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Soil Degradation under a Changing Climate: Management from Traditional to Nano-Approaches

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IN THE ERA of anthropogenic climate change, soil and other compartments of the agroecosystem suffer from various forms of degradation, meaning there is an urgent need for appropriate soil management. Under arid and semi-arid conditions, the degradation of soil and water are particularly severe globally, causing a decline in agricultural productivity. Soil degradation has led to decreased soil quality, global food insecurity, ecosystem health problems, and non-sustainable development issues. Several human activities have worsened soil degradation, especially under global climate change. With growing interest in nanotechnology, can this science offer solutions/approaches to engineer soil and water amendments to overcome soil degradation and water scarcity? What are the possible nanomaterials and their mechanisms that might be used to protect the environment. This study focuses on soil degradation causes and consequences, as well as different management approaches including traditional, geographic information systems and remote sensing, and nano approaches for the management of soil degradation. Soil degradation that may be experienced after the intensive application of nanomaterials is a major concern that urgently needs to be researched. There is also a need to assess the long-term environmental impacts of nanoparticles, which may have potential for leaching and accumulation in soil from which they enter the food chain, causing many problems for human health.

Keywords: Nano-agriculture, Nanotoxicity, Water security, Food security, Global warming, Chilling stress, Cold stress.

1. Introduction

Soil is the most vital component of the global ecosystem that supports us directly and indirectly. It supplies needs ranging from food to clean water, energy, clothing, and shelter. Soil is a non-renewable natural resource that must be conserved and maintained. Soil is controlled by the soil-forming factors (parent material, time, topography, organisms, and climate; Figure 1) and management can mimic or alter these factors. So, soil management should include a focus on climate change mitigation (Certini and Scalenghe 2023). Several studies have focused on the impact of climate change on soil with themes such as climate change and soil viral diversity (Jansson and Wu 2023), impacts of climate change on agroecosystems (Bao et al. 2023), climate change and soil microbiome feedback (Mukhtar et al. 2023), the crucial interactions between climate and soil (Certini and Scalenghe 2023), role of soil microplastic pollution in climate change (Chia et al. 2023), climate change on soil biodiversity (Leal Filho et al. 2023), role of pollutants on soil microbial communities under climate change (Wang et al. 2024), and changing precipitation and ecosystem multifunctionality (Zhai et al. 2024). A healthy soil ecosystem is crucial for sustainable development and food security in rural areas (Guo and Liu 2022). How-

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ever, rapid urbanization and intensive agricultural activities have led to the degradation and pollution of agricultural soil (Wang et al. 2024).

Soil degradation is defined as “a change in soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries” (FAO 2020). It leads to the physical, chemical and biological decline in soil quality (Lal 2022), causes a decline in soil fertility (Wang et al. 2021), loss of soil organic matter (Gregory 2023), erosion (Lal 2022), adverse changes in acidity, salinity or alkalinity (Xu et al. 2023), excessive flooding, and/or the accumulation of toxic chemicals and pollutants (Liu et al. 2023). Many recent books have been published focusing on soil degradation issues such as soil management and climate change (Muñoz and Zornoza 2018), the impact of agriculture on soil degradation (Abdullahi et al. 2023; Pereira et al. 2023; Ganzour et al. 2024; Sári et al. 2024a), global degradation of soil and water resources (Li et al. 2022), and increasing understanding of soil degradation (Saljnikov et al. (2022a).

Therefore, this mini-review focuses on soil degradation under changing climate. The causes and consequences of soil degradation along with hazards and management using different approaches will be highlighted. Geographic information systems (GIS) and remote sensing (RS) as well as nano-management will be also discussed.

2. Soil under climate change

Soil is the most important part of our global land resources. It is the upper-most layer of earth and functions as a living organism or symbiotic system. Soil has many functions that can be grouped into the following domains: (1) Soil is the main source for biomass production from plants/crops for food, feed, fiber and renewable energy. (2) Soil can filter and buffer organic and inorganic components to remove pollutants from the environment or isolate pollutants from organisms. (3) Soil is the main reservoir of gene and biodiversity from plants, animals, and microorganisms. (4) Soil is the foundation for residential, technical, and industrial structures and infrastructures. (5) Soil is a major source of materials and minerals. (6) Soil is a reservoir of natural and cultural heritage, such as for the Egyptian civilization and its early irrigation systems. (7) Soil has the ability to regulate biochemical processes by cycling nutrients, water and carbon, and energy through the biosphere, pedosphere, atmosphere, and hydrosphere (Saljnikov et al. 2022b).

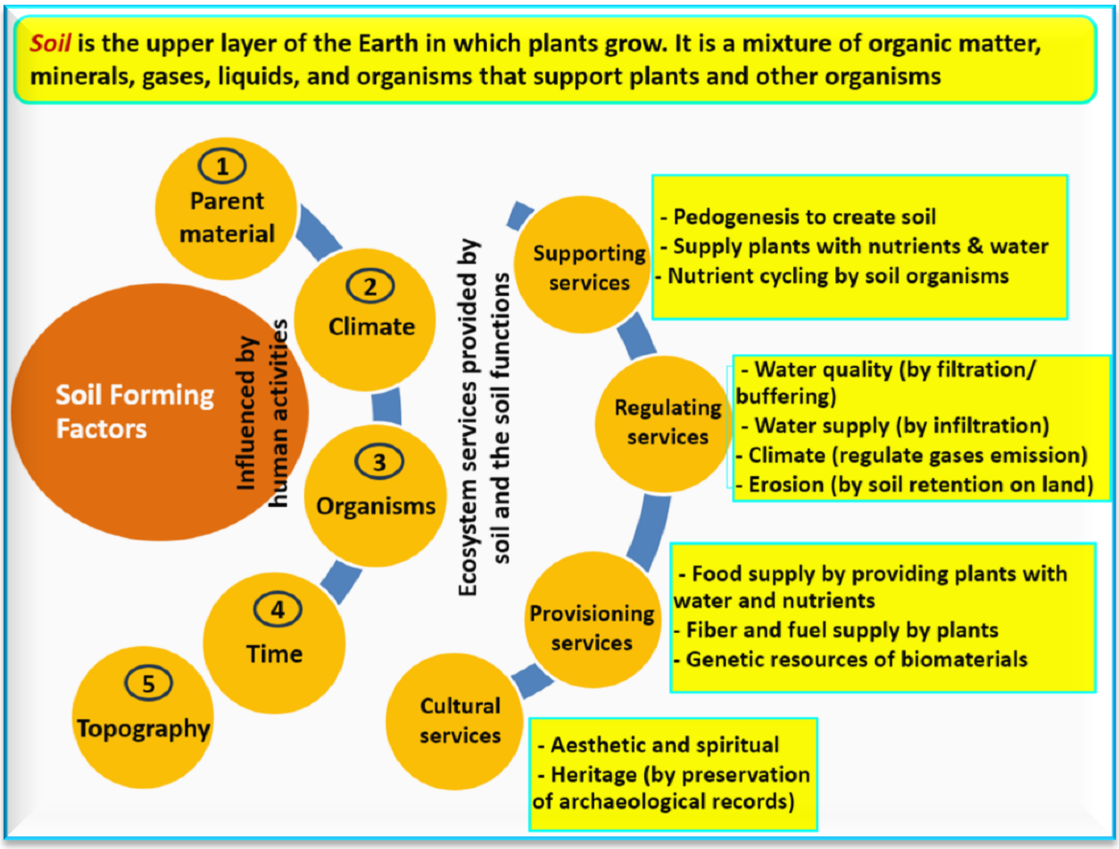

Fig. 1. Soil definition, its forming factors, and different soil functions.

There are strong interactions between soils and climate in both directions, that is, soils influence climate and climate influences soils (Brevik 2012). Climate is one of the main factors controlling soil formation, which means climate change has many impacts on soil and its productivity. Soil in warmer or wetter climates develops more rapidly than soils in cooler or drier climates, and each climate type has certain common distinguishing characteristics. The increase in atmospheric temperature with global climate change averages 0.2°C/decade (Lal 2020). Greenhouse gases, mainly carbon dioxide, now make up more than 417 ppm in Earth's atmosphere (Du et al. 2022). Global depletion of soil-organic carbon stock is estimated at 133 Pg C due to historic land use changes and corresponding soil degradation (Lal 2020). The role of soil in climate change mitigation through carbon sequestration has been confirmed by many workers (e.g., Kaith et al. 2023; Liu et al. 2023; Pant et al. 2023). Themes in soil carbon sequestration research has included organic carbon sequestration under perennial energy crops (Xu et al. 2024), factors that drive organic carbon sequestration under various manure treatments (Ren et al. 2024), and impacts of water deficit on carbon sequestration under old apple orchards (Li et al. 2024), among many others. In another study, the cultivation of Miscanthus and witchgrass in marginal land enhanced soil carbon sequestration depending on root biomass and quality (Xu et al. 2024).

3. Soil degradation causes and consequences

Due to intensive human activities, including agriculture and industrialization, several environmental problems have developed. These problems have caused degradation of natural resources including soil (land), water, and air. According to FAO, soil degradation is defined as "*a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries*" (FAO 2020). Soil degradation could be referred as a decline in soil quality and its functionality caused by natural and/or anthropogenic processes (Figure 2). Major processes of soil degradation may involve physical, chemical, physico-chemical, biological, hydrological and ecological attributes (Kogut 2023). Different classifications and types of soil degradation that cause harmful impacts on ecosystem health, global food security, and sustainable development are shown in Table 1. Degrees of soil degradation can be determined by comparison with a reference non-degraded soil and include weakly (<10%), moderately (10–25%), strongly (26–50%), and very strongly (>50%) degraded, and degradation rates can be grouped as slow (> 20 years), accelerated (10–20 years), and fast (<10 years) (Mamontov 2022). Different soil processes under degradation and their consequences were reported by Lal (2022) (Figure 3). Many human activities might cause adverse impacts on soil and cause its degradation. These activities include urbanization, agro-industrialization, deforestation, overgrazing, and poor farming practices (Kogut 2023).

It is important to reduce soil degradation as much as possible. Reduction strategies include the use of conservation tillage techniques (e.g., no-till or reduced tillage), crop rotations, avoiding over-irrigation, and proper fertilizer management, with one of the main goals being to increase SOM (Duchene et al. 2023; Dutta et al. 2023). It is important for farmers to watch closely for early warning signs of degradation and implement smart farming techniques (Keshavarz and Sharafi 2023) and nanotechnology (Chi et al. 2020; El-Ramady et al. 2023) guided by tools such as GIS (Abdi et al. 2023) to counter degradation.

Table 1. Degradation classifications for irrigated soils (adapted from Mamontov 2022; Kogut 2023).

Classification type	Reasons and consequences
Physical	Depletion of fertile topsoil up to total loss due to physical impacts (flooding, surface run-off, landslides, wind, intensive tillage, heavy machinery use). Long-term physical degradation harms soil fertility, composition, and soil structure.
Chemical	Unfavourable changes in soil chemistry, particularly those caused by synthetic fertilizers and pesticides, that diminish plant nutrition: beneficial microbes and humus content decline; and soil pH shifts outside of desirable ranges.
Physico-chemical	Irrigation induced alkalization, and magnesium-based alkalinity; reduction of CEC and buffering; alkalization and acidification
Ecological	Decreased land productivity due to environmental factors, mainly climate change (altered precipitation patterns, increasing temperatures, extreme weather events). Deforestation and the loss of ground cover contribute to the ecological degradation of soil by exposing it to erosion and causing disruptions in ecosystems.
Biological	Decreased microbial activity due to destructive biochemical reactions, especially in bare/unprotected soil, reduces yields and makes land less amenable to crop production
Hydrological	Hydrological soil degradation develops due to excessive irrigation or raised water tables that create excess moisture within the soil profile causing over-wetting and waterlogging

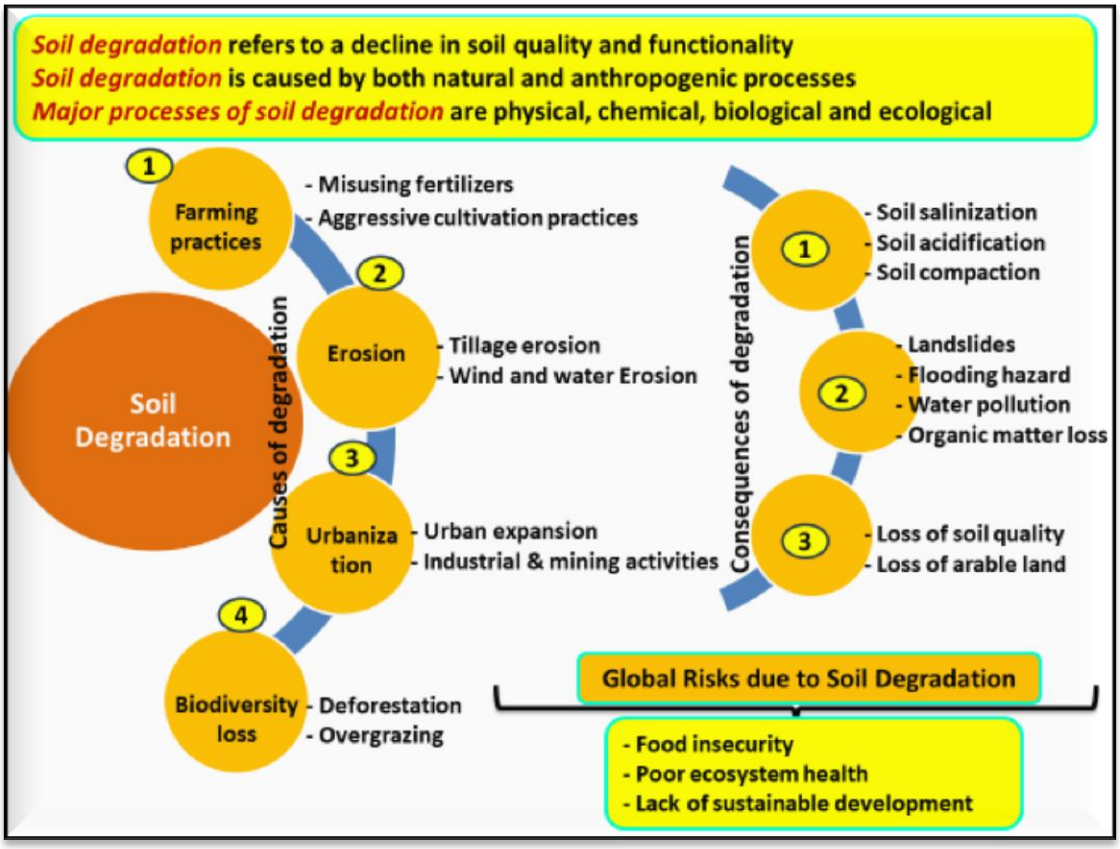

Fig. 2. A graphical depiction of the definition of soil degradation, its causes, and consequences.

4 .Soil degradation management

4.1 Traditional approaches

There are many approaches that can prevent or minimize the damage from soil degradation. Traditional approaches include conservation tillage (Ding et al. 2023), integrated soil fertility management (Dutta et al. 2023), improvement of soil properties and reclamation (Yang et al. 2023), sustainable land management (Pompeu et al. 2023), and irrigation system management (Andrews et al. 2022). Conservation tillage and application of biochar are common strategies to enhance both SOC content and microbial growth / diversity, which causes improvement of soil physical, chemical, and biological properties (Ding et al. 2023). Sustainable land management (SLM) practices are comprehensive management of all available natural resources to improve livelihoods, support watershed management, and organize different land uses (forestry, pasture, agriculture) in an integrated way to strengthen soil ecosystem services as well as combat and adapt to local climate change (Pompeu et al. 2023).

4.2 GIS and remote sensing

Soil degradation has many consequences including acidification, salinization, soil erosion, desertification, nutrient deficiency, compaction, and heavy metal pollution (Wang et al. 2023). Over the last few years, improvements in remote sensors coupled with advancements particularly in computer science and GIS have led to improved earth observing capabilities, including the mapping of spatially distributed phenomena such as land degradation (Makaya et al. 2019). Recent advances in algorithm development and the rise of cloud-based computing and storage capacity have greatly enhanced the application potential of RS for soil degradation studies (Fu et al. 2021; Shokr et al. 2022; Elseedy et al. 2024). Remote sensing technology is more cost and time effective as a large area of land can be monitored for land degradation compared to direct field observation (Kumsa and Assen 2022). In essence, the extraction of information to measure soil degradation is an inversion process based on RS data and mathematical models. Although the current number of earth observation satellites has increased sharply, the temporal resolution and availability of satellite sensors with an extremely high spatial resolution (<10 m) are usually insufficient, limiting their capability in soil degradation monitoring. Compared to traditional satellite platforms, Unmanned Aerial Vehicles (UAV) can operate at low altitudes (5–200 m) and avoid the effects of cloud cover to a certain extent, presenting clear spatiotemporal advantages (Krenz et al. 2020) . Remote sensing technology, particularly on a large scale, can serve as an effective alternative to field investigation. With recent advances in earth observation and imaging technology, remotely sensed satellite imagery with high spatio-temporal and spectral resolution is more accessible than ever before (Zhou et al. 2020). Additionally, there are different ways to classify RS-based data, such as the energy type (passive or active sensors), the platform (ground-, air, or space-borne), the region of the spectrum (optical, thermal infrared, and microwave), and the spectral bands (panchromatic, multi-spectral, hyperspectral) (Li et al. 2021). Compared to conventional field soil investigation, RS presents a series of superiorities: wide view field, high efficiency, low cost, real-time information acquisition and periodic surface coverage (Figure 4; Wang et al. 2023). Despite these advantages, it is crucial to include adequate soil sampling for validation in any RS based study (Brevik et al. 2016; Diaz-Gonzalez et al. 2022).

Methods for studying land degradation using RS data and GIS depends on the satellite images, which can be analyzed using RS programs (e.g., ENVI software) and then entered into GIS programs (e.g., ArcGIS) to make prediction maps (IDW) to produce soil degradation maps. Digital image processing (DIP) describes the procedures and methods followed to transform raw multispectral imagery and space borne data into enhanced products that can be useful in surficial mapping. Basically, DIP deals with four topics: (1) radiometric corrections (2) geometric corrections, (3) image enhancement, and (4) image classification. For preprocessing, processing and analyses of Landsat 8 images ENVI software is often used. GIS can be used to produce interpolation maps of soil parameter through a variety of algorithms in the software. In general, these techniques are based on calculations for each grid node by considering surrounding points (Wang et al. 2023), with the exact details depending on the type of interpolation used.

Application of RS and GIS to study soil degradation depends on the monitoring and modelling of different processes that can provide a better understanding of the causes of soil degradation. These models are also considered important guides to the implementation of preventative and restorative soil degradation strategies. These models differ depending on the studied soil degradation issue, such as soil erosion. Many models or indices have been applied in the study of soil erosion such as the Wind Erosion Equation (WEQ), Revised Wind Erosion Equation (RWEQ) and Wind Erosion Predication System (WEPS), Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), and improved Revised Universal Soil Loss Equation RUSLE2, Water Erosion Prediction Project (WEPP), Système Hydrologique Européen (SHE), European Soil Erosion Model (EUROSEM), Soil Erosion Model for Mediterranean regions (SEMMED), Chemicals Runoff, and Erosion from Agricultural Management Systems (CREAMS), and the (Brevik et al. 2017; Wang et al. 2023).

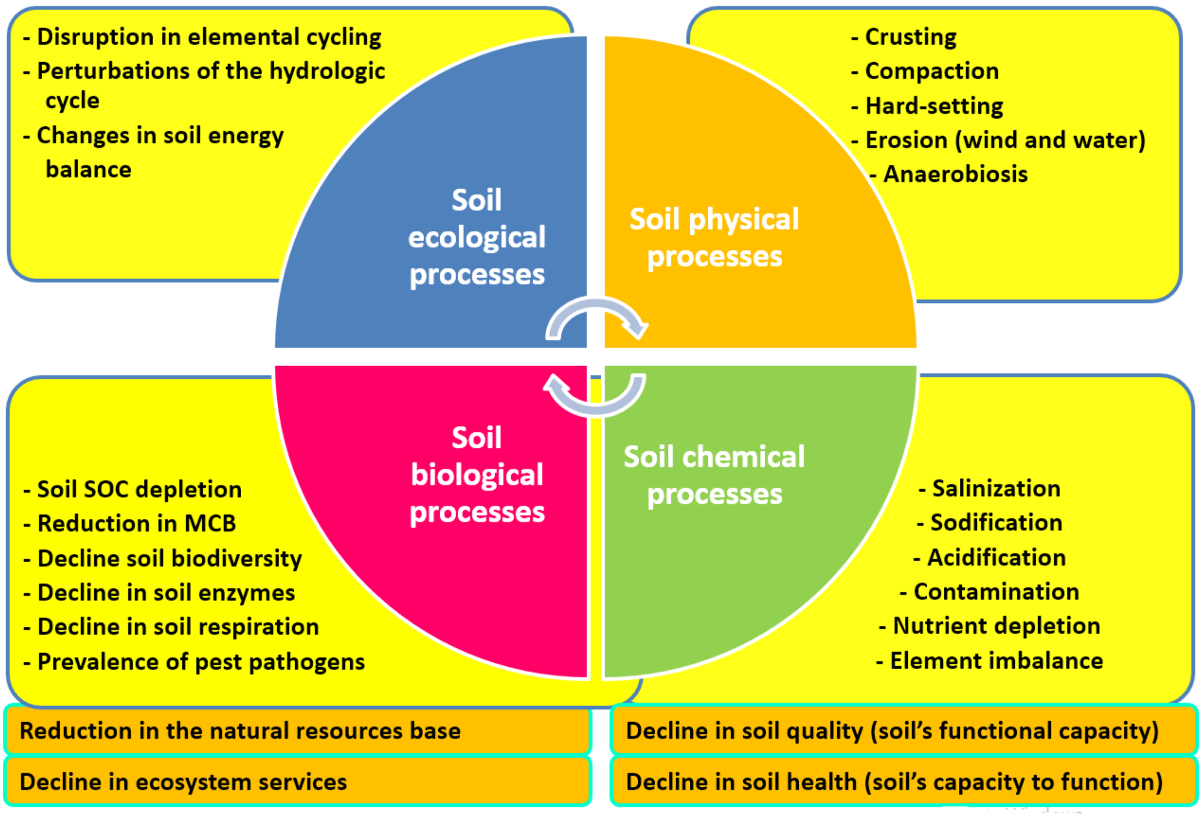

Fig. 3. Different soil processes under degradation and the resulting consequences (adapted from Lal 2022). Abbreviations: SOC, soil organic carbon; MCB, microbial C-biomass.

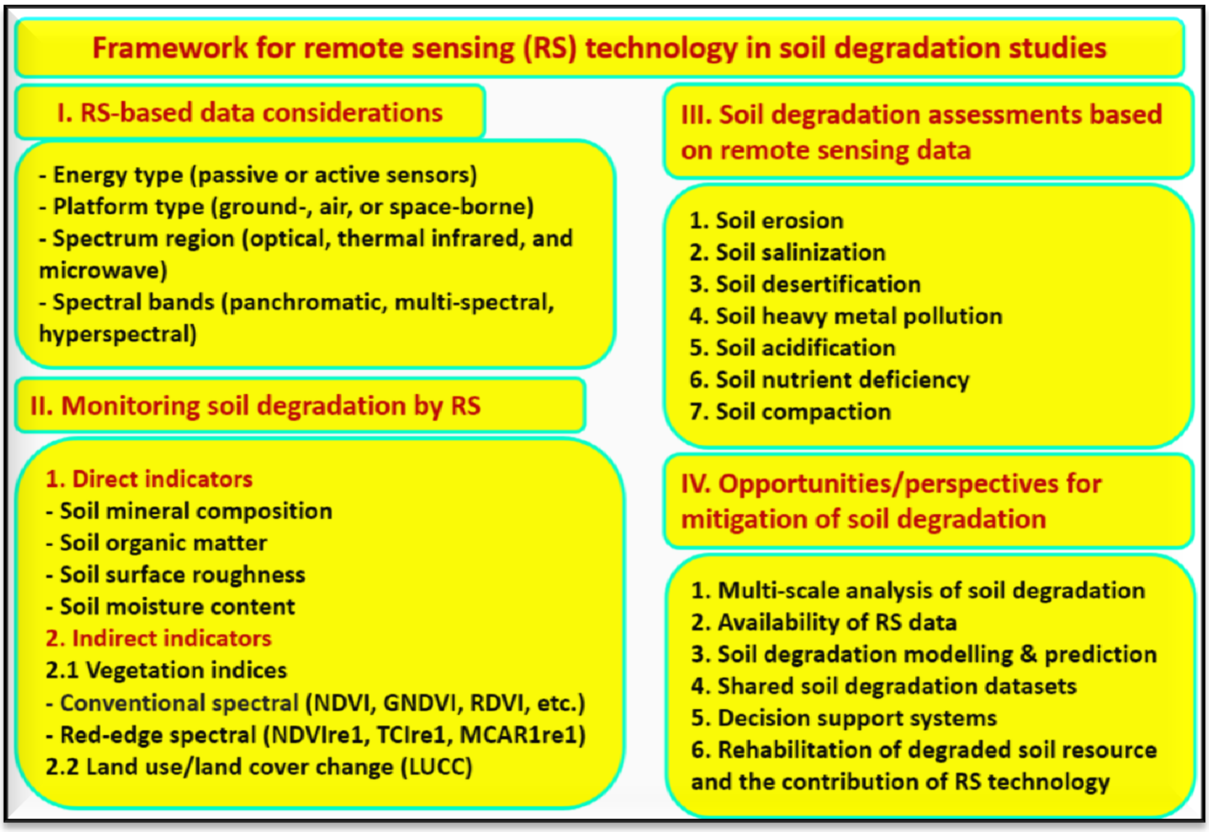

Fig. 4. Remote sensing-based data in soil degradation studies, different monitoring approaches, and different assessments, as well as opportunities for mitigation (adapted from Wang et al. 2023).

4.3 Nano-management of soil degradation

Tools important for the nano-management of soil degradation are summarized in Figure 5. Nanofertilizers (NF) can be used to supply crops with their needed nutrients at the right time, place, form, and dose. There are many types of NF based on the kind of nanoparticles (NPs) and size of NPs. The application rate depends on the type of NF as well as the crop species and soil characteristics (mainly soil pH, electrical conductivity, texture, cation exchange capacity, organic matter content, etc.). Several published studies have confirmed the potential role of NPs in improving soil conditions and plant performance when applied at the right dose/time/form and place (Table 2). The NF are available in different forms (mineral, organic, biological and nano-fertilizers) (Figure 6). The main factors influencing their effectiveness are related to the properties of the soil, crops, and applied NF. This may explain whether NF can solve the soil degradation problem or relieve other stressful conditions (Barłóg et al. 2022). Many recent reports confirmed the positive role of NF at alleviating a variety of stresses by enhancing biological processes in crops, including germination, seedling stage, flowering, fruiting, and even post-harvest (e.g., Shalaby et al. 2022; Abdel-Aziz et al. 2023). Several studies on nano-management can be found with focus on different topics such as agro-wastes (El-Ramady et al. 2020), carbon sequestration (El-Ramady et al. 2021), crop production (Singh et al. 2024), mitigation climate change (Sári et al. 2024b).

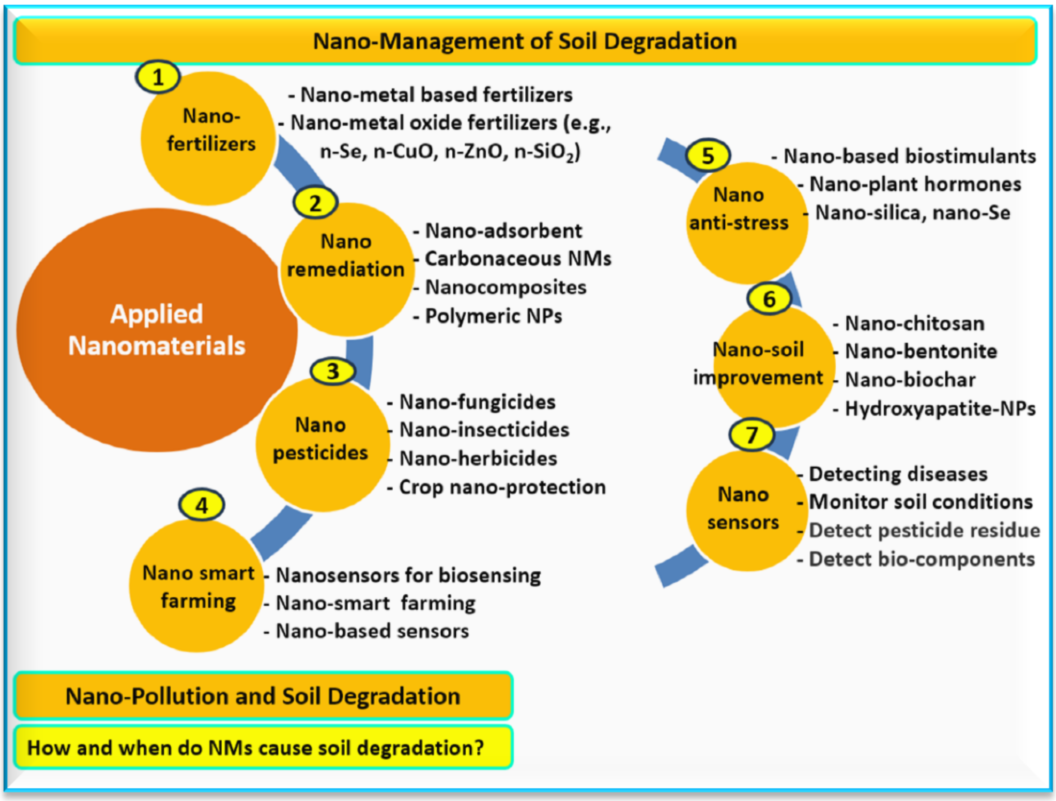

Fig. 5. Ways that nano-management may help address soil degradation.

Table 2. The role of nanomaterials (NMs) in fighting stresses that result from soil degradation.

Applied NMs	Degradation type	Role of applied NMs	Reference
Functional carbon nanodots	Soil polluted with Cd and Pb	Improved plant root growth, activated plant HM- detoxification and induced soil enzyme activities associated with soil nutrient recycling, up-regulated the microbial diversity and the soil immune system	Cao et al. (2024)
Nano-gypsum (1.0 – 2.0 %)	Degraded and soft soil	A combination of cement and nano-gypsum led to remarkable improvement of geotechnical and mechanical properties and durability of soft soil	Haji and Mir (2023)
Nano-ZnO (50 - 1000 mg Zn kg^{-1})	Nano pollution	Nano ZnO was toxic leading to soil pollution, unstable bacterial communities, and decoupling of taxonomic and functional diversities compared to the bulk soil	Dinesh et al. (2023)
Biochar and bentonite-supported nano zero-valent iron	Multi-metal contaminated soil (Pb, Cr, Cd)	The nano-form increased immobilization of Cd, Cr, and Pb by reduction, adsorption, co-precipitation, and complexation of the metals; enhanced soil enzyme activities (urease, dehydrogenase, and fluorescein diacetate hydrolase), and microbial activity	Jin et al. (2023)
Attapulgite based nano-enabled glyphosate	Glyphosate-polluted soil	The slow release of attapulgite based nano-enabled glyphosate improved soil phosphatase activity, the organic P-pool, and proliferation of the soil bacterial community	Hou et al. (2023)
Nano-biochar	Microplastic contaminated soil	Nano-biochar was effective at removing antibiotic resistant genes (ARGs) in microplastic polluted soil by decreasing horizontal gene transfer of ARGs, potential host-bacteria abundance, and promoting soil properties (pH, DOC, and NH_4^+-N)	Su et al. (2023)
Rhamnolipid modified nano zero-valent iron (nZVI)	Ni-polluted soil	Nano-Fe enhanced recovery of soil bacterial community diversity, reduced the toxicity of nZVI and decreased Ni leachate. The dominant bacteria were *Firmicutes*, *Proteobacteria* and *Actinobacteria* under stress	Zhao et al. (2023)
Nano-gypsum	Soil salinity and land degradation	Nano-gypsum reduced soil pH, EC and SAR by providing Ca^{2+} to replace Na^+ on the exchange sites and improving soil health	Patle and Sharma (2022)
Nano-gypsum (120-960 kg ha^{-1})	Saline-sodic soil	Nano-gypsum at 240 kg ha^{-1} improved hydro-physical, chemical soil properties and spinach growth comparing with other doses and both control and conventional gypsum rates	Salama et al. (2022)

Abbreviations: EC (electrical conductivity), SAR (sodium adsorption ratio), DOC (dissolved organic carbon)

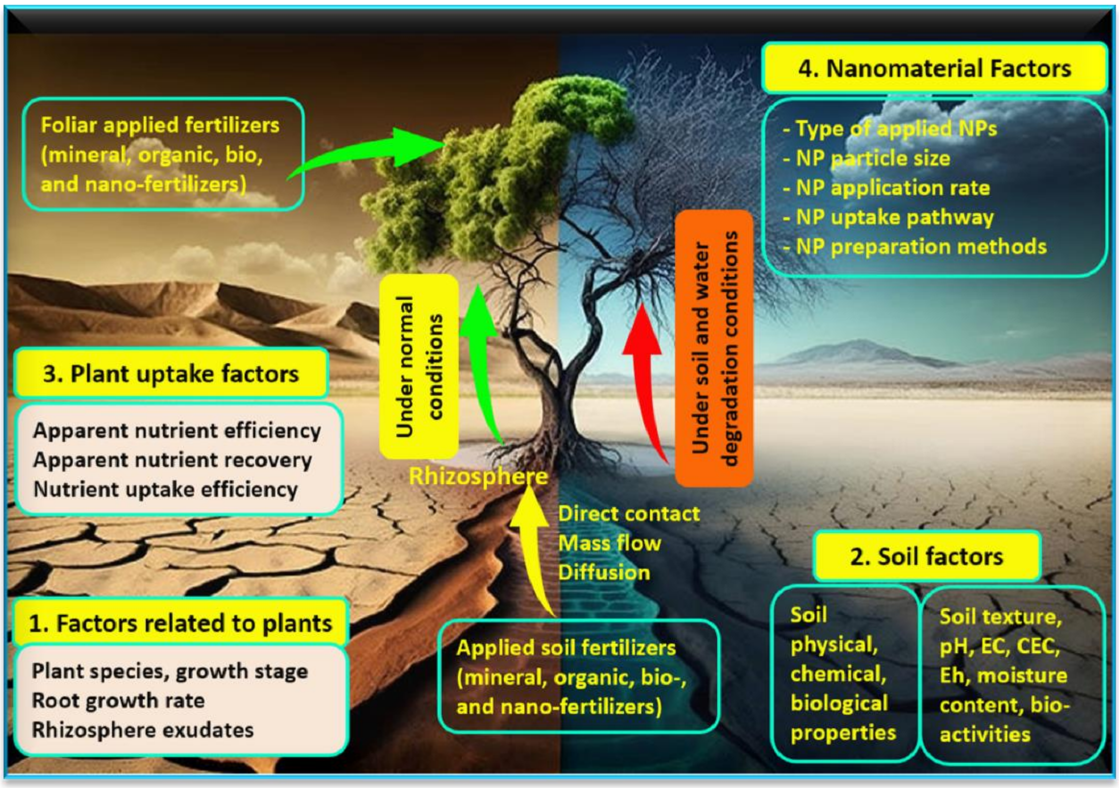

Fig. 6. Nano-pathways of nano-fertilizers that may be used to combat soil and water degradation and factors that control their effectiveness. Abbreviations: NPs (nanoparticles), pH (potential of hydrogen in the soil), EC (electrical conductivity, a measure of soil salinity), CEC (cation exchange capacity), Eh (redox potential), bio (biological).

NPs applied to degraded soil can improve soil structure by increasing aggregate stability and through that increase water retention in sandy soils (Chaudhary et al. 2023). Moreover, NPs can alter the distribution of soil pore sizes, influencing water movement, root penetration, and nutrient diffusion (Kalhor et al. 2022). Nanonutrients can act as carriers of essential nutrients for crops and enhance nutrient use efficiency, ensuring controlled release and targeted delivery to plant roots. Carbon nanomaterials are an emerging soil amendment to enhance soil fertility in sandy soils at application rates of 200 to 400 ppm, which can increase crop biomass and improve crop physiology and soil biochemical quality by increasing soil N and K availability in soil along with crop nutrient uptake (Nepal et al. 2023). Nanosilica is a promising soil stabilizer that can improve soil strength, hydraulic conductivity, and compressibility (Kannan and Sujatha 2022). There is an urgent need to integrate nanotechnology with traditional practices on the farm level. This may maximum the role of NPs in mitigating climate change and enhancing resilience.

Despite their potential to help solve a range of soil degradation issue, there are still many questions with NMs. When do NMs applied for soil remediation or as nano-agrochemicals cause serious problems leading to soil degradation? What are the ethical and social issue considerations that need to be addressed? Questions like these represent a great challenge that faces researchers and requires much more investigation Anything that leads to soil degradation should try to be avoided. Despite considerable progress in the field of plant breeding and the continual release of new varieties, the real improvement in nutrient use efficiency is small. To guide selection of suitable varieties for the actual climatic and soil conditions of a given farm many items should be considered, such as (1) identifying soil conditions that constrain crop growth, (2) growth and architecture of the crop’s root system, and (3) the availability of water and nutrients (Barłóg et al. 2022).

5. Conclusions

Climate change is a crucial challenge. Addressing it will require more effort at the farm level from researchers, farmers, and policy makers. Soil degradation can occur and be quite severe under climate change. Changes in soil quality status can result in diminished ecosystem capacity to provide goods and services. Soil degradation is a complex and dynamic process that includes past, present, and future degradation processes. Soil degradation mechanisms are divided into physical-, chemical-, ecological, and biological-degradation. The main consequences of soil degradation include acidification, erosion, salinization, desertification, nutrient deficiency, compaction, and heavy metal pollution. The effective and rapid assessment of soil degradation to inform soil management to prevent and remediate degraded soils has attracted a great amount of attention from scholars and governments. The traditional approaches to mitigate soil degradation focus on items such as conservation tillage, integrated soil fertility management, improvement of soil properties and reclamation, sustainable land management, and irrigation system management. The nano-approaches focus on the application of nanomaterials (especially nano-agrochemicals including nanofertilizers and nano-pesticides) to ameliorate the impacts of degradation soil and water. This is a very rich area of future investigation to determine the right time, dose, and place to utilize NMs. However, it is also important to recognize that NMs carry their own pollution and degradation risks, and these must also be investigated to inform best management practices of NM use in agroecosystems.

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