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NUTRIENT RECYCLING AS A PROMOTER OF SOIL HEALTH MANAGEMENT: A REVIEW

Ali, Abubakar Suleiman[1]
aasuleiman@fudutsinma.edu.ng; +234-8167398348
[1]Department of Soil Science, Faculty of Agriculture,
Federal University Dutsin-Ma, Katsina State, Nigeria

ABSTRACT

Soil health is a fundamental component of sustainable agriculture, affecting both productivity and environmental quality. One of the key factors in maintaining soil health is nutrient recycling, a process where nutrients are reused within the ecosystem to maintain fertility and structure. This literature review explores the significance of nutrient recycling in soil health management, discussing its role in preventing soil degradation, improving agricultural productivity, and ensuring sustainability. Key nutrient cycles, challenges in nutrient management, and current techniques to enhance nutrient recycling are examined. This review provides insight into the growing importance of nutrient recycling practices for ensuring long-term soil health and agricultural sustainability.

Key words: nutrient recycling; soil health; sustainable agriculture

INTRODUCTION

Soil health constitutes a pivotal factor in determining agricultural productivity, environmental sustainability, and the resilience of ecosystems. It encompasses the physical, chemical, and biological characteristics of soil that allow it to serve as an essential medium for plant growth, water infiltration, nutrient cycling, and carbon sequestration (Schröder *et al*., 2016; FAO, 2005). Among the myriad of factors that affect soil health, nutrient recycling is particularly significant as a fundamental process that not only maintains soil fertility but also underpins sustainable agricultural practices (Cordeiro and Sindhøj, 2024).

Nutrient recycling is defined as the innate process through which critical elements, such as nitrogen, phosphorus, and potassium, are transformed within the soil ecosystem. This process entails the decomposition of organic matter, the mineralization of nutrients, and their subsequent assimilation by plants (Paul *et al*., 2014). Through microbial activities and interactions with plants, these nutrients become bio-available and are perpetually reused, thereby diminishing the reliance on synthetic fertilizers. The effective implementation of nutrient recycling not only conserves natural resources but also alleviates nutrient losses via leaching or volatilization and improves soil structure and biodiversity (Aasfar *et al*., 2021).

In the context of agricultural systems that are increasingly challenged to yield greater food production on reduced land areas while minimizing ecological impacts, the adoption of sustainable soil management practices is of paramount importance. This literature review intends to scrutinize the importance of nutrient recycling within the framework of soil health management. It will delve into the mechanisms underlying nutrient cycling, the contributions of soil microorganisms, the effects of agricultural practices on nutrient dynamics, and the strategies to augment nutrient recycling for enduring soil sustainability.

MATERIALS AND METHODS

The present investigation utilized a comprehensive literature review methodology, amalgamating contemporary academic and institutional publications to evaluate the significance of nutrient recycling in the context of soil health. The sources were meticulously selected from peer-reviewed journal articles, reports, and recent scholarly research pertaining to soil science and agronomy. The analytical framework concentrated on an examination of the biological and ecological principles governing nutrient cycling and management practices within diverse agroecosystems.

Soil Health Components

Soil health constitutes a complex construct that amalgamates a variety of soil attributes and processes, incorporating the physical, chemical, and biological facets that collectively ascertain a soil's capacity to operate as a vital living system. This system underpins the productivity of both plant and animal life, preserves or enhances the quality of air and water ecosystems, and bolsters human health and habitation (Schröder *et al*., 2016). The concept accentuates the dynamic and interrelated nature of soil properties, highlighting that soil health transcends mere absence of degradation, embodying the presence of conditions that enable soils to execute their fundamental functions proficiently.

1. Physical Properties

The physical attributes of soil encompass texture, structure, porosity, and moisture retention. These characteristics significantly influence a soil's capability to sustain plant growth by impacting root penetration, water infiltration, and aeration. Soils characterized by health exhibit robust aggregation, sufficient pore space facilitating air and water movement, and resilience against erosion. For example, soils possessing optimal texture and structure promote superior root development and moisture retention, thereby augmenting plant vitality and productivity (FAO, 2005). The physical attributes of soil such as texture, structure, porosity, and moisture retention play a foundational role in nutrient cycling by mediating microbial activity, root exploration, and the diffusion of dissolved nutrients. Recent studies emphasize that well-aggregated soils with stable pore networks enhance organic matter protection and microbial habitat diversity, thus promoting efficient carbon sequestration and nitrogen mineralization (Lehmann *et al*., 2020). Conversely, compacted or poorly structured soils restrict oxygen diffusion, favoring anaerobic conditions that slow decomposition and promote methane emissions (Rumpel et al., 2022). For instance, clay-rich soils may retain nutrients effectively but limit their mobility, while sandy soils facilitate leaching, necessitating balanced management (Kallenbach *et al*., 2021).

2. Chemical Properties

Chemical characteristics, including soil pH, nutrient composition, cation exchange capacity, and salinity, are vital for determining the accessibility of nutrients to plants. A balanced array of chemical properties ensures optimal nutrient availability while mitigating toxicity risks. For instance, soils within an appropriate pH range enhance the accessibility of essential nutrients, while an adequate cation exchange capacity facilitates effective nutrient retention and release (Schröder *et a*l., 2016). Soil chemical properties (pH, nutrient availability, cation exchange capacity [CEC], and salinity) directly govern nutrient cycling by influencing solubility, adsorption, and microbial transformations. A meta-analysis by Zhou *et al.* (2023) demonstrated that acidic soils (pH < 5.5) reduce phosphorus availability by enhancing aluminum fixation, whereas neutral to slightly alkaline soils optimize macro- and micronutrient accessibility. High CEC soils (e.g., those rich in clay or organic matter) exhibit superior nutrient retention but may require microbial mediation to release immobilized nutrients (Jaiswal *et al*., 2022). Emerging research also highlights salinity-induced disruptions to nitrification, stressing the need for adaptive practices like organic amendments (Singh, 2023).

3. Biological Properties

Biological characteristics relate to the diversity and activity of soil organisms, such as bacteria, fungi, earthworms, and protozoa. A diverse microbial community plays a pivotal role in organic matter decomposition, nutrient cycling, and disease suppression. The presence of a varied and active assemblage of soil organisms fortifies the resilience of soil ecosystems, enhancing their ability to recuperate from disturbances and sustain functionality (Bargali, 2024). The biological component such as microbial diversity, faunal activity, and enzyme production are the engines of nutrient cycling. Recent metagenomic studies reveal that bacterial-fungal synergies (e.g., mycorrhizal associations) accelerate litter decomposition and stabilize nitrogen in micro-aggregates (Banerjee *et al*., 2024). Earthworms, through bioturbation, enhance phosphorus mobility by 20–30% in temperate soils (Frouz *et al*., 2023). However, intensive agriculture reduces microbial functional diversity, impairing nutrient turnover; regenerative practices (e.g., cover cropping) can restore these functions (Bargali, 2024; Thakur *et al*., 2023).

Indicators of Soil Health

Indicators of soil health comprise quantifiable properties of soil or plant systems that provide insights into the functional efficacy of the soil. These indicators may manifest as physical, chemical, or biological properties, processes, or characteristics of soils. For instance, the content of soil organic matter, microbial biomass, enzyme activities, and nutrient availability are frequently utilized indicators. Monitoring these indicators is instrumental in evaluating soil quality and informing management strategies, thereby facilitating the identification of soil conditions conducive to sustainable agricultural practices (USDA NRCS, 2024). Nonetheless, this review will predominantly emphasize the roles of nutrient recycling in influencing soil health status.

Nutrient Recycling in Soil Health Management

The process of nutrient recycling is essential to the management of soil health, enabling the perpetual circulation of nutrients within the soil-plant-animal-microbe nexus. This phenomenon guarantees the accessibility of vital nutrients necessary for plant development while concurrently minimizing ecological detriment. The efficient recycling of nutrients curtails the reliance on synthetic fertilizers, lessens nutrient leaching, and improves soil structure and biodiversity (Schröder *et al.*, 2016; FAO, 2005).

Mechanisms of Nutrient Cycling

The fundamental mechanisms governing nutrient cycling within soils encompass decomposition, mineralization, immobilization, nitrification, and denitrification. These processes are intricately interconnected and modulated by an array of soil characteristics.

a. Decomposition: This process entails the activity of soil microorganisms that decompose organic matter, liberating nutrients in forms that are accessible to plants. Several factors, including temperature, moisture, and the carbon-to-nitrogen (C:N) ratio of organic materials, significantly influence this process. Organic materials characterized by elevated C:N ratios, such as straw, may induce nitrogen immobilization as microorganisms utilize available nitrogen to decompose the material (Noma and Sani, 2008: Girkin and Cooper, 2023).

b. Mineralization: This refers to the transformation of organic nutrients into inorganic forms, such as ammonium and nitrate, which can be readily assimilated by plants. The process is contingent upon the availability of organic carbon and the activity level of soil microorganisms.

Conditions that promote microbial activity, such as optimal moisture levels and temperature, serve to augment mineralization rates (Schröder *et al*., 2016).

c. Immobilization: pertains to the absorption of inorganic nutrients by soil microorganisms, temporarily diminishing their availability to plants. This phenomenon manifests when the C:N ratio of decomposing organic matter is elevated, resulting in a microbial nitrogen demand that surpasses its availability within the soil (Girkin and Cooper, 2023). Immobilization is a transient occurrence; as microorganisms perish, the immobilized nutrients are subsequently released back into the soil via mineralization.

d. Nitrification and Denitrification: are microbial processes that facilitate the conversion of ammonium to nitrate and nitrate to nitrogen gas, respectively. Nitrification encompasses the oxidation of ammonium to nitrite and subsequently to nitrate by nitrifying bacteria. Conversely, denitrification involves the reduction of nitrate to nitrogen gas by denitrifying bacteria, typically transpiring under anaerobic conditions. These processes significantly influence nitrogen availability and loss within soils, thereby impacting nutrient management strategies (Girkin and Cooper, 2023).

Role of Soil Microorganisms in Nutrient Cycling

Soil microorganisms serve a fundamental role in ecosystem functionality, particularly regarding the nutrient cycling mechanisms that underpin plant growth and the overall health of soil ecosystems. A study by Zhan (2024) emphasizes the critical role of bacteria and fungi in decomposing organic matter, thereby facilitating the release of essential nutrients like nitrogen (N), phosphorus (P), and carbon (C) into the soil. These nutrients are indispensable for plant development and are rendered bioavailable through various microbial metabolic activities.

A salient illustration of microbial participation in nutrient enrichment is exemplified by the symbiotic association between Rhizobium species and leguminous plants. These bacteria possess the capability to convert atmospheric nitrogen into ammonia, a form readily assimilable by plants, thereby diminishing reliance on synthetic nitrogen fertilizers (Udvardi et al., 2024). This process of biological nitrogen fixation not only proves to be economically advantageous for agricultural practices but also aligns with principles of environmental sustainability.

Fungi, particularly mycorrhizal fungi, also assume a critical role in nutrient cycling by establishing symbiotic relationships with plant roots. These fungi augment the absorptive capacity of roots, thereby facilitating the acquisition of less mobile nutrients, most notably phosphorus. Furthermore, they enhance soil structure through the promotion of soil aggregation, which subsequently benefits root development and water retention capabilities (Paravar and Wu, 2024).

Impact of Agricultural Practices on Nutrient Cycling

Agricultural practices exert significant influences on the nutrient cycling mechanisms that regulate soil health and fertility. Intensive and unsustainable agricultural methods, including monocropping, excessive soil tillage, and the over application of chemical fertilizers, can disrupt nutrient cycles and precipitate soil degradation. Monocropping, for instance, diminishes soil biodiversity, exhausts specific soil nutrients, and heightens susceptibility to pest and disease pressures (Belete *et al*., 2024, Mahmud *et al* 2024 and Sani *et al* 2019). Likewise, excessive tillage intensifies soil erosion, reduces organic matter content, and disrupts the microbial communities integral to nutrient cycling (Belete *et al*., 2024). The dependence on chemical fertilizers, while effective in the short term, can induce nutrient imbalances, foster soil acidification, and degrade microbial activity, thereby undermining long-term soil fertility (Zhang *et al*., 2024).

Conversely, sustainable agricultural practices, including crop rotation, cover cropping, reduced tillage, and the application of organic amendments, can facilitate nutrient recycling and enhance soil health. Crop rotation aids in maintaining nutrient equilibrium by diversifying plant species and interrupting pest life cycles (Bender *et al*., 2016). Cover cropping contributes to the enhancement of soil organic matter and provides habitats for beneficial soil microorganisms, which in turn bolsters nutrient cycling (Finney *et al*., 2016). Reduced tillage, by minimizing soil disturbance, assists in preserving soil structure, mitigating erosion, and supporting microbial populations essential for nutrient transformations (Li *et al*., 2024a). Organic amendments such as compost or manure offer a gradual release of nutrients and bolster soil microbial activity, further advancing nutrient cycling and soil fertility (Alemu *et al*., 2016).

Techniques for Enhancing Nutrient Recycling in Soil Management

Efficient nutrient recycling constitutes a foundational element of sustainable soil management and agricultural productivity. A variety of techniques have been developed and employed to optimize nutrient cycling, each presenting unique ecological and agronomic advantages. These methodologies frequently promote soil biodiversity, organic matter retention, and microbial activity, which are key determinants of nutrient availability and soil fertility (Zama and Lungelo, 2023).

a. Organic Farming Practices

Organic agriculture prioritizes the incorporation of natural inputs and biological mechanisms to sustain and augment soil fertility. A fundamental method utilized in this context is composting, which converts organic refuse into stable humus, thereby enriching the soil with vital macronutrients and micronutrients while simultaneously enhancing soil structure and microbial activity (Small *et al.*, 2024). In a similar vein, green manures, particularly leguminous varieties such as clover and vetch, are extensively employed in organic farming systems to facilitate the biological fixation of atmospheric nitrogen via symbiotic relationships with rhizobia, consequently diminishing reliance on synthetic nitrogen fertilizers (Zhang *et al.*, 2024). Crop rotation, another essential tenet of organic agriculture, contributes to nutrient equilibrium, disrupts pest and disease cycles, and fosters a more resilient agroecosystem (Li *et al*., 2024b).

b. Agroecological Approaches

Agroecology applies principles of ecology to the formulation of sustainable agricultural systems that operate in concert with ecological processes. Techniques such as agroforestry, which incorporates arboreal species into agricultural ecosystems, can enhance nutrient recycling by promoting deep nutrient uptake and adding organic matter through leaf litter and root turnover (Wanjari *et al*., 2024). Polyculture, defined as the simultaneous cultivation of multiple crop species, improves nutrient utilization efficiency and can diminish dependence on synthetic fertilizers (Li *et al*., 2024c). Furthermore, Integrated Pest Management (IPM) fosters ecological equilibrium by decreasing pesticide applications, which in turn aids in preserving beneficial soil organisms crucial for nutrient cycling (Kremen and Miles, 2012).

c. Conservation Tillage Practices

Conservation tillage, encompassing methodologies such as no-till and reduced tillage, minimizes soil disruption and aids in the preservation of soil structure and organic matter. These practices enhance microbial activity, improve water infiltration, and mitigate erosion, thereby facilitating the natural cycling of nutrients within the soil (Li *et al*., 2024d). Conservation tillage further alleviates carbon losses and nurtures beneficial soil biota that contribute to nutrient transformations (Li *et al*., 2024d).

d. Application of Biofertilizers

The employment of biofertilizers, which consist of living microorganisms such as nitrogen-fixing bacteria and phosphorus-solubilizing fungi, serves as an efficacious strategy for enhancing nutrient availability and promoting soil health. These microorganisms augment nutrient uptake by plants and stimulate biological nutrient cycling processes, particularly within nutrient-deficient soils (Wei *et al*., 2024). Biofertilizers are increasingly acknowledged for their capacity to diminish dependence on chemical inputs and to sustain long-term soil fertility (Bhattacharyya *et al*., 2016).

Technological Innovations in Soil Health and Nutrient Recycling

Recent advancements in technology have profoundly altered methodologies related to soil management and nutrient recycling, facilitating more precise, sustainable, and data-informed agricultural practices. These innovations not only enhance nutrient use efficiency but also promote the enduring health and productivity of agricultural soils.

Precision agriculture leverages technologies such as GPS, geographic information systems (GIS), and remote sensing to enable site-specific management of nutrients and other inputs. These instruments facilitate the targeted application of fertilizers, thereby minimizing waste, mitigating environmental repercussions, and enhancing nutrient use efficiency (Zhang *et al*., 2024a). Variable rate technology (VRT), for instance, allows farmers to apply nutrients at varying rates across a field according to soil nutrient heterogeneity, thereby improving both crop yields and environmental stewardship (Zhang *et al*., 2024b).

a. Soil Health Monitoring Tools

The advancements in the domain of soil health monitoring have culminated in the creation of sophisticated digital tools and diagnostic kits that evaluate biological, chemical, and physical parameters indicative of soil health. These instruments frequently encompass assessments of microbial activity, organic matter composition, and enzymatic functions, which are imperative for the processes of nutrient cycling (Bünemann *et al*., 2018). The implementation of real-time monitoring engenders adaptive nutrient management strategies that are attuned to the prevailing soil conditions, thereby fostering a more efficient and sustainable utilization of resources (Celik *et al*., 2019).

a. Microbial Inoculants

Advancements in biotechnology have facilitated the production and commercial application of microbial inoculants, which introduce advantageous microorganisms into the soil matrix to enhance nutrient availability and promote plant growth. Products formulated by enterprises such as Loam Bio utilize fungal strains, particularly mycorrhizal fungi, to bolster nutrient cycling and contribute to the sequestration of soil carbon (Loam Bio, 2023). These microbial innovations are integral to sustainable agricultural practices, as they bolster soil biodiversity, enhance nutrient uptake efficacy, and improve resilience against climatic stressors (Sessitsch *et al*., 2019).

Global Implications of Nutrient Recycling for Soil Health

The process of nutrient recycling is paramount in fostering sustainable agricultural practices and addressing overarching global environmental challenges. The proficient cycling of nutrients not only sustains soil fertility but also plays a significant role in climate change mitigation and the assurance of long-term food security, thereby constituting a fundamental element of global agricultural and environmental policy.

a. Sustainable Agriculture

One of the most immediate advantages derived from enhanced nutrient recycling is its pivotal contribution to sustainable agriculture. By optimizing the utilization of organic matter and biological processes, nutrient recycling diminishes the dependence on synthetic fertilizers, which are frequently expensive, energy-intensive to manufacture, and environmentally detrimental when utilized excessively (van der Wiel *et al*., 2024). Sustainable nutrient management techniques improve soil structure, microbial activity, and nutrient availability, thereby fostering resilient agricultural systems that are both economically and ecologically sustainable (Lakhani *et al*., 2025). Furthermore, integrated nutrient recycling methodologies, such as the amalgamation of organic and inorganic fertilizers, have demonstrated potential in augmenting crop productivity while safeguarding environmental integrity (Vanlauwe *et al*., 2015a).

b. Climate Change Mitigation

Well-maintained soils significantly contribute to climate change mitigation by functioning as carbon sinks. Soils characterized by elevated organic matter content sequester carbon dioxide through biological mechanisms such as microbial respiration and the decomposition of organic matter (Wang *et al*., 2024). Practices that enhance nutrient recycling, including composting, cover cropping, and reduced tillage, facilitate soil carbon storage and mitigate greenhouse gas emissions (Paustian *et al*., 2016). In this context, nutrient recycling emerges as a natural climate solution, with far-reaching implications for diminishing the carbon footprint of agricultural practices.

c. Food Security

The preservation of soil fertility through nutrient recycling is also critical for the assurance of global food security. As the global population experiences continual growth, the demand on agricultural systems to sustainably produce an increased food supply intensifies. Soils that have been degraded due to nutrient depletion or sub-optimal management practices exhibit diminished productivity, thereby jeopardizing long-term food availability (FAO, 2015). By enhancing nutrient use efficiency and conserving soil health, nutrient recycling aids in sustaining high yields and bolstering resilient food systems capable of adapting to changing conditions of climate and market fluctuations.

Challenges in Nutrient Recycling

Although nutrient recycling presents a myriad of agronomic and environmental advantages, a variety of challenges impede its extensive implementation, particularly within developing regions. These obstacles are frequently interrelated and stem from economic, informational, and institutional deficiencies.

a. Economic Constraints

A principal hindrance to the acceptance of nutrient recycling methodologies is economic constraint, particularly among smallholder and resource-limited farmers. Practices such as the establishment of composting infrastructure, the application of biofertilizers, and the utilization of precision technologies typically necessitate initial financial outlays that exceed the capabilities of numerous small-scale producers (Rahmadani *et al*., 2024). Furthermore, the protracted time-frame for realizing a return on investment derived from enhanced soil fertility may deter farmers from adopting such practices, especially when they are confronted with immediate financial exigencies (Pretty *et al*., 2011). In numerous instances, restricted access to credit and financial services exacerbates this dilemma, rendering farmers incapable of making investments in sustainable nutrient management technologies (Snapp *et al*., 2010).

b. Knowledge Gaps

Inadequate knowledge and limited extension services represent significant barriers to the effective implementation of nutrient recycling methodologies. A considerable number of agricultural practitioners lack access to training and educational resources that could enhance their understanding and proficiency in the application of nutrient cycling strategies (FAO, 2017). The insufficient dissemination of local research findings and a lack of collaborative efforts between farmers and researchers frequently lead to sub-optimal adoption rates, even in the presence of cost-effective technological solutions (Franke *et al*., 2014). Additionally, cultural perceptions and attitudinal barriers may hinder the adoption of practices such as composting or the integration of livestock waste, which are often regarded as labor-intensive or unattractive.

c. Policy and Institutional Barriers

The lack of supportive policies and institutional frameworks constitutes another significant obstacle. Numerous national agricultural policies continue to emphasize immediate productivity enhancements through conventional inputs, often neglecting more sustainable and integrated approaches to nutrient management (Sumberg *et al*., 2013). Weak institutional support, disjointed governance frameworks, and insufficient investment in soil health research further impede the advancement and implementation of nutrient recycling methodologies (Vanlauwe *et al*., 2015b). The presence of incentives, subsidies, and regulations favoring synthetic fertilizers over organic alternatives may also skew farmer decision-making and market dynamics (Palm *et al*., 2014).

CONCLUSION

The study underscore the critical importance of nutrient recycling in preserving soil fertility, mitigating environmental repercussions, and fostering sustainable food systems. Notwithstanding the established advantages, the adoption of such practices is obstructed by economic, educational, and institutional impediments. Addressing these challenges necessitates a coordinated approach encompassing research, policy formulation, and farmer involvement. The study also concluded that, nutrient recycling is indispensable for fostering soil health and promoting sustainable agricultural practices. Methods such as composting, the application of biofertilizers, and the reduction of tillage play a significant role in enhancing nutrient retention and cycling. Nonetheless, obstacles including limited awareness, elevated implementation costs, and policy stagnation must be surmounted.

RECOMMENDATIONS

This paper proffers the following recommendations:

1. Augment farmer education and extension services.
2. Facilitate financial incentives for sustainable agricultural practices.
3. Allocate resources towards research and development of innovative nutrient management solutions.
4. Encourage collaborative and community-centric approaches to soil health initiatives

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