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Agricultural soil and sustainability: Challenges and opportunities

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Abstract

Soil, the foundation of terrestrial ecosystems, plays a pivotal role in sustaining life on Earth. However, various anthropogenic activities have led to soil degradation, threatening its ability to support agricultural productivity, biodiversity, and ecosystem services. This article provides an overview of the challenges facing soils in the context of sustainability. It discusses the impacts of factors such as land use change, deforestation, industrial agriculture, urbanization, pollution, and climate change on soil health. Furthermore, it explores sustainable soil management practices and their potential to mitigate soil degradation while promoting long-term environmental, social, and economic sustainability. Emphasis is placed on the importance of adopting holistic approaches that integrate scientific knowledge, technological innovations, and socio-economic considerations to safeguard soil resources for future generations.

Keywords: Soil, sustainability, degradation, land use change, agriculture, climate change, management practices, biodiversity, ecosystem services

Introduction

Soil stands as a fundamental component of terrestrial ecosystems, playing a pivotal role in supporting life on Earth. Its significance lies in its multifaceted functions, encompassing nutrient cycling, water retention, carbon sequestration, and habitat provision for diverse biological communities. However, the relentless pressures exerted by anthropogenic activities have led to widespread soil degradation, posing profound challenges to the sustainability of ecosystems and human well-being. Understanding the intricate dynamics between soil health and sustainable development is imperative for devising effective strategies to mitigate degradation and promote resilience in soil systems (Singh, A. 2022 & Telo da Gama, 2023) ^[14, 16].

This introduction delineates the overarching challenges confronting soils in the context of sustainability while elucidating the inherent opportunities for transformative action. The discourse traverses the realms of soil degradation drivers, encompassing land use alterations, intensified agricultural practices, urbanization, contamination, and climate change perturbations. These stressors collectively jeopardize soil integrity, fertility, and functionality, thereby compromising its capacity to support vital ecosystem services and maintain biodiversity (Bhattacharyya, R. *et al.*, 2015) ^[4].

Simultaneously, this narrative underscores the inherent opportunities embedded within sustainable soil management practices. By embracing principles of conservation, regeneration, and holistic ecosystem stewardship, it becomes plausible to mitigate degradation trajectories while fostering soil resilience and adaptive capacity. This juxtaposition of challenges and opportunities underscores the urgency of concerted efforts to recalibrate human-soil interactions towards pathways that prioritize long-term sustainability and planetary well-being (Dong, X. *et al.*, 2023) ^[5].

In essence, this article endeavours to navigate the intricate nexus between soil and sustainability, elucidating the pressing challenges that imperil soil health and the transformative opportunities inherent within sustainable soil management paradigms. Through a synthesis of scientific insights, technological innovations, and interdisciplinary perspectives, it seeks to pave the way for informed decision-making and collective action

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towards safeguarding soil resources for present and future generations (Hou D, *et al.*, 2020) ^[9].

Factors contributing to soil degradation

Soil degradation, a multifaceted phenomenon driven by diverse anthropogenic activities, stands as a formidable challenge to the sustainability of terrestrial ecosystems. Understanding the intricate interplay of factors precipitating soil degradation is imperative for devising effective strategies to mitigate its impacts and promote soil resilience (Gomiero, T. 2016) ^[8]. This section delineates the primary factors contributing to soil degradation, encompassing land use changes, intensified agricultural practices, urbanization, pollution, and climate change perturbations.

Land Use Changes

Human-induced alterations in land use patterns, including deforestation, conversion of natural habitats to agricultural or urban landscapes, and expansion of infrastructure, exert profound impacts on soil integrity and functionality. Deforestation disrupts soil structure, accelerates erosion rates, and diminishes soil fertility, leading to irreversible degradation in many cases. Similarly, the conversion of natural ecosystems to croplands or urban areas alters hydrological regimes, exacerbates soil erosion, and diminishes soil organic matter content, compromising its capacity to support vegetation and sustain ecosystem services (Bennett, E.M. *et al.*, 2009) ^[3].

Intensified Agricultural Practices

The intensification of agricultural production systems, characterized by monoculture cropping, excessive fertilizer and pesticide usage, mechanization, and irrigation, exerts immense pressure on soil health and productivity. Monoculture cropping depletes soil nutrients, disrupts microbial communities, and increases susceptibility to pest and disease outbreaks, leading to diminished crop yields and soil degradation over time. Excessive application of fertilizers and pesticides results in soil pollution, contamination of water bodies, and disruption of ecological balances, exacerbating environmental degradation (Urrea, J. *et al.*, 2019) ^[19].

Urbanization

Rapid urbanization, driven by population growth, migration, and economic development, leads to the expansion of built-up areas at the expense of natural landscapes and agricultural lands. Urban sprawl alters soil structure and composition, disrupts hydrological processes, and increases surface runoff and soil sealing, thereby exacerbating flood risks and diminishing soil permeability and water retention capacity. Moreover, urban activities generate significant quantities of solid waste, sewage, and industrial effluents, which contaminate soils and compromise their suitability for agricultural or recreational purposes (McGrane, S. J. 2016) ^[11].

Pollution

Anthropogenic pollutants, including heavy metals, pesticides, industrial chemicals, and plastics, pose significant threats to soil health and ecosystem integrity. Contamination of soils with heavy metals, arising from industrial activities, mining operations, and improper waste disposal practices, leads to soil toxicity, reduced microbial

activity, and impaired plant growth. Similarly, the accumulation of pesticides and agrochemical residues in soils disrupts soil biota, contaminates groundwater resources, and poses risks to human health and food safety (Alengebawy A, *et al.*, 2021) ^[1].

Climate Change Perturbations

The escalating impacts of climate change manifested through alterations in temperature regimes, precipitation patterns, extreme weather events, and sea-level rise, exert profound influences on soil processes and functions. Increased temperatures accelerate soil organic matter decomposition, alter microbial activity, and exacerbate soil moisture deficits, leading to enhanced soil erosion, desertification, and loss of soil fertility. Erratic precipitation patterns intensify droughts, floods, and soil erosion, exacerbating land degradation and compromising agricultural productivity (Dong, X. *et al.*, 2023) ^[5].

Soil degradation emerges as a complex and multifaceted phenomenon, driven by the interplay of diverse anthropogenic activities and environmental perturbations. Recognizing the underlying factors contributing to soil degradation is imperative for formulating targeted interventions aimed at promoting sustainable soil management practices and fostering soil resilience in the face of global environmental change.

Impacts of soil degradation

Soil degradation, resulting from various anthropogenic activities and environmental perturbations, engenders profound impacts on terrestrial ecosystems, agricultural productivity, and human well-being. Understanding the multifaceted consequences of soil degradation is essential for devising holistic strategies to mitigate its impacts and promote sustainability. This section delineates the far-reaching impacts of soil degradation, encompassing implications for food security, water quality, biodiversity loss, carbon emissions, and land degradation (Bhattacharyya, R. *et al.*, 2015) ^[4].

Food Security

Soil degradation undermines global food security by compromising the productivity and resilience of agricultural systems (Tomlinson, I. 2013). Diminished soil fertility, erosion-induced loss of topsoil, and declining water retention capacity reduce crop yields, exacerbate yield variability, and threaten the livelihoods of millions of smallholder farmers worldwide. Moreover, soil degradation renders agricultural lands more susceptible to the adverse impacts of climate variability, pests, and diseases, further exacerbating food insecurity in vulnerable regions (Gomiero, T. 2016) ^[8].

Water Quality

Soil degradation exacerbates water quality degradation by increasing sedimentation, nutrient runoff, and contamination of surface and groundwater resources. Erosion-induced sedimentation, facilitated by degraded soil structure and loss of vegetation cover, impairs aquatic ecosystems, reduces water clarity, and undermines the ecological integrity of rivers, lakes, and coastal areas. Similarly, agricultural runoff laden with agrochemicals, pesticides, and nutrients leads to eutrophication, algal blooms, and waterborne pollution,

posing risks to human health and aquatic biodiversity (Wantzen, and Mol, 2013) ^[20].

Biodiversity Loss

Soil degradation poses a significant threat to global biodiversity by altering habitat suitability, disrupting ecosystem functioning, and diminishing species diversity. Degraded soils support fewer plant species and harbour impoverished microbial communities, leading to reduced ecosystem resilience and diminished provisioning of ecosystem services. Furthermore, soil degradation exacerbates habitat fragmentation, invasive species spread, and loss of native vegetation, thereby accelerating biodiversity decline and compromising ecosystem stability and resilience (Sun, X., *et al.*, 2023) ^[15].

Carbon Emissions

Soil degradation exacerbates greenhouse gas emissions by releasing stored carbon into the atmosphere and diminishing soil carbon sequestration capacity. Degraded soils exhibit reduced organic matter content, diminished microbial activity, and increased susceptibility to erosion, resulting in the loss of soil carbon stocks and emissions of carbon dioxide and other greenhouse gases. Moreover, land-use changes associated with soil degradation, such as deforestation and conversion of natural habitats to croplands or urban areas, further exacerbate carbon emissions and contribute to climate change feedback loops (Rodrigues, *et al.*, 2023) ^[12].

Land Degradation

Soil degradation contributes to broader land degradation processes, including desertification, salinization, and land abandonment, exacerbating environmental degradation and diminishing land productivity. Erosion-induced loss of topsoil, soil compaction, and decline in soil fertility render landscapes less productive and resilient, undermining their capacity to support agricultural activities and sustain rural livelihoods. Moreover, soil degradation exacerbates land degradation processes such as desertification, salinization, and soil sealing, further compromising ecosystem services and exacerbating socioeconomic vulnerabilities (Bhattacharyya, R.*et al.*, 2015 & Gomiero, T. 2016) ^[4, 8].

Soil degradation emerges as a multifaceted phenomenon with far-reaching implications for soil health, ecosystem integrity, and human well-being. Recognizing the interconnected impacts of soil degradation underscores the urgency of adopting holistic approaches to soil management that promote sustainability and resilience in terrestrial ecosystems. Through concerted efforts to mitigate soil degradation and restore degraded soils, it becomes possible to safeguard vital ecosystem services, enhance food security, and promote long-term environmental sustainability (Karlen, and Rice, 2015) ^[10].

Sustainable soil management practices

Amidst the burgeoning challenges posed by soil degradation, the adoption of sustainable soil management practices emerges as a paramount imperative to safeguard soil health, enhance ecosystem resilience, and promote long-term sustainability. This section elucidates a spectrum of sustainable soil management practices, encompassing conservation agriculture, agroforestry, organic farming, soil conservation measures, and land restoration techniques

(Fahad, S. *et al.*, 2022) ^[6]. These practices embody holistic approaches that integrate ecological principles, technological innovations, and socio-economic considerations to foster soil resilience and mitigate degradation trajectories. (Gomiero, T. 2016 & Hou D *et al.*, 2020) ^[8, 9].

Conservation Agriculture

Conservation agriculture represents a paradigm shift in agricultural production systems, emphasizing minimal soil disturbance, permanent soil cover, and diversified crop rotations. By reducing tillage intensity, conserving soil moisture, and enhancing soil organic matter accumulation, conservation agriculture mitigates soil erosion, improves soil structure, and promotes biodiversity. Moreover, conservation agriculture enhances soil carbon sequestration capacity, mitigating greenhouse gas emissions and contributing to climate change mitigation efforts (Farooq, M.2023) ^[7].

Agroforestry

Agroforestry systems integrate trees, shrubs, and crops in complementary arrangements to optimize resource use efficiency, enhance soil fertility, and diversify agricultural production. Through symbiotic interactions between trees and crops, agroforestry systems improve soil nutrient cycling, increase organic matter inputs, and enhance soil moisture retention capacity. Furthermore, agroforestry systems provide additional ecosystem services such as habitat provision, carbon sequestration, and erosion control, thereby enhancing landscape sustainability and resilience (Fahad, S. *et al.*, 2022) ^[6].

Organic Farming

Organic farming practices eschew synthetic inputs and prioritize ecological approaches to soil fertility management, pest control, and weed suppression. By relying on natural fertilizers, composting, crop rotations, and biological pest control, organic farming enhances soil health, biodiversity, and ecosystem resilience. Moreover, organic farming systems reduce the reliance on external inputs, mitigate soil pollution risks, and enhance the nutritional quality of food products, contributing to human health and environmental sustainability (Benbrook, C. *et al.*, 2022) ^[2].

Soil Conservation Measures

Soil conservation measures encompass a suite of engineering, vegetative, and management practices aimed at reducing soil erosion, improving soil structure, and enhancing soil moisture retention capacity. These measures include contour ploughing, terracing, bunding, vegetative buffers, and cover cropping, which mitigate soil erosion, retain soil moisture and enhance soil fertility. Additionally, soil conservation measures contribute to watershed management, flood mitigation, and water quality improvement, thereby enhancing ecosystem services and landscape resilience (Fahad, S. *et al.*, 2022) ^[6].

Land Restoration Techniques

Land restoration techniques encompass reclamation, reforestation, afforestation, and revegetation efforts aimed at restoring degraded soils and landscapes to their natural or productive states. Through targeted interventions such as

soil amendment, revegetation with native species, and ecological restoration, land restoration techniques enhance soil fertility, biodiversity, and ecosystem services. Furthermore, land restoration efforts contribute to carbon sequestration, climate change mitigation, and socio-economic development, thereby fostering sustainable land use practices and enhancing ecosystem resilience (Tilman, D, 2002 & Fahad, S. *et al.*, 2022) ^[17, 6].

Sustainable soil management practices represent a cornerstone of efforts to address soil degradation and promote long-term sustainability in terrestrial ecosystems. By embracing principles of conservation, regeneration, and ecosystem stewardship, it becomes possible to mitigate degradation trajectories, enhance soil resilience, and safeguard vital ecosystem services for present and future generations. Through concerted efforts to mainstream sustainable soil management practices, it becomes plausible to reconcile human needs with planetary boundaries and forge pathways towards a more sustainable and resilient future (Gomiero, T. 2016, Hou D. *et al.*, 2020, Fahad, S. *et al.*, 2022 & Dong, X. *et al.*, 2023) ^[8, 9, 6, 5].

Integrating science, policy, and stakeholder engagement

Achieving sustainable soil management necessitates the integration of scientific knowledge, policy interventions, and stakeholder engagement to address the multifaceted challenges posed by soil degradation. This section elucidates the critical importance of integrating science, policy, and stakeholder engagement in advancing soil sustainability agendas, fostering interdisciplinary collaboration, and promoting informed decision-making processes. By bridging the gap between research, policy, and practice, it becomes possible to develop effective soil conservation strategies that reconcile environmental imperatives with socioeconomic considerations (Gomiero, T. 2016, Hou D. *et al.*, 2020, Fahad, S. *et al.*, 2022, Dong, X. *et al.*, 2023) ^[8, 9, 6, 5].

Scientific Knowledge

Scientific research serves as the foundation for evidence-based soil management practices, providing insights into soil processes, ecosystem dynamics, and the impacts of anthropogenic activities on soil health. By advancing understanding of soil degradation mechanisms, identifying sustainable land management practices, and assessing ecosystem services provided by soils, scientific knowledge informs policy formulation and implementation. Moreover, interdisciplinary research collaborations facilitate the integration of diverse perspectives and methodologies, enhancing the robustness and applicability of soil management strategies.

Policy Interventions

Government policies, regulatory frameworks, and institutional mechanisms play a crucial role in shaping soil management practices, incentivizing sustainable land use behaviours, and mitigating soil degradation risks. Policy interventions such as land-use planning, soil conservation regulations, agri-environmental schemes, and payment for ecosystem services programs provide incentives for adopting sustainable soil management practices (Fahad, S. *et al.*, 2022) ^[6]. Furthermore, international agreements and conventions, such as the United Nations Convention to Combat Desertification (UNCCD) and the Sustainable

Development Goals (SDGs), provide frameworks for global cooperation and action on soil sustainability (Singh, A. 2022 & Telo da Gama, 2023) ^[14, 16].

Stakeholder Engagement

Stakeholder engagement, encompassing collaboration between government agencies, agricultural producers, local communities, civil society organizations, and academia, fosters participatory decision-making processes and promotes ownership of soil conservation initiatives (Fahad, S. *et al.*, 2022) ^[6]. Engaging stakeholders in the design, implementation, and evaluation of soil management policies ensures that diverse perspectives and interests are considered, enhancing the legitimacy and effectiveness of interventions. Moreover, fostering dialogue, knowledge exchange, and capacity building among stakeholders facilitates the co-creation of innovative solutions and promotes collective action towards shared sustainability goals.

Challenges and Opportunities

Despite the inherent benefits of integrating science, policy, and stakeholder engagement for soil sustainability, several challenges persist, including institutional fragmentation, inadequate funding, conflicting interests, and knowledge gaps. Addressing these challenges requires concerted efforts to enhance interdisciplinary collaboration, strengthen policy coherence, and foster inclusive governance mechanisms. Moreover, harnessing emerging technologies, such as remote sensing, geographic information systems (GIS), and citizen science initiatives, offers opportunities to enhance monitoring, modelling, and decision-support tools for soil management (Sahbeni, G. *et al.*, 2023) ^[13].

Integrating science, policy, and stakeholder engagement stands as a cornerstone of efforts to promote soil sustainability and address the complex challenges posed by soil degradation. By fostering interdisciplinary collaboration, aligning policy objectives with scientific evidence, and engaging stakeholders in decision-making processes, it becomes possible to develop context-specific soil management strategies that reconcile environmental, social, and economic imperatives. Through collective action and shared responsibility, it becomes plausible to safeguard soil resources for present and future generations, thereby ensuring the resilience and sustainability of terrestrial ecosystems.

Future directions and conclusions

The trajectory of soil sustainability hinges upon concerted efforts to address persistent challenges, embrace emerging opportunities, and advance transformative solutions. This section delineates future directions aimed at enhancing soil resilience, promoting sustainable land management practices, and fostering interdisciplinary collaboration to reconcile environmental imperatives with socio-economic considerations.

Enhancing Research and Innovation

Future research endeavours should prioritize filling knowledge gaps, elucidating soil degradation mechanisms, and developing innovative solutions to enhance soil health and resilience. Embracing interdisciplinary approaches, leveraging emerging technologies, such as remote sensing, molecular biology, and artificial intelligence, and promoting

open data sharing and collaboration are essential for advancing scientific understanding and developing evidence-based soil management strategies (Sahbeni, G. *et al.*, 2023) ^[13].

Mainstreaming Sustainable Land Management

Mainstreaming sustainable land management practices necessitates integrating soil conservation principles into agricultural policies, land-use planning, and development agendas. Encouraging the adoption of conservation agriculture, agroforestry, organic farming, and soil conservation measures through policy incentives, capacity building, and extension services is critical for promoting sustainable land use practices and mitigating soil degradation risks (Fahad, S. *et al.*, 2022) ^[6].

Strengthening Governance and Policy Coherence

Enhancing governance mechanisms, strengthening policy coherence, and fostering multi-stakeholder partnerships are essential for mainstreaming soil sustainability agendas at local, national, and global levels. Aligning soil conservation policies with broader sustainable development goals, enhancing coordination between government agencies, and engaging stakeholders in decision-making processes are pivotal for fostering inclusive and participatory governance frameworks (Singh, A. 2022 & Telo da Gama, 2023) ^[14, 16].

Promoting Education and Awareness

Raising awareness about the importance of soil conservation, promoting environmental education, and fostering a culture of stewardship is imperative for fostering behavioural change and promoting sustainable land management practices. Integrating soil sustainability principles into formal education curricula, engaging with local communities through outreach programs, and leveraging social media and digital platforms for knowledge dissemination are essential for promoting soil conservation literacy and fostering public engagement (Fahad, S. *et al.*, 2022) ^[6].

Conclusions

In conclusion, soil sustainability stands as a critical imperative for safeguarding terrestrial ecosystems, promoting agricultural productivity, and ensuring the well-being of current and future generations. Despite the formidable challenges posed by soil degradation, there exist promising opportunities to advance transformative solutions and promote resilience in soil systems. By embracing interdisciplinary collaboration, integrating scientific knowledge with policy interventions, and fostering stakeholder engagement, it becomes possible to forge pathways towards a more sustainable and resilient future. Through collective action and shared responsibility, we can safeguard soil resources, enhance ecosystem resilience, and promote the sustainability of terrestrial ecosystems for generations to come.

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