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Ashwani Kumar
Department of Biotechnology, KVSCOS, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh, India

Manjul Mungali
Department of Biotechnology, KVSCOS, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh, India

Akhilesh Kumar Dwivedi
Ph.D. Scholar, Department of Biotechnology, KVSCOS, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh, India

Meenakshi
PG Scholar, Department of Biotechnology, KVSCOS, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh, India

Sakshi
Department of Biotechnology, KVSCOS, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh, India

Corresponding Author:
Ashwani Kumar
Department of Biotechnology, KVSCOS, Swami Vivekanand Subharti University, Meerut, Uttar Pradesh, India

Assessment of nano-hydroxyapatite (nHAP) adequacy in contemporary farming for soil health stipulation: A comprehensive review

Ashwani Kumar, Manjul Mungali, Akhilesh Kumar Dwivedi, Meenakshi and Sakshi

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Abstract
The utilization of Nano-hydroxyapatite (nHAP) in agriculture has garnered significant attention in recent years due to its unique properties and potential benefits for enhancing crop growth and soil fertility. This review explores the diverse applications of Nano-hydroxyapatite in agricultural practices and highlights its multifaceted utility. Nano-hydroxyapatite, a nanoscale form of calcium phosphate, exhibits excellent biocompatibility and bioactivity, making it an attractive candidate for agricultural purposes. One key area of focus is its role in soil amendment and nutrient management. Nano-hydroxyapatite can serve as a slow-release fertilizer, gradually supplying essential nutrients such as calcium and phosphorus to plants. Its nanoscale structure enhances nutrient uptake efficiency, promoting healthier plant growth and improved crop yields. Furthermore, nano-hydroxyapatite demonstrates the ability to enhance soil structure and water retention, contributing to better soil quality and reduced water requirements for crops. Its interaction with soil microorganisms also influences microbial activity, potentially benefiting nutrient cycling and overall soil health. Beyond its direct impact on plants and soil, nano-hydroxyapatite has been investigated for its potential in crop protection. Studies suggest its role in the development of nanopesticides, providing a targeted and controlled release of pest management agents. Despite the promising applications, challenges and potential environmental impacts of nano-hydroxyapatite in agriculture warrant further research and careful consideration. This review provides a comprehensive overview of current research findings, discussing the potential advantages and challenges associated with the integration of nanohydroxyapatite in agricultural practices. As the agricultural sector seeks sustainable and innovative solutions, the exploration of nanohydroxyapatite opens avenues for improved resource efficiency and enhanced crop productivity.

Keywords: Nano-hydroxyapatite (nHAP), contemporary farming, soil health stipulation, phosphate fertilizer

Introduction

The incorporation of cutting-edge materials is a promising opportunity to address issues with crop yield and soil health in the quest of sustainable agriculture practices. Nano-Hydroxyapatite (nHAP) is a hydroxyapatite in nanoscale form that has become a promising option for improving soil fertility and reducing the environmental effects of contemporary farming practices. With the need to increase food production while reducing environmental damage, nHAP adequacy in modern farming is becoming a crucial area of focus for the worldwide agricultural landscape. Because hydroxyapatite is a naturally occurring mineral in soils, its nanoscale dimensions play a function in increasing the surface area and reactivity of nHAP, its nano-sized analog. These special qualities offer chances for focused soil management treatments, with possible advantages extending from increased hydration retention to better nutrition availability. Establishing nHAP's position as a sustainable soil health stipulant requires an understanding of the nuances of its interactions with soil components and how it affects plant growth [1].

The goal of this thorough study is to summarize and apprise the body of research on nHAP evaluation in modern farming techniques. This paper looks at the physicochemical characteristics of nHAP, how it improves soil health, and some practical uses in an effort to give a comprehensive overview of nHAP's suitability for contemporary agriculture.

Furthermore, our objective is to recognize deficiencies in existing understanding and suggest directions for further investigation, tackling the advantages and difficulties related to the incorporation of nano HAP into farming systems. With the world's communities trying to maintain a delicate balance between environmental preservation and agricultural productivity, the potential of nHAP in supporting sustainable soil management methods is becoming more and more important. By providing insightful analysis, this study hopes to support informed decision-making and creative solutions for a resilient and sustainable agricultural future for scholars, policymakers, and practitioners involved in the developing conversation on nanomaterial's in agriculture. A large amount of human bone is composed of the mineral hydroxyapatite, which is a naturally occurring type of calcium apatite. The term "Nano-Hydroxyapatite" (nHAP) describes hydroxyapatite particles that have undergone nanoscale synthesis. Growing interest has been shown in the possible application of nano hydroxyapatite as a phosphate fertilizer in agriculture in recent years. The nature of nano hydroxyapatite, which contains phosphorus, an essential ingredient for plant growth, is the basis for the concept of using it as fertilizer. A significant component of ATP (adenosine triphosphate), DNA, RNA, and other chemicals necessary for plant metabolism is phosphorus. Phosphate fertilizers have historically been used to provide phosphorus to plants; however, due to worries regarding the environmental effects of these fertilizers, researchers are looking at other possibilities [3].

Hydroxyapatite has the potential to be used as a phosphate fertilizer for plant growth. Phosphorus is a mineral that is vital to plants and may be obtained gradually from this source. In plants, phosphorus is essential for a number of metabolic activities, such as root formation, nucleic acid synthesis, and energy transfer [4].

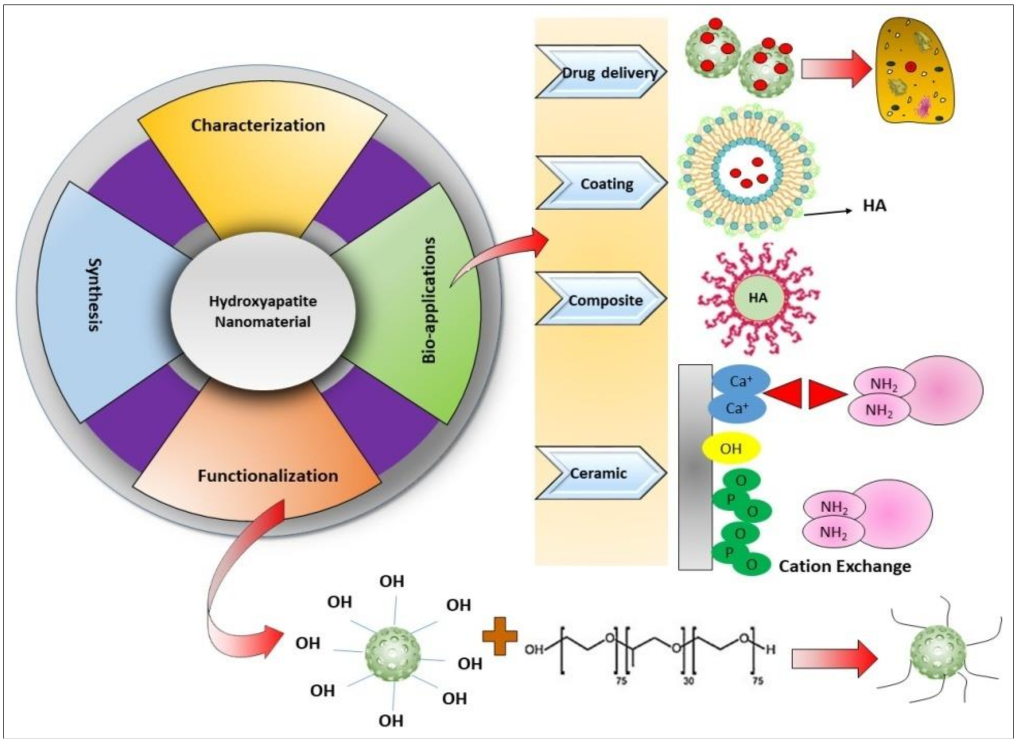

Fig 1: Functionalization and Bioapplication Effects of Nano hydroxyapatite (nHAP) in different fields

Plants typically get their phosphorus from conventional phosphate fertilizers, but worries about sustainability and environmental contamination have prompted research into alternate sources, such as hydroxyapatite. The following are important considerations when using hydroxyapatite as a phosphate fertilizer to plants.

Modest-Release Features: Phosphorus can be gradually released over time by hydroxyapatite. By lowering the possibility of nutrient leakage into the environment and increasing nutrient use efficiency, this slow-release characteristic can help guarantee a consistent supply of phosphorus to fig. 1.

Calcium Provision: In addition to phosphorus, hydroxyapatite is a source of calcium, another nutrient that is necessary for plant growth. For the synthesis of cell walls, cell division, and other physiological functions, calcium is essential.

pH Modification: Hydroxyapatite has the ability to modify the pH of soils. It may require less additional pH-adjusting chemicals because it is typically less acidic than some conventional phosphate fertilizers.

Effect on the Environment

Because hydroxyapatite is a naturally occurring mineral, using it as fertilizer might not have as much of an adverse effect on the environment as using some synthetic phosphate fertilizers. But it's crucial to take into account the entire environmental impact, which includes hydroxyapatite mining and processing [4].

Microbiological Interactions

The microbial communities may be impacted by the addition of nano hydroxyapatite to the soil. Given their critical role in soil health and nutrient cycling, it is imperative to comprehend the interactions between nano hydroxyapatite and soil microorganisms [2].

Table 1: Effects of Nano hydroxyapatite (nHAP) as phosphorus fertilizer on different plants and soil health [1]

Material	Species	Treatment	Experimental Conditions	Results
nHAP, 16 nm	*Glycine max*	21.8 mg L-1 as P	Perlite-peat moss (1:1), nutrient solution, Greenhouse.	Increased growth rate (+32.6%), aerial biomass (+18.2%) and seed yield (+20.4%) than control. Stimulation of root elongation; no plant toxicity.
nHAP, 94-163 nm	*Solanum lycopersicum*	0,2,20,200,500,1000, 2000 mg L-1	Germination, hydroponics.	Stimulation of root elongation; no plant toxicity found.
nHAP (+), nHAP (0), nHAP (-), average size 25.7 nm	*Helianthus Annuus*	bulk-HA, triple superphosphate (TSP) 150 kg ha^{-1} nHAP (+); nHAP (0); nHAP (-); triple Superphosphate (TSP); rock phosphate (RS),	Glasshouse pot experiment; P-deficient Ultisol (pH 4.2) and Vertisol (pH 8.2).	In Ultisol nHA (-) more effective in supplying Pthan TSP; in Vertisol nHAP did not increase plant growth.
nHAP, primary size 22 nm	*Triticum aestivum*	0-150 mg kg-1 P nHAP	Soil columns; glasshouse pot experiment; Andisol and Oxisol.	Increased shoot dry matter and P uptake than bulk-HA but less than the conventional P fertilizer.
nHAP with natural and synthetic humic substances (HA)	*Zea mays*	nHAP-natural HA; nHAPsynthetic HA; Superphosphate; Nha.	Growth chamber; pot experiment	Early growth, better salt stress tolerance and Yield.

Nano-Hydroxyapatite (nHAP) efficacy in bioremediation for environmental improvement

Water contaminated by heavy metals is now a major environmental problem worldwide. The production of adsorbents from waste materials or inexpensive, environmentally benign materials can aid in the cleanup of environmental contamination. The current work revolves around the synthesis of nanocomposites from raw precursors such as hydroxyapatite, clays, and wasted tea waste biochar. In this case, two nanocomposites, called TV-NC and TK-NC, were created and then used to remove heavy metals from aqueous solutions. Applying a variety of adsorption kinetic and isotherm models to experimentally computed data indicates that Cr(VI), Ni(II), and Cu(II) can be favorably adsorbed from the system by TK-NC and TV-NC while adhering to general-order kinetics and the R-P adsorption model, indicating a transition in adsorption kinetics order and the involvement of multiple adsorption processes [5]. In the current study, sawdust was directly chemically activated to produce pellets containing activated carbon while a binder was made of clays. The findings demonstrated that the adsorption capacity increased for all applied heavy metal ions following the coating of ACC pellets with HAp nanoparticles. The most Pb (II) was adsorbed, and pH 6 produced the best outcomes. The pseudo-second-order kinetic model was followed during the adsorption process. The highest adsorption capacity of 56 and 47 mg/g by ACC-HAp and ACC pellets, respectively, as shown by the Pb (II) adsorption isotherm, which is better matched to the Langmuir model. HCl was used to get the best desorption results at pH 1 and 1.5. As a result, the regeneration process involved desorption, distilled water rinsing, and HAp nanoparticle re-coating [6].

To efficiently address the removal of harmful cadmium ions from water, a novel polymer bio-composite based on nano-hydroxyapatite (n-Hap) and chitosan (CS) (CS/n-Hap) was produced. To clarify and comprehend the adsorption mechanism, adsorption tests were conducted with consideration to temperature, adsorbent dosage, pH, starting Cd (II) concentration, and contact time. The Cd (II) adsorption capability of the CS/n-Hap bio-composite was superior in comparison. Moreover, the thermodynamic analysis indicated that the adsorption of Cd (II) onto CS/n-Hap was spontaneous and endothermic. After five successive cycles, the regeneration study only found a 3% reduction in Cd (II) uptake by CS/n-Hap. Thus, a straightforward and easy method was created here to create a material that is both economical and environmentally benign and that can be effectively used to remove harmful heavy metal ions from water [7].

Biowastes are promising resources for producing biomaterials while lowering harmful environmental consequences. These include biowastes from industries, sewage, household wastes, and agriculture. In order to produce value-added products (calcium phosphates or CaPs) derived from biomaterials, this study focused on using waste-derived materials (egg shells as a calcium source, struvite as a phosphate source, and CH_3COOH as dissolution media) in a continuous flow hydrothermal synthesis route. This study demonstrated the potential of eggshells and struvite as sustainable precursors and dissolving media, respectively, for the production of CaPs with different morphologies [8]. Despite several technological improvements and breakthroughs, wastewater treatment continues to be a major issue on a global scale. Providing a broad overview of the latest developments in this field, the primary objective of this review is to demonstrate the adsorptive removal of heavy metals using hydroxyapatite-based adsorbents. As the current review is being developed, an effort has been made to appropriately acknowledge the most recent data regarding the synthesis methods and targeted pollutants. This includes crucial details about the morphological properties of the adsorbent materials, the efficacy of processes, and the synthesis methods and precursors [9].

The development of hydroxyapatite (HA)/gold (Au) nanocomposites to boost the adsorption of methylene blue (MB) dye from wastewater is demonstrated in the current work. After the HA/Au nanocomposite was synthesized, it was examined utilizing FTIR, XRD, SEM, and EDX analysis. On the synthetic composite, batch experiments were used to carry out adsorption investigations. The effects of temperature, pH, dye concentration, and adsorbent quantity were investigated. Using the agar well diffusion method, the dye-adsorbed waste products have also been tested against the bacteria *Micrococcus luteus*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*. The outcomes show that, from an economic perspective, the synthetic sample used as an adsorbent was suitable for efficiently treating MB dye from wastewater and dye-adsorbed waste as an efficient antibacterial agent [10].

Nano-Hydroxyapatite (nHAP) utility in modern agriculture

One of the world's most dynamic crops, avocados are especially important in tropical regions where climate fluctuation phenomena have a significant impact on sustainability and productivity. Tools based on nanotechnology might be a solution to help plants adjust to and lessen these occurrences. The two goals of this study were to: (i) determine temperature and precipitation changes in Colombian avocado-producing regions; and (ii) assess the effectiveness of nCa as a substitute to lessen avocado stress in conditions that mimic climatic variability. Depending on the cluster, the avocado seedlings exhibit varied reactions (p<0.05), with a decline in physiological behavior and development occurring in between 10% and 35% of cases. Furthermore, the climatic stress was lowered by the nano CaP (p<0.05) in a range of 10 to 22.5% [11]. One of the conditions for society's health is the practice of healthy eating. Foods that are naturally occurring are especially recommended more and more because of their high nutrient content. The foundation of all these advancements is the more efficient use of land in harmony with the least amount of negative effects on the environment and the health of living things, with an eye toward researching and developing technologies that incorporate the idea of One Health into their operations and end products. This review article will discuss how maintaining agriculture can have a direct impact on the quality of the most sought-after foods in modern society and how new nanotechnology-based alternatives can lead to effective and secure solutions for all life on Earth [12].

The current agricultural development has set requirements for lowering the dangerous accumulation of agricultural chemicals and enhancing nutritional quality in order to assure food safety. Food security and sustainable agriculture enabled by nanotechnology are being investigated as new study areas more and more. In comparison to conventional fertilizers, nano-fertilizers have the potential to be more effective since they may be applied in smaller amounts while still guaranteeing plant uptake, providing the inorganic nutrients that plants require, and enhancing the process by which plants create organic nutrients. In addition to nano-fertilizers, other agricultural applications of nanotechnology impact crop productivity and nutrient quality. The use of nanomaterials to enhance nutritional quality has been the subject of current research, which will be reviewed in this article along with recommendations for future directions [13].

Because of their quick absorption and precise distribution of nutrients in plants, nano-fertilizers-innovative materials made using nanotechnology techniques-have the potential to displace conventional fertilizers. In the current study, pomegranate peel (PPE) and coffee ground (CE) extracts were used in an environmentally friendly green synthesis strategy to create phosphorous-containing hydroxyapatite nanoparticles (nHAP), a novel phosphorus nano-fertilizer. Using the measurement of biochemical parameters like photosynthetic activity, carbohydrate levels, metabolites, and biocompatibility changes in *Punica granatum* L., nHAPs were physicochemically described and biologically evaluated. The MTT assay was used to examine cytocompatibility with mammalian cells using the Vero cell line. The nHAPs were characterized for size and surface charge using zeta potential analysis and dynamic light scattering (DLS), and for morphology using transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Using DLS and TEM, respectively, it was discovered that the nHAPs had different forms and average sizes of 229.6 nm, 120.6 nm (nHAPs PPE) and 167.5 nm, 153 nm (nHAPs CE). Overall, the current findings demonstrated that the produced nHAPs had a detrimental effect on the chosen biochemical, cytotoxic, and genotoxic parameters. This suggests that the assessment of nHAP created using this method has a variety of uses, particularly as a nano-fertilizer [14].

Recently, foliar or soil applications of nanofertilizers-a novel technology with a lower environmental impact-have been studied in an effort to increase food output. In this work, nano calcium phosphate (NCaP) was effectively produced, analyzed, and used. To find the most effective phosphorus treatments, a pot experiment was conducted on (*Phaseolus vulgaris* L.) plants over the course of two consecutive seasons in 2016 and 2017. The highest increase was achieved by applying 20% NCaP to the soil together with 5% NCaP topically. To lessen the drawbacks of conventional sources, the current study suggests utilizing NCaP as a substitute source of P [15]. In a field in situ experiment, conventional hydroxyapatite (0.25 mm) and micro hydroxyapatite (3 μm) were added in order to examine the remediation effect of hydroxyapatite with varying particle sizes. The findings demonstrate that adding hydroxyapatite in three distinct particle sizes considerably raises the pH, total phosphorus, and soil organic carbon. This improvement suggests that there are potential dangers that could lead to an increase in total Cu and Cd in soil when pollution sources are still present. Additionally, there is a notable rise in the amount of colloid present in the soil, as well as a notable increase in the percentage of colloidal Cu and Cd dispersion, ranging from 49.9% to 120% and 30.3% to 181%. This finding shows that the application of hydroxyapatite may significantly raise the likelihood of Cu and Cd migrating as dust and colloid [16].

Due to the recent century's rapid population growth, there has been a constant increase in the need for food supplies. As an alternative to conventional chemical or mineral fertilizers, the use of nanomaterials to improve plant nutrition is gaining popularity in this respect. The effectiveness of macro- and micronutrients in plants can be improved with the use of this technique. With an emphasis on P fertilizers, this paper outlines the state of the art and potential applications of nanotechnology in the biofortification of plant nutrition. It also discusses the difficulties, detrimental effects on the environment, and harmful repercussions of nanotechnology research that has been done to increase crop productivity. Additionally covered are the possible applications and advantages of fertilizers based on nanoparticles in sustainable and precision farming [17]. The amazing potential of hydroxyapatite nanoparticles as nano-fertilizers with significant effects on increasing plant yields is noteworthy.

The findings demonstrated that the development and physiological characteristics of the maize plant were enhanced by the application of fertilizers containing nano-hydroxyapatite phosphate. When compared to simple and triple superphosphate fertilizers, this would yield greater results. The results of this experiment demonstrated that synthetic nano-hydroxyapatite methods prevent phosphorus loss, which is advantageous given the benefits of nano-hydroxyapatite fertilizers and high production levels. As a result, it is advised to use nano-phosphate fertilizers in food resource management to obtain a favorable quantitative yield. Additionally, they might be thought of as a good way to address environmental issues [18].

The paper outlines a unique and environmentally benign method for producing nanohydroxyapatite (nHAP). Different potassium dihydrogen orthophosphate monobasic (K2HPO4) phosphate concentrations have been used in the *Bacillus licheniformis* - mediated production of non-HAP. Two steps in the mechanism promote the synthesis: (i) P is solubilized by organic acids released extracellularly by the bacterial strain, and (ii) P and Ca gel. The nHAP particles were characterized by XRD analysis and electron microscopy. The size and shape of the powdered crystalline particles, which ranged in size from 30 to ± 5 nm, were determined by the concentration of phosphate. The particles have no negative effects on the microbes that support plant development. A variety of uses are possible for the evaluation of nHAP produced in this manner using a 2% P source [19].

The findings of a study on the hydrodynamic diameter of lavender and basil essential oils (EOs) in water, as well as solutions containing hydroxyapatite (HAp) and EOs of lavender (L) and basil (B), are presented here for the first time. According to the biological investigations, the HapL material exhibited increased antimicrobial activity, suggesting that HAp might be used as a carrier for low concentrations of lavender essential oil that had antibacterial qualities. By interfering with membrane potential, lavender EO was found to be effective against E. coli through flow cytometry analysis. This effect was amplified by the EOs' incorporation into the microporous structure of HAp, which increased the membrane depolarization effect. These discoveries might aid in the creation of fresh antibacterial substances [20]. Copper (Cu) contamination of soil has become a major global issue, resulting in lower agricultural productivity and negative health impacts for humans as a result of entering the food chain. *Festuca rubra* L. was used in a glasshouse pot experiment to assess the possible utility of halloysite as an immobilizing agent in the assisted phytostabilization of Cu-contaminated soil. Cu accumulated in the roots, limiting its toxicity to the aerial parts of the plant. Cu content in the studied portions of *F. rubra* differed considerably with increasing quantities of Cu and when halloysite was given to the soil. The results of the bioconcentration and translocation factor measurements for the halloysite treatment show how useful F. rubra is when used in phytostabilization methods [21].

Miscellaneous applications of Nano-Hydroxyapatite (nHAP)

A calcium phosphate with numerous uses, especially in the biomedical industry, is hydroxyapatite (HA). Particularly in the domains of nanomedicine and regenerative medicine, ion-doped HA nanoparticles (nHA) are being produced for their enhanced bioactivity. Five nHA materials were evaluated in this study for their ecotoxicological effects: commercial hydroxyapatite (HA), titanium-doped hydroxyapatite (Ti-HA), alginate/titanium-doped hydroxyapatite hybrid composite (Ti-HA-Alg), superparamagnetic iron-doped hydroxyapatite (Fe-HA), and a synthetic calcium hydroxyapatite (CaP-HA). In addition to the usual reproduction test (28 days), an extension to the standard for an additional generation (56 days) was carried out using the soil ecotoxicology species *Folsomia candida* (Collembola). We also discovered that adding size as an extra endpoint is quite pertinent [22]. Adolescents frequently suffer from dental caries, which can cause cavitation or the irreversible loss of teeth. Analysis employing FT-IR, XRD, TGA, FE-SEM-EDX, and HR-TEM was used to characterize the isolated nano HA. The cells are alive and the nano HA obtained through alkaline hydrolysis is harmless. The isolated HA promotes L929 cell growth. In healthy premolars, the isolated nano HA's ability for remineralization was assessed by surface microhardness testing, DIAGNO dent/laser fluorescence measurement, and SEM-EDX analysis. Mineralization can be induced and minerals can be deposited by thermally calcined HA and alkali-treated HA, according to surface morphological observations in SEM and EDX investigations. Thus, HA derived from *Epinephelus chlorostigma* may prove to be a viable biomaterial in the treatment of early caries [23].

The most common biological material found in mammals, hydroxyapatite (HAp), has recently been shown to have some modest antibacterial qualities. Metagenomics offers an array of instruments to examine the concurrent interactions of substances with more extensive microbial populations, potentially assisting in the enhancement of HAp's antibacterial efficacy. In contrast to bacteria that cause disease in humans, HAp showed a preference for binding to less pathogenic bacteria. Taxa that have a favorable impact on agriculture were mostly captured by HAp, suggesting that this may have provided it an evolutionary advantage as a biological material. The ability of HAp to specifically ensnab Gram-negative bacteria and so modify the microbiome composition could lead to significant developments in the environmental and biomedical fields [24].

Using phosphate rock and date palm petiole wood as natural, alternative Moroccan resources, we provide a unique method for the in situ synthesis of cellulose microfibrils-grafted hydroxyapatite (CMFs-g-HAPN (8%)) as an adsorbent in this study. The CMFs-g-HAPN (8%) adsorbent has maximal adsorption capacities of 143.80 and 83.05 mg/g, respectively, toward Pb (II) and Cu (II). Furthermore, the multicycle adsorption/desorption experiments showed that the CMFs-g-HAPN (8%) adsorbent could be recycled and utilized for a maximum of three cycles. The CMFs-g-HAPN's 8% regeneration capability and the high adsorption capabilities of both the metals under study indicate that it can be used as a competitive adsorbent on a broad scale [25]. This study suggests using biogenic hydroxyapatite (BHap), which is made from the waste bones of cattle, as an adsorbent for this harmful pollution. The interaction between BHap and glyphosate (GLY) was investigated using calorimetric research and density functional theory (DFT). The measurement of immersion enthalpy in the experiment revealed a substantial interaction, which was supported by the results of DFT simulations for exothermic chemisorption. According to these findings, hydroxyapatite shows great promise as an adsorbent material for the adsorption of GLY in aqueous solutions. Furthermore, it was found that the GLY adsorption into this material is favored by the fact that the GLY-hydroxyapatite contact is larger than the water-hydroxyapatite interaction [26].

In terms of composition, hydroxyapatite (HA) resembles genuine bone, and its structure is advantageous in biomedical applications. Because of their promising biocompatibility, these nanomaterials play a vital function in several biological disciplines, including sustained drug and gene delivery, bio-imaging, magnetic resonance, cell separation, and therapy of hyperthermia. This review focused on the chemical makeup of HA-NMs, their function in biomedical applications, ion-doping, and current advancements in synthesis and surface modification techniques. As coating materials, bone implants, drug delivery vehicles, ceramic, and composite materials, HA-NMs play a significant role. Here, we attempt to provide a synopsis of HA-NMs along with recommendations for further work [27]. Because of its strong biocompatibility, osseointegration, and osteoconduction, calcium phosphate (CaP) bioceramics are employed extensively in the field of bone regeneration in both orthopedics and dentistry. Theories about the dissolution and reprecipitation of CaPs as bone, as well as the formation of transitory precursor phases in biomineralization, are examined. There are many different types of CaPs available, including nano-CaP, coatings and cements made of composite materials, biphasic and triphasic CaP formulations, functionally graded materials (FGMs), and antibacterial CaPs. Finally, we look ahead to the future of CaPs [28].

Conclusion

In summary, the evaluation of Nano-hydroxyapatite (nHAP) sufficiency in modern farming for soil health requirements presents a complex picture that need careful thought and ongoing research. This thorough analysis has examined a number of nHAP application aspects in agriculture, illuminating both the potential advantages and difficulties of this technology. The results highlight how nHAP can improve soil health by increasing microbial activity, regulating pH, and improving nutrient availability. The special qualities of the nanoparticles can greatly support sustainable farming methods by lessening the damaging effects of traditional agricultural techniques on soil quality. On the other hand, nHAP incorporation into farming systems must be approached cautiously and optimistically. To ensure responsible and sustainable consumption, it is imperative to conduct a thorough investigation of the long-term effects, environmental repercussions, and potential risks associated with widespread adoption. To enable the use of nHAP for a wide variety of farmers, cost-effectiveness and accessibility issues must also be taken into account. Embracing innovative solutions becomes crucial as agriculture faces enormous problems, such as declining soil fertility and climate change. This review's evaluation of nHAP emphasizes how revolutionary it may be for managing soil health. To traverse the challenges and optimize the advantages of incorporating nano-hydroxyapatite into modern farming operations, however, a comprehensive and cooperative strategy involving scientists, legislators, and farmers is necessary. By doing this, we can work to create an agricultural future that is more productive, resilient, and sustainable.

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