

Applications of Nanomaterials in Soil Science and Agriculture: Enhancing Stability and Bioavailability Through Nano-encapsulation

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Abstract

The present research project focused on the development and use of nanomaterials for enhancing natural security in agricultural, feed, and food sectors. Protein-based and polysaccharide-based nanomaterials, which self-assemble into micelle-like structures, have shown promise in improving the stability, bioavailability, and delivery of vital nutrients, agrochemicals, and medications through nano-encapsulation techniques. Nanomaterials such as modified nanoclays, including montmorillonite, have been employed in food packaging to enhance mechanical strength and create barriers against oxygen, flavors, and moisture. Nano-encapsulation has also proven effective in enhancing the optical properties of materials for their use in beverages. In soil science, nanotechnology has been crucial in understanding the nanoscale interactions between organic and inorganic components of soil matrices, influencing nutrient delivery and microfauna activity. Engineered nanomaterials, regulated under the European Novel Food Regulation, have been instrumental in agricultural advancements, notably through the use of nano-silver, nano-titanium dioxide, nano-silica, and nanocomposites. As one of the six Key Enabling Technologies, nanotechnology plays a pivotal role in the innovation of primary agricultural production, animal feed, food processing, and food contact materials. However, the potential risks posed by nanomaterials to human health and the environment have been a subject of significant concern. Risk assessments and safety evaluations of nanomaterials applications in agriculture, food, and feed are essential for understanding their exposure potential and ensuring safe use in these sectors.

Keywords: Nanomaterials in agriculture, nano-encapsulation in food systems, nanotechnology in soil science, engineered nanomaterials, nonclay food packaging

INTRODUCTION

The events and issues surrounding nanomaterials (NMs) created to reticulate natural security are the focus of the present research project. Protein-based NMs have been constructed from molecules that can assemble themselves, such as structures resembling micelles. Polysaccharides are now considered

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to be naturally occurring compounds that can be found in a variety of settings, including plants (pectin, guar gum); animals (chitosan, chondroitin sulphate); algae (alginates); and microorganisms (dextran). The use of nano-encapsulation has improved the stability, bioavailability, and delivery of nutrients, such as vitamins, minerals, agrochemicals, and medications. The ability of nano-encapsulated materials to have altered optical properties has been crucial for their use in clear beverages. Clays and other inorganic NMs have had their surfaces altered to allow for the functional coating of organic materials, improving the

materials' dispersion in polymer matrices and facilitating the creation of nanocomposites. Food packaging has used modified nanoclays, such as montmorillonite, to increase mechanical strength and/or create a barrier against gases, such as oxygen; volatile ingredients, such as flavors; and moisture.

These NMs have been classified as engineered NMs under the amended European Novel Food Regulation (European Parliament and Council, 2015), and this should be considered when assessing their potential uses in agriculture/feed/food. The scientific study of all the components of soil, such as the matrix that provides nutrients to living things, is known as soil science. The microfauna and fauna that support the underlying processes are of interest to soil scientists. According to science, soil is a complex mixture of chemicals and organisms that fall into the nano organization/disorganization scale; some of these organisms have been organized at the nanoscale, while others have not. In its place, the following classes of nanotechnology are recognized: (a) molecular or atomic nanotechnology; (b) nanomaterials; (c) bionanomaterials; (d) molecular mimics; and (e) nanoelectronics. While nanobiology is relevant to soil biology and other areas, NM science is relevant to the study of soil structure and composition. Both fields use instruments to identify nanoscale amounts of substances that are important to soil processes. Applications of nanotechnology in environmental science and soil science have derived materials aspects of soils from both inorganic and organic structures, so that structures in soil solution and organic matter have developed from the structure of inorganic matter. The development of agriculture and feed has been facilitated by the application of NMs in the form of nano-encapsulates, nano-silver, nano-titanium dioxide, nano-silica forms, and nanocomposites. As a means of fostering the creation of novel products and applications in a number of industrial sectors, such as primary agricultural production, animal feed, food processing, novel foods, food additives, and food contact materials (agriculture/feed/food), nanotechnology has been one of the six Keys Enabling Technologies (KETs). In order to account for the safety evaluation of such products from rated schemes of agreeability toward exposure potential to NMs, risk from newly applied NMs in agriculture/food/feed products, and so forth, to human health and the environment have been assessed. The applicability of agricultural, feed, and food products has been ad hoc and systematized database searched based on estimation from currently used products, that is, already in the market, agriculture, feed, and food sectors.

CLASSIFICATION OF SOIL

Soils have been classed as Inceptisols, Entisols, Mollisols, Histosols, Oxisols, Vertisol, Ultisols, Andisols, and Gelisols.

Inceptisols

The term 'Inceptisols' have been derived from a Latin term 'inceptum' meaning beginning that is, soils that have exhibited minimal horizon development.

Entisols

Entisols are young, immature soils that have many features from their original parent material and little to no horizonation. Entisols make up roughly 16% of the planet's land area today and can be formed in any climate with active deposition or erosion. Entisols are frequently discovered in parent materials that are resistant to weathering, such as sand, or at locations where recently deposited materials, like alluvium, have been found.

Mollisols

Mollisols—soft soils found in grassland ecosystems—have been studied since the Latin word mollis means 'soft'. They are distinguished by a dense, shadowy surface horizon. This productive surface horizon—also referred to as a mollic epipedon—is the outcome of the gradual addition of organic materials that come from plant roots. The buildup of organic materials high in calcium has produced mollusks. Mollisols have a deep surface horizon that is abundant in organic matter, calcium, and magnesium.

Histosols

The primary idea behind histosols has been soils that are primarily organic. Bogs, moors, peats, and mucks are some common names for histosol soils. Soils with high organic content are the result of accumulated dead plant and animal tissues and the products of their decomposition being preserved under such conditions.

Oxisols

The term 'oxisol' comes from the French word 'oxyde', which refers to extremely weathered soils that are mainly found in intertropical regions of the world. These soils are frequently rich in iron (Fe) and aluminium (Al) oxide minerals and have few weatherable minerals. Organic matter, oxides, quartz, and kaolinite have historically made-up oxides. The feel and structure of oxisols have both been misleading. At first glance, they feel like a class of loamy size from particulate matter without any structure.

Vertisol

A vertisol, sometimes known as a vertosol, is a type of soil matter that has deep fissures that have developed during dry seasons or years and are full of expansive clay minerals, many of which are called montmorillonite. The natural vegetation mostly consists of grass, savanna, or forests. The majority of uses for these soils have been as forests, croplands, or rangelands.

Ultisols

Ultisols are subsurface horizons where clays have accumulated. The presence of Fe oxides causes these clays to have strong yellowish or reddish colors. Lime and fertilizers have been added to ultisol soils to increase agricultural productivity.

Andisols

The Japanese term 'ando', which means 'black soil', has been adopted to refer to andisols, which are soils that have been formed in volcanic ash or other ejecta. Unlike other types of soils, andisols are characterized by the predominance of glass and products of short-range-order colloidal weathering, including ferrihydrite, imogolite, and allophane. Andisols have been formed in the cinders and volcanic ash close to or downstream from volcanic activity. Andisols have not developed much because they have not been extensively weathered, meaning that they have been formed in deposits from recent geological events. These soils have a high potential for productivity.

Gelisols

The term 'gelisols' comes from the Latin word 'gelare,' which means 'to freeze'. These soils are found in extremely cold climates and contain permafrost up to 2 m below the surface. Geographically speaking, these soils are restricted to high-latitude polar regions and have localized areas at high altitudes in mountains. The use of gelisols in engineering has been significantly limited by permafrost because large structures, such as buildings, sink when the frozen earth thaws after they are built. Gelisols are found in Canada, Alaska, and Siberia.

AGRICULTURAL SOIL SCIENCE IN TECHNOLOGY

In soil science, Tarafdar and Adhikari clarified the use of nanotechnology [1]. A common term used to describe material with sizes roughly between 1 and 100 nm is nanotechnology. The subjective is regarded as a nanoparticle if one of the dimensions lies in this range. In the context of soil science, nanoscale materials have suggested that gravity is becoming less significant while surface tension and van der Waal forces are becoming more significant. Thus, schemes from similar bulk matter-oriented property modifications lying as the same, such as melting point, physical strength, surface area, penetration power, electric conductance, optical effect, magnetism, etc., have changed due to suggestive issued property relevance. The field of nanotechnology has united ethics in the fields of engineering, physics, biology, and chemistry. By enabling improved input management and conservation, applied nanotechnology has scripted the development of nano-pesticides, nano-

nutrients, nano-sensors, nano-magnets, nano-films, nano-filters, and other products that have altered agricultural production. Since then, the breadth of applications for nanotechnology has relied on its high surface area to volume ratio; further developments have included high reactivity and small size for improved uptake by plants and soil.

Nanotechnical Agronomy of Soil

Nanomaterials for products and applications in agriculture, feed, and food were clarified by Peters et al [2]. Food processing, animal feed, agricultural production, food additives, and food itself have all benefited from the use of nanotechnology. The diversity of NMs has been redefined by nano-encapsulates, silver, titanium dioxide, and silica, based on the scope and approach convened. As a result, developed applicability has been investigated for nanocomposites in food additives, biocides, pesticides, and materials that come into contact with food. Known as agriculture/feed/food, nanotechnology is one of the six KETs that have been studied for primary agricultural production, animal feed, food processing, novel foods, food additives, and food contact materials. The KETs subsidy scheme has paved the way for the development of sophisticated and sustainable economies. In agricultural, feed, and food systems, NMs have been naturally occurring, with nature acting as the product's manufacturer; in other cases, synthetic NMs—that is, derived from the use of natural or engineered components—have been added. There are three types of engineered NMs used in agri-food— inorganic, organic, and combined materials such as surface-modified clays. Subjectively, inorganic NMs have been investigated as metal oxides, salts, and materials that are entirely carbon-based, including clay, carbon nanotubes, fullerenes, and carbon black. It has been proposed that materials used in food-related applications either contain fractions of particles in the nanosize range or are primary particles. For instance, silicon dioxide is utilized as an anti-caking agent in food processing under the trade name Synthetic Amorphous Silica (SAS), which is registered in the EU under the food additive number E551. Certain metals can be found in food or health supplements as nanoparticles. Nano-selenium and colloidal suspensions of metallic elements, such as gold, platinum, and silver, have combined to form composites. Proteins, carbohydrates, and fats are examples of nanostructured organic ingredients found naturally in agri-food and feed products; these components typically self-assemble into higher-order structures. The same materials have also been used to create nano-emulsions, nano-encapsulates, and food-grade polymers. Nano-encapsulates are composed of an organic shell and a bioactive ingredient-containing core. Using their broad range of solubility, application-tuned organic NMs have been shown to be driven by reputable hydrophilic compositions in terms of the opposite scheme, known as the lipophilic surface, provided by phosphor-lipid-based NMs, such as liposomes and micelles. NMs in soils were clarified by Wilson et al. [3]. Soils are intricate mixtures of particles ranging in size from millimeters to nanometers, with or without moisture. Technical advancements in nanotechnology have been evaluated through subjective structural investigation using techniques such as atomic force microscopy and transmission electron microscopy. The arrangement of colloidal material in soils has been shown to include humic acids, phyllosilicates, and iron oxide nanoparticles. Humic material has been described as a supramolecular host-guest system that is micellular. Humic material is restructured and rearranged by reticulation in response to changes in the environment, such as pH and ionic strength. The identification of individual cells, DNA molecules, proteins, genes, and other biological structures in soils has been tested using nanotechnology. In terms of biochemistry, macromolecular chemistry, or surface science, nanotechnology has been a synthesis of chemistry, physics, biology, and engineering.

Autogenous Moistening of Nano Soil

The assessment of artificial food for residents has been suggested by the histories of green spaces, with an investigation into how to accommodate variations in climate brought about by heat and drought. The renowned plan has matched the vulnerability and adaptability of gardens. The recommended skew includes a specified limit and the standard amount of water that gardens must supply. And so on; climate must worsen for standard vegetation allowed by standard. Differentiated scopes, including ambient temperature, water use, vegetation, ground cover, and soil management, have been used to evaluate

results for affected rates of soil moisture gain and loss. The proposed plan was logically and conclusively derived from the abrupt shift in the range of humid, different weather. Stable water levels in soils have been maintained through plot-level soil management. Plots with higher soil quality are determined by their ability to retain water. Although initially, water was added to the soil at slow rates and soil moisture was lost at slow rates following irrigation, this has resulted in soils with more stable and consistent moisture profiles over time. As a result, stable soils have responded to water use restrictions by absorbing heat and drought, allowing them to retain water for an extended period of time following each event in the soil, such as a critical suit-in-plantation merge [4].

Quality of Agronomical Soil

Laishram et al. [5] clarified the differences between healthy and poor soil. The ability of soil to operate as a vital living system within boundaries of land use has been defined as the quality of soil health. According to research, matter that has maintained biological productivity while maintaining the standard of the surrounding environment and human health is referred to as functional soil or quality soil. Conversely, soil has been described as a limited, non-renewable, dynamic living resource, which reflects the state of the soil. In order to create a healthy environment, interactions between plants and soil have been conceptualized as part of soil health. If not, deficiencies in soil health and quality have led to soil nutrient imbalances, overfertilization, pollution, and soil loss. Deficit soil perversion has therefore lessened detrimental effects on agricultural productivity and long-term sustainability.

Sustainable Presence of Organic Matter in Agronomical Nano Soil

The relationship between soil organic matter and inputs and properties of the soil was clarified by Voltr et al. [6]. The justification for the organic matter content of soil comes from chemistry, specifically from the stability of Soil Organic Carbon (SOC) and the availability of Hot Water Extractable Carbon (HWEC). Therefore, a basic factor influencing soil productivity has been investigated. A thorough analysis of changes in HWEC and SOC has been used to evaluate Soil Organic Matter (SOM). Variations in HWEC and SOC content raise questions about how soil management practices and physicochemical characteristics are related to each other. Various strategies have been developed, including the use of digestate, mineral and livestock fertilizers, and post-harvest residues. According to the use of the variables referred to, one- and multi-dimensional linear regressions have suggested conferring status. Data from different soils have been collected, with each locative's climatic conditions being assigned a value. Findings indicate that SOC content has increased while HWEC content has decreased. Regression modelling has shown a decrease in pH and soil saturation as a result of digestate, or nutrient-rich materials, produced by anaerobic digestion in climatic regions. HWEC content is influenced by natural soil fertility or soil type, phosphorus content, digestate application, saturation of soil sorption complex, and amount of total nitrogen (N) applied, according to Multivariate Linear Regression (MLR) models. It has been proposed that the following factors may have an impact on stable SOM—HWEC content (17%), soil texture (0.01–0.001 mm) (10%), and organic matter and animal production nutrients (10%). However, mineral fertilization also has detrimental effects on soil texture and depth. By preserving the current state of the soil and enhancing its physical, chemical, and biological characteristics, SOM has guaranteed the productivity of agro-ecosystems, or the quality and health of the soil. Analyzed celebrity has scripted perversion to the extent of food analogy.

Natural Rain to Secure Production

The combined impact of tillage and organic fertilization on soil quality was clarified by Sharma et al. [7] Subjective low-productivity areas have limited fertility and soil organic matter, which has led to a logical decline in the physical and biological characteristics of the soil. The maize–wheat cropping system has been scripted to identify soil quality indicators, and the rescue system has integrated nutrient management as sub-treatments to improve soil quality. The maintained soil quality, as indicated by the Soil Quality Index (SQI) of 1.10, has scriptural problems because it is composed of 50% organic and 50% inorganic matter. In contrast, the definitive SQI deviated to 1.08 when 100% N was added.

Enhanced Effect of Nitrogenous Fertilizer Additive

The detrimental effects of nitrogenous fertilizer application on soil health were explained by Singh [8]. Soil has been a natural resource and a medium for plant growth; however, anthropogenic interventions such as tillage, irrigation, and fertilizer application have altered the soil. After applying nitrogen (N) fertilizer for crop production, the health of the soil changes due to alterations in the amount of organic matter present, microbial activity, and acidity of the soil. Soil N has been stored in SOM. An analysis of the same queue has supported the preference for plants/crops that resemble naturally occurring nitrogenous ingredient forms rather than those that are fertilized. From now on, the ideal amount of fertilizer to apply to crops has been calculated from the limit of addition so as not to cause a decrease in organic matter or negatively impact soil microbial activity. If not, a prescriptive limit for nitrogenous fertilizers is obtained from a typified rate of formation or a plant-wide yield that is tended to be maximized. Parallel to the build-up of SOM and microbial biomass, optimal crop production has prescriptive issues.

Effects of Engineered Nano Soil to Plantation

Plant growth effects of engineered NMs were clarified by Aslani et al. [9]. An essential living element of the terrestrial ecosystem is the plant kingdom. Therefore, engineered NMs based on carbon and metal/metal oxides have been executed in a descriptive manner in this section to describe the effects of modern trends in NMs on plants. Measured from the option of influences to seed germination, plant growth has been indicative of detection in response to excess content of engineered NMs. The growth of seedlings has been logically linked to the shoot-to-root ratio as a result of the assessed purview. Research has focused on the toxicological front to support additives by examining whether nanosurfaced matter is free-standing to claim toxicity or if it steered fast for substrate occupation. As a result, after addition, freely dispersing NM has been suggested to have harmful effects. Clues that have been evaluated include the ways in which various engineered NM types have an impact on plant capabilities and subject behaviour.

GLOBAL AGRONOMICAL SUSTAINABILITY MANAGEMENT

According to White et al. [10], soil management is essential for sustainable agriculture. Since soil has always been necessary for the survival of living things, it serves as their primary source of mineral nutrients. Soil management has made sure that neither a mineral element shortage nor intentional plant toxicity occurs. As a result, appropriate planning has been made to ensure the inclusion of essential mineral elements in the food chain. The evaluation of crop productivity, environmental sustainability, and human health has led to the classification of soil management practices into direct and indirect categories. The implied figure-of-merit was once proposed as a populous, extensive combined scope. The achievement of future food security has been linked to soil management, as demonstrated by add-in-addendum or respect for moral sustenance modes and manners in order to plan through nutrient management based on soil conservation practices. It makes sense that the assigned scope be used to prevent additional soil degradation from contamination or erosion, as well as to ensure regular access to nutrient-rich food for balanced diets.

CONCLUSION

The integration of nanotechnology into the agricultural, feed, and food sectors has led to significant advancements in nutrient delivery, packaging, and overall productivity. Nanomaterials such as protein-based and polysaccharide-based nanoparticles, modified nanoclays, and engineered compounds like nano-silver and nano-titanium dioxide have demonstrated substantial potential to improve stability, bioavailability, and functionality in these applications. However, despite these benefits, the safety and environmental impact of nanomaterials remain critical concerns. Comprehensive risk assessments and regulatory measures are essential to ensure that these innovations contribute positively and sustainably to food security while minimizing potential adverse effects on human health and ecosystems. Continued research and careful implementation will be pivotal in harnessing the full potential of nanotechnology within these vital sectors.

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