ISSN 2522-9400 **European Modern Studies Journal** Vol 5 No 6
available at journal-ems.com

Fabricated Nanomaterials in Soil Improvement Technologies and Their Applications

G. Vani Padmaja and Shruti Srivastava
Catalyse: The power foundation, India

Abstract. In the era of rapid urbanization and with drastic climate changes, global agricultural systems and production are facing numerous, unprecedented promising challenges. To achieve high food security, optimum nutrition levels in the food production, advanced nanotechnology and nano-engineering are one of the important handy tools for boosting up of the soil improvement, healthy crop production and assuring sustainability. Nanotechnology and fabricated nanomaterials have excellent applications to improve soil chemistry, improving agricultural production by increasing the efficiency of inputs and minimizing relevant losses. Nanomaterials offer a wider specific efficient surface area to nano-fertilizers and nano-pesticides. Besides these, specifically designed nanomaterials are widely used as unique carriers of agrochemicals to facilitate the site-targeted controlled delivery of nutrients in the soil with increased crop protection. Due to their direct and intended applications in the precise management and control of soil inputs (fertilizers, pesticides and herbicides), nanotools such as nanobiosensors, nanosilica composites, fabricated nanomaterials etc support the development of high-tech agricultural techniques. This article emphasizes more on the nano-clay, nano-silica, nano-fibres, nano-alumina, CNTs etc are highly effective and efficient engineered manufactured nanomaterials which are very helpful in improving the soil properties and preventing from the depletion of natural resources, thus enhancing the soil sustainability which could not be attained through the conventional techniques.

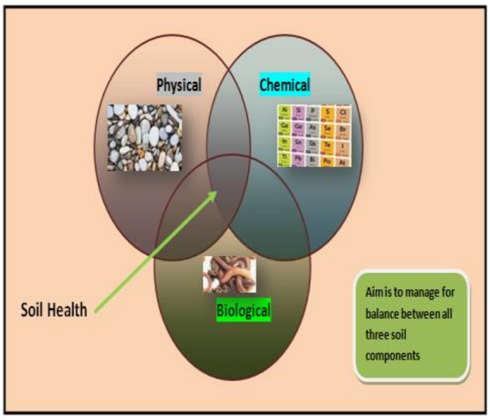
Keywords: nano-biosensors, nano-clays, nano-fertilizers, nanosilica, CNTs, sustainability, nano-engineering

Introduction

The field of agriculture is facing wide spectrum of challenges which include unpredictable climate changes, fast urbanization and industrialization, sustainable less efficient crop yields, declining soil organic matter (SOM), multi-nutrient deficiencies, shrinking arable of natural resources and various environmental problems like accumulation of pesticides and fertilizers, runoff, soil depletion etc. Many technologies have been developed to overcome these issues that have the potential to increase crop productivity and helps in reducing the soil related environmental issues. To resolve these problems, there is an urgent need to explore efficient technologies and emerging frontier technologies such as 'Nanotechnology' which could precisely detect and deliver the correct quantity of nutrients, pesticides, other mineral nutrients that promote increased productivity with ensuring food and environmental safety. Many studies were focused on the soil improvement by certain conventional methods which include the addition of materials like cement, mineral additives like silica fume, fly ash, rice husk ash, cement, lime etc. Nanomaterials (NMs) and fabricated nanomaterials have the capacity to improve the soil quality and helps in the removal of contaminants like heavy metals, unwanted microorganisms and others toxic elements (Majeed, Taha, & Jawad, 2014; Huang, & Wang, 2016; Ibrahim, et al., 2016). Specifically designed NMs are extensively being examined as a means to improve the quality of agricultural soils, and thus increase the sustainable agricultural practices. Because of their small size and large surface area, nanoparticles and engineered nanomaterials being very reactive, have many unique properties like enhanced cation exchange capacity, improved specific nutrient delivery and long-lasting nutrient release that are potentially feasible and helpful in soil restoration problems. The application of nanoparticle systems can alter and improve the crop management system, along with reduction of the consumption of pesticides and contamination risks, resulting in safer agricultural practices for farmers, consumers, and the environment. Nanomaterial engineering can be applied in either ways: (a) To study the soil structure in nanometer range for better understanding of soil nature, as well as in examining the performance of soils with various nanostructures; (b) in studying soil variations and manipulation at the atomic or molecular scale, by the addition of specifically fabricated nanomaterials to soil. This article emphasizes mainly on the potential benefits of self designed nanomaterials for innovative solutions in the soil improvement technologies. Structurally engineered colloidal SiO_2 and laponite could be used to prevent the liquefaction of soils based on special rheological properties (do Espirito Santo Pereira, et al., 2021; Raja, & Husen, 2020).

Engineered Nanomaterials in Soil Chemistry

As per the geographical and topological conditions soil nature and texture varies and the fertility, productive capacity of the soil can be enhanced as per the requirement by the fabricated engineered nanomaterials, manufactured of the desired properties. Field soil texture reflects the percent composition of sand (2- 0.2mm), silt (0.2- 0.002mm), clay (<0.002mm) in the soil which is useful for the estimation of water holding capacity, leaching property, erodibility, sub- surface compaction, susceptibility to water repellence etc.



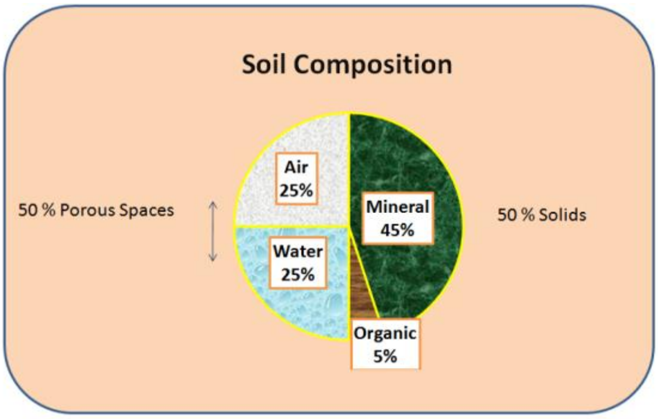


Figure 1. Composition of soil

Engineered and fabricated nanomaterials could be applied as amendment agents for the efficient phytoremediation techniques and also to be applied as stabilizers to increase the performance of the soil. Nanotechnology-based applications are low cost and more efficient, simple to use and imply on more effective treatment and remediation methods that may considerably reduce soil pollution. Nanobio-remediation techniques of soil might provide a sustainable solution for revitalizing and remediation of the tarnished soil resources. Soil system could be considered as a four dimensional system where a broad three dimensional soil structural fabric is filled by dynamic and reactive colloidal constituents (Farooqi, et al., 2021; Qian, et al., 2020; Wu, et al., 2021). Thermodynamically, colloidal clays and colloidal organic matter (i.e., humus) would tend to form complexes in the soil so as to attain stability ($dG < 0$) and thus one of the natural phenomena of protecting the earth system. Recent studies show that fabrication of various nanomaterials are engineered as per the desired properties like nanomaterials (sorbents of hazardous pollutants), nano-based smart delivery system (use of halloysite), nano-enhanced products (e.g. nanofertilizers and nanopesticides), and nanoporous materials (e.g. hydrogels and zeolites). The combination of nanotechnology with the geotechnical engineering could pave a new path for providing solutions for the challenging problems in the soil improvement technologies. Designed CNTs are very widely used in maintaining the compressive strength of the soil. Development of manufactured nanodevices and nanomaterials possessing enhanced reactivity due to higher solubility, higher availability of active surface atoms relative to the interior of structure, unique magnetic/optical properties, reactive electronic states, and efficient catalytic reactivity that are different from conventional bulky materials are boost to the maintenance of the soil quality and maintenance (McKee, & Filser, 2016; Tahir, Sagir, & Asiri, 2021).

Nanoclays for Soil Permeability

The evaluation of the soil for compressive strength, effective shear strength and Atterberg's limit test parameters are studied for the soil stabilization. The highly unique properties of nanoclays are exclusively applied for carbon stabilization and management in the soil. Nano-clays are composed of thin layers with each layer of thickness of one to few nanometers length from a few hundred to several thousand nanometers. Various types of nanoparticles including carbon nanotubes, nanocarbon, nano-clays and metal oxides are currently used to modify the polymer applications. Physical parameters of nano-clays can be studied as:

1) Molecular mass (g / mole) - 540.46
2) Average weight (g / cm^3) - 2.35
3) Monoclinic crystals
4) White, yellow in color.

Nano-clay is an inorganic, hydrophilic in nature whereas the polymer matrix used to make nano-composite materials is organic and often hydrophobic. To increase the compatibility between the nanoclays and the polymer, the nano-clay could be modified and novel mixing techniques can be introduced (Zaytseva, & Neumann, 2016; Ali, Mehmood, & Khan, 2021). Nanoclays are layered silicates of 0.7 nm thickness of single layer, while double layer is of 1 nm thick. The interlayer can be specifically modified using surfactants, metal ions to attain the desired properties such as to improve the plasticity and swelling capacity (Bukit, Frida, & Harahap, 2013) (Figure 2a).

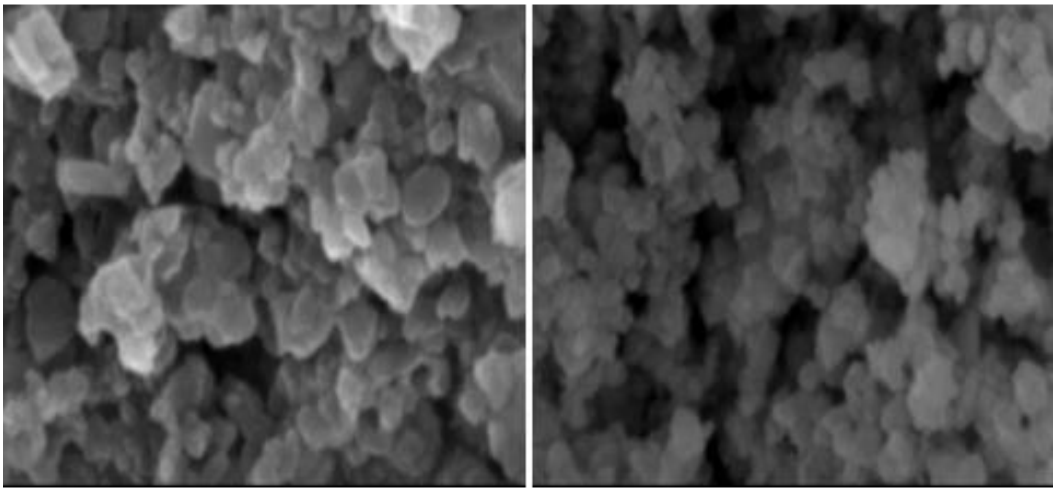


Figure 2a. SEM micrographs of bentonite nanoclay

Surface properties of nanoclays depend on the a) charge of the nanosheet, b) nature of surface atoms, and c) interlayer exchangeable cations. Electrical conductivity of nanoclays is due to the surface charge of the nanoclays. It is studied that the surface of nanoclays is negatively charged because of the substitution of Al^{+3} or Mg^{+2} ions with silicon. One of the modern techniques is the ion exchange technique, metal/ metal complex impregnation, acid treatment etc. Various purification techniques are employed like hydrocyclone, sedimentation method, centrifugation, chemical methods etc. The various studies reveal the long-term release and interaction dynamics of fabricated nanoclays in the soil along with their desired chemical modification and transformation predicting their fate, interaction and transport in the soil media (Khalid, 2014; Vani Padmaja, & Shruti, 2020). The modern soil stabilization techniques include stabilization by nanomaterials by studying the following properties of the soil (Figure 2b & 2c):

a) Atterberg's limit
b) Compaction characteristics

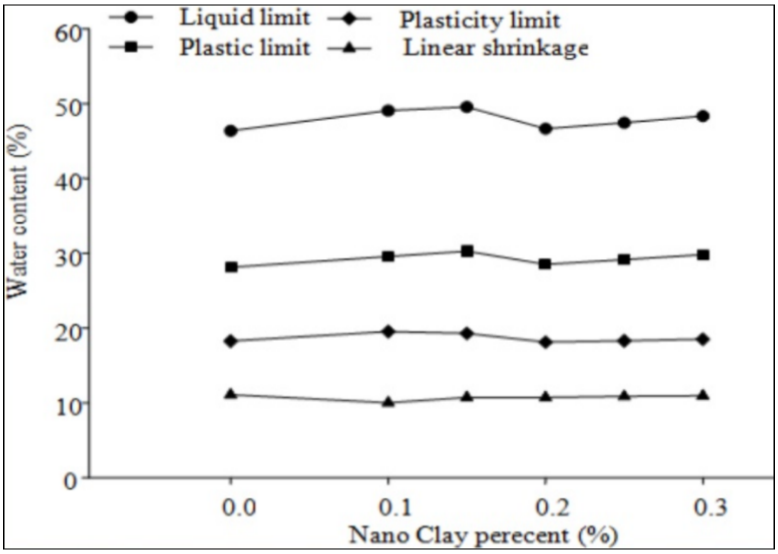


Figure 2b. Atterberg's limit

The studies of the various soil samples infer that the addition of nanoclays led to increase in the liquid limit to 49%, plastic limit increases up to 32% and decrease in the plasticity limit of the soil to 17%. The variation in the optimum moisture content for one sample increases up to 25.4% and for other decreases up to 22%.

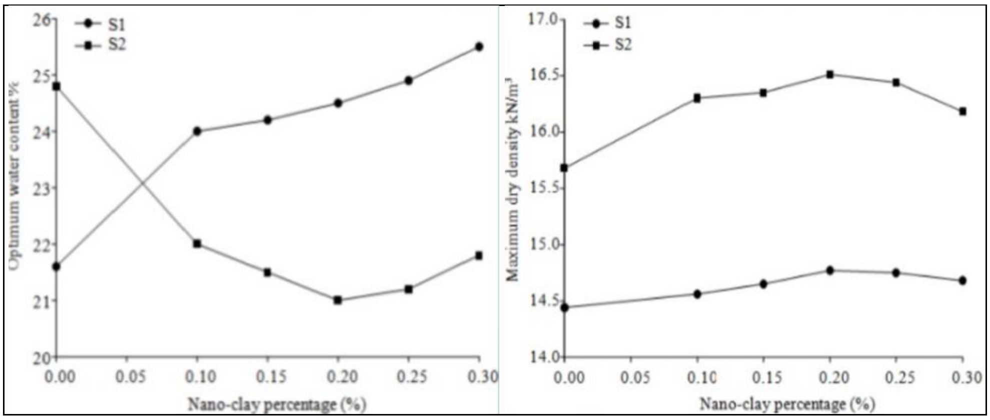


Figure 2c. Compaction characteristics for samples of soil

An increase in the maximum dry density of the soil samples shows the overall increase in the soil improvement. The addition of different nanomaterials causes variation in the compaction characteristics (maximum dry density and optimum moisture content) of the soil and thus fabricated, engineered nanomaterials can be applied for the soil improvement technologies as desirable (Pramanik, et al., 2020; Sarkar, Datta, & Biswas, 2014; Lisuzzo, et al., 2020; Baragaño, et al., 2021). The encapsulation of different bioorganisms like

Trichoderma harzianum, Pseudomonas fluorescens loaded through nano-clay polymer composites could be used to control fungal-nematode disease complex to control the moisture and nutrient deficiency thereby causing low level of production. Certain results showed that the application of nanoclay had significant reduction of soil erosion in different wind speeds and has high aggregate stability when used in soils (structure less and unstable), which is a major reason to control wind erosion by application of nanoclay. Thus studies reveal that the nanoclay works as a binder because of its adhesive nature and generate aggregates in the soil providing stability to the soil and reducing soil erosion (Piplai, et al., 2020; Abbasi, Farjad, & Sepehri, 2018; Yang, & Tang, 2012). Nanomaterial additives can influence the specific properties of soil by altering its physico-chemical behavior. Generally, their properties become remarkably different when materials approach the nanoscale. Due to the smaller dimensions, nanomaterials possess a very high specific surface area and react more actively with other particles in the soil matrix, thus different nanostructures exhibit different properties (Abbasi, Farjad, & Sepehri, 2018; Mazloomi, & Jalali, 2019; Majeed, & Taha, 2013). The existence of even a trace amount of engineered nanoparticles can result in desired properties and excellent effects on the engineering properties of the soil and thereby can influence the strength, permeability, indices, and resistance properties of soil.

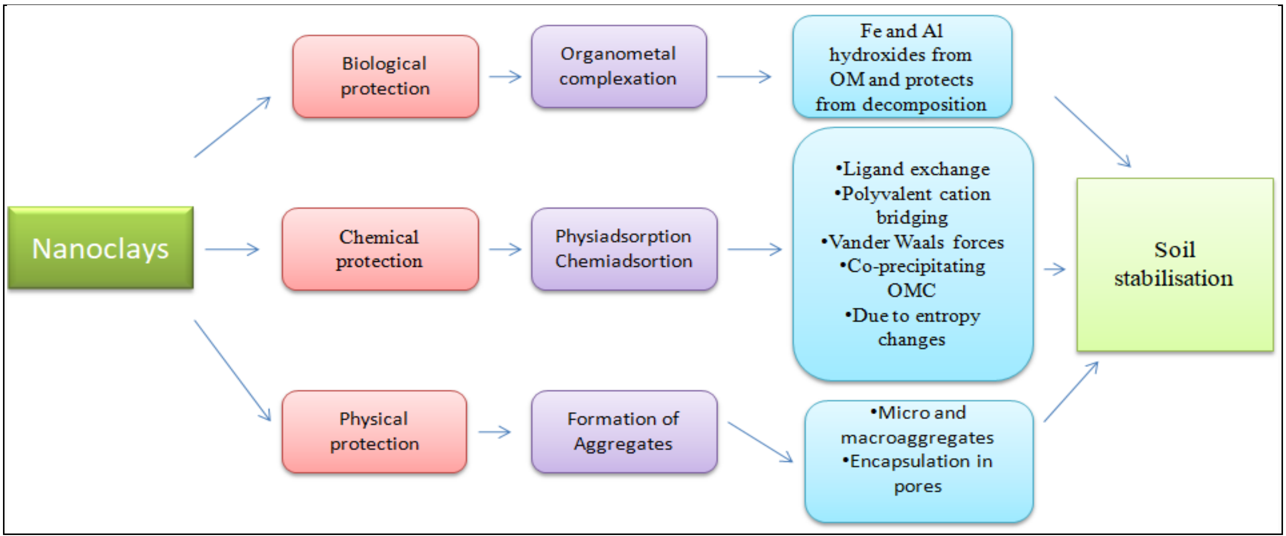


Figure 3. Application of nanoclays in soil stabilization

Research studies show that addition of different nanomaterials result in change in the permeability of clay on adding different amounts of nano-oxides (gamma-aluminum oxide powder (γ-Al_2O_3) and nano-copper oxide (CuO)) were mixed with clay at different percentages (i.e., 2%, 4%, and 6%). With the increase in percentage of nano-oxides content, the void of clay was filled with nanomaterials and the permeability coefficient was decreased. Li was used for the electro-osmosis method to study the influence of nano-montmorillonite on the electro-osmosis and mechanical properties of soil results show that it can effectively improve the shear strength of soil, but has no significance effect on the electro-osmosis drainage of soil (Paul, et al., 2021; Cheng, et al., 2020; Guo, et al., 2018; Lian, et al., 2021; Mathur, & Roy, 2021).

Nanosilica for Soil Porosity

Nano-silica is a type of nanomaterial which exhibits strong adsorption property. Sol-gel technique is one of the latest methods employed in which a metal or a metalloid element surrounded by various reactive group of atoms, ligands are taken as precursors for the synthesis of these colloids. The laboratory synthesis of nanosilica using the sol-gel technology has been studied and metal alkoxides such as tetramethoxysilane (TMOS) and tetraethoxysilane (TEOS) are preferred because they react readily with water, are accompanied by three reactions: hydrolysis, alcohol condensation and water condensation as shown (Figure 4). On adding water to silty clay, nano-silica produces a viscous gel through the absorption double layer. The extent of bonding between silty clay particles due to viscous gel is much stronger than that of the absorbed water and increases the area of contact between the silty clay particles (Tabarsa, et al., 2018; Changizi, & Haddad, 2016; Vani Padmaja, 2015; Hu, et al., 2018; Buazar, 2019).

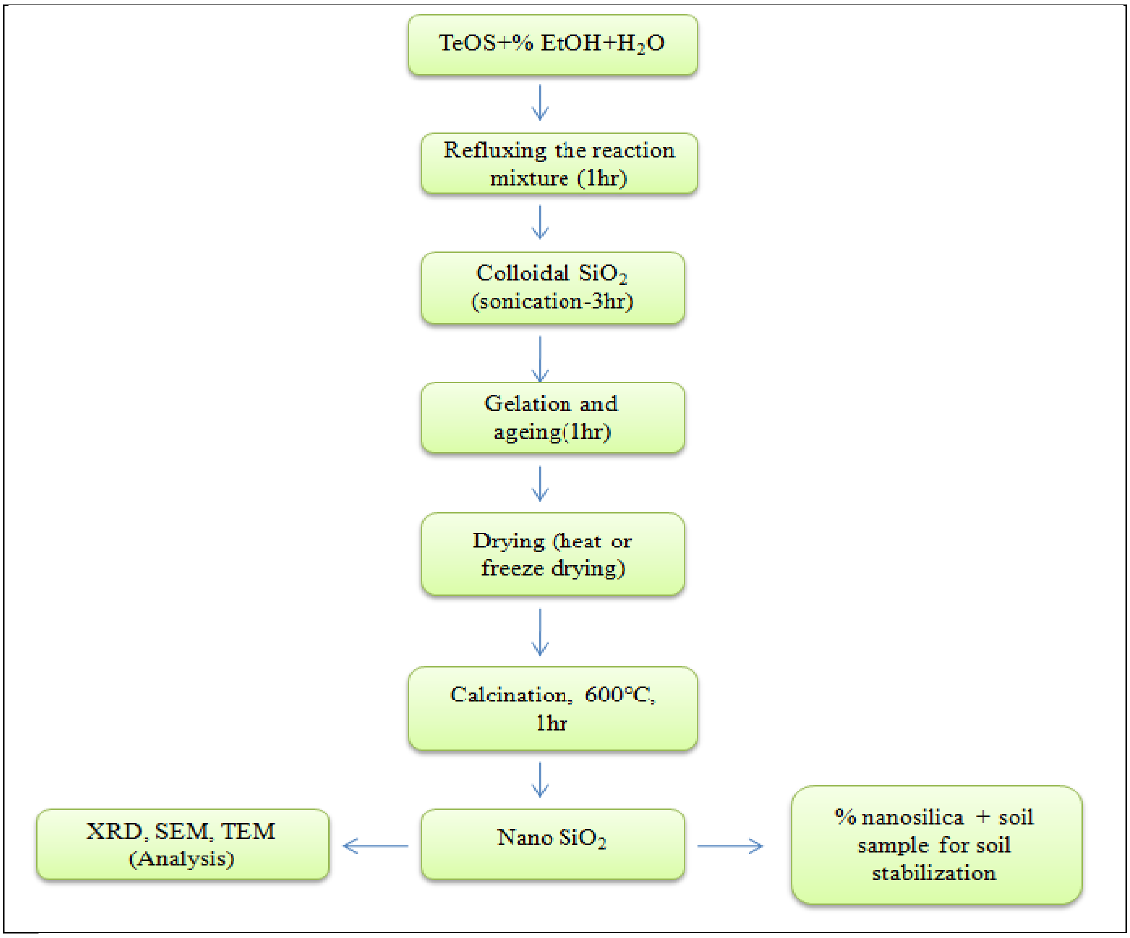


Figure 4a. Schematic presentation of sol-gel technique for the nano-SiO_2 preparation

An increase in the nano-silica content increased the porosity and decreased the average pore diameter. The formation of viscous gel by addition of nano-silica into silty clay enhanced the bonding and filled the gaps between particles of silty clay and blocked the migration of water in the oil. The microscopic pore structure of the sample was generally uniform with increasing nano-silica content, which resulted in an increase in unconfined compressive strength and a decrease in frost heaving displacement. The engineered silica NPs in the soil are absorbed by intergranular water, which causes the pores in the soil to be filled with nanosilica. Research studies show that MPTS/nano-SiO2 has long-term stabilization effects on Cd in agricultural soil and it has the property of potential amendment for the Cd-contaminated agricultural soils (Baragaño, et al., 2021; Kacha, & Shah, 2019; Nazir, 2020; Wang, et al., 2020; Lian, et al., 2021; Boroumand, Behbahani, & Dini, 2020; Wang, et al., 2020).

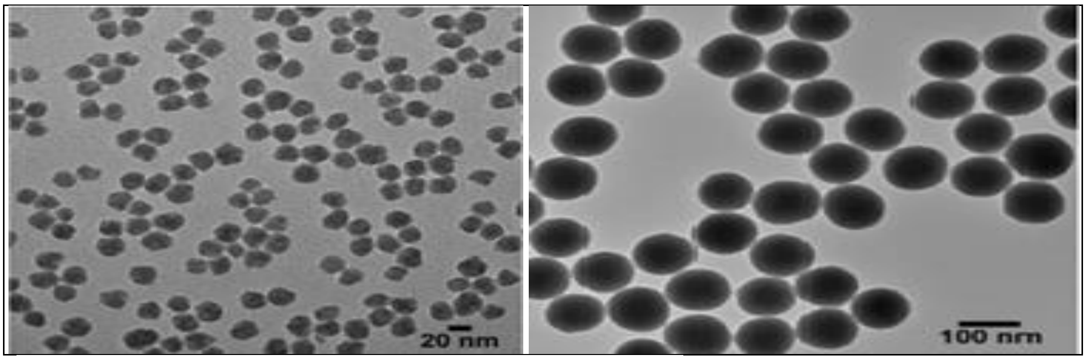


Figure 4b. TEM micrographs of Si nanoparticles

Studies show that TEM micrographs of the Silica nanoparticles are spherical in shape and can be produced at large scale with sizes ranging from 10 nanometers to micrometers in diameter (Figure 4b). The TEM images clearly illustrate that careful control over the growth conditions produces uniform particles with low coefficients of variation (CV). Colloidal silica particles are amorphous, or non-crystalline, meaning that the atoms do not have long-range order, similar to the atomic structure of bulk glass. Due to high ion - charge, silica stabilized soil absorbs hydrated ions and thereby, enhances soil moisture content. Silica nanostabilizers hold promising highly applicable material for weak soil stabilization because of cost-effectiveness, highly durability, and reliable stabilization (Joseph, et al., 2021; Prajapati, & Shankar, 2020; Ramesh, et al., 2010; Lehmann, et al., 2020; Mandal, et al., 2021; Gao, 2021). Recent results show that increase in the percentage in green nanosilica content can steadily boost up the maximum dry unit weight of nanosilica-stabilized soil. The polymer-SiO_2 based multifunctional, with highly active binding sites, nano sized dendritic systems exhibit excellent adsorption properties which could be applied for the removal of heavy toxic metal ions from the soil (Nehra, et al., 2021; Seleiman, et al., 2021). Thus fabricated and engineered nanodendritic systems of desired properties have extensive ability of binding the toxic heavy materials from the soil, thereby improving the soil quality and providing soil stability.

Result and Discussion

Nanostructures and nanomaterials have drawn a lot of attention because of their unique properties due to small size, structurally active binding sites and could be engineered, fabricated as per the desired properties. Research studies show the effect of natural nanoparticles and engineered nanoparticles as well in improving the properties and providing the stability to the soil. The incorporation of specifically fabricated nanoparticles in the soil with intraparticle voids in nano scale, exhibit the higher liquid and plastic limits, and the presence of fibrous nanoparticles enhances the soil shear strength (Gan, Jia, & Yang, 2021; Lowry, Avellan, & Gilbertson, 2019; Ali, Mehmood, & Khan, 2021). The presence of even a small amount of nanoparticles in the soil have significant effect in the physical and chemical behavior and engineering properties of soil. This manuscript emphasizes more on the study of engineered nanomaterials which could result in extraordinary effects on the engineering properties of the soil and provides novel ways to improve the quality of the soil. The study reveals that the fabricated nanomaterials had a huge influence on the compressive strength, permeability, indices, and resistance properties of the soil and desired nanomaterials can be manufactured.

Conclusion

This article emphasizes more on the recent applications of the innovative multidisciplinary nanotechnological skills and methodologies for enhancing the properties of the soil and its application in soil improvement technology. With the increase in the upcoming challenges such as nutritional deficiency, rapid climatic changes, excessive usage of toxic agrochemicals, fertilizers and pesticides, rapid climatic changes, heavy metal contamination of the soil, a very effective and efficient nanotechnological techniques are the need of the hour for the sustainable agriculture which could overcome the disadvantages of the conventional methodologies. Studies also show that various fabricated and engineered nanomaterials like polymeric nanocomposites, Ag nanoparticles, nano alumino silicates, TiO_2 nanomaterials, carbon nanomaterials are extensively used in the soil remediation processes and thus highly applicable in restoring and improving the soil.

Acknowledgement

The authors are thankful to the Indian Council of Agricultural Research (ICAR), Ministry of Agriculture (Govt. of India), for the financial support, Krishi Vigyan Kendra (Ghaziabad) for financial support and also to the scientific research based organization "Catalyse: The Power Foundation, India for organizing the conference "National Conference in "Focus on organic Agri-Enterprise".

References

Abbasi, N., Farjad, A., & Sepehri, S. (2018). The use of nanoclay particles for stabilization of dispersive clayey soils. *Geotechnical and Geological Engineering, 36*(1), 327-335.

Ali, S., Mehmood, A., & Khan, N. (2021). Uptake, Translocation, and Consequences of Nanomaterials on Plant Growth and Stress Adaptation. *Journal of Nanomaterials, 2021*, 6677616. https://doi.org/10.1155/2021/6677616

Baragaño, D., Forján, R., Sierra, C., & Gallego, J. L. R. (2021). Nanomaterials for soil remediation: Pollutant immobilization and opportunities for hybrid technologies. In *Sorbents Materials for Controlling Environmental Pollution* (pp. 701-723). Elsevier.

Boroumand, N., Behbahani, M., & Dini, G. (2020). Combined effects of phosphate solubilizing bacteria and nanosilica on the growth of land cress plant. *Journal of Soil Science and Plant Nutrition, 20*(1), 232-243.

Buazar, F. (2019). Phycosynthesis and enhanced photocatalytic activity of zinc oxide nanoparticles toward organosulfur pollutants. *Scientific Reports, 9*, Article number: 15147.

Bukit, N., Frida, E., & Harahap, M. H. (2013). Preparation Natural Bentonite in Nano Particle Material as Filler Nanocomposite High Density Poliethylene (Hdpe). *Chemistry and Materials Research*, *3*(13), 10-20.

Changizi, F., & Haddad, A. (2016). Effect of nano-SiO_2 on the geotechnical properties of cohesive soil. *Geotech. Geol. Eng.*, *34*, 725-733.

Cheng, G., Zhu, H. H., Wen, Y. N., Shi, B., & Gao, L. (2020). Experimental investigation of consolidation properties of nano-bentonite mixed clayey soil. *Sustainability, 12*(2), 459.

do Espirito Santo Pereira, A., Caixeta Oliveira, H., Fernandes Fraceto, L., & Santaella, C. (2021). Nanotechnology potential in seed priming for sustainable agriculture. *Nanomaterials, 11*(2), 267. doi: 10.3390/nano11020267.

Farooqi, Z. U. R., Qadeer, A., Hussain, M. M., Zeeshan, N., & Ilic, P. (2021). Characterization and physicochemical properties of nanomaterials. In *Nanomaterials: Synthesis, Characterization, Hazards and Safety* (pp. 97-121). Elsevier.

Gan, C. D., Jia, Y. B., & Yang, J. Y. (2021). Remediation of fluoride contaminated soil with nano-hydroxyapatite amendment: Response of soil fluoride bioavailability and microbial communities. *Journal of Hazardous Materials, 405*, 124694.

Gao, C. (2021). Genome engineering for crop improvement and future agriculture. *Cell, 184*(6), 1621-1635.

Guo, F., Aryana, S., Han, Y., & Jiao, Y. (2018). A review of the synthesis and applications of polymer–nanoclay composites. *Applied Sciences, 8*(9), 1696.

Hu, K., Chen, X., Chen, J., & Ren, X. (2018). Laboratory investigation of the effect of nano-silica on unconfined compressive strength and frost heaving characteristics of silty clay. *Soil Mechanics and Foundation Engineering, 55*(5), 352-357.

Huang, Y., & Wang, L. (2016). Experimental studies on nanomaterials for soil improvement: a review. *Environmental Earth Sciences, 75*(6), 497.

Ibrahim, R. K., Hayyan, M., AlSaadi, M. A., Hayyan, A., & Ibrahim, S. (2016). Environmental application of nanotechnology: air, soil, and water. *Environmental Science and Pollution Research, 23*(14), 13754-13788.

Joseph, S., Saianand, G., Benzigar, M. R., Ramadass, K., Singh, G., Gopalan, A. I., ... & Vinu, A. (2021). Recent advances in functionalized nanoporous carbons derived from waste resources and their applications in energy and environment. *Advanced Sustainable Systems, 5*(1), 2000169.

Kacha, S. M., & Shah, S. G. (2019). Review of the Nanomaterials Used for the Soil Stabilization. In *Proceedings of the Indian Geotechnical Conference 2019* (pp. 111-118). Springer, Singapore.

Khalid, N. (2014). Effect of Nanoclay in Soft Soil Stabilization. In *InCIEC* (pp. 905-914).

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, *1*(10), 544-553.

Lian, M., Wang, L., Feng, Q., Niu, L., Zhao, Z., Wang, P., ... & Zhang, Z. (2021). Thiol-functionalized nano-silica for in-situ remediation of Pb, Cd, Cu contaminated soils and improving soil environment. *Environmental Pollution, 280,* 116879.

Lisuzzo, L., Cavallaro, G., Parisi, F., Riela, S., Milioto, S., & Lazzara, G. (2020). Colloidal stability and self-assembling behavior of nanoclays. In *Clay Nanoparticles* (pp. 95-116). Elsevier.

Lowry, G. V., Avellan, A., & Gilbertson, L. M. (2019). Opportunities and challenges for nanotechnology in the agri-tech revolution. *Nature Nanotechnology*, *14*(6), 517-522.

Majeed, Z. H., Taha, M. R., & Jawad, I. T. (2014). Stabilization of soft soil using nanomaterials. *Research Journal of Applied Sciences, Engineering and Technology, 8*(4), 503-509.

Majeed, Z. H., & Taha, M. R. (2013). A Review of Stabilization of Soils by using Nanomaterials. *Australian Journal of Basic and Applied Sciences*, *7*(2), 576-581.

Mandal, S., Pu, S., Adhikari, S., Ma, H., Kim, D. H., Bai, Y., & Hou, D. (2021). Progress and future prospects in biochar composites: application and reflection in the soil environment. *Critical Reviews in Environmental Science and Technology, 51*(3), 219-271.

Mathur, P., & Roy, S. (2021). Insights into the plant responses to drought and decoding the potential of root associated microbiome for inducing drought tolerance. *Physiologia Plantarum, 172*(2), 1016-1029.

Mazloomi, F., & Jalali, M. (2019). Measuring and simulating leaching of nutrients from a calcareous soil amended with sewage sludge and poultry manure. *Authorea*, *15*, 2020. DOI: 10.22541/au.159225108.86020884

McKee, M. S., & Filser, J. (2016). Impacts of metal-based engineered nanomaterials on soil communities. *Environmental Science: Nano, 3*(3), 506-533.

Nazir, R. (2020). Biogenic Nano-Particles and their Use in Agro-ecosystems. In *Green-Nanotechnology for Precision and Sustainable Agriculture* (pp. 317-357).

Nehra, M., Dilbaghi, N., Marrazza, G., Kaushik, A., Sonne, C., Kim, K. H., & Kumar, S. (2021). Emerging nanobiotechnology in agriculture for the management of pesticide residues. *Journal of Hazardous Materials, 401*, 123369.

Paul, R., Karthikeyan, K., Vasu, D., Tiwary, P., & Chandran, P. (2021). Origin and mineralogy of nano clays of Indian Vertisols and their implications in selected soil properties. *Eurasian Soil Science, 54*(4), 572-585.

Piplai, T., Parsai, T., Kumar, A., & Alappat, B. J. (2020). Understanding Interactions of Nanomaterials with Soil: Issues and Challenges Ahead. *Environmental Nanotechnology, 3*, 117-141.

Prajapati, M. K., & Shankar, K. (2020). Application of Nanotechnology in sustainable agriculture and its current status. *Indian Farmer*, 7(10), 932-941.

Pramanik, P., Ray, P., Maity, A., Das, S., Ramakrishnan, S., & Dixit, P. (2020). Nanotechnology for Improved Carbon Management in Soil. In *Carbon Management in Tropical and Sub-Tropical Terrestrial Systems* (pp. 403-415). Springer, Singapore.

Qian, Y., Qin, C., Chen, M., & Lin, S. (2020). Nanotechnology in soil remediation−applications vs. implications. *Ecotoxicology and Environmental Safety, 201*, 110815.

Raja, M. A. & Husen, A. (2020). Nanomaterials for Agriculture and Forestry Applications. *Micro and Nano Technologies*, 491-503.

Ramesh, K., Biswas, A. K., Somasundaram, J., & Rao, A. S. (2010). Nanoporous zeolites in farming: current status and issues ahead. *Current Science, 99*(6), 760-764.

Sarkar, S., Datta, S. C., & Biswas, D. R. (2014). Synthesis and characterization of nanoclay–polymer composites from soil clay with respect to their water-holding capacities and nutrient-release behavior. *Journal of Applied Polymer Science, 131*(6).

Seleiman, M. F., Almutairi, K. F., Alotaibi, M., Shami, A., Alhammad, B. A., & Battaglia, M. L. (2021). Nano-fertilization as an emerging fertilization technique: why can modern agriculture benefit from its use?. *Plants, 10*(1), 2.

Tabarsa, A., Latifi, N., Meehan, C. L., & Manahiloh, K. N. (2018). Laboratory investigation and field evaluation of loess improvement using nanoclay–A sustainable material for construction. *Construction and Building Materials*, *158*, 454-463.

Tahir, M. B., Sagir, M., & Asiri, A. M. (2021). Photocatalyst of waste water treatment. *Current Analytical Chemistry*, *17*(2), 138-149(12).

Vani Padmaja, G. (2015). Preparation of Orthosilicic Acid by Sol-Gel Technique using tetraethyl orthosilicic acid (TEOS) and its applications. *IJSRP*, *5*(8), 2250-3153.

Vani Padmaja, G., & Shruti, S. (2020). Engineered nanoparticles in air pollution remediation technologies. *Research Journal of Chemistry and Environment*, *24*(5), 148-151.

Wang, Y., Liu, Y., Zhan, W., Niu, L., Zou, X., Zhang, C., & Ruan, X. (2020). A field experiment on stabilization of Cd in contaminated soils by surface-modified nano-silica (SMNS) and its phyto-availability to corn and wheat. *Journal of Soils and Sediments, 20*(1), 91-98.

Wang, Y., Liu, Y., Zhan, W., Zheng, K., Lian, M., Zhang, C., ... & Li, T. (2020). Long-term stabilization of Cd in agricultural soil using mercapto-functionalized nano-silica (MPTS/nano-silica): A three-year field study. *Ecotoxicology and Environmental Safety, 197*, 110600.

Wu, F., Jiao, S., Hu, J., Wu, X., Wang, B., Shen, G., ... & Wang, X. (2021). Stronger impacts of long-term relative to short-term exposure to carbon nanomaterials on soil bacterial communities. *Journal of Hazardous Materials, 410*, 124550.

Yang, K., & Tang, Z. (2012). Effectiveness of fly ash and polyacrylamide as a sand-fixing agent for wind erosion control. *Water, Air, & Soil Pollution*, *223*(7), 4065-4074.

Zaytseva, O., & Neumann, G. (2016). Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications. *Chem. Biol. Technol. Agric., 3*, 17.