zn and Ag	Spot of tomato	Xanthomonas perforans	High photocatalytic activity and bacterial reduction	Paret et al. (2013) [48]
Porous hollow silica	2,4-Dichlorophenoxyacetate	–	Improved herbicide activity period	Hussein et al. (2005) [49]
Lignin	Diuron	–	Improved controlled release rate	Yearla and Padmasree (2016) [50]

A. Nanocarriers and Delivery Systems

Nanotechnology is transforming agriculture by enabling the precise and effective delivery of agrochemicals including fertilisers, insecticides, and herbicides. Nanocarriers, which range in size from 1 to 100 nanometres, are at the verge of this breakthrough [51-53]. These carriers, which include lipid-based systems, polymeric nanoparticles, metal-based nanoparticles, and nanoemulsions, are meant to encapsulate, transport, and release active substances in a regulated fashion [54]. Nanocarriers improve agrochemical stability, effectiveness, and sustainability by preserving them from early degradation and guaranteeing targeted distribution. Lipid-based nanocarriers, such as liposomes, are biocompatible and effective in transporting both hydrophobic and hydrophilic molecules [55]. Similarly, polymeric nanoparticles derived from biodegradable materials such as chitosan allow for controlled release applications, even with metal-based nanoparticles such as silver and zinc oxide offer functionalised choices for effective pesticide delivery [56]. These technologies offer applications such as pesticide protection from environmental degradation, slow nutrient release in fertilisers, and gene delivery systems for plant transformation [57]. Nanocarriers contribute significantly to the efficiency and sustainability of pesticide delivery. By altering the surface of nanoparticles with ligands or antibodies, they can selectively bind to insect or weed targets while minimising nontarget impacts [58]. Furthermore, nanoemulsions (stable mixes of oil, water, and surfactants) increase the solubility and bioavailability of active chemicals. Nanocarriers also aid in gene delivery systems, a cutting-edge technology that protects plants from infections and improves genetic features. Nanocarriers are currently being investigated for their potential role in improving biostimulant and micronutrient delivery, plant stress tolerance, and metabolic activity. The incorporation of natural extracts or biostimulants into nanocarriers has a synergistic impact, encouraging plant growth and resistance under abiotic stress conditions [59]. Furthermore, research on nano-based seed coating technologies is gaining pace, which will improve germination rates and early-stage growth by providing essential nutrients and protective agents directly to the seed surface [60]. Exploring their involvement in plant-microbe interactions has the potential to widen their uses, since nanocarriers can improve microbial inoculant delivery for soil fertility and plant health [61].

B. Controlled Release and Targeted Action

Nanocarriers have the potential to achieve controlled release and focused activity. Controlled release is the regulation of the timing and amount of active component supplied. This is accomplished via processes such as diffusion-controlled release, stimuli-responsive release, and degradation-controlled release [62]. Fertilisers with controlled-release systems release nutrients progressively over time, meeting crop requirements at various development stages. This decreases nutrition loss from leaching or volatilisation, increasing nutrient utilisation efficiency [63]. Similarly, controlled-release pesticides provide long-term protection by keeping a consistent supply of active chemicals, reducing the need for frequent reapplication. Herbicides supplied using nanocarriers can also be customised to target specific weed indicators, minimising non-target plant harm. Targeted action complements-controlled release by ensuring that active chemicals reach specified locations such as insect populations, plant roots, or disease hotspots [64]. Functionalised nanoparticles, which can detect specific markers on pests or diseases, are very useful in this application. These approaches minimise damage to beneficial creatures while optimising pest or disease management. Additionally, root-specific delivery systems that release nutrients or agrochemicals at the root zone improve plant health and production. Nano-spray-based foliar sprays stick better to plant surfaces, avoiding wash-off during rains and giving protection. Hydrogels and self-healing nanocarriers are two examples of innovations that improve the capacity to accurately and effectively transport nutrients or agrochemicals. Hydrogels coupled with nanocomposites maintain moisture while allowing active chemicals to be released gradually [65]. Self-healing nanocarriers repair themselves in response to environmental stress, maintaining consistent performance. Nanosensors combined with nanocarriers provide real-time monitoring of environmental variables, prompting precise action as needed. These improvements ensure that agriculture grows more efficient and sustainable [66]. Nanocarriers have also demonstrated promise in delivering numerous agrochemicals in a single formulation by means of dual or sequential release mechanisms, thereby increasing the efficiency of combined fertiliser and pesticide treatments [67]. Advanced functionalisation techniques, such as the use of DNA aptamers or bio-recognition molecules, have paved the door

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to ultra-specific targeting capabilities, particularly for disease hotspots and pest infestations. In addition, advances in hydrogel-integrated nanocarriers serve a dual purpose: they control the release of active compounds while also retaining soil moisture, solving water shortage concerns. Nano-based foliar sprays with greater adhesion qualities are also being developed, allowing for better application in extreme weather circumstances like as severe rainfall or drought [68].

C. Environmental and Economic Impacts

The environmental and economic implications of nano-enhancements in agriculture are significant, addressing critical sustainability and efficiency issues. These methods are beneficial to the environment by reducing chemical runoff and water pollution. Conventional farming techniques frequently result in overapplication of fertilisers and pesticides, which pollutes soil and rivers [69]. The controlled-release capabilities of nanocarriers limit the possibility of such events, therefore maintaining aquatic ecosystems and increasing soil health by reducing hazardous residue accumulation. This also protects soil bacteria, which is essential for long-term soil fertility [70]. In addition, the precise distribution of nitrogen-based fertilisers minimises volatilisation, which is a key contributor to agricultural greenhouse gases [71]. Biodegradability is another important environmental benefit of many nanocarriers, particularly those produced from natural polymers such as chitosan or cellulose. These materials decay naturally in the environment, preventing long-term contamination [72]. Nano-enhancements also improve insect resistance management by distributing pesticides in a targeted manner, reducing usage and decreasing the development of resistance in pests and diseases. This results in a more balanced and sustainable ecology. Nano-enhancements provide considerable cost reductions [73]. Nanocarriers' accuracy and efficiency need less fertiliser, pesticide, or herbicide to get the intended results. This immediately cuts farmers' input expenses. Furthermore, the longer duration of action given by controlled-release systems reduces labour expenses by minimising the number of applications [74]. Crop yields increase as fertiliser efficiency and pest control improve, adding to the economic benefits. Post-harvest losses, a key agricultural concern, are also reduced by nano-coatings that protect crops from microbial infection and moisture loss during storage and transportation. Crops cultivated using nanoenhancements frequently exceed higher safety and environmental criteria, making them more appealing in premium markets. This brings up new prospects for farmers, especially in areas where sustainable farming techniques are highly prized [75]. However, the high initial costs of developing and using nanotechnology continue to be a hurdle. Small-scale farmers may find these technology cost prohibitive without government assistance or subsidies [76]. Furthermore, legal barriers and a lack of clear rules for the use of nanomaterials in agriculture cause ambiguity among stakeholders, delaying wider acceptance. Despite these obstacles, the future of nano-enhancements in agriculture appears optimistic [77]. Research is being conducted to solve cost and scalability challenges, with an emphasis on generating biosourced nanocarriers from renewable materials such as starch or cellulose. Smart systems that combine nanotechnology, artificial intelligence (AI), and the Internet of Things (IoT) are being developed to provide real-time monitoring and precise treatments [78]. Clear regulatory frameworks are required to ensure the safe and successful use of nanomaterials while also establishing public confidence. With continuing innovation and appropriate deployment, nanotechnology has the potential to transform agriculture, making it more sustainable, efficient, and productive. Nanocarriers' environmental benefits include lowering agriculture's carbon impact. By optimising nutrient delivery, these technologies assist to reduce the requirement for intensive farming inputs, cutting greenhouse gas emissions associated with traditional methods [79]. Furthermore, nanotechnology's ability to repurpose agricultural waste through biocompatible nanocarriers, such as those made from cellulose or lignin, offers a long-term solution for waste management and material recycling [80]. Economically, the use of nanocarriers in precision agriculture can assist farmers move to data-driven farming, where real-time nanosensor integration allows them to make more informed decisions, lowering input costs and increasing profitability [81]. To close the gap for small-scale farmers, however, cost-effective production methods must be innovated, as well as government-supported incentive schemes to assure fair adoption. The various benefits of nanocarrier enhanced fertilizer are demonstrated in Figure 2.

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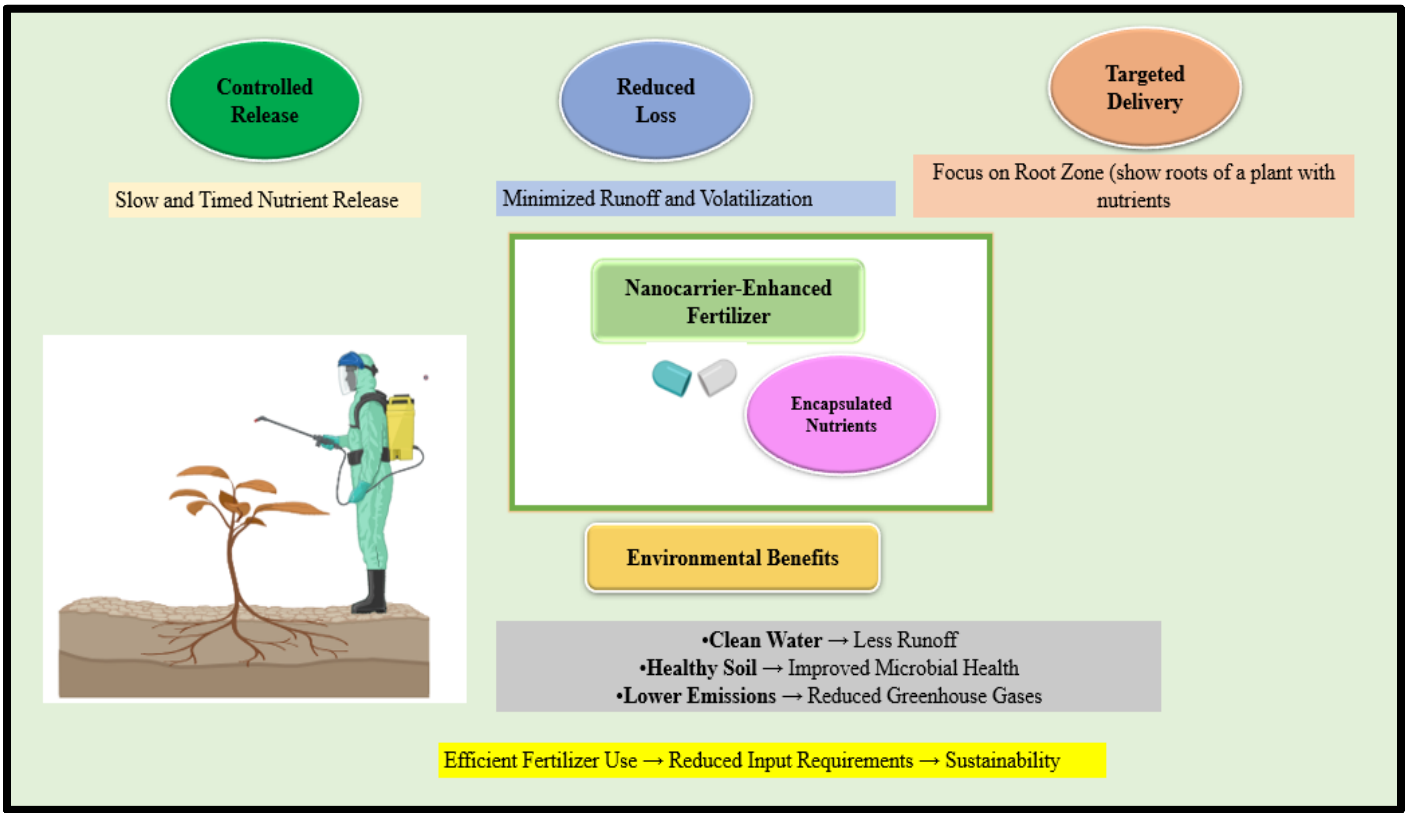

Fig 2 The Various Benefits of Nanocarrier Enhanced Fertilizer

VI. CHALLENGES AND LIMITATIONS

Among the primary consequences of climate change are rising temperatures and altered rainfall patterns, which can lead to a number of other issues like stressed plants, weed growth, and spore multiplication during food storage. Furthermore, this problem is being made worse by the excessive and unregulated use of fertilizers and pesticides in contemporary agriculture. NPs are preferred for nutrient uptake, plant defense, and biofortification because plants are experiencing additional stressors as a result of global warming. Therefore, it is essential to keep researching the advantages and potential drawbacks of these technologies, enhancing their functionality, and creating new nanotechnological solutions [13][18].

Numerous phyto-synthesized NPs provide promising prospects for boosting crop output and promoting sustainable farming in the agricultural sector. Among the primary ones are worries about their potential effects on the environment and potential harm to organisms that are not their targets. It is essential to carry out thorough research and put effective legislation into place to guarantee responsible and safe use. It's also essential to look into how these nanoparticles affect soil health over the long run and how resistance develops in agricultural systems. Because they actively address these problems and promote moral behavior, phyto-synthesized NPs can help create sustainable agriculture [14].

Contemporary technology has greatly improved the world in many ways, though they also have drawbacks. Therefore, it is impossible to ignore the negative effects of nanotechnology, even though it is a frontier of scientific growth in the present day. All biotic and abiotic elements of the ecosystem, including soil, air, water, animals, insects, plants, and people are susceptible to the harmful impacts of nano-formulations released into the environment. It exhibits detrimental impacts on every type of life within an environment. One of the high-risk factors that could endanger the agriculture industry's future is nano phytotoxicity. Damage to a plant or environment brought on by the release of dangerous concentrations of nanoparticles is known as nano phytotoxicity. Through phytotoxicity research, the possible effects of nanoparticles on the environment can be examined. Particle size, concentration, and soil conditions all can be affect by phytotoxicity. For example, because they are tiny, Ag NPs with a size of 5–10 nm can easily move and collect in various plant sections, increasing their toxicity. Plants cultivated in conditions containing TiO2 nanoparticles at greater concentrations showed damage, while plants maintained at a lower concentration of 0.5 g/L showed benefits. Plant structural damage, oxidative stress induction, and disruption of reproductive development are among the detrimental consequences of nano phytotoxicity [18].

A. Technical Hurdles

Since nanotechnology in agriculture is still a relatively young field, there is no regulation and oversight to guarantee its appropriate and safe application. Concerns regarding the possible hazards of applying nanotechnology in agriculture and the requirement for strict laws to safeguard the environment and public health are raised by the absence of regulation. There can be various technical hurdles such ecological risks, human health risks, high costs, ethical concerns and lack of regulation [15].

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B. Safety Concerns and Regulatory Frameworks

A number of countries throughout the world have been actively examining whether their regulatory frameworks are appropriate for managing nanotechnologies in order to approve nano-based products, as the world's population has increased need for food. As a result, various national regulations for nano-based agricultural products from feed to food as well as international safety assessment guidelines and laws have been contextualized. The laws governing the application of nanotechnology in agriculture vary from nation to nation. The U.S. Department of Agriculture (USDA) oversees agricultural biotechnology products in the United States, whereas the Environmental Protection Agency (EPA) regulates pesticides.

The European Chemicals Agency (ECHA) and the European Food Safety Authority (EFSA) oversee the use of nanotechnology in foods and pesticides inside the European Union. This entails assessing the human health effects, environmental release potential, agri-product labeling, and the toxicity of the employed nanomaterials. To ensure the quality and safety of agricultural products based on nanotechnology, international standards have been established. A number of nanotechnology-related standards have been created by the International Organization for Standardization (ISO), such as ISO/TS 80004-1, which defines and uses terms for nanomaterials. The Food and Drug Administration (FDA), the Environmental Protection Agency (EPA), the Toxic Substances Control Act (TSCA), and the United States Department of Agriculture (USDA) are among the government agencies that oversee agricultural products based on nanotechnology in the United States. The US Food and Drug Administration has authorized the use of some nanoparticles in food applications. According to the FD&C Act, food and cosmetic items must be appropriately labeled and safe to use. The use of organic labeling on agricultural goods is governed by the National Organic Program (NOP). Federal agencies are required by the Nanotechnology Research and Development Act (NRDA) statute to coordinate their nanotechnology-related research and development activities. Generally speaking, these organizations share the objective of guaranteeing the effectiveness and safety of agricultural products based on nanotechnology while also making sure that they adhere to relevant laws.

➢ *Europe:*

To protect human health and the environment, a number of laws apply to agri-products based on nanotechnology, including fertilizers, insecticides, and additives for animal feed. Before they may be used or sold, all plant protection products must be approved. The following list of important European legislation and regulations pertaining to agri-products based on nanotechnology includes the year and reference (EFSA Scientific Committee, 2011; ECHA, 2012).

➢ *Australia:*

The national industrial chemicals notification and assessment scheme (NICNAS), the Australian Pesticides and Veterinary Medicines Authority (APVMA), Food Standards Australia New Zealand (FSANZ), the Ministry of Agriculture and Rural Affairs (MARA), the State Administration for Market Regulation (SAMR), the National Health Commission (NHC), the Ministry of Ecology and Environment (MEE), and the Therapeutic Goods Administration (TGA) are some of the pertinent laws, safety standards, and regulations for nanotechnology-based agri-products in Australia.

➢ *India:*

The Department of Biotechnology (DBT), the Ministry of Environment, Forests, and Climate Change (MoEFCC), the Food Safety and Standards Authority of India (FSSAI), and the Indian Council of Agricultural Research (ICAR) are among the organizations and laws in India that are responsible for regulating agricultural products based on nanotechnology. These are various Indian laws, safety precautions, and rules pertaining to agricultural goods made using nanotechnology. These include the following: MoEFCC Notification on Manufacture, Storage, and Import of Hazardous Chemicals Rules (1989), FSSAI Regulations on Food Additives (2011), ICAR Guidelines on Nanotechnology Research in Agriculture (2010), Indian Pharmacopoeia Commission (IPC) Guidelines on Nanoparticle Characterization (2019), The Environment (Protection) Act, 1986, Hazardous Waste (Management, Handling, and Transboundary Movement) Rules, 2016, The Food Safety and Standards Act, 2006, Insecticides Act, 1968, The Seeds Act, 1966 and DBT Guidelines on Safety Assessment of Foods Derived from Genetically Engineered Plants and Microorganisms (2017). Other guidelines and rules established by the relevant regulatory bodies may also apply to India's laws, safety precautions, and regulations pertaining to agri-products based on nanotechnology. It is crucial to remember that these rules are always changing and could be modified, and there might be more local or regional standards and guidelines [16].

C. Cost and Accessibility Issues

In order to maximize profit, the farming community frequently concentrates on lowering the cost of agricultural inputs. Farmers use fungicides, herbicides, and fertilizers to maximize crop productivity in order to achieve this goal [10]. There is a notable trade-off between increased crop productivity and the current situation. The top five nations for the number of publications on agro-based nanoparticle research between 2000 and 2018 were the US, China, India, Brazil, and Iran. According to a follow-up study, the top three countries for nanotechnology research from 2009 and 2021 were the US, China, and India. Consideration must be given to the substantial risk, legal, social, and economic ramifications of nanotechnology. Financially speaking, nanotechnology has the potential to transform a number of sectors, including agriculture, healthcare, and energy. It can create novel materials with special qualities, increase productivity, and reduce production costs. But it's also important to consider the significant expenses of research and development as well as possible liability problems. Therefore, in order to guarantee the safe and responsible development and application of nanotechnology, governments and regulatory bodies must endeavor to establish suitable legal frameworks [15].

Due to the rising scarcity of arable land and water resources, the agriculture industry can only grow if contemporary technologies are used effectively to increase resource use efficiency while causing the least amount of harm to agro-ecology. With the aid of satellite technology and nano biosensors, crop input requirements are identified in controlled environments and precision farming, and necessary quantities are given at the appropriate time and location. Nanostructured formulations could more precisely release their active ingredients in response to biological demands and environmental cues by using processes like conditional release, slow/controlled release, or targeted delivery. Utilizing nanotechnology increases the efficiency of nutrient utilization, decreases soil toxicity, limits the possible adverse effects of excessive dosage, and decreases application frequency. Therefore, there is a great chance that nanotechnology may help achieve sustainable agriculture, particularly in underdeveloped nations [82].

VII. FUTURE PERSPECTIVES AND OPPORTUNITIES IN NANO-MATERIALS FOR AGRICULTURE

Nanotechnology, a field that includes the manipulation of matter at the atomic or molecular level, has the potential to transform agriculture by offering novel answers to issues such as food security, environmental sustainability, and resource efficiency [83]. Recent advances in nanomaterials have created new opportunities for increasing agricultural output and boosting sustainability. This section focusses into nanomaterial developments, their integration with smart farming practices, and the prospects for worldwide adoption and widespread implementation. One of the most potential uses of nanomaterials in agriculture is the creation of nanofertilizers [84]. Traditional fertilisers often suffer from inefficiencies caused by nutrient runoff, leaching, and misuse, which may give rise to environmental damage. Nano-fertilizers, on the other hand, are meant to distribute nutrients more slowly and precisely, improving plant absorption and reducing waste [85]. Recent research has demonstrated the ability of biopolymer-based nano-capsules to supply important nutrients such as nitrogen, phosphorus, and potassium more efficiently, resulting in greater crop yields and a lower environmental impact [86]. For example, 2023 research found that nano-capsules may enhance phosphorus bioavailability in soils while reducing water runoff, a frequent concern with traditional fertilisers. Also, materials such as carbon nanotubes and graphene oxide are being investigated to improve nutrient absorption by plant roots, thereby increasing agricultural output [87]. Nano-pesticides are another groundbreaking invention. Traditional insecticides frequently cause unintended effects, such as toxicity to non-target species, pest resistance, and environmental pollution. Nano-pesticides, on the other hand, may be engineered to target pests more specifically, eradicating the need for huge doses while also lowering the possibility of adverse consequences. For example, recent study in 2024 shown that nano-silver particles might efficiently prevent fungal diseases in crops, providing an alternative to typical chemical pesticides [88, 89]. Furthermore, nano-encapsulated pesticides can have a longer shelf life and be released gradually, thereby increasing their effectiveness and lowering environmental contamination. These advances have the potential to improve crop protection while simultaneously drastically reducing pesticide-related health concerns and environmental impact. The condition of the soil is another crucial area where nanomaterials are having a substantial influence. Nanomaterials, such as biochar nanoparticles, have been found to improve soil fertility by increasing water retention, nutrient availability, and microbial activity [8]. By boosting beneficial microbial activity and raising the carbon content of the soil, biochar nanoparticles may assist healthier crop growth. The potential of nanomaterials, like nano-zinc oxide, to increase plant tolerance to saline soils has also been examined this is an increasing concern in areas where soil salinity is a problem. These developments could assist farmers in semi-arid and arid environments in overcoming obstacles related to soil fertility and enhancing agricultural output in these places [90].

Modern agriculture is increasingly incorporating smart farming, which makes use of cutting-edge technologies like sensors, drones, Internet of Things (IoT) devices, and big data analytics. These technologies can be further improved and agricultural operations optimised by integrating nanomaterials [91].

Precision agriculture, for instance, is expected to heavily rely on nano-sensors. These incredibly sensitive sensors are able to track environmental variables including pH, temperature, and humidity as well as plant health and soil conditions. Farmers may make better decisions about irrigation, fertilisation, and pest management by installing these sensors in the soil or on plants to get real-time data on the health of their crops and soil [91]. Through the identification of biomarkers or minute alterations in plant physiology, recent advancements in nanosensor technology have demonstrated their capacity to discover early indicators of disease in crops. By minimising the need for broad-spectrum pesticide applications and increasing crop resilience, this early detection may result in more focused and effective responses. Another promising field involves the utilisation of nanomaterials in autonomous vehicles and drones. Tasks like planting, crop health monitoring, and pesticide or fertiliser spraying are increasingly being performed by drones and robots. The efficiency and endurance of these systems can be greatly increased by adding nanomaterials. Drones with nano-coatings, for example, may be more resilient to external elements including corrosion, moisture, and UV rays. Additionally, these drones can be equipped with nano-sensors to collect vital information on crop stress, nutrient content, and soil moisture levels, allowing farmers to minimise waste and maximise resource utilisation [92]. Through the reduction of water and fertiliser use, this integration may also aid in the development of more sustainable farming methods. One of the most important issues facing agriculture today is water management, especially in areas where water is scarce. Nanomaterials present an achievable approach to increase water efficiency. Materials like graphene oxide and carbon nanotubes, for instance, have demonstrated promise in the filtration and purification of water. These materials could be

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employed in sensors to track the quality of the water or in irrigation systems to clean water sources. Additionally, to lessen water loss from evaporation, superhydrophobic coatings composed of nanomaterials can be applied to crops or irrigation systems. In areas with low water supplies, these water-saving devices may be extremely important for facilitating more effective irrigation and preserving this valuable resource [93]. Despite the enormous promise of nanomaterials in agriculture, a number of obstacles still stand in the way of their broad acceptance and extensive use. The high cost of creating certain nanomaterials is one of the main obstacles. For instance, it can be costly to synthesise high-quality carbon nanotubes or graphene, which restricts farmers' access to these materials, especially in developing nations. But as nanotechnology develops further and production techniques become more economical, nanomaterials should become more affordable, opening them up to a wider spectrum of farmers around the world [94]. The scalability of production is another important consideration in the widespread use of nanomaterials. Though a lot of the advantages of nanomaterials have been shown in lab or small-scale field tests, it will take a substantial investment in infrastructure and technology to move to large-scale production and use. To provide scalable solutions that can satisfy the rising demand for sustainable farming practices, governments, academic institutions, and the commercial sector must work together [95]. Additionally, there has to be a clear and established regulatory framework surrounding the use of nanomaterials in agriculture. The long-term effects of nanomaterials on the environment and human health continue to raise concerns, and studies into their safety are continuously being conducted. Guidelines must be created by regulatory agencies to guarantee the responsible and secure usage of these materials [96].

In addition, underdeveloped countries, where there is a greater need for resource efficiency and enhanced food production, must adopt nanomaterials if they are to have a significant worldwide influence. Farmers' success in these areas will depend on their ability to obtain reasonably priced nanotechnologies and the training they need to apply them successfully [97]. In order to ensure that nanomaterials can be utilised to enhance agricultural practices in areas with the greatest need, international cooperation including collaborations between governments, non-governmental organisations, and the corporate sector will be crucial. Nanomaterials have enormous potential to transform agriculture. New developments in soil improvement materials, nanopesticides, and nanofertilizers present promising chances to boost agricultural output while lessening the influence on the environment. These materials can facilitate more accurate, effective, and sustainable agricultural methods when combined with smart farming strategies [98-100]. However, before these improvements can be broadly used, issues with cost, scalability, safety, and regulation need to be resolved. Nanomaterials have the potential to revolutionise global agriculture and increase food security and sustainability for future generations if research and cooperation are sustained.

VIII. CONCLUSION

The integration of nanotechnology in agriculture heralds a transformative approach to achieving food security amidst growing challenges. By enhancing efficiency in fertilizer and pesticide use, improving soil health, and enabling precision agriculture, nanotechnology addresses critical issues like climate change, resource scarcity, and pest resistance. Success stories underscore its potential, with nanoformulations delivering targeted action, reduced environmental impact, and significant economic benefits. However, widespread adoption requires overcoming barriers such as high costs, lack of regulation, and potential environmental risks. Future prospects lie in advancing biodegradable nanomaterials, creating scalable production methods, and fostering global collaboration among stakeholders. By bridging scientific innovation with sustainable practices, nanotechnology can pave the way for an agricultural paradigm that meets present needs while preserving resources for future generations.

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