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Nanotechnology and Nanoparticles for High Altitude Agro-ecosystem and Environmental Sustainability

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Abstract

High-altitude agro-ecosystems are widely distributed throughout the world. In the Indian subcontinent, Himalayan region represents the high-altitude ecosystems, which demand extensive management due to their increasing deterioration in recent times. The extremely low temperature, proneness to natural calamities, recurring floods, droughts, low soil moisture and fertility, high solar intensity impose constraints for sustenance of hill agriculture. To enhance crop productivity to sustain increasing population, hill farmers are using excessive amount of fertilizers and pesticides, which on leaching and runoff cause environmental pollution and toxicity to non-target species. Therefore, there is an urgent need to develop innovative technology for enhancing agricultural productivity for improving the livelihood of hill farmers. One way to think of nanotechnology is as a technology that will pave the way for environmentally sustainable growth of agriculture and forestry in high-altitude regions in the coming years and thus implementing the nano-principles in agricultural practices can impart vast opportunity for dealing with global agricultural challenges. Nanoparticles may be employed as sensors for monitoring various agricultural parameters. The adoption of nano-based agrochemicals, ceramic apparatus, filters, and layering processes represents promising avenues for standardizing and enhancing agricultural practices, thereby transforming conventional agricultural approaches. The review provides insights into the present and prospective capabilities, viewpoints, and applications of nanotechnology in farming and environmental sciences.

Keywords: *Nanoparticles, Hill agriculture, Nanotechnology, Biopolymers, Nanocomposite.*

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INTRODUCTION

The alpine farming region is one of the exceptionally distinctive, delicate, and untouched ecosystems in the world, requiring comprehensive management. It is essential reservoir of various natural resources and origin of chief rivers of India and neighboring countries. Low temperature decreased vegetation and constantly changing temperature are some of the common characteristics of the Hal-agro-ecosystem. The central and foothills of Himalayan region constitute the Hal-agro-ecosystems of India. The Himalayan range extending over 3500 km across India and neighboring countries and covering an area of about 43 lakh km^2 is the youngest mountain range around the world. Indian Himalaya Region (IHR 16% area of India) is a popular term used for the Himalayan range within ten different states across India. It is a highly diverse zone, encompassing snow-covered peaks, glaciers, alpine meadows, cold deserts, and thick forest ranges, representing an immensely fragile and vulnerable mountainous ecosystem [1].

HILL AGRICULTURE AND IT'S CONSTRAINTS

Agricultural productivity is in direct correlation to the surrounding environment, thus all interactions existing between the two are essential for assessing the sustainable nature. The majority of people of IHR region are dependent on agriculture, forestry, and livestock for their subsistence. However, the agricultural fields at high altitudes of IHR have low soil fertility, low crop production, gravel soil with very low moisture, scanty water, sloppy areas, plant diseases along with extremely low temperature zones [2]. This area is most vulnerable to natural calamities, climate change, environmental degeneration with reference to deforestation, anthropogenic activities, soil erosion, deforestation, nutrient imbalance, invasive weeds, hydrological imbalances, poor productivity, degradation of land, water resource management thus creating constraints and un-sustainability for hill agriculture [3]. The uncontrolled and rising uses of pesticides for increasing productivity and extremely low temperature impose an adverse effect on the Hal-agro-ecosystem [4]. However, there are very limited technological innovations present for advancement of agricultural practices in high altitude areas, those which are even if available are not conveniently obtainable small farmers. Therefore, the soil quality and fertility of high-altitude regions is deteriorating [5]. Thus, it the need of the hour to explore and assess unconventional methods, for enhancing agricultural productivity to improve the livelihood of hill farmers [6].

NANOTECHONOLOGY

Nanoscience, the study of materials and phenomena at the nanometer scale, influencing various aspects of its surroundings from genes to ecosystems. Thereafter, nanotechnology emerged as revolutionary technology and is being employed in wide fields such as: medical, materials physics, biotechnology, energy sector, environmental management and plant and agricultural science [7]. The methods of synthesis of various nanomaterials (NMs) were recognized and in recent times, huge number of nano particles are being synthesized and employed in diverse fields [8,9].

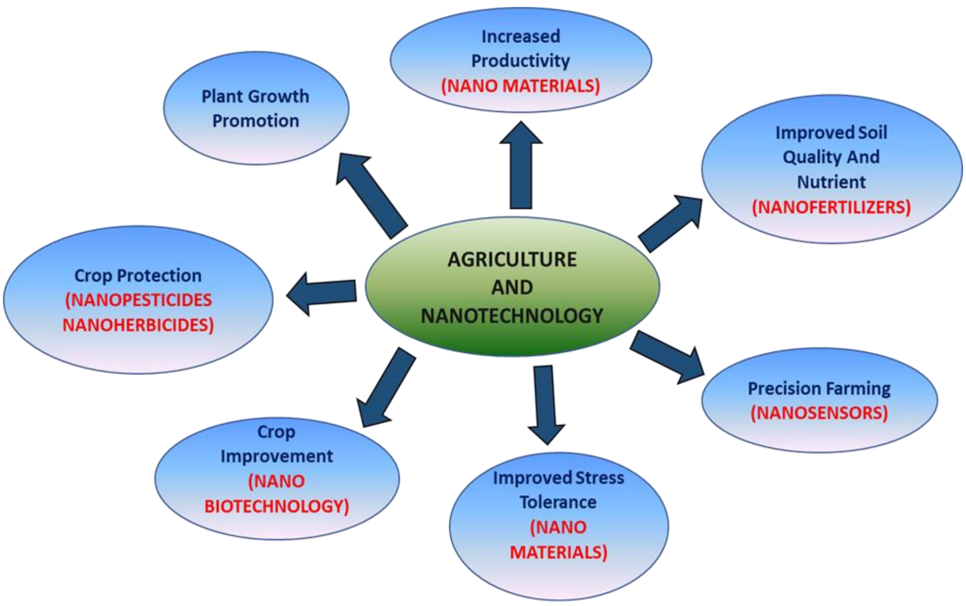

Figure 1. Agricultural Use of Nanotechnology [10]

The majority of hill population rely on agriculture for its livelihood, however currently the hill farmers are meeting several global issues as discussed earlier. These challenges are additionally aggravated by the exponentially increasing population and in turn increasing food demand. In developing nations, the farming sector is the foundation of national economy and taking into consideration the world's receding natural resources, agricultural products may be regarded as the fundamental of commerce and manufacturing soon. Thus, this abovementioned schema will further impose greater pressure on agricultural sector of developing nations. The sustainability of farming industry is thus highly dependent on development and advancement of innovative techniques. Nanotechnology can therefore be regarded as an upcoming novel technology for providing proper distribution of nutrients and chemical controls to the plants so as to elevate crop production shown in Figure 1. Additionally, it aids in environmental remediation, adds nutritional value to crops and helps in plant genetic modification [10]. The evolution of nanodevices, Nano capsules, nano sensors and nano fertilizers has resulted in identification and cure of plant pathogens, improved water management, selected nutrient delivery and time of harvesting and thus enhancing agricultural productivity [11]. Nanotechnology is crucial for the sustainability of the agricultural sector and precision farming by maximizing productivity.

Nanoparticles: Creation and Functions

Nano-sized particles range from 1 to 100 nm in size [12,13], possessing distinct physicochemical properties compared to their original bulk material [14]. Nanoparticles are synthesized artificially using various physicochemical or biological processes involving the use of bacteria and other microbes. Environmental toxicity, animal, human health risks, and other issues are related to chemical synthesis [15]. However, beyond the vulnerability of plant species, the actual impact of nanomaterials (NMs) on plants is contingent upon factors.

Nanoparticles typically consist of metals/metal oxides and carbon [16,17]. Metal oxide-based NPs are derived from modified metal NPs and include magnetite (Fe_3O_4), iron oxide (Fe_2O_3), cerium oxide (CeO_2), aluminum oxide (Al_2O_3), zinc oxide (ZnO), silicon dioxide (SiO_2), and titanium oxide (TiO_2). Carbon-based NPs consist entirely of carbon [18] and encompass fullerenes, carbon nanotubes (CNT), graphene, activated carbon, and carbon nanofibers (CNF). Commonly, two processes termed as "top-down" and "bottom-up" methods are employed for synthesizing NPs. The top-down method constructs NPs by utilizing externally controlled tools for cutting and shaping larger entities. This approach is time-consuming, expensive, and not suitable for mass production. Common approaches for the "top-down" method include microfabrication, milling, drilling, grinding, laser ablation, sputtering, and thermal decomposition [19,20]. In the "bottom-up" method, assembly of molecular components is carried out by chemical processes to synthesize NPs, employing molecular recognition. This approach is more economical and preferred, utilizing processes such as welding, riveting, sol-gel, spinning, chemical vapor deposition, and pyrolysis [21,22,23].

Role of Nanotechnology in Farming

Nutrient-deficient soils, environmental deterioration, poor productivity, water resource management and improper pest management are the crucial agricultural setbacks of Hal-agro-ecosystem that should be addressed to increase the yield of good quality crops. Therefore, agricultural nanotechnology can be an emerging tool to provide greater dividends for developing nations and successfully address productivity problems in IHR.

Nanomaterials as Delivery Agents of Agriculture Chemicals

NPs may be employed as carriers of various agricultural chemicals including fertilizers, pesticides and plant growth promoters thus acting as nanoscale delivery agents. These NP delivery agents confer several benefits in agronomic practices such as: stable nature, resistant to environmental degradation, less chemical run off thus enhancing the efficiency of chemical agents and reducing environmental issues. These nanoscale delivery agents can also be fabricated to "anchor" to plant roots, rhizospheric zone and organic matter by employing structural affinity between the NPs and targeted structures [24]. By allowing the chemical agents to be absorbed gradually, the controlled release methods lower the risk of temporal overdose, chemical quantity used, input, and waste creation. Coating the surface of agricultural chemicals with nanoparticles (NPs) enhances the adhesion of the chemical agent to plant surfaces. Nanostructured matrix systems, including nano-capsules, nanospheres, and nanovesicles, have been developed and functionalized using sensitive polymer materials for efficient pesticide delivery. These advancements hold promise for safe and sustainable agricultural practices [25,26].

Nanobiosensors

NPs can also be employed as field sensing agents (nano biosensors) for live monitoring of the plant growth, soil moisture and fertility, temperature, nutrient level, pests, weeds and other environmental stresses. Biosensors typically comprise of receptor and transducer that sense physical and chemical signals by using biological or organic recognition elements for detection of analytes [27]. They are advanced forms of biosensor that are highly compressed and can detect very low amount of specific analyte (parts per trillion-ppt) by using physico-chemical transducer [28]. In the case of nano biosensors, NPs work as the receptor for reception of electrical or chemical signals for recognizing analytes. Nano biosensors have greater surface area to volume ratio, highly sensitive, specific, stable, long shelf life and employ fast electron-transfer kinetics and thus are better than conventional and last generation sensors [29].

Wireless networks of Nano sensors can be strategically deployed across fields to gather essential data, aiding in the reduction of resource inputs and the maximization of crop yield [30]. These Nano sensors can provide valuable information regarding optimal sowing and harvesting times, as well as the levels and requirements of water, fertilizers, pesticides, plant physiology, plant diseases, and other environmental conditions. Additionally, Nano sensors can offer insights into soil nutrient conditions, including total carbon, sodium chloride, phosphate, organic matter, and residual nitrate [28]. Consequently, nanosensors have the potential to mitigate excessive usage of water, fertilizers, and pesticides while enhancing crop yield [31,32]. Moreover, nanosensors have been effectively utilized for monitoring various metals and organic contaminants in water.

Enhancing Plant Traits to Withstand Environmental Stresses and Diseases

Recently, many researchers have concentrated on improving plant resistance to different environmental stresses like aridity, saltiness, and phytopathogens. Consequently, the genomes of several significant crop cultivars are being thoroughly scrutinized. The progress in nanotechnology, including the utilization of nanoparticles (NPs), has facilitated gene sequencing, potentially establishing a rapid and cost-effective method for genome assessments [33]. Nanotechnology can also be utilized for creating genetically modified plants or atomically modified plants. According to Abd-Elsalam and Alghuthaymi, the use of nanogenomics-based techniques in plant breeding can shorten the total amount of time needed for breeding while improving the precision of trait selection and gene transfer. Agrawal and Rathore suggest that using nanoparticles, nanocapsules, and nanofibers for nanogenetic manipulation could be a useful strategy for enhancing the sustainability of agricultural development. Various experiments show that plasmid DNA may be successfully transmitted into tobacco and maize tissues utilising the gene gun approach in conjunction with gold-capped nanoparticles. [34,35]

Nanotechnology and Soil Fertility Management

Micronutrient deficiency in high altitude soil is mainly due to high soil erosion and flushing conditions. Most farmers in the IHR still adhere to conventional agricultural practices. Fertilizers is pivotal in enhancing soil nutrient levels and subsequently improving crop productivity. The employment of fertilizers and pesticides in that present scenario leads to excess in IHR results in environmental and natural resource deterioration, development of pesticide resistance in pests; depletion of soil micro flora [36]. Thus, nanofertilizers also called smart fertilizer can act as crucial components for sustaining soil fertility and also help in sustaining agricultural productivity depicted in Figure 2. Nanofertilizers are nutrient fertilizers consisting of nanostructured formulations designed to deliver nutrients targeting sites, thereby enhancing nutrient use efficiency (NUE) and reducing environmental degradation as compared to traditional fertilizers which have to be applied in bulk due to low plant uptake efficiencies.

Nutrient management relies on the presence of ions in available forms such as iron reactions, where nanoparticles (NPs) can aid to facilitate nutrient access to plants. Nanofabricated materials containing nutrients are typically presented in aqueous suspension or hydrogel forms, enabling easy application, storage, and distribution [17]. Nanoparticles containing nutrients can be synthesized through various methods, including adsorption and ligand-mediated conjugation. The synthesis of nanofertilizers by nanoencapsulation of fertilizers can be achieved through encapsulation in nanomaterials, coating with thin film layer polymer, or delivery in nanoparticle form. [37].

Recently, The Sri Lankan Institute of Nanotechnology has devised a distinctive nitrogen nanofertilizer encapsulated with urea, including hydroxyapatite nanoparticles (which exhibit rod-shaped structures with an average aspect ratio of 10), facilitating precise targeting and gradual nitrogen release. In another study by Sharonova et al., a phosphorus nanofertilizer was produced through ultrasonic dispersion of untreated natural phosphorite to create a phosphorite suspension in water, with particle sizes ranging from 60 to 120 nanometers. Additionally, zinc oxide nanoparticles were employed to augment phosphorus absorption in Mung bean plants. [38,39]

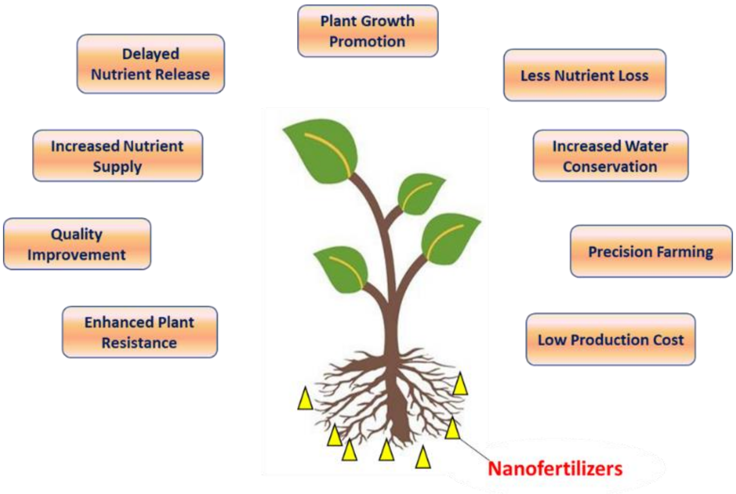

Figure 2. Utilization of Nano-fertilizers for Growth Performance of Crops [36].

Nanotechnology and Pest Management

To meet the requirements of basic nutrition demand of an exponentially increasing population, pesticides are used excessively throughout the world to remove pests and pathogens. In practice, A small fraction of pesticides (roughly 0.1%) effectively reaches designated target areas, with the majority being dispersed into the surrounding environment due to runoff, spray drift, off-target deposition, and photodegradation. The conventionally used pesticides have been observed to be carcinogenic and cytotoxic, thus are hazardous to the ecosystem. The variations in climatic conditions in IHR region enhances pest or disease expansion and conventional plant protection methods are being used by the farmers of this region for controlling the pests. The application of nanotechnology can also be realized for pest control thus offering new insights for pest management. By attaching to the pests' cell walls, nanoparticles can kill them, effectively controlling pests with little harm to the environment and less toxicity to non-target species [50]. Furthermore, their ability to monitor plant infections in real-time using nano sensors [40] adds to their efficacy.

Bhagat et al. introduced a nanogel synthesized using a pheromone to control plant pathogens in various crops. Rouhani et al. have also evaluated the Ag and Ag-Zn nanoparticles for controlling the pest *Aphis nerii*. The exceptional antimicrobial activity of TiO_2 has been reported for monitoring and conquering plant diseases by several authors [41,42,43]. Additionally, Kaur et al. reported that silver nanoparticles possess antifungal activity against Fusarium, resulting in a 73.33% reduction in infection compared to the commercial fungicide CuOCl (which achieved a 26.67% reduction). [44] Borgatta et al. evaluated $Cu3(PO4)2·3H2O$ nanosheets and CuO nanoparticles for reducing Fusarium wilt in watermelon. [45] In addition to their pesticidal activities, nanoparticles are also utilized for the efficient and safe application of pesticides, herbicides, and fertilizers at minimum doses, thereby reducing human exposure [46,47]. On entrapment of fungicide metalaxyl in mesoporous silica nanoparticles (MSNs), a delayed release was reported by Wanyika [48]. In a study by Campos et al., the fungicides tebuconazole and carbendazim were encapsulated in solid lipid nanoparticles (SLNs) and showed less leaching (4.8%) than commercial formulation (17%). Nanotechnology also allows monitoring of plant disease mechanisms (flagellar motility and biofilm formation) thus enabling better treatment methods for crop protection. Zaini et al. conducted research on the plant pathogenic mechanism, specifically focusing on the kinetics of bacterial colonization and biofilm production of xylem-inhabiting bacteria. They utilized micro-fabricated xylem vessels with nano-sized features for their study. With the continuous advancements in nanofabrication and characterization techniques. [49,50]

NANOTECHNOLOGY AND VEGETATIVE DEVELOPMENT REGULATION

Studies investigating the uptake mechanism of nanoparticles (NPs) facilitate the appropriate utilization of nano formulations, fertilizers, or pesticides. The connections of NPs with plants and the environment are contingent upon their physical properties and adaptability to the environment as well as exposure time and position. Once internalized by the plant, NPs can induce various changes that enhance plant physiology and growth see Table 1. Some researchers have reported alterations in nitrogen metabolism, photosynthesis, metabolic pathways, enzyme activities, vegetative development, and water permeability of seeds in response to NPs [35].

Lu et al. reported that the use of TiO2 and SiO2 nanoparticles enhanced the propagation and growth of Glycine max. Hafiz et al. described that copper nanoparticles can improve wheat plant growth. Improved yield of maize was reported by Taheri et al. with the use of ZnO nanoparticles in nutrient-deficient soils. Additionally, on the application of Cu and Fe nanoparticles in wheat, enhanced growth, stress tolerance, superoxide dismutase (SOD) activity, and sugar content were observed through proteomic analysis [51,52,53,54].

Table 1. Impact of Nanomaterials on Agronomic Physiology, Metabolism and Growth**.**

Nanoparticle	Crop Species	Treatment	Physiological Activities/Response
nTiO2	*Oryza sativa*	100,200, 500 mg L^{-1}	TCA, (PPP) Pentose phosphate pathway, metabolism of (Starch and Sucrose) and (Glyoxylate and dicarboxylate) [55]
C-nanodots	*Arabidopsis thaliana* (Columbia ecotype, wild)	125-1000mg L^{-1}	Carbohydrate metabolism, Cell wall stress [34]
C60 fullerols	*Cucumis sativus*	100-200mg L^{-1}	Increased accumulation of antioxidants [35]
Fe3O4 NPs	*Brassica juncea L.*	500 mg L^{-1}	Sulfur-related gene transcripts increased as toxicity decreased. [32]
Ag NPs	*Ricinus communis* L.	2000 mgL^{-1}	Augmented enzymatic performance of phenolic content and ROS enzymes [20]
TiO2 NPs	*Vicia faba*	0.01–0.03%	Elevation in shoot elongation, expansion of leaf area, and augmentation in root dry mass, coupled with an increase in the concentrations of soluble sugars, amino acids, and enzymatic functions.[28]
TiO2 NPs	*Spinacia oleracea*	0.25%	nitrogen metabolism improved, photosynthesis; enhanced plant growth [13]
ZnO NPs	*Cucumis sativus*	400 mg kg^{-1}	Micronutrients (Copper, Magnesium, and Zinc), improved starch content [41]
Fe3O4 NPs	*Triticum aestivum*	2000mg L^{-1}	Reduction in heavy metal uptake and mitigation of their toxicity.[3]
Ag-NPs	*Trigonella foenumgraecum*L.	200 µL	Promotes the improvement of both plant growth and diosgenin generation. [26]
MWCNTs	*Hordeum vulgare, Glycine max,*	100 µg/mL	Germination and growth of seedlings Enhanced [18]

	Zea mays		
MWCNTs	*Triticum aestivum, Zea mays, Arachis hypogaea, Allium sativum*	50 μg/mL	Enhanced and quick germination, higher biomass buildup, and enhanced capacity for seeds to absorb water [45]
SiO2 NPs	*Oryza sativa*	2.5 mM/L	Enhanced heavy metal detoxification and promoted growth by reducing bio-concentration. [56]
Ag NPs	*Vigna sinensis*	50 mg L^{-1}	Growth and biomass by soil bacterial diversity and stimulating root nodulation Enhanced [33]
ZnO	*Coffea arabica*	10 mg L^{-1}	Net photosynthesis, Growth and biomass enhanced [49]
ZnO	*Triticum aestivum*	20 mg L^{-1}	Grain yield and biomass Increased [57]

NANOTECHNOLOGY AND ENVIRONMENTAL REMEDIATION

Nano remediation stands as an exceptionally unique and economically significant technology for the remediation of toxic pollutants by leveraging nanoparticles (NPs) [58]. Reactive nanomaterials such as nanoscale zeolites, metal oxides, carbon nanotubes, nanofibers, bimetallic nanoparticles, and others are harnessed in the nano remediation process for the deterioration and purification of pollutants. NPs can catalyze the deterioration of toxic materials and improve the efficacy of microbes for degradation of toxic products and reduce toxicity of pollutants to bioagents. nZVI nanoparticles have been described to be appropriate for *in situ and ex situ* degradation due to their ability to catalyze chemical reduction, mitigation of contaminants including organochlorine pesticides (lindane, DDT), chlorinated solvents (PCBs, PCEs, TCE, DCE), inorganic anions, and heavy metals (arsenic and chromium), nitrates.

Nanomaterials can play a crucial role in enhancing the bioavailability of organic pollutants to microorganisms utilized for remediation, thereby facilitating the breakdown of hazardous compounds in soil. Therefore, using NPs in conjunction with bioremediation can be created as a creative way to get around some of the drawbacks of this environmentally friendly method. Singh et al. assessed the degradation of lindane from polluted soil using a strain of Sphingomonas sp. and stabilized Pd/Fe0 bimetallic nanoparticles. Le et al. assessed the potential of combined biodegradation and chemical oxidation by nanoparticles for polychlorinated biphenyl (PCB) bioremediation. [59,60]

NANOTECHNOLOGY AND NANOSEED SCIENCE

Seed is indeed a remarkable gift from nature to humanity, representing a biological system with the inherent ability for self-perpetuation and resilience in adverse environmental conditions. Nanotechnology offers a promising avenue to fully unlock and utilize the potential of seeds. Verifying genetic purity involves confirming the pollen load that is causing contamination. Temperature, humidity, wind speed, and crop pollen output all affect pollen flight. The main factor contributing to low productivity in IHR is the vulnerability of the seeds to biotic and abiotic environments. The final yield in crop production is influenced by the factors of seed quality, namely seed weight, and size.

Seeds may be imbibed with nanoencapsulations with microbial strains and are known as Smart seed. These seeds can lower seed count, confirm right field stand and enhance crop productivity [61]. Nanomembranes could sense the level of water, therefore coating seeds with them will allow them to drink water only when their germination process is ready. Potential research areas include the utilization of bioanalytical Nano sensors for detecting seed aging, reducing storage damage, monitoring moisture content during storage, and aerially broadcasting seeds embedded with magnetic particles.

CONCLUSION

India, being primarily an agrarian economy, is also grappling with challenges in the agriculture sector, requiring concerted efforts to bolster productivity. The hill agro ecosystem exhibits various environmental stresses, climate variability, extremely low temperature, flood, drought, hypoxia, high solar intensity and thus limiting crop productivity in the region. Thus, there is a need for innovative technologies that ensure the development of hill farmers and subsequently do not affect the diversity of life. Nanotechnology represents a promising avenue for conserving natural resources while preserving the integrity of the natural ecosystem. Moreover, nano-fertilizers having targeted delivery systems can be employed for proper nutrient management without nutrient loss. NPs can also be utilized as a "magic bullet," comprising of beneficial genes, herbicides, and organics, with a targeted delivery system for enhancing crop productivity. It is estimated that the advancements in the field of agro nano technology will assist the conception of precision farming thus encouraging the best use of natural resources for agricultural purposes. Thus, the application of NPs in IHR agricultural practices can play a pivotal role in improving crop production. The role of nanomaterials in various agricultural applications needs more detailed investigation in terms of production, toxicological effects, and its intensive use at the grassroots level for development of sustainable agricultural practices in high altitude regions.

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