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Review Article

Harnessing Nanotechnology for Precision Agricultural Advancements

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Abstract

Agriculture is the most fundamental and stable sector as it is the producer which provides raw materials to the food and feed industries. Nano-technology is an evolving technology that has promising results in the field of agriculture and agricultural products. Nanotechnology can transform the agricultural and food industry with the help of various innovative tools for the molecular management of diseases, rapid disease detection, and enhancing the ability of plants to absorb nutrients. Nanotechnology has emerged as a promising field for revolutionizing agriculture by providing innovative solutions for improving crop production, enhancing nutrient delivery, managing water resources, and remediation of contaminated soils. This overview discusses the various applications of nanotechnology in agriculture, including crop protection, increasing crop yields, and sustainable farming practices. The use of nanomaterials in agriculture raises concerns about their environmental impact, safety, and ethical considerations, necessitating further research and collaboration to ensure the responsible integration of nanotechnology in agriculture. This article explores the potential benefits and challenges of utilizing nanotechnology in agriculture and emphasizes the importance of considering human health and environmental factors in developing sustainable nanotechnology solutions for the agricultural sector. In this review, we summarize recent endeavors at innovative uses of nanotechnologies in agriculture that may help to meet the rising demand for food and environmental sustainability.

Keywords: Nanotechnology, Nanoparticles, Precision agriculture, Sustainable farming

Introduction

The term "nanomaterial" originates from the Greek prefix "nano," denoting "dwarf," and pertains to the scale of one billionth of a meter (10^-9 m). In scholarly discourse, "nanomaterial" specifically encompasses materials exhibiting dimensions typically ranging from 1 to 100 nanometers [1]. Nanotechnology is positioned as the sixth paradigm-shifting technological advancement of contemporary times, following pivotal historical revolutions such as the Industrial Revolution of the 18th century, the advent of Nuclear Energy in the 1940s, the Green Revolution in the 1960s, the rise of Information Technology in the 1980s, and the dawn of Biotechnology in the 1990s [2]. The exponential growth of the human population contrasts with the arithmetic increase in food resources, resulting in a shortage of food supply. Precision agriculture encompasses a spectrum of methodologies aimed at enhancing farming precision to maximize yields while minimizing waste [3].

Nanotechnological advancements present a significant avenue for the development of novel pest management solutions. Presently, agricultural fertilizers, pesticides, antibiotics, and nutrients are conventionally administered through spray or drench applications onto soil or plants, or via feed or injection methods for animals [4]. Nanotechnology is poised to emerge as a promising adjunct to conventional plant breeding techniques, genetic engineering, and molecular plant breeding shortly. The favorable attributes of nanoparticles have been demonstrated to augment seed germination rates in crop plants [5]. Nanotechnology introduces novel technologies and materials within molecular biology for the detection of plant pathogenic microorganisms. Specifically, targeted treatments against pathogens enhance plant resilience against pests [6], utilizing biofertilizers sourced from diverse organisms such as cyanoalgae and rhizobacteria. Furthermore, nanoparticles facilitate plant nutrient absorption, enabling immediate uptake of nanofertilizers [7]. Nanomaterials find application across a spectrum of fields, from intricate biomedical sciences to construction endeavors. In agriculture, nanomaterials are harnessed in various capacities, contributing to advancements in agricultural practices [8]. The integration of nanotechnological advancements is pivotal for sustainable food production, ensuring both safety and security [9]. Nano-biotechnology has now emerged as an integration between nanotechnology and Biotechnology [10]. Nanotechnology can transform the agricultural and food industry with the help of various innovative tools for the molecular management of diseases, rapid disease detection, and enhancing the ability of plants to absorb nutrients [11] (Figure 1).

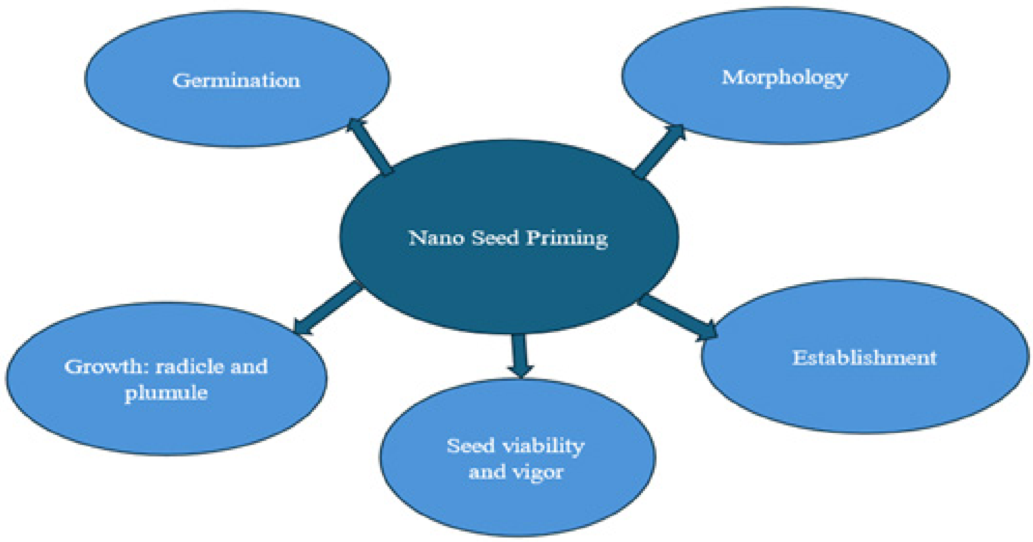

Figure 1: Benefits of nano seed priming. (*Loyal, et al*., 2022).

Nanomaterials for Crop Enhancement

Nanomaterials and nanotechnologies have garnered significant attention across diverse disciplines such as physics, chemistry, materials science, and engineering, constituting a truly interdisciplinary domain spanning all realms of science and engineering [12]. Leveraging nanotechnology holds promise for augmenting crop yield through heightened efficacy of agricultural inputs such as fertilizers and pesticides, thereby mitigating crop loss. The compendium “Nanotechnology for Agriculture” sheds light on the strides made in applying nanotechnology within agriculture, with a specific emphasis on enhancing crop production and safeguarding crops [13]. In the pursuit of sustainable agriculture, the utilization of nanotechnology has been recognized as an innovative and auspicious avenue to meet the escalating global population’s food demands. This technology has not only transformed the landscape of nutrient provision with the introduction of Nano Fertilizers (NFs) but has also contributed significantly to plant protection endeavors through the advancement of nano pesticides [14].

Nanotechnology is emerging as a pivotal player in confronting a broad spectrum of environmental dilemmas by furnishing innovative and efficacious remedies [15]. Its application holds promise for ensuring food security by bolstering crop output through precision farming, judicious water management, and safeguarding against pests and diseases [16]. The employment of Nanoparticles (NPs) in agriculture presents a dual natured proposition. While they demonstrate recognized beneficial impacts as fertilizers and pesticides, the uptake and translocation of these particles by plants can potentially disrupt their physiological functions [17]. Exposure to nanomaterials can stimulate early plant germination and amplify plant productivity. The exponential advancement in nanotechnology has unfurled new frontiers, both in fundamental understanding and practical applications, within materials science and engineering, notably in the realm of nanobiotechnology [18]. The influence of Nanoparticles (NPs) varies depending on the specific plant species under consideration. For instance, the aqueous suspension of aluminum oxide NPs demonstrated enhancements in radish root growth but exhibited diminished effects in cucumber. Conversely, the aqueous suspension of titanium oxide stimulated root growth in wheat while impeding it in cucumber [19]. Germination tests and assessments of root elongation capacity were conducted using sixty seeds per treatment for each species. However, further interdisciplinary investigations are imperative to gain deeper insights into potential environmental hazards associated with nanomaterials [20]. NPs present in plant growth media regulate water balance through the seed coat, thereby influencing seed germination. Notably, TiO2 and CeO2 NPs were observed to impact seed germination as well as cotyledon growth duration across ten distinct plant species [21].

Seed germination stands as a pivotal process in contemporary agriculture, representing the lifeline of plants and ensuring their continued existence. The potential applications and advantages of nanotechnology in fostering plant growth and augmenting yield are immense [22]. Recent research endeavors have shed light on the physiological reactions of plant seedlings to nanoparticles during germination, revealing considerable variation in the impact on seed germination and root growth across different plant species and types of nanoparticles [23]. Nanoparticles synthesized for seed treatment serve as priming materials, facilitating germination. These nanoparticles are employed as soaking agents for pre-germination treatment, after which pre-germinated seeds are cultivated in Petri dishes containing a sand medium [24]. Nanocomposites refer to composite materials wherein at least one phase exhibits dimensions in the nanometer scale (1nm = 10–9m) [25].

The integration of nanotechnology within agricultural practices encompasses multiple facets including the targeted delivery of fertilizers to augment plant growth and productivity, as well as the deployment of sensors for soil quality assessment and the utilization of pesticides for effective pest and disease management [26]. In the realm of material synthesis, the fabrication of Nanocomposites with polymers diverges from conventional methodologies, involving sequential processes such as premixing, extrusion, and drying [27]. In response to the escalating challenges posed by global climate change, nanomaterials present a viable avenue for expeditious nutrient assimilation, notably through the application of encapsulated and nano-gel-based fertilizers [28]. Addressing the widespread issue of salt-affected soils, particularly prevalent in arid and semi-arid regions, studies have demonstrated the efficacy of foliar application of Si-Zn nanoparticles in ameliorating soil electrical conductivity while concurrently enhancing nodule mass, root length, and total leaf area of plants [29]. Carbamate pesticides, owing to their potent insecticidal properties, are extensively employed in contemporary agriculture to bolster crop yields. Employing a multi-faceted analytical approach encompassing various microscopic and spectroscopic techniques, the formation of AuNCs-MnO2 nanocomposite was verified [30]. Furthermore, investigations into the cultivation of vegetable crops under saline conditions have elucidated the beneficial impact of nanoparticle implementation on seed germination and antioxidant activity. Chemically-modified natural or synthetic zeolites have been harnessed to mitigate sodium accumulation in saline soils [31]. Certain plant species have shown evidence of the deleterious effects resulting from the simultaneous application of Heavy Metals (HMs) and nanoparticles. At elevated concentrations, nanoparticles may exhibit toxicity towards plants, rendering them unsuitable for employment as nano-fertilizers [32]. The synergy between these substances is often associated with the production of hydroxyl radicals, interference with vital cellular functions, and potential anti-biofilm properties. The synthesis of silver nanoparticles (Ag-NPs) was confirmed through optical assessment, whereby the color of biogenetically produced silver nanoparticles changed to a characteristic chromatic brown [33].

Precision Nanofarming for Sustainable Agriculture

Precision agriculture represents a fundamental paradigm shift in agricultural management, aiming to reconcile the escalating demand for food with the imperative to safeguard ecosystems, biodiversity, and natural resources [34]. In response to the adverse environmental impacts associated with traditional farming practices, nano fertilizers have been introduced to enhance seed germination rates, seedling growth, and photosynthetic activity [35]. Nanotechnology serves as a contemporary platform for agricultural innovation across industries, offering a pathway to enhance agricultural productivity through the development of efficient nutrient and pest management systems, alongside the improvement of crop varieties and fertilizers while minimizing ecosystem harm [36]. The incorporation of nanotechnology into fertilizer formulations holds promise for optimizing release profiles and enhancing uptake efficiency, thereby delivering substantial economic and environmental advantages [37]. Nanotechnology also holds potential for devising effective and sustainable strategies for environmental remediation, epitomized by the concept of nanoremediation as a holistic approach to environmental sustainability [38]. Nano-farming encompasses the application of nanoparticles and nanomaterials in diverse agricultural practices, including nano-priming of vegetable seeds, and has significantly contributed to both pre-and post-harvest stages, as well as various food processing methods [39]. Precise management of fertilizers stands as a crucial prerequisite for sustainable agricultural development, with nano-copper and nano-silver emerging as exemplary nanomaterials with active properties [40]. Leveraging tools and technologies from nanobiotechnology can further augment agricultural productivity by facilitating genetic modifications in plants and targeted delivery of genes and drug molecules at the cellular level [41].

Precise utilization of improvised fertilizers employing nanotechnology represents a viable strategy, entailing the development of nanofertilizers, to augment agricultural productivity and address the escalating global food demand amidst a burgeoning population [42]. Nanosensors designed for detecting pesticide residues offer numerous benefits, including compact configurations, heightened sensitivity, narrow detection thresholds, exceptional selectivity, and rapid response times. The integration of intelligent nano sensors facilitates targeted nutrient dissemination by crop requirements, a pivotal component in realizing the objectives of precision agriculture [43]. Deployment of nanosensors across agricultural landscapes, tethered to the Global Positioning System (GPS), ensures timely data acquisition and succinct field assessments [44]. The advent of nano biosensors has catalyzed advancements in diverse areas such as protein expression analysis, metabolite quantification, as well as stress, moisture, and pathogen detection [45]. Nanotechnology offers instrumental means for engineering the relatively conserved plastid genomes of chloroplasts and mitochondria. However, the development of smart nanobiotechnology-based sensors tailored for monitoring crop health encounters various challenges about applicability, precision, and resilience in real-world agricultural settings [46]. Nanosensors endowed with high sensitivity, selectivity, multiplexing capabilities, nonphoto bleaching resilience, and optical communication interfacing with existing Near-Infrared (nIR) agricultural apparatus represent an emerging arsenal for chemical phenotyping and the surveillance of crop vitality [47].

Nanosensors facilitate continuous monitoring of diverse environmental parameters, furnishing farmers with unprecedented insights into soil conditions, crop health, and other pivotal variables [48]. In response to apprehensions regarding the ecological ramifications of employing chemically synthesized nanomaterials, the concept of green nanotechnology entails the fabrication of nanomaterials utilizing plant-based systems [49]. Conventional methodologies for applying fertilizers, such as spraying and broadcasting, result in losses through leaching, drift, runoff, evaporation, soil moisture-induced hydrolysis, and microbial and photolytic degradation, leading to minimal concentration reaching the intended target site [50]. Nanotechnology presents avenues to enhance the sustainability of food production by furnishing superior sensors for monitoring physical, chemical, and biological properties and processes; technologies for pathogen control to bolster food safety and diminish food wastage; and enhanced membranes and sorbents for decentralized water treatment and resource recovery from plants [51].

Nanomaterials for Soil Health Improvement

Safeguarding soil microbial biomass and preserving biodiversity stands out as a significant concern within the realm of sustainable soil management [52]. Remediation, characterized as the systematic removal of pollutants from the environment through chemical or biological methods, has emerged as a pivotal area of study. Recent advancements have underscored the control and mitigation of contaminants across air, soil, sediments, and water bodies as paramount environmental challenges [53]. The application of nanotechnology or nanotechniques in soil remediation appears promising for reducing pollutant levels in contaminated soil. The escalating global economic scenario has led to a rise in instances of soil contamination, highlighting the pressing need for effective remedial measures [54].

The advancement of nanomaterials represents a promising avenue for innovation in the realms of soil science and food nutrition. Nanomaterials have been observed to elevate the expression of water channel genes, thus playing a pivotal role in enhancing water permeability and nutrient uptake during seed germination [55]. Utilizing nanotechnology for the synthesis of nanomaterials from biochar and water treatment residues is poised to revolutionize soil quality enhancement and augment canola yield in degraded soil [56]. The notably high specific surface area of nanomaterials significantly amplifies the efficiency of the decontamination process, with the nanometer scale of nanoparticles enhancing their effectiveness in infiltrating contaminated soil (*Cao, et al.*, 2021). In alkaline environments, functional groups within organic matter may dissociate, intensifying the bioavailability of heavy metals associated with organic matter and subsequently impacting metal absorption within the soil food chain [57].

The escalating anthropogenic and technogenic activities are introducing potentially hazardous metals, agrochemicals, and excessive nutrients into the soil. Soil, being the foundation of crop production, plays a pivotal role in nutrient uptake by plants [58]. Efforts to clean contaminated soils have been complicated by a multitude of contaminants across various classes and types. Moreover, composites decorated with nanoparticles have demonstrated highly efficient performance in environmental pollutant decontamination [59]. Nanotechnology is being harnessed for the development of pollution sensors. The distinctive attributes of nanoparticles facilitate the creation of highly compact, precise, and sensitive pollution-monitoring devices (nanosensors) for detecting pollutants in both air and water [60]. The rapid expansion of nanotechnology and its widening application scope have spurred intensive development of novel materials, although considerations must be given to the associated high costs and secondary pollution risks associated with traditional remediation approaches [61]. Soil constitutes a complex system from multiple perspectives. For instance, the soil matrix comprises solid, liquid, and gas phases. The proliferation of nanoparticles in soil may elevate their concentration and consequently escalate their environmental impacts and ecological risks [62]. Materials undergo significant alterations when their geometric dimensions decrease to the nano-scale. Soil nanoparticles, which measure less than 100 nm, may exhibit either crystalline or non-crystalline structures with short-range order [63].

Soils serve as repositories for nanosized particles, with nanoparticles being critical adsorbents that influence nutrient and pollutant transport, organic matter fixation, and catalysis of new mineral phase precipitation. Investigating nanoscale constituents within intact soil structures holds significant promise for future research [64]. Nanotechnology plays a vital role in refining existing crop management techniques. Surface-modified hydrophobic nano-silica has demonstrated efficacy in controlling various agricultural insect pests [65]. Additionally, the incorporation of magnetic nanophase iron into soils holds the potential for carbon sequestration and maintenance or enhancement of soil function in contemporary agricultural practices, particularly in phosphorus cycling [66].

Nanotechnology in Pest and Disease Management

Controlling plant pests and diseases conventionally relies on the use of pesticides and chemicals, which have demonstrated adverse environmental consequences. The adoption of nanotechnology in plant protection presents a promising multidisciplinary strategy encompassing nanomaterials-based pesticides [67]. Nanotechnology holds potential benefits for pesticides, including toxicity reduction, enhanced shelf-life, and increased solubility of poorly water-soluble pesticides, all of which could yield favorable environmental outcomes [68]. Insects inhabit diverse environments, constituting over two-thirds of known animal species globally. Porous Hollow Silica Nanoparticles (PHSNs) loaded with validamycin (a pesticide) could serve as an effective delivery system for water-soluble pesticides, facilitating controlled release [69]. Nanotechnology offers avenues for combatting plant diseases through controlled delivery of functional molecules or as a diagnostic tool for disease detection [70]. Nanoparticles hold promise in crop protection, particularly in plant disease management, potentially mirroring the action of chemical pesticides against pathogens [71].

Ensuring plant protection and food safety remains crucial for mitigating economic losses attributed to spoilage microorganisms. Nanotechnology has the potential to revolutionize this landscape by fostering the development of innovative tools capable of minimizing production inputs while maximizing agricultural outputs, thus addressing the escalating demand for global sustainability [72].

Economic Sustainability of Nanotechnology in Agriculture

Nanotechnology holds significant promise in various aspects of agriculture, including augmenting food quality and safety, reducing agricultural inputs, and facilitating the absorption of nanoscale nutrients from the soil [73]. However, the adoption of nanotechnology in commercial agriculture necessitates comprehensive investigations to screen and optimize nanomaterials for diverse plant species [74]. Among commercially available nanopesticides, copper (Cu)-based Nanoparticles (NPs) are extensively manufactured and deployed not only in agriculture but also in food preservation and water treatment applications [75]. Furthermore, nanofertilizers hold promise for enhancing tolerance to abiotic stress and can be utilized synergistically with microorganisms, termed nano biofertilizers, to provide additional benefits [76].

Nanotechnology offers the potential to revolutionize current agricultural practices by enhancing input management and conservation in crop production, animal husbandry, and fisheries [77]. Nonetheless, concerns regarding the impact of nanomaterials on human health and the environment serve as significant constraints to the development of the global nanomaterials market [78]. Despite these challenges, nanotechnology emerges as a promising technological advancement globally, as evidenced by analyses of economic indicators publicly accessible for evaluating nanotechnology's contribution to economic development [79-82].

Conclusion

The utilization of nanotechnology offers significant advantages to both farmers in terms of food production and to the food industry through the innovation of new products via food processing, preservation, and packaging. Nanotechnology presents considerable potential in revolutionizing agriculture by enhancing crop protection, facilitating nutrient delivery, and remedying soil conditions. Its applications in agriculture hold promise for increasing crop yields, optimizing water utilization, and mitigating environmental impacts. However, the potential benefits of nanotechnology in agriculture and food production must be carefully weighed against concerns regarding soil health, water quality, and environmental integrity. Addressing safety and ethical considerations surrounding the use of nanomaterials in agriculture is imperative to ensure the sustainability of these technological advancements.

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Conflict of Intertest

None.

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