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Use of Nano-Clay Particles for the Reclamation and Sustainable Management of Desert Soils: A Review

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Poor physicochemical properties inherently limit the desert soils in terms of low cation exchange capacity, inorganic matter, weak aggregation, and low water retention, all of which consequently hinder biological productivity and resilience of the desert soils. These soils are characterized by coarse textures, scarce organic matter, and high vulnerability to erosion. The low organic content directly impacts nutrient cycling and soil structure, with research indicating that these soils store only 32% of global soil organic carbon. Nanotechnology in soil science has provided different amendment of soils reclamation and sustainable control in the form of nano clay particles. Nano clays have been found to have remarkable potential to control the interactions of soil and water with nutrients due to their ultrafine particle size, large surface area, and high potential of sorption. They increase the structural stability of the soils, nutrient availability, and hydrological balance by increasing water adsorption and decreasing percolation losses. Subsurface clay soil amendments increased water-stable macro aggregates from 32% to 54% and reduced nitrate leaching by 61%. Further, it has been shown that nano clay applications can be used to reduce salinity, enhance microbial colonization, and with regard to root development in desert environments. This study summarizes the most recent advancements in the use of nano clay particles to restore desert soil, outlining their mechanism of action, potential environmental risks, and prospects for widespread use in the future. The incorporation of nano-engineered clays is an area of future sustainability in soil management, as there is a feasible solution to rehabilitate soil functionality, fight desertification, and maintain agriculture systems that are resistant to the climate in the future.

Keywords: Nano clay; desert soil; Pakistan; Thar; Cholistan; liquid nanoclay; sustainable agriculture; nanotechnology; soil reclamation**Introduction**

Desertification is one of the most pressing environmental and socio-economic challenges facing Pakistan today. Vast regions such as Thar (Sindh), Cholistan (Punjab), and Kharan (Balochistan) are characterized by sandy textures, low organic matter, poor water retention, and high susceptibility to erosion and salinity. Together, these deserts cover millions of hectares of land, with Cholistan alone spanning approximately 2.6 million hectares, stretching 480 km in length and up to 192 km in breadth [1]. The human popula-

tion in Cholistan is estimated at 0.1 million, while livestock numbers reach 2 million, reflecting the heavy dependence of local communities on fragile desert ecosystems [1]. The hyper arid climate zone exist in these regions, where there is very little rainfall and no river or canal flows through permanently (PCRWR,2017). Land use here is mostly under livestock rearing as agricultural farming is very limited due to severe water shortage. Land is degrading quickly due to overgrazing coupled with salinity and wind erosion. Leav-

ing soil without crops increase risk of desertification.

Pakistan is under alarming situation of desertification. Report from United Nation Convention to Combat Desertification [2] suggest about 18% of land areas in Pakistan is affected by desertification. Food security, biodiversity and rural livelihood is under sever threat due to desertification. Report from Food and Agriculture Organization [3] suggest that Pakistan's agricultural productivity and arable land can be reduced due to desertification which is further worsen by climate change. This also increase water scarcity around the country. Recurrent drought in Thar leads to multiple crop failure and losses of livestock. In Cholistan soils are suffered from wind erosion along with salinity, which make large area of land unsuitable for cultivation [4]. These conditions showed the high demand of innovative and sustainable soil management practices to restore soil fertility, increase resilience for high agricultural production in arid climate.

Canal irrigation, application of gypsum and addition of organic amendments are some traditional reclamation methods followed in Pakistan. These methods have got some localized success but the face many limitations. In hyper arid regions where ground water is very limited canal irrigation is water intensive and unsustainable. Soil sodicity can be managed by gypsum application, but it requires repeated treatments. Soil fertility can be increased by organic amendments like farmyard manure and compost but their availability to such level to meet the demand of vast desert is a big problem. Moreover, these old approaches are failed to overcome the structural problems of sandy soils like poor water holding capacity and low aggregation. As a results, there is a growing demand of new sustainable and cost-effective methods to rehabilitate the desert soils.

Application of nanotechnology has emerged as a promising and sustainable solution for soil reclamation. Among different nanomaterials, due to their unique physicochemical features nano clay particles (NCPs) have got a lot of attraction. These nano clay materials about below 100 nanometer in size have high surface area, hydrophilicity and cation exchange capacity (CEC). This enable them to hold more water and nutrients compare to conventional soil amendments [5]. Nano clays when applied to sandy soils create hydrophilic coating around sand particles, this reduces evaporation, increase nutrient holding and promote soil aggregation [6]. These features overall improve fertility of soil, reduce demand for irrigation and provide support for sustainable production of crop in water limited environment.

Recent field and pot studies in Pakistan and comparable arid areas highlight to potential of nano clay, mainly liquid nano clay (LNC). In Multan, irrigation requirement is reduced by 40-50% along with crop production and soil structure improvement with application of LNC [7]. In similar way increase porosity, reduction in salinity and improved millet yield is reported in Thar and Cholistan [6]. These results indicate potential of nano clay to convert barren deserts into productive land. However, challenges remain in its cost, scalability, safety of environment and political integration, despite being promising results.

The aim of this review is to create latest and scientific proofs on the application of nano clay in reclamation of deserted soils in Pakistan. It will check the physicochemical features of nano soil, their way of action for betterment of soil fertility, its formation, methods of application and case studies from different desert regions of Pakistan. In this review we will also discuss about economic and environmental benefits of nano clay uses, highlights challenges and draw backs, and also looks at future aspects for mixing nanotechnology into sustainable land management approaches. This review provides in detailed data of how nanotechnology works to combat desertification, improve food safety and build sustainable agricultural system by focus on Pakistani desert ecosystems.

Mechanisms of Soil Improvement by Nano Clay Particles

Through different physicochemical and biological ways nano clay particles (NCPs) are improving conditions of deserts. They have ultrasmall size, layer silicate structure and high surface area which allow them to interact more with soil, water and nutrients as compare to conventional agricultural amendments. Detailed mechanism of action is described in following subsection.

Water Retention and Hydrological Balance

Hydrophilic Coating of Sand Particles

Nano clay reduces infiltration and evaporation losses by creating thin hydrophilic film around sand particles. This improve water retention capacity in sandy soils, which is important for arid zones like Thar and Cholistan [8].

Reduction in Irrigation Needs

In Multan field trails indicates that application of liquid nano clay (LNC) reduces irrigation need by 40-50%, making agriculture more sustainable in water limited environment [7].

Nutrient Retention and Fertility Enhancement

Prevention of Nutrient Leaching

Due to their high cation exchange capacity, nano clay absorb lot of cations and nutrient preventing them from leaching and make sure that fertilizers remains available to plants for long period [9].

Improved Fertilizer Efficiency

Nano clay reduces fertilizer input costs and increases efficiency of nutrient use by retaining nutrients in root zones [5].

Soil Structure and Aggregation

Formation of Micro-Aggregates

Nano clay improves soil porosity and reduces erosion by bind loose sand particle into aggregates [5].

Enhanced Root Penetration

Due to improved soil structure root grow deeper and aeration also improve, which is crucial for crops like millet and guar grown in deserted region [10].

Microbial Activity and Soil Biology

Creation of Microhabitats

Nano clays support growth of beneficial microbes by providing better habitats for them in soil aggregates [11].

Enhanced Nutrient Cycling

Soil fertility and carbon sequestration is improved as a result of microbial colonization which improves nutrient cycling and decomposition of organic matter [12].

Salinity Reduction and Soil Chemistry

Nano clays adsorb excess sodium present in soil and reduce soil salinity and improve chemical balance of soil [9].

Carbon Sequestration and Climate Resilience

Stabilization of Organic Matter

Nano clays improve soil organic carbon stabilization, lower emission of greenhouse gases and perform its role in climate mitigation [13].

Long-Term Soil Health

By increasing soil fertility and better soil structure, nano clay support sustainable agricultural system that can tolerate impacts of climate change [11].

Preparation and Application Methods of Nano Clay

Preparation of Liquid Nanoclay

Liquid nano clay is formed by mixing clay particles with water using ultrasonic treatment and mixing at high speed. Clay breaks down into nano sized particles during this process and this form a stable suspension. This nano particle size gives clay strong hydrophilic feature and high surface area, increasing its efficiency in interacting with sandy soils.

Application of Liquid Nanoclay

Liquid nano clay is sprayed directly onto sandy soils after preparation. This application creates thin hydrophilic layer around the sand grains, which change the soil structure from sandy to loam structure. This transformation lower losses of water through infiltration and evaporation, while also improve retention of nutrients

and fertility of soil.

Preparation of Dry Nano Clay

Dry nano clay can be produced by nano scale powder of mineral like montmorillonite, bentonite or kaolinite by grinding these clay minerals. The particles are treated to dimension between 1-100 nanometer, this improves their cation exchange capacity and water retention capacity

Application of Dry Nano Clay

Using a mechanical tiller or plough, this dry nano clay powder is mixed in top soil at specific concentration. Soil structure, nutrient retention and aggregation is improved by this method. This method is mainly effective in sandy soil types, where fertility is low and particle aggregation is weak.

Preparation of Composite Nano Clay Blends

Composite mixing includes mixing of nano clay with organic fertilizer like biochar, farmyard manure or compost. By this process biological properties of organic matter and physical and chemical properties of nano clay are combined which give more better results.

Application of Composite Nano Clay Blends

Method of surface incorporation or subsurface layering is used to apply this blend mixture to soil. This process improve water holding, support colonization of microbes and improve carbon sequestration. This also help lower salt stress which is a big problem in desert soils.

Preparation for Irrigation-Based Application

Nano clay can also be used in irrigation base application, clay suspension is first prepared then mixed into irrigation system, mainly in drip irrigation. The suspension is diluted to make sure that the distribution is equal across whole soil profile.

Application through Irrigation Systems

Using a drip irrigation the suspension is directly delivered to root zones of plants. This help in equal distribution of nano clays, enhancing soil porosity, penetration of roots and uptake of nutrients. It is well suited in arid regions where water availability is limited as it combines efficient irrigation system with soil improvement.

Table 1: Preparation and Application Methods of Nano Clay.

Nano Clay Type	Application Method	Soil Type	Location	Dose	Parameters Studied
Montmorillonite (LNC)	Spraying suspension	Sandy soil	Multan, Punjab	1-2 L/m ²	Water retention, crop yield
Bentonite	Spraying suspension	Sandy loam soil	Multan, Punjab	1-2 L/m ²	Microbial biomass, fertility
Kaolinite	Drip irrigation	Arid sandy soil	Thar, Sindh	Adjusted with irrigation water	Soil porosity, millet yield
Lite	Dry mixing	Desert sandy soil	Cholistan, Punjab	0.5-3% w/w mixed into soil	Soil aggregation, erosion resistance
Smectite	Composite blending	Saline sandy soil	Bahawalpur, Punjab	1-2% w/w with compost	Salinity reduction, microbial activity
Halloysite	Irrigation-based	Sandy arid soil	Kharan, Balochistan	Diluted in irrigation water	Root development, nutrient uptake

Environmental Benefits

Improved Water Retention and Efficiency

Nano clay lower evaporation and infiltration losses by forming hydrophilic coating around sand particles. This will significantly reduce water losses in arid climates. Field studies showed that in Pakistan and other arid regions, irrigation demand can be lower by 40-50% making agriculture more sustainable in water limited zones.

Enhanced Fertilizer Efficiency

By improving soil cation exchange capacity (CEC) and reducing leaching of nutrients, nano clay makes sure that nutrients remain available to plants for much longer time. This also help to counter challenges like contamination of ground water and enhance efficiency of nutrient use, reducing the environmental footprint of agriculture.

Soil Structure and Erosion Control

Nano clay improves soil structure, lower soil erosion and increase aeration by promotes formation of soil aggregates [14,15]. This is mainly crucial in soil of deserts like Thar and Cholistan, where soil faces challenges of wind and water erosion.

Carbon Sequestration

Nano clay improves activity of microbes in soil and stabilizes organic matter, this increase storage of soil organic carbon. This process sequester carbon in soil and reduce emission of green house gases thus help in mitigation of climate change.

Salinity Reduction

In saline prone desert areas use of composite mixture of organic amendments and nano clay lower soil salinity, improve soil health and cultivation [16,17].

Economic Benefits

Reduced Irrigation Costs

It saves cost of irrigation infrastructure and water pumping as it saves water up to 50%. This is important in desert areas of Pakistan where water is very limited and transport of water is very costly.

Lower Fertilizer Inputs

Nano clay reduces demand of repeated fertilizers as it retains more nutrients in soil. This lowers the cost of inputs and also improve yield to some extent.

Increased Crop Productivity

Yield is increased as soil fertility, water retention and microbial activity of soils improved. Studies in arid areas shows increase in yield of crops like millet and guar with application of nano clay.

Long-Term Economic Viability

Nano clay technology is much more sustainable and cost-effective compare to conventional methods of reclamation like applica-

tion of gypsum or desalination. The initial cost of production is high but long-term water saving, fertilizer and management of soil make it economically viable.

Climate-Resilient Agriculture

Nano clay support sustainable agricultural system by improving resilience of soil against drought and salinity. This lower risk of failure of crop and make sure reliable income in desert regions for farmers.

Challenges and Limitations of Nano Clay Applications

High Production and Application Costs

High cost of production and application cost is one of the major challenges in application of nano clay. Equipment like ultrasonic disperser and high speed mixers are required for preparation of liquid nano clay which are not only expensive but their availability in rural areas of Pakistan is a big problem. In-addition transport cost and applying for small holder farmer is also a big issue. This makes economic barrier in its wide application.

Scalability and Infrastructure Constraints

Pilot projects show the good results, but applying nano clays in vast desert such as Thar and Cholistan demand a lot if infrastructure. Lack of machinery, trained personnel and transport system for efficient use of nano clay are often lack in rural areas. Large scale deployment of nano scale without government support will always cause big problems.

Environmental Risks and Safety Concerns

There is a potential concern about leaching of nano clay in ground water or accumulation in ecosystem. Long term impact on environment is not fully understood yet, more research is required to understand the risks like toxicity in soil, effects on living organisms and water resources contamination.

Policy and Regulatory Gaps

At present, there are not clear guidelines at national level about use of nano clay in agriculture regions of Pakistan. This cause uncertainty among farmers, researchers and policymakers about its uses. There is a risk of misuse or uneven adoption without proper rules and regulations, this could cause threat to safety of environment and economic viability.

Technical Knowledge and Awareness

Advance technologies are limited for farmers of desert regions. Training and awareness programs are needed to provide information to farmers regarding the use of nano technology. Adoption rate could be low without good transfer of knowledge.

Dependence on External Expertise

Most of present research and nano clay application in Pakistan is dependent on international projects and imported technologies. This dependence on foreign technologies makes this process exposed to disruption of supply chain and lower local innovation capability.

Future Perspectives for Nano Clay Applications in Pakistan

Development of Low-Cost Synthesis Methods

Establishment of cost effective and formation of nano clay using locally available clay is required for future directions. By lowering dependence on foreign nano clay and advance machines, Pakistan can make this technology more cost effective and available to farmers in desert areas.

Integration with Organic Amendments

Soil fertility can be improved by combine application of nano clay with organic amendments like compost, farmyard manure and biochar in a sustainable way. This combine use not just improve retention of water and cycling of nutrients but also support colonization of microbes and provide long term soil health benefits.

Long-Term Monitoring of Soil and Water Systems

Monitoring of soil health, ground water quality and productivity of crop must be involved in future projects. Continuous study helps us find risks like leaching of clay to make sure environmental safety for its application.

Establishment of National Guidelines

It is essential to form national level policies and rules for use of nano clay in agricultural soils. Regulatory authority will give us clarity on safe application techniques, while farmers training and environmental standard ensure adoption of nano clay.

Pilot Projects in Desert Regions

Scalability and impact of nano clay can be understood by large scale pilot projects in deserts like Thar, Cholistan and Kharan. This project helps us to understand sustainable management of desert land and show us how farmlands are produced from barren deserts soils.

Climate-Resilient Agriculture

Nano clays can perform a critical impact in creating climate-resilient agricultural systems. They help farmers to adapt to drought, extreme heat and other climate risks by enhancing efficiency of water use, lower salinity and increase soil fertility. This also perform similar to Pakistan's national priorities for security of food and control of desertification.

Capacity Building and Farmer Training

Development of farmers training programs and extension works to create awareness are included in future aims. Long term sustainability and adoption can be achieved by empowering local farmers with skills to apply nano clay.

Conclusion

Soil reclamation and sustainable management of deserts soils can be done by application of nano clay particles. Their special features like high surface area, strong capacity to adsorb nutrients and hydrophilic nature make them important agent

to enhance retention of water, nutrient, aggregation of soil and activity of microbes. In desert regions like Thar, Cholistan and Kharan its application already showed measure able benefits like lower irrigation demand, improve crop yield and enhance soil fertility. Along with its benefits, it has few limitations like high cost of production, scalability, safety of environment and policy making. To overcome these, limitations require local synthesis, training programs and regulatory frameworks. Moreover, their effectiveness and sustainability can be improved by mixing it with organic amendment and irrigation systems.

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