Chapter 3

Nature-Based Solution and Regenerative Circular System Design towards Agricultural Land Management Bioremediation: A Review

Ade Brian Mustafa

A. Sustainability of Agricultural Soils

Agriculture is expected to assist countries in achieving multiple development goals nowadays. These objectives include food security, increased employment, environmental stewardship, and lower poverty and undernourishment rates (Otsuka, 2021). Agricultural land resources should be used to ensure the sustainability of the living environment, preserve biological balance, and increase soil resource quality. Sustainable agricultural development refers to the ability to use agricultural land indefinitely and the application of effective and efficient agricultural land utilization (Nasikh et al., 2021). The world's rapidly growing population has placed additional strain on the soil resource to meet increased demand for food, fiber, and soil-derived

A. B. Mustafa
Shanghai Jiao Tong University, China, e-mail: adebrianmustafa@gmail.com

Mustafa, A. B. (2022). Nature-based solution and regenerative circular system design towards agricultural land management bioremediation: a review. In R. Trialih, F. E. Wardiani, R. Anggriawan, C. D. Putra, & A. Said (Eds.), *Indonesia post-pandemic outlook: Environment and technology role for Indonesia development* (27–48). DOI: 10.55981/brin.538.c502
ISBN: 978-623-7425-85-4 E-ISBN: 978-623-7425-89-2

materials. Novel approaches are needed as a result of such pressures. Increased and intensified agricultural production has pressured the soil to its limits in many parts of the world, resulting in soil degradation and, eventually, the loss of agricultural land (Pozza & Field, 2020).

Agriculture is reliant on healthy soils, and both are required for food security (Hurni et al., 2015). There is substantial evidence that farming intensification has a negative impact on soil diversity, which may have implications for present and future food security. For example, intensive soil use as agricultural expansion in Brazil's Maranhão, Tocantins, Piauí, and Bahia (MATOPIBA) region induced changes in soil physical properties to critical levels, reducing soil physical quality, and limiting soil functions such as plant growth, water availability, air diffusion, and soil resistance to degradation (Santos et al., 2021). It also indicated that long-term agricultural land usage altered soil bacterial and archaeal communities, as well as their potential N cycle functions in both bulk soil and rhizosphere (Merloti et al., 2022). Both the preservation of considerable levels of functional biodiversity in the soil and the management of functional diversity above the surface are intimately intertwined. Both are extremely susceptible to changes in the soil ecosystem (El Mujtar et al., 2019). In addition, more evidence and instruments are needed to establish legislative and regulatory coherence to fulfill the SDGs, which are inextricably linked, whether they are for achieving food security or sustainability on Earth (Vidar, 2021).

The multitude of artificial chemicals is growing by the day, and many of them are recalcitrant, with the majority of them being xenobiotic. Pesticide demand has increased from 0.2 million tons in 1950 to 5 million tons in 2000, according to a Food and Agriculture Organization (FAO) report, resulting in the loss of arable land, the death of non-targeted bacteria, birds, and native wildlife, and posing a risk to humans. It is estimated that 10 million tons of harmful chemicals are emitted into the environment each year. These contaminants are carcinogenic and long-lasting, wreaking havoc on ecosystems, jeopardizing environmental health, and causing harm to all living creatures (Arora, 2018).

Most agricultural approaches use organic or inorganic inputs to boost crop yield. Inputs include fertilizers, biosolids, antibiotics, insecticides, and other chemicals. Capturing and treating agricultural waste streams is problematic due to the wide geographic territory and reachability of agricultural contaminants. The removal of these substances is commonly accomplished through bioremediation. It is based on the biological process that degrades, converts, or mineralizes concentrated contaminants into non-toxic compounds through biological mechanisms (Evans, 2018). Bioremediation is among the most recent applications for eliminating organic toxins using natural resources, including fungi, bacteria, microorganisms, and vegetation (Yadav et al., 2021). Bioremediation is a long-term and cost-effective workable alternative to these ecological problems, in which microorganisms in the ecological system transform, degrade, and remove pollutants (Turan et al., 2022).

B. Bioremediation in the Agricultural Sector

A large number of chemical compounds are used in the industry and agriculture sectors for human benefit. Some of these chemicals end up as soil contaminants, resulting in a wide range of complex mixtures being released into the environment (Adriano et al., 2015). Identifying and eliminating the principal causes of heavy metal contamination in soil-plant systems is the first step in fighting heavy metal contamination. Environmental rules must be more strictly supervised and enforced, especially in the case of significant emitters like mineral extraction and processing, smelting, and other metal-consuming enterprises. It is indeed crucial for constructing regional and national databases of metals and metalloids abundance in irrigation water and atmospheric fluxes. This could allow for a more realistic assessment of present contamination levels and future trend projections. If irrigation water has a high concentration of metals or metalloids, simple and effective procedures for eliminating contaminants before the water reaches the field should be devised; if this is not practicable, alternative clean water sources should be explored. In addition, rather than total concentration, metal phytoavailability is the focus of risk management in soil contamination with metals-related problems, and there are numerous strategies to avoid metal through phytoavailability. Liming of acidic soils is recommended, primarily in locations where there is a high danger of pollutant accumulation (e.g., Cd, Pb). Liming materials come in various forms, each with its acid-neutralizing capacity, rate constants, and expense. Furthermore, phytoremediation has been promoted as a low-cost, environmentally acceptable method of cleaning up polluted soils (Zhao et al., 2015).

Because of their proclivity for dispersion, long-distance movement, and bioaccumulation in the food supply chain, organochlorine pesticides (OCPs) threaten global ecology and hinder human health. During OCP phytoremediation, processes such as phytoaccumulation, rhizoremediation, and phytotransformation are known to occur. Vegetation has been found to significantly boost OCP elimination from the soil when compared to unplanted soil due to uptakes within plant tissues and high microbial degradation of OCP within the root zone. Discovering and implementing strategies to promote plant growth and rhizospheric microbial interaction and bioaugmenting potential pesticide degraders to improve degradation and incorporating biosurfactant producers to continually improve pesticide bioavailability in the rhizospheric soil could all aid field progress (Singh & Singh, 2017).

Bioremediation has included the use of algae and plants. Microbes like *Pseudomonas japonica, Pseudomonas fluorescens, Pseudomonas aeruginosa, Brevibacterium iodinum Saccharomyces cerevisiae,* and *Alcaligenes faecalis* have been found to participate actively in bioremediation. Moreover, *Anaeromyxobacter, Saccharibacteria, Desulfomicrobium, Terrimonas, Sphingobium, Comamonas, Zoogloea, Acinetobacter,* and *Thiobacillus* have all demonstrated anaerobic degradation of polycyclic aromatic and heterocyclic refractory organic compounds like indole, pyridine, and quinoline. Phytoremediation, which includes phytodegradation, phytoextraction, phytostabilization, phytotransformation, or rhizodegradation, and rhizofiltration, uses green plants. Phytoremediation has also been reported with *Citrus limetta, Solanum tuberosum, Luffa acutangular, Cucumis sativus,* and *Citrus limon*. Bioremediation occurs when a microorganism interacts with the pollutant that is being remedied. The interaction is determined by the pollutants' metabolic and chemical properties. The availability of metal ions and other toxic compounds, site characteristics, temperature, pH, moisture content, nutrient availability, redox potential, and oxygen concentration are all important environmental factors affecting bioremediation (Ghosh et al., 2021).

In addition to their role as bioremediation causatives, microbial activity has another dimension because it also fosters soil fertility through their diverse compounds. Many of these metabolites can be classified into different groups, such as xenobiotic degradation intermediates, biotransformed intermediates, and even rhizobacteria-produced plant growth factors. In addition to its ability to break down hydrocarbons, *Pseudomonas* has previously shown indole acetic acid synthesis, nitrogen fixation, and phosphate solubilization. These are important components for encouraging plant growth and increasing soil fertility. Furthermore, field studies revealed that an engineered *Escherichia coli* containing atrazine chlorohydrolase effectively removed atrazine from polluted soil (Rebello et al., 2021). Scientists from all over the world have been searching for innovative engineering possibilities to incorporate microbe-stimulating materials. Continually advancing bioaugmentation technologies are expected to provide researchers with a better understanding of cell genetic manipulation and overcome microbiological constraints. Many pollutants escape microbe degrading activity, owing to the microbes' inability to interact with or attach to the contaminants' surfaces. New methods should be developed to enhance the efficacy of microbes and, thus the efficiency of bioremediation (Vishwakarma et al., 2020).

Pesticide biodegradation takes various paths depending on the pesticide, environment, and microbe. Fungi and bacteria serve as important in pesticide biodegradation. Fungi biotransform pesticides by incorporating trivial structural changes, rendering into non-toxic forms, and releasing the substance into the soil for further biodegradation by bacteria. Several fungi such as *Avatha discolor, Stereum hirsutum, Pleurotus ostreatus, Hypholoma fasciculare, Flammulina velupites, Dichomitus squalens, Coriolus versicolor, Auricularia auricula,* and *Agrocybe semiorbicularis* have demonstrated their ability to degrade pesticides like organophosphorus compounds, chlorinated, dicarboximide, phenylurea, triazine, and phenylamide. Furthermore, microbes commonly reported in pesticide bioremediation include *Mycobacterium* sp., *Phanerochaete Chrysosporium*, *Pandoraea* sp., *Klebsiella* sp., *Bacillus* sp., and *Pseudomonas* sp., (Odukkathil & Vasudevan, 2013).

Pollutant presence and concentration are not expected to affect microorganism growth, indicating their potential to affect the bioremediation process. Furthermore, fertilizer addition is preferred for an optimum C:N:P = 100:10:1 balance to promote microbial biostimulation for appropriate bioremediation, and bioremediation of soil contaminated with hydrocarbons and pesticides was possible by utilizing bio-stimulation of native microbial communities (Islas-García et al., 2015).

C. Integrating Nature-Based Solutions and Agro-Bioremediation

Nature-based solutions (NbS) are treatment technologies and redevelopment strategies that are nature-based, cost-effective, ecologically friendly, socially inclusive, economically viable, and well-received by the wider public. The NbS concept is innovative, and further research is needed to understand its benefits and drawbacks better and improve its applicability. NbS delivers various ecosystem services, supports the sustainable production of products and resources, and protects ecosystem integrity (Kumar & Kunhamu, 2022). Green and sustainable remediation (GSR) has also emerged in recent years, asking for how to maximize the "net environmental benefit" while also taking social and economic gains into account (Song et al., 2019).

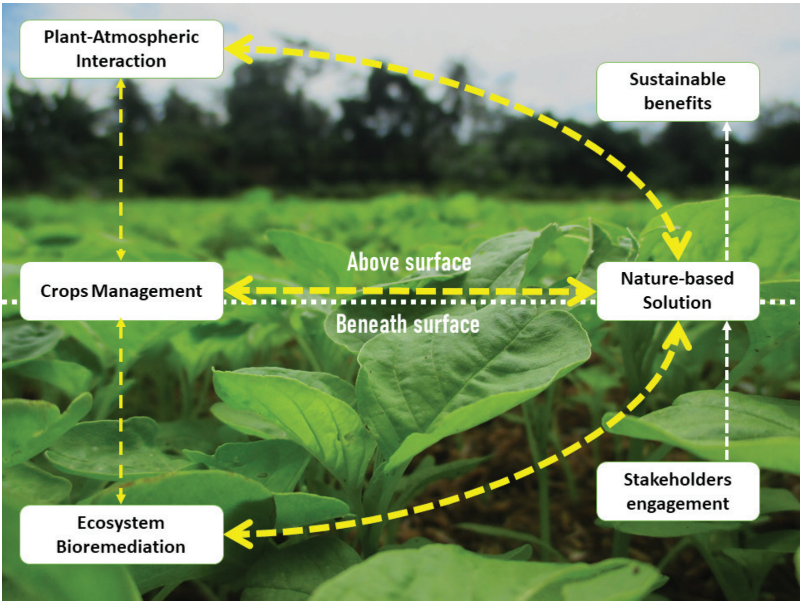

Figure 3.1 The Framework of NbS and Agro-Bioremediation

Additionally, because of their multifunctionality, agroecology and other regenerative food systems are the most promising alternative for food security, contributing to resilience through broader spectrum of diversity and self-sufficiency (Anderson & Rivera-Ferre, 2021).

Figure 3.1 shows the integration framework between two surface interactions under NbS and agro-bioremediation. In the agricultural areas, the interaction of both surfaces is interlinked. From above ground, solar radiation, wind, air temperature, humidity, rainfalls, and even farming management are factors that influence plant growth. While in below the surface, the soil characteristics, microbes-plant interaction, water content, and mineral nutrients are examples of factors affecting plant growth. Thus, it is highlighted to streamline ecosystem restoration thoroughly by bioremediation and NbS agricultural landscape management. NbS should play an essential role in these surfaces, through extensive support and engagements from relevant stakeholders, and could eventually achieve sustainable benefits. It aligns with Schreefel et al. (2020) stated that regenerative agriculture concentrates on the environmental aspects of sustainability, which encompasses elements such as enhancing and improving soil health, optimizing resource management, mitigating climate change, improving nutrient availability, and improving water quality and availability, outlined by both principles (e.g., improve soil quality) and actions (e.g., use perennials). Transitioning to regenerative agriculture entails more than a set of 'climate-smart' mitigation and adaptation strategies backed by technical innovation, policy, education, and outreach (Gosnell et al., 2019).

Grasses are the most prevalent functional group of herbaceous species utilized for phytoremediation, owing to their vast diversity and a broad range of stress tolerance. They often develop sod or dense cover, which can be used for various applications. There is a substantial global seed business to facilitate the commercial dissemination of grasses for various reasons. Flowering ornamentals, sedges, and rushes are other monocots suitable for smaller projects. The chemistry of herbicides, their physiological and morphological properties, plant detoxification mechanisms, and plant-rhizosphere interactions all affect remediation mechanisms (i.e., their hydrophobicity, solubility, and phytotoxicity). In the configuration of the tree–shrub–multispecies grass ecosystems for contaminant remediation, determining biotic and abiotic stress gradients in plant microenvironments is crucial. Understanding the spatially and temporally aspects of each stress, as well as the measures that alleviate specific stresses, is an important element of this. Microbial symbionts could also affect the success of phytoremediation activities and the species or genotypes chosen. By enhancing nutrient uptake, absorbing heavy metals, and shielding the host from metal toxicity, arbuscular mycorrhizal (AM) fungus can aid some host plants in adapting and surviving. Soils and landscape restoration is also a transdisciplinary synthesis of soil management and restoration in various landscapes. Real-world examples of successful bioremediation technologies include (1) short-rotation woody crops used to improve ecosystem services at landfills, (2) riparian buffer systems used to reduce agrichemical flow from agroecosystems, (3) urban afforestation used to develop forests in municipalities, and (4) grasslands used for soil phosphorus phytoremediation, and (5) surface mine reclamation employs woody species (Casler et al., 2021).

Plant-microorganism interactions enable various functions, including phytostabilization, storage in specific portions of the plant (phytoextraction and phytoaccumulation), and degradation of pollutants from soil, water, sludge, and sediment. Compost and biochar, for instance, have been researched for their ability to increase soil fertility and structure while also supporting plants in the removal of toxins from polluted soil. Carbonaceous materials are usually neglected wastes, although their application in products aligns well with the circular economy's goals. Phyto-assisted bioremediation is an environmentally friendly technology that produces a byproduct (biomass) that can be profitably valorized to produce energy or new materials, lowering the technology's costs compared to traditional soil remediation strategies (Ancona et al., 2022). In today's environment, the bulk of organic and inorganic (heavy metals) contaminants could be controlled sustainably by promoting the circular bioeconomy and establishing a sustainable engineered process by employing engineered biochar. The use of bioengineered biochar methods for pollutant removal has various advantages. Some benefits include carbon sequestration potential, microbial growth-promoting activities, environmental friendliness, water retention, long-lasting, improved soil fertility, the ability to immobilize pollutants, and low cost. Microbes can be inoculated and immobilized on biochar to develop a successful soil bioremediation mechanism. The enzymes responsible for contaminant detoxification in the approaches are released by the immobilized microbes. These enzymes are responsible for breaking down environmental target substrates into simpler substances (Liu et al., 2021).

Traditional approaches like salt leaching and soil amendments and NbS like phytoremediation have all been tried and tested with varying degrees of success. Cyanobacteria have emerged as a possible biotechnological tool for ecosystem restoration because of their unique properties, such as increasing carbon and nitrogen and promoting soil stabilization. When a vegetal mesh covered the inoculated soils, the cyanobacteria were able to deal with abiotic stress and soil erosion. The application of habitat improvement measures to reduce physiological stress and the detrimental impact of overland flow and precipitation yielded better outcomes (Román et al., 2021). Furthermore, the nano-sand-stabilizer may successfully stimulate cyanobacterial colonization and proliferation, hence favoring the establishment of biocrust. This study demonstrates viable biotechnology for fast repairing sand and promoting biocrust growth in desert areas (Li et al., 2021). Cyanobacteria can endure a wide range of salinities, and certain species can adapt to fluctuations in salinity. Their effectiveness in agricultural salty soil remediation has been shown, primarily through laboratory testing, but limited research has focused on their applicability in natural ecosystem restoration (Rocha et al., 2020).

NbS frameworks in agricultural operations are defined as the use of natural processes or components to improve ecosystem functions in agriculturally affected habitats and landscapes and livelihoods, and other socio-cultural functions. One of the NbS framework's selling points is that it shows how to change patterns in which crop production leads to environmental problems (e.g., agrochemical spills into waters), which causes additional challenges for farm productivity (e.g., polluted soils, water threatening pollinators, and food safety), and how particular challenges are intertwined across landscapes. NbS in agriculture will require the identification of entry sites and the support of a varied range of actors in the production landscape to be effective throughout agricultural societies, local government extension workers, and downstream value chain actors at the regional and global levels. Public and private actors should build partnerships based on a shared aim of recovering important production landscapes through NbS to ensure wide support and the most significant possibility for long-term management reform. Restorative NbS techniques involve long-term commitments, which can be assisted by policy (Simelton et al., 2021).

Unlike traditional remediation approaches, which are expensive, time-consuming, and can result in secondary contamination, tree-based phytoremediation is a non-invasive, cost-effective option with a wide range of uses. It is a low-cost strategy relating to urban green infrastructure (parklands, corridors, and urban agriculture), which has numerous advantages, including improved general environmental, well-being, socio-cultural, and financial circumstances for the city's population. Initially, urban green infrastructure comprises various tree species that can minimize soil contamination, particularly the contamination due to toxic heavy metals (HMs). The ability of vegetation to maintain, absorb, and break down pollutants (including HMs) from contaminated urban soils, allowing for their reuse and transformation into environmentally friendly locations. This is connected to urban ecosystem regeneration relying on tree species' responsibilities (Ilic et al., 2020).

Notwithstanding, urban agriculture or cropping is gaining popularity around the world. As a result, phytomanagement application along with phytoremediation could be the best option for city dwellers' desire for nature in the urban landscape. Because many urban soils have higher concentrations of trace metals likely Cd, Cu, Mn, and Zn than soils in rural or forests, it is essential to determine whether remediation methods such as phytoremediation are in advance. Nature-based solutions, particularly phytotechnologies, offer potential methods of dealing with contaminated urban soils. However, the major drawback of this technique is related to the time aspect, which it takes to reduce metal concentrations in the soil. To address this issue, low trace metal-accumulating vegetables (safe cropping system) can be cultivated alongside metal hyperaccumulating plants (in situ phytoextraction). Without any regulatory restrictions, this association cropping would allow the area to be used for vegetable farming. Due to time restrictions, laws and regulations are expected to evolve and validate the use of phytotechnologies to clean up soils (only once substantially contaminated) before the lands are reused for vegetable cropping(Bouzouidja et al., 2019).

D. Land Management Bioremediation and Circular Economy Systems

When agricultural species serve as vegetation in NbS, they perform numerous functions. Grass strips, for example, control soil erosion and increase crop yields, and vetiver grass can act as phytoremediation by trapping phosphorous. Physical factors such as slope angles and root structures also affect the efficiency of crop plantations. Furthermore, weed mulch and simple weed strips are used to create micro-terraces, ultimately resulting in less soil erosion and higher productivity. Planting trees also aids in the capture of airborne particles and pollutant gases. Overgrazing can reduce the soil's ability to trap contaminants, resulting in these and other suspended sediments. Legumes further provide supplementary ecological services such as enhanced biological diversity, preserved erosion, and improved soil structure (Miralles-Wilhelm, 2021). Essentially, natural tree (shrubs and trees) regeneration in agricultural landscapes necessitates the strategic planning of land-sparing and land-sharing approaches throughout broad spatial scales to accomplish production and preservation needs (Sato et al., 2016).

By restoring ecosystems and rebuilding natural capital, the circular economy cannot only slow but ultimately stop biodiversity loss and reverse it. On the other hand, the circular economy is currently receiving insufficient attention as a systemic approach. Despite playing an important role in biodiversity, the circular economy's regenerative and restorative attributes have customarily been left out of the well-known 3Rs—"reduce, reuse, recycle"—regarding the waste hierarchy. The 3Rs emphasize reducing the adverse impact of human activities by 'turning off the tap' on waste, soil contamination, and resource demand, whereas the second set of 3Rs focuses on the potential benefits of reversing the world's degrading ecosystems. Frequently associated, the favorable 3Rs are not more important in and of themselves, and reducing waste and pollution should continue to be a top priority. Many heavily contaminated sites will need to be remedied before restorative and regenerative practices can be used to aid natural decontamination processes used in biological-based technologies such as phytotechnologies and microbial processes (Schröder et al., 2021). Circularity has the ability to provide practical solutions for strengthening such vulnerable systems. Large-scale investment in regenerative, peri-urban agriculture, for example, could provide foods closer to customers while reducing environmental impact and fragility. According to a study undertaken by the Ellen MacArthur Foundation, a circular scenario might contribute to a 50% decline in pesticide and artificial fertilizer consumption across Europe by 2030, compared to 2012 (United Nations Environment Programme, 2021).

Ecosystem restoration improves natural cycles by restoring the functionality of degraded soils. Healthy soil is required for the closure of biological processes that produce organic resources and also use organic material to maintain soil fertility and productivity. All nutrients would be appropriately restored to the biosphere in a circular system. In the urban environment, this means that nutrients are collected in the organic component of municipal solid waste and wastewater streams, treated, and returned to the soil in the form of organic fertilizer (Ellen MacArthur Foundation, 2017). The contribution of soils to provisioning, regulation, and maintenance services emphasizes the importance of soil properties in a circular economy. Soil and natural resource play critical roles in the circular economy, such as providing space for societal activities. They serve as a repository for mineral resource stocks and provide opportunities to generate biobased resources to substitute mineral resource utilization. Their function in the biogeochemical cycles is significant for completing the water, nutrient, and soil purification cycles once these resources have been deposited in the soil as waste. As a result, soil recovery and reuse are required to ensure the future supply of natural resources and services to an increasing global population. The circular economy establishes a framework for managing natural capital as an asset, including biodiversity, water, fossil fuels, mineral resources, and soil. Thereby, it encourages efficient use and management (Breure et al., 2018). Furthermore, the vermicomposting approach provides a window of opportunity for bacteria and earthworms to work together to degrade waste and stimulate nutrients (Lirikum et al., 2022). Vermicompost has been shown to assure agricultural sustainability, enhance waste management, contaminant remediation, biogas production, and livestock feed production, making it a viable circular economy strategy (Kamar Zaman & Yaacob, 2022).

The narrative of biological agents as remediation in the circular system could also be the bioeconomy framework. The bioeconomy efficiently uses biological (bio-based) resources through efficient production and conversion mechanisms, culminating in economic and environmental benefits while simultaneously facilitating the transition to a more sustainable society. Thus, phytotechnologies and bioremediation depend on the ability of specific plants, fungi, or bacteria to degrade, stabilize, or eradicate contaminants in diverse environmental compartments. Nevertheless, no reference markets or economically viable alternatives have been offered, and the entire value chain has yet to be thoroughly researched. Admittedly, the biomass produced due to phyto- and bioremediation interventions has been labeled as waste. While acknowledging the importance of pollution prevention, human society must make significant efforts to prevent pollution and repair growing areas of the territory through comprehensive and coordinated policy approaches. A political agenda that prioritizes the prevention, repair, and restoration of contaminated environments is driving the importance of rhizosphere, soil, and coastline management in pertaining to human activities at the macro scale (Francocci et al., 2020). Additionally, the circular economy would be really sustainable only if it contributes to societal reform. Significant adjustments are required in global, regional, and national contexts from a policy standpoint. For effective progress, policies at all levels of government must be aligned and coordinated (Connor, 2021).

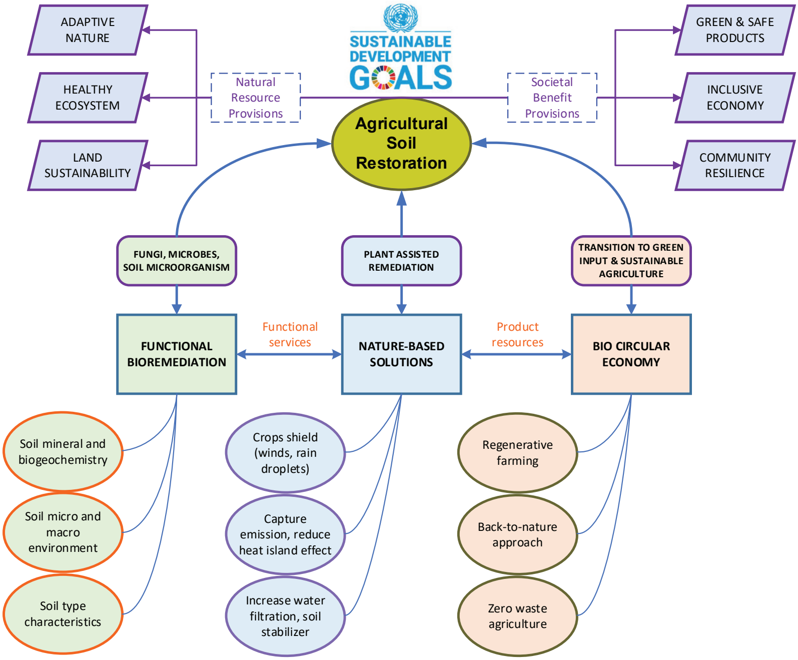

Figure 3.2 Agro-Symphony in Bioremediation, Nature-Based Solution, and Circular Economy

The interrelationship of each aspect in bioremediation, NbS, and circular economy for sustainable agricultural land management is depicted in Figure 3.2. Improving soils in their micro-environment is critical because it can affect the conditions above ground. The addition of NbS features such as phytoremediation plants also serves other functions to protect the environment where bioremediation occurs. Furthermore, as proper and healthy soil quality for the agricultural landscape is achieved, the circular economy framework can be implemented. As a result of the holistic management of soil restoration, sustainable agriculture is achieved.

Sustainable land restoration incorporates sustainability principles into land management and rehabilitation. Furthermore, implementing circularity principles into restoration solutions such as resource and product reuse, recycling, and recovery can significantly help long-term sustainable soil restoration. Chemical immobilization, rhizospheric engineering, and meta-transcriptomics are technological interventions used to grow crops on contaminated or polluted land. Crop diversification strategies can aid in the restoration of degraded lands by improving soil fertility, supporting sustainable agriculture, and boosting rural participation. This requires finding natural variations that are nutritionally comparable to typical agricultural plants which are resilient enough to survive on degraded soils. Efficient waste management processes for recycling and reuse of industrial wastes can help restore circularity by reducing the amount of land required for waste disposal and reducing dangerous chemicals entering soil systems. Coal and urban waste compost can be combined to form "technosol, " then applied to mined areas to stimulate plant cover and land restoration. Incorporating these ideas into restoration efforts can also benefit the environment (Priyadarshini & Abhilash, 2020). By combining waste-derived technosols into land recycling for green areas, cities and megacities can become more sustainable, and agricultural output and human health could significantly improve. This also provides human food security and ecosystem services and serves as a substrate for urban agroforestry systems if constructed from technosols materials. In urban regions, the addition of created technosols and de-sealed soils can assist in the restoration of ecosystem functioning and food supply services. It is a viable option for assisting our nature bounce back (Rodríguez-Espinosa et al., 2021).

Agricultural transformation, including the adoption of sustainable intensification technology, is thus likely to occur only if public investments in farmer assistance are ensured, even in locations with significant yield discrepancies (Silva et al., 2021). Because restoration is such a complex undertaking, it involves improvements in a variety of fields as well as the long-term application of traditional and indigenous knowledge (including biocultural knowledge). Furthermore, restoring degraded landscapes is essential for sustaining the land's biocultural relevance. As a result, integrating land restoration research at multiple sizes and levels is critical for producing realistic and actionable restoration packages based on nature-based solutions and ecosystem-based methods to achieve a successful restoration milestone (Abhilash, 2021).

E. Conclusion

Improving agricultural land ecosystems currently necessitates positive collaboration from diverse stakeholders and society. The sustainability of the land is in our collective hands. Therefore, we must protect this limited resource for the sake of future generations' continuity. Land restoration based on bioremediation, which combines the principles of nature-based solutions and the circular economy, will generate a long-term benefit. On the one hand, integrative restoration could improve soil from the micro and macro environment structures. Additionally, the implementation of regenerative agriculture can support an interconnected cycle loop, and appropriate land quality can be achieved for sustainable agricultural purposes. The benefits of the nexus will be amplified in the future as land restoration efforts are maximized.

References

Abhilash, P. C. (2021). Restoring the Unrestored: Strategies for Restoring Global Land during the UN Decade on Ecosystem Restoration (UN-DER). *Land*, *10*(201), 1–17. https://doi.org/10.3390/land10020201

Adriano, D. C., Bollag, J. M., Frankenberger, W. T., & Sims, R. C. (2015). Bioremediation of contaminated soils. In *Bioremediation of Contaminated Soils* (Third Edit). Elsevier Inc. https://doi.org/10.2134/agronmonogr37

Ancona, V., Rascio, I., Aimola, G., Caracciolo, A. B., Grenni, P., Uricchio, V. F., & Borello, D. (2022). Plant-assisted bioremediation: Soil recovery and energy from biomass. In *Assisted Phytoremediation* (pp. 25–48). Elsevier Inc. https://doi.org/10.1016/b978-0-12-822893-7.00012-4

Anderson, M. D., & Rivera-Ferre, M. (2021). Food system narratives to end hunger: extractive versus regenerative. *Current Opinion in Environmental Sustainability*, *49*, 18–25. https://doi.org/10.1016/j.cosust.2020.12.002

Arora, N. K. (2018). Bioremediation: a green approach for restoration of polluted ecosystems. *Environmental Sustainability*, *1*(4), 305–307. https://doi.org/10.1007/s42398-018-00036-y

Bouzouidja, R., Bouquet, D., Pierart, A., Shahid, M., Guern, C. Le, Jean-Soro, L., Dumat, C., & Lebeau, T. (2019). Metal Contamination in Urban Soils Use of Nature-Based Solutions for Developing Safe Urban Cropping. In J. C. Sanchez-Hernandez (Ed.), *Bioremediation of Agricultural Soils* (1st Editio, p. 22). CRC Press. https://doi.org/10.1201/9781315205137

Breure, A. M., Lijzen, J. P. A., & Maring, L. (2018). Science of the Total Environment Soil and land management in a circular economy. *Science of the Total Environment*, *624*, 1125–1130. https://doi.org/10.1016/j.scitotenv.2017.12.137

Casler, M. D., Hallett, R. A., & Lin, C. (2021). Bioremediation and soils. In J. A. Stanturf & J. Mac A. Callaham (Eds.), *Soils and Landscape Restoration* (Vol. 9, pp. 237–273). https://doi.org/10.1016/B978-0-12-813193-0.00009-6

Connor, K. E. O. (2021). Microbiology challenges and opportunities in the circular economy. *Microbiology*, 1–3. https://doi.org/10.1099/mic.0.001026

El Mujtar, V., Muñoz, N., Prack Mc Cormick, B., Pulleman, M., & Tittonell, P. (2019). Role and management of soil biodiversity for food security and nutrition; where do we stand? *Global Food Security*, *20*(April 2018), 132–144. https://doi.org/10.1016/j.gfs.2019.01.007

Ellen MacArthur Foundation. (2017). *Urban Biocycles*. https://ellenmacarthurfoundation.org/cities-urban-biocycles

Evans, L. (2018). Bioremediation Techniques for Agricultural Pollutants. In *Reference Module in Earth Systems and Environmental Sciences*. Elsevier Inc. https://doi.org/10.1016/b978-0-12-409548-9.11259-x

Francocci, F., Trincardi, F., Barbanti, A., Zacchini, M., & Sprovieri, M. (2020). Linking Bioeconomy to Redevelopment in Contaminated Sites : Potentials and Enabling Factors. *Frontiers in Environmental Science*, *8*(September), 1–13. https://doi.org/10.3389/fenvs.2020.00144

Ghosh, S., Sharma, I., Nath, S., & Webster, T. J. (2021). Microbial Ecology of Wastewater Treatment Plants. *Microbial Ecology of Wastewater Treatment Plants*, 11–40. https://doi.org/10.1016/c2019-0-04695-x

Gosnell, H., Gill, N., & Voyer, M. (2019). Transformational adaptation on the farm: Processes of change and persistence in transitions to 'climate-smart' regenerative agriculture. *Global Environmental Change*, *59*(November), 101965. https://doi.org/10.1016/j.gloenvcha.2019.101965

Hurni, H., Giger, M., Liniger, H., Mekdaschi Studer, R., Messerli, P., Portner, B., Schwilch, G., Wolfgramm, B., & Breu, T. (2015). Soils, agriculture and food security: The interplay between ecosystem functioning and human well-being. *Current Opinion in Environmental Sustainability*, *15*, 25–34. https://doi.org/10.1016/j.cosust.2015.07.009

Ilic, Z. H., Solomun, M. K., & Sumatic, N. (2020). *Phytoremediation: Nature based solution for contaminated urban soils*. https://doi.org/10.5194/egusphere-egu2020-828

Islas-García, A., Vega-Loyo, L., Aguilar-López, R., Xoconostle-Cázares, B., & Rodríguez-Vázquez, R. (2015). Evaluation of hydrocarbons and organochlorine pesticides and their tolerant microorganisms from an agricultural soil to define its bioremediation feasibility. *Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes*, *50*(2), 99–108. https://doi.org/10.1080/03601234.2015.975605

Kamar Zaman, A. M., & Yaacob, J. S. (2022). Exploring the potential of vermicompost as a sustainable strategy in circular economy: improving plants' bioactive properties and boosting agricultural yield and quality. *Environmental Science and Pollution Research*, *29*(9), 12948–12964. https://doi.org/10.1007/s11356-021-18006-z

Kumar, B. M., & Kunhamu, T. K. (2022). Nature-Based Solutions in Agriculture: A Review of the Coconut (Cocos nucifera L.)-Based Farming Systems in Kerala, "the Land of Coconut Trees." In *Nature-Based Solutions*. Elsevier Inc. https://doi.org/10.1016/j.nbsj.2022.100012

Li, Z., Chen, C., Gao, Y., Wang, B., Wang, D., Du, Y., Liu, L., Wu, Z., & Cai, D. (2021). Synergistic effect of cyanobacteria and nano-sand-stabilizer on biocrust formation and sand fixation. *Journal of Environmental Chemical Engineering*, *9*(1), 104887. https://doi.org/10.1016/j.jece.2020.104887

Lirikum, Kakati, L. N., Thyug, L., & Mozhui, L. (2022). Vermicomposting: an eco-friendly approach for waste management and nutrient enhancement. *Tropical Ecology*, *0123456789*. https://doi.org/10.1007/s42965-021-00212-y

Liu, H., Kumar, V., Yadav, V., Guo, S., Sarsaiya, S., Binod, P., Sindhu, R., Xu, P., Zhang, Z., Pandey, A., & Kumar Awasthi, M. (2021). Bioengineered biochar as smart candidate for resource recovery toward circular bio-economy: a review. *Bioengineered*, *12*(2), 10269–10301. https://doi.org/10.1080/21655979.2021.1993536

Merloti, L. F., Pedrinho, A., Mendes, L. W., Gontijo, J. B., da Fonseca, M. de C., Chaves, M. G., Chaves, S. S. de F., Camargo, P. B. de, & Tsai, S. M. (2022). Long-term land use in Amazon influence the dynamic of microbial communities in soil and rhizosphere. *Rhizosphere*, *21*(November 2021), 100482. https://doi.org/10.1016/j.rhisph.2022.100482

Miralles-Wilhelm, F. (2021). Nature-based solutions in agriculture: Sustainable management and conservation of land, water and biodiversity. In Https://www.fao.org/publications/card/en/c/CB3140EN/ (Ed.), *Nature-based solutions in agriculture: Sustainable management and conservation of land, water and biodiversity*. Food and Agriculture Organization of the United Nations and The Nature Conservancy. https://doi.org/10.4060/cb3140en

Nasikh, Kamaludin, M., Narmaditya, B. S., Wibowo, A., & Febrianto, I. (2021). Agricultural land resource allocation to develop food crop commodities: lesson from Indonesia. *Heliyon*, *7*(7), e07520. https://doi.org/10.1016/j.heliyon.2021.e07520

Odukkathil, G., & Vasudevan, N. (2013). Toxicity and bioremediation of pesticides in agricultural soil. *Reviews in Environmental Science and Biotechnology*, *12*(4), 421–444. https://doi.org/10.1007/s11157-013-9320-4

Otsuka, K. (2021). Strategy for Transforming Indonesian Agriculture. *Bulletin of Indonesian Economic Studies*, *57*(3), 321–341. https://doi.org/10.1080/00074918.2021.2002387

Pozza, L. E., & Field, D. J. (2020). The science of Soil Security and Food Security. *Soil Security*, *1*(8), 100002. https://doi.org/10.1016/j.soisec.2020.100002

Priyadarshini, P., & Abhilash, P. C. (2020). Fostering sustainable land restoration through circular economy-governed. *Restoration Ecology*, *28*(4), 719–723. https://doi.org/10.1111/rec.13181

Rebello, S., Nathan, V. K., Sindhu, R., Binod, P., Awasthi, M. K., & Pandey, A. (2021). Bioengineered microbes for soil health restoration: present status and future. *Bioengineered*, *12*(2), 12839–12853. https://doi.org/10.1080/21655979.2021.2004645

Rocha, F., Lucas-borja, M. E., Pereira, P., & Muñoz-rojas, M. (2020). Cyanobacteria as a Nature-Based Biotechnological Tool for Restoring Salt-A ff ected Soils. *Agronomy*, *10*(9), 1–15. https://doi.org/10.3390/agronomy10091321

Rodríguez-Espinosa, T., Navarro-Pedreño, J., Lucas, I. G., & Belén Almendro-Candel, M. (2021). Land recycling, food security and Technosols. *Journal of Geographical Research*, *4*(3), 44–50. https://doi.org/10.30564/jgr.v4i3.3415

Román, J. R., Chamizo, S., Roncero-Ramos, B., Adessi, A., De Philippis, R., & Cantón, Y. (2021). Overcoming field barriers to restore dryland soils by cyanobacteria inoculation. *Soil and Tillage Research*, *207*(November 2020). https://doi.org/10.1016/j.still.2020.104799

Santos, R. S., Wiesmeier, M., Cherubin, M. R., Oliveira, D. M. S., Locatelli, J. L., Holzschuh, M., & Cerri, C. E. P. (2021). Consequences of land-use change in Brazil's new agricultural frontier: A soil physical health assessment. *Geoderma*, *400*(April), 115149. https://doi.org/10.1016/j.geoderma.2021.115149

Sato, C. F., Wood, J. T., Stein, J. A., Crane, M., Okada, S., Michael, D. R., Kay, G. M., Florance, D., Seddon, J., Gibbons, P., & Lindenmayer, D. B. (2016). Natural tree regeneration in agricultural landscapes: The implications of intensification. *Agriculture, Ecosystems and Environment*, *230*, 98–104. https://doi.org/10.1016/j.agee.2016.05.036

Schreefel, L., Schulte, R. P. O., de Boer, I. J. M., Schrijver, A. P., & van Zanten, H. H. E. (2020). Regenerative agriculture – the soil is the base. *Global Food Security*, *26*(June), 100404. https://doi.org/10.1016/j.gfs.2020.100404

Schröder, P., Forslund, T., & Sell, M. (2021). *The role of the circular economy in addressing the global biodiversity crisis*. Chatham House. https://circulareconomy.earth/publications/the-role-of-the-circular-economy-in-addressing-the-global-biodiversity-crisis?utm_source=twitter&utm_medium=pacecircular&utm_campaign=socialmedia&utm_term=4d191ecb-fd4b-46ad-a686-e66951e11d28

Silva, J. V., Reidsma, P., Baudron, F., Laborte, A. G., Giller, K. E., & van Ittersum, M. K. (2021). How sustainable is sustainable intensification? Assessing yield gaps at field and farm level across the globe. *Global Food Security*, *30*(November 2020). https://doi.org/10.1016/j.gfs.2021.100552

Simelton, E., Carew-reid, J., Coulier, M., Damen, B., & Howell, J. (2021). NBS Framework for Agricultural Landscapes. *Frontiers in Environmental Science*, *9*(August), 1–16. https://doi.org/10.3389/fenvs.2021.678367

Singh, T., & Singh, D. K. (2017). Phytoremediation of organochlorine pesticides: Concept, method, and recent developments. *International Journal of Phytoremediation*, *19*(9), 834–843. https://doi.org/10.1080/15226514.2017.1290579

Song, Y., Kirkwood, N., Maksimovi, Č., Zheng, X., Connor, D. O., Jin, Y., & Hou, D. (2019). Science of the Total Environment Nature based solutions for contaminated land remediation and brown fi eld redevelopment in cities : A review. *Science of the Total Environment*, *663*, 568–579. https://doi.org/10.1016/j.scitotenv.2019.01.347

Turan, M., Argin, S., Bolouri, P., Arjumend, T., Ersoy, N., Yıldırım, E., Güneş, A., Ekinci, M., & Birinci, D. (2022). Bioremediation of contaminated soil with plant growth rhizobium bacteria. *Assisted Phytoremediation*, 265–284. https://doi.org/10.1016/b978-0-12-822893-7.00013-6

United Nations Environment Programme. (2021). *Circularity to Restore the Earth*. United Nations Environment Programme. https://www.unep.org/news-and-stories/speech/circularity-restore-earth

Vidar, M. (2021). Soil and Agriculture Governance and Food Security. *Soil Security*, 100027. https://doi.org/10.1016/j.soisec.2021.100027

Vishwakarma, G. S., Bhattacharjee, G., Gohil, N., & Singh, V. (2020). Current status, challenges and future of bioremediation. In *Bioremediation of Pollutants* (pp. 403–416). Elsevier Inc. https://doi.org/10.1016/B978-0-12-819025-8.00020-X

Yadav, M., Singh, G., & Jadeja, R. N. (2021). Bioremediation of organic pollutants: a sustainable green approach. In *Sustainable Environmental Clean-up*. Elsevier Inc. https://doi.org/10.1016/b978-0-12-823828-8.00006-2

Zhao, F., Zhu, Y., Tang, Z., & Mcgrath, S. P. (2015). Soil Contamination in China: Current Status and Mitigation Strategies. *Environmental Science & Technology*, *49*, 750–759. https://doi.org/10.1021/es5047099