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Soil Regeneration through Permaculture: Integrating Organic Matter, Soil Microorganisms, Biochar, and Conservation Agriculture for Sustainable Soil Fertility Restoration

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Abstract
Background. Soil degradation is a major challenge to sustainable agricultural development because it reduces soil fertility, disrupts microbial activity, degrades soil structure, lowers water retention, and decreases agroecosystem productivity. Permaculture-based soil regeneration offers an ecological restoration strategy integrating organic matter management, soil conservation, and biodiversity enhancement.
Aims. This article analyzes soil regeneration mechanisms by integrating compost, indigenous microorganisms, biochar, nutrient-supporting plants, cover crops, organic mulching, and minimum tillage.
Methods. This conceptual review used descriptive analysis and thematic synthesis of soil regeneration materials and relevant scientific principles.
Result. The synthesis indicates that soil regeneration is a multidimensional process involving the simultaneous restoration of physical, chemical, and biological soil properties. Organic matter contributes to soil aggregation, cation exchange capacity, and substrate availability for soil organisms. Microorganisms facilitate organic matter decomposition and nutrient cycling, while biochar may improve selected soil properties depending on its characteristics and environmental conditions. Cover crops and reduced soil disturbance help control erosion, protect the soil surface, and support biological activity.
Conclusion. This article proposes an Integrated Permaculture-Based Soil Regeneration (IPSR) conceptual framework linking regenerative management practices, soil health restoration, and agroecosystem resilience. The proposed framework requires empirical validation across different soil types and agricultural systems.

Keywords: soil regeneration; permaculture; soil organic matter; soil microorganisms; biochar; regenerative agriculture; soil health.

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INTRODUCTION

Soil is a fundamental natural resource that supports food production, nutrient cycling, water management, carbon storage, and biodiversity sustainability. Soil functions not only as a plant growth medium but also as a complex biological system that interacts among minerals, organic matter, water, air, plant roots, and soil organisms. In intensive agricultural systems, various management activities can reduce soil quality if not accompanied by adequate conservation measures. Over-tillage, limited return of organic residues, compaction by heavy equipment, erosion, and the use of agricultural inputs that do not match needs can disrupt the balance of soil ecosystems.

The Soil Regeneration material compares soil that has undergone intensive tillage with soil managed without long-term plowing. The illustration emphasizes the importance of biopore channels, root tissues, and soil structures that support water movement and plant growth. Soil degradation is also linked to broader environmental issues, including climate change, organic carbon loss, and the decline in agroecosystems' ability to cope with drought and extreme rainfall.

Conventional approaches focused on increasing production through nutrient inputs alone are not necessarily enough to restore the soil's full ecological function. Therefore, an approach is needed that not only improves chemical fertility but also rebuilds the soil's physical structure and biological life.

Permaculture is an ecological design approach that emphasizes integrated resource management, using natural processes, recycling biomass, promoting plant diversity, and reducing environmental disturbances. In the context of soil regeneration, permaculture principles can be applied through composting, using organic matter, managing microorganisms, biochar, mulch, ground cover crops, and reducing the intensity of soil tillage.

An evaluation is conducted on the present condition of agriculture, highlighting concerns related to soil degradation and reliance on fossil fuels, in relation to attaining food security for an ever-expanding global populace. Soil is described as "the delicate, living epidermis of the Earth," yet its vitality and vulnerability have often been overlooked amid agriculture's global expansion. Given its crucial role in the interconnected soil-water-air-energy system, how we manage soil can significantly influence climate change, yielding positive or negative effects depending on whether we maintain or harm it. Regenerative agriculture fundamentally aims to boost soil health or rehabilitate severely damaged soil, thereby

symbiotically improving water quality, vegetation, and land productivity. Using regenerative agricultural techniques can increase soil organic carbon (SOC) in existing soils and support the formation of new soil. This process extracts carbon from the atmosphere while enhancing soil structure, health, fertility, crop yields, water retention, and aquifer replenishment—thereby mitigating flooding and drought, as well as further soil erosion from reduced runoff. Given that localized food production has been shown to maintain soil integrity and quality, urban agriculture should be regarded as a vital prospective asset to regenerative farming in the future, provided the techniques used are inherently 'regenerative'. If localization is to emerge as a primary strategy for addressing the significantly diminished reliance on fossil fuels and maintaining soil integrity – alongside heightened food production in urban areas – it will be essential to integrate holistic ('systems') design methodologies like permaculture and the circular economy (which reduce and repurpose 'waste') into the current urban framework. Alongside cultivating food in urban environments, initiatives such as weatherproofing and thermally insulating current buildings, as well as adopting a more localized lifestyle, will significantly reduce our total energy usage. To reduce our reliance on fossil fuels, strategies to lower overall energy use should be considered as important as expanding low-carbon energy generation. In summary, transitioning from the linear model of 'take, make, dispose' to the systemic, circular approach of 'reduce, reuse, recycle, regenerate' is essential to meet the needs of future generations. (Rhodes, 2017).

Agricultural output rose to meet the growing global demand for food, fiber, and energy, driven by a burgeoning world population and rising purchasing power. Despite the expansion and diversification of agricultural production system objectives, the overarching aim of sustainable food security persists. A recurring question is whether agricultural production systems, particularly in emerging nations, can achieve their objectives sustainably. For instance, some argue that sustainable agriculture practices must meet the current population's food and fiber needs without jeopardizing food security or the economic, social, and environmental factors essential for future generations. The demand for higher yields has been partially met, yet it has more than doubled in recent years due to monoculture. Monoculture is a cultivation framework that prioritizes specialization and productivity and has largely shaped contemporary agriculture. Alongside intensive industrial food production came another agricultural development that was, in its own right, groundbreaking. Known as the Green Revolution, these agricultural practices led to significant increases in food production. The integration of new technology, high-yield genetically engineered crop varieties, agrochemicals (such as inorganic

fertilizers and insecticides), and regulated water supply has significantly increased crop output. Certainly, both the Green Revolution and monoculture agricultural practices offered distinct advantages. Economies of scale have significantly improved farm performance by increasing production efficiency and reducing costs. This has created opportunities for agricultural producers not only to feed a growing global population but also to improve health and nutrition by providing specialized, nutrient-dense crops and animal products. Numerous advantages of specialized mono-cropping systems at the field level for meeting the growing need for substantial food and energy supplies have been thoroughly documented. Currently, these advantages and profits are often forfeited or reduced because farmers fail to balance the pros and cons. Because these specialized agricultural systems depend heavily on foreign inputs, they pose current and future challenges to the sustainable use of our natural resources. Contemporary agriculture significantly affects sustainability and requires prudent management in the future. Contemporary agricultural methods have led to negative unforeseen effects that harm environmental integrity and sustainability. Moreover, the benefits of monoculture have been unevenly distributed, with adverse effects far more severe in emerging nations. Environmental and ecological issues, including land degradation, biodiversity loss, and water contamination, have disproportionately impacted and exposed the vulnerabilities of impoverished populations or resource-limited farmers in developing nations (Mc Lennon et al., 2021).

Problem Formulation

This article discusses three main issues: how degradation affects the physical, chemical, and biological properties of soils; how various permaculture practices contribute to restoring soil function; and how these practices can be integrated into a scientifically evaluable soil regeneration framework.

Research Objectives

This article aims to identify the factors that cause soil degradation, analyze the mechanisms of soil health restoration through a permaculture approach, and develop a conceptual model for integrating soil regeneration technologies to support the productivity and sustainability of agroecosystems.

State of the Art

Soil science has shifted from a fertility-management approach dominated by external inputs to restoring soil ecosystem function. The soil health approach treats soil as a living system that can support plant productivity, regulate water and nutrient cycles, and maintain environmental quality. Lal (2020) emphasizes the importance of soil management in supporting agricultural sustainability and environmental resilience. Lehmann and Joseph (2015) describe biochar's potential as a soil-improving material, while Bender et al. (2016) highlight the importance of soil biodiversity for agroecosystem sustainability. Studies on conservation agriculture also show the importance of reducing soil disturbances, maintaining soil surface cover, and diversifying crops. These developments provide a basis for integrating biological, physical, and ecological approaches in soil regeneration.

Research Gap

Although various soil restoration techniques have evolved, research gaps remain.

First, studies of compost, biochar, microorganisms, and ground cover crops often focus on the effects of each treatment, but responses to combinations of these practices may vary with soil conditions.

Second, the effectiveness of integrating regeneration technologies cannot be generalized across all soil types, climates, and cultivation systems.

Third, evaluations of soil regeneration success often focus on specific fertility indicators, whereas restoring soil function requires simultaneous physical, chemical, biological, and productivity measurements.

Fourth, the permaculture approach requires a more measurable evaluation framework so that it can be tested through field research.

Research Novelty

The novelty of this article is the development of an Integrated Permaculture-Based Soil Regeneration (IPSR) conceptual framework that integrates seven soil management practices into a single soil health restoration system.

The conceptual contribution of IPSR lies in the incorporation of the three dimensions of recovery:

1. Physical: soil structure, aggregation, porosity, infiltration, and water storage capacity.
2. Chemistry: organic carbon, cation exchange capacity, pH, and nutrient availability.

3. Biology: microbial biomass, enzyme activity, soil organism biodiversity, and decomposition processes.

This model also links these three dimensions to plant productivity and agroecosystem resilience. This novelty is conceptual and has not yet been tested empirically.

RESEARCH METHODS

Research Design

The article uses a conceptual study approach with descriptive analysis and thematic synthesis. The main source is the Soil Regeneration document, which discusses soil properties, soil degradation, soil organisms, composting, local microorganisms, biochar, nitrogen-contributing plants, mulching, and minimum processing. This article is not an experimental research and does not use data from field measurements. Table 1 shows the variables and indicators.

Stages of Analysis

The analysis followed four stages.

First stage: Identify regeneration components. Group regeneration practices by ecological function and working mechanisms.

Second stage: Mechanism analysis. Identify the relationship between management practices and changes in the physical, chemical, and biological properties of the soil.

Third stage: Integrative synthesis. Constructing conceptual relationships between regeneration practices to form an IPSR model.

Fourth stage: Preparation of evaluation indicators. Develop parameters for empirical testing.

Variables and Indicators

Table 1. Research Variables and Indicators

Dimensions	Observation indicators	Suggested evaluation methods
Physical	Fill weight, porosity, aggregate stability	Ring sample, aggregate test
Chemistry	pH, C-organic, N-total, P-available, KTK	Laboratory analysis
Biology	Soil respiration, microbial biomass, enzyme activity	Microbiological analysis
Hydrology	Infiltration and soil moisture	Infiltrometer, humidity sensor

Agronomy	Biomass and crop yields	Growth and harvest measurement
Ecology	Land cover and biodiversity	Vegetation and biota survey

DISCUSSION

Soil Degradation and Degradation of Ecological Function

Soil degradation occurs when the soil's ability to carry out its ecological functions decreases. Physically, degradation can be characterized by compaction, reduced aggregate stability, the formation of impermeable layers, and an increased erosion risk. Chemically, degradation can involve decreased organic carbon, nutrient imbalance, acidification, salinization, or contaminant accumulation. Biologically, degradation can shift microbial communities and reduce the activity of certain organisms. These three dimensions are reciprocally related. Degradation of organic matter can worsen soil aggregation, while compaction can reduce pore space and inhibit root development. Therefore, soil restoration requires an approach that goes beyond mere fertilizer application.

Regenerative agriculture aims to enhance soil fertility. Regenerative agriculture fosters robust soil that can yield high-quality, nutrient-rich food while improving the land rather than depleting it, ultimately resulting in fruitful farms, thriving communities, and prosperous economies. Regenerative agriculture is dynamic and comprehensive, incorporating permaculture and organic farming techniques such as conservation tillage, cover crops, crop rotation, composting, mobile animal shelters, and pasture cropping to enhance food production, raise farmers' incomes, and improve soil quality. Tenets of regenerative agriculture: Enhance soil fertility; collaborate with entire systems, not Isolated components; gradually enhance entire agroecosystems, soil, water, and biodiversity; integrate the farm with its broader agroecosystem and bioregion; develop designs and adopt a holistic approach. Choices that reflect the worth and connections of agricultural contributors, articulate the importance of every individual, farm, and system, make comprehensive decisions targeting particular systemic alterations, Foster and cultivate fair and mutual relationships among all parties involved, create frameworks for non-linear, multi-capital reciprocity, perpetually advance and develop individuals, farms, and communities to realize their potential, and consistently enhance agroecological practices and cultures. Agriculture shapes the global landscape.

Organic Matter as the Foundation for Soil Regeneration

Soil organic matter is an important component that connects the physical, chemical, and biological properties of soil. Organic matter comes from plant residues, dead organisms, root exudates, and other decomposition products. In source materials, organic matter is described as forming aggregates, reducing bulk density, increasing cation exchange capacity, mineralizing nutrients, and forming complexes with microelements. Increasing organic matter can help maintain soil moisture and provide energy for microorganisms. However, its effectiveness depends on the material's characteristics, the compost's maturity rate, the application dose, soil texture, and environmental conditions.

The Role of Soil Microorganisms

Microorganisms are a major component of the decomposition of organic matter and nutrient transformation. Bacteria, fungi, actinomycetes, and other organisms in the soil food network perform interrelated functions. Heterotrophic bacteria help decompose organic substrates. Fungi help decompose more complex materials and can contribute to aggregate formation. Certain microorganisms also support nitrogen fixation, phosphate dissolution, and symbiotic relationships with plants. Source materials introduce the use of local microorganisms (MOLs), effective microorganisms (EMs), and some locally sourced fermentation formulations. The practice is interesting to study as a relatively low-cost biological approach. Nonetheless, home fermentation solutions do not automatically have a consistent microbial composition or proven agronomic benefits. Their effectiveness and safety need evaluation through microbial identification, contamination testing, and controlled experiments.

Composting and Soil Fertility Restoration

Compost is a controlled decomposition product of organic matter. Composting can use a variety of methods, including windrow composting, hot composting, vermicomposting, bokashi, and household-scale composting. Mature compost can improve soil structure, provide nutrients, and support soil organisms. Composting success depends on a balance of carbon- and nitrogen-rich materials, moisture, aeration, temperature, and decomposition time. Immature compost can cause nitrogen immobilization, root growth disorders, or phytotoxicity issues. Therefore, check compost maturity and quality before application.

Biochar as a Soil Conditioner

Biochar is a carbon-rich material produced by heating biomass under oxygen-limited conditions. Biochar can improve some soil properties, especially in soils with limited water or nutrient retention capacity. Using biochar with compost can provide complementary benefits: compost provides more easily decomposed organic matter, while biochar is more persistent. The source material introduces terra preta as inspiration for combining organic matter and charcoal. However, mixing compost and biochar does not automatically produce soil with the same characteristics as historical terra preta soils. Biochar's influence depends on the biomass type, pyrolysis temperature, particle size, dose, pH, and the recipient soil's characteristics.

Ground Cover Crops and Nitrogen Contributors

Ground cover plants function to protect the soil surface from rainfall, reduce erosion, provide biomass, and help maintain root activity. Certain legume plants can form a symbiosis with nitrogen-fixing bacteria, contributing biological nitrogen. The source material lists several potential crops, including turi, lamtoro, gamal, kaliandra, soybeans, mung beans, and kefir. Species selection should consider climatic suitability, water needs, competition with major crops, and the risk of unintended spread.

Organic Mulching and Moisture Conservation

Organic mulch is a layer of plant material that is placed on the soil surface. Mulch can reduce evaporation, protect the soil from erosion, suppress certain weeds, and add organic matter as it decomposes. The effectiveness of mulch depends on the material type, thickness, decomposition rate, rainfall, and cultivation conditions. Mulch also needs to be managed so it doesn't create excessive moisture around the base of the plant or increase certain pest problems.

Minimum Tillage

Minimum tillage aims to reduce mechanical disturbance to soil structures and organisms. This approach can maintain root tissue, biopores, and aggregate stability, especially when combined with soil cover and crop diversification. However, its application needs to be adapted to field conditions. In soils that have undergone heavy compaction, limited mechanical remedial action may be required before a minimum tillage system is implemented sustainably.

Conceptual Model Of Integrated Soil Regeneration

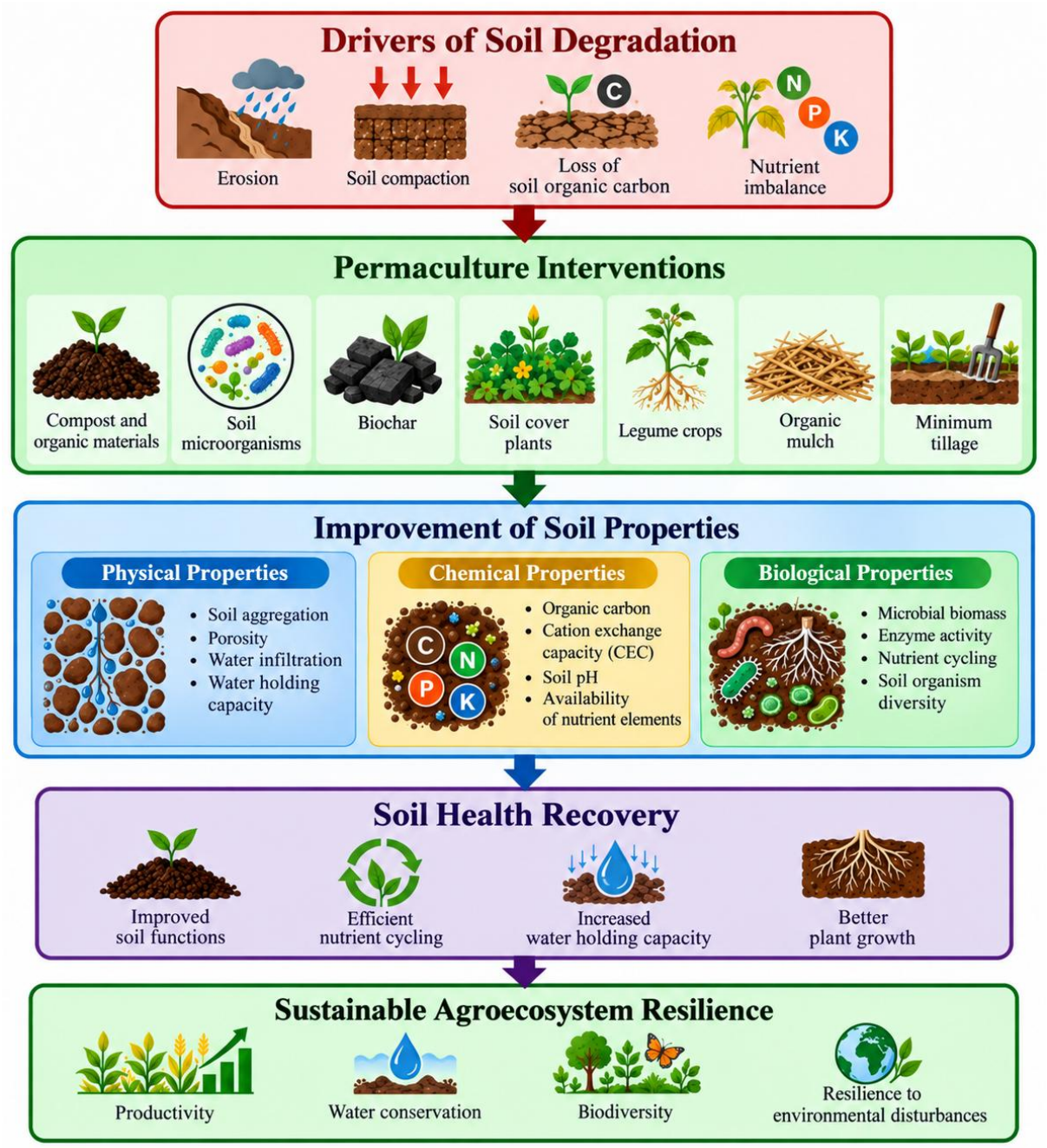


Figure 1. IPSR conceptual framework. The relationships between variables are conceptual hypotheses, not the result of empirical testing.

Advanced Research Hypothesis

The model can be tested using several hypotheses:

H1: Integrating compost and biochar increases organic carbon content and improves soil physical properties compared to the control without the improver.

H2: Using organic matter with the characterized microbial inoculant increases soil biological activity compared with applying organic matter without inoculants.

H3: The combination of ground cover crops, mulching, and minimum tillage improves aggregate stability and water infiltration.
H4: Integrated improvement of the physical, chemical, and biological properties of the soil is positively related to plant growth and productivity.
H5: The soil regeneration response is influenced by texture, initial pH, organic carbon content, and local climatic conditions.

Pamungkas et al. (2024) Reported That Decreased soil quality due to reduced nutrient content is one cause of decreased plant quality and yield. Using humic acid organic matter with N fertilizer is one effort to increase soil nutrients while improving plant growth and yield. Soil analysis showed an increase in N-total and organic C. Aprilia et al. (2024) assert that Papaya is highly sought after by consumers because to its saccharine flavor and rich vitamin and mineral composition. However, in recent years, papaya output has fluctuated due of poor soil structure and nutrient deficits, resulting in poor seed growth and subpar seedlings. Efforts should determine the optimum planting media to sustain papaya nurseries, including vermicompost fertilizer. The experimental findings indicated a notable influence of vermicompost fertilizer proportion on the growth rate and root length of plants at 15, 30, and 45 days after planting (DAP), alongside root volume, stem diameter, plant height, leaf count, fresh weight, and dry weight of plants at 30, 45, and 60 DAP, yet showed no significant variation in growth capacity for plants at 7 and 14 DAP.

Sondari et al. (2025) demonstrate that the nutritional profile of arid land in Pamulihan District exhibits low phosphorus (P), moderate potassium (K), and low C-Organic content. The nutritional status of P, K, and C-Organic in the arid region of Pamulihan District was delineated utilizing a semi-detailed map at a scale of 1:50,000. Nutrient status tests in the dry land of Pamulihan District, particularly in the villages of Cigendel, Citali, Haurngombong, Pamulihan, and Sukawangi, indicated low, medium, and high phosphorus (P) levels, mostly low, with an area of 216.29 ha (55%). Potassium (K) analysis revealed moderate and elevated concentrations, primarily moderate, encompassing 246.14 hectares (62.61%). C-Organic analysis revealed minimal concentrations within a region of 393.13 hectares (100%). Fertilizing suggestions were formulated based on each plant's specific nutrient requirements, in accordance with the fertilizing criteria outlined in the Dry Land Soil Test Kit (PUTK). Komariah & Sondari (2026) found that husk charcoal as a soil medium consistently produced better outcomes than manure across many growth metrics. Consequently, using a 5% HNO_3 scarification with husk charcoal soil media is recommended as the most effective pre-planting

procedure to improve germination, viability, and vigor, and to yield superior initial development of Arabica coffee seeds. Kartini et al. (2024) indicated that leaching depletes soil nutrients, adversely affecting plant development and yield quality. Using KCl fertilizer alongside humic acid is a strategy to improve soil nutrients, promote plant development, and boost output. This study was carried out in Seda Village, Mandirancan District, Kuningan Regency, between June and August 2024. The methodology employed was an experimental approach with a completely randomized design (CRD), comprising 16 treatments replicated twice. The observed variables comprised leaf count, plant stature, tiller quantity, root volume, dry mass per cluster, relative growth rate, and fresh mass per cluster. The findings indicated that applying 1.2 g of KCl per plant, with 0 g of humic acid, resulted in favorable growth and production in spring onion plants.

Sondari et al. (2024) asserted that NPK fertilizer is a technological advancement in agriculture that aids farmers in delivering plant nutrients due to its composition of many nutrient types. Trichoderma sp. is a microbe or biological agent that enhances the physical, chemical, and biological characteristics of soil. Trichoderma fungus enhances soil porosity, facilitating root nutrient uptake, particularly phosphate (P), and augmenting microbial activity. Trichoderma sp. is a decomposer and a promoter of plant growth. The methodology employed is a Randomized Complete Block Design (RCBD). The first element is the use of NPK Phnska Plus fertilizer, while the second element concerns the dosage of Trichoderma sp. and the quadratic regression analysis. An interaction effect exists between NPK fertilizer dosage and Trichoderma dosage across all measured parameters. Applying 6 grams of NPK fertilizer per plant (P2) and 20 grams of Trichoderma per plant resulted in a notable increase in weight relative to the alternative treatments. The independent variable explains 55% of the variability in the treatment variable; 45% remains unexplained.

Fistarani & Handayani (2023) discovered that organic fertilizers enhance soil fertility; nevertheless, nutrient availability is typically limited due to their poor nutritional composition. The reaction of plants to organic fertilizers will be gradual due to the slow-release nature of these fertilizers. Therefore, it is vital to use fast-release inorganic fertilizers such as Pearl NPK fertilizer to boost plant development. Noertjahyani and colleagues (2026): The integration of the Knia variety with goat manure resulted in the longest plant height, whilst the pairing of the Mencir variety with goat dung yielded the most blooms at 30 days post-transplanting and the heaviest fruit weight. Permaculture allegedly provides many remedies for the adverse effects of practices like monoculture farming and industrial food production, aiming to create and

foster a sustainable community in alignment with natural ecosystems. It adopts solution-focused strategies to address modern social and environmental issues. This review article examines the methodologies employed by permaculture practitioners to attain sustainable growth while preserving current conditions, as well as how permaculture can harmonize landscape and society to sustainably supply food, shelter, and energy (Devi et al., 2022).

CONCLUSION

Soil regeneration is an agroecosystem management approach that restores the physical, chemical, and biological functions of soil in an integrated manner. Based on a synthesis of soil regeneration materials, organic matter, microorganisms, biochar, ground cover crops, organic mulching, and minimum tillage have complementary mechanisms that support soil health. Organic matter contributes to aggregate formation, nutrient provision, and soil biological activity. Microorganisms support nutrient decomposition and transformation, while biochar can improve certain soil properties. Ground cover crops, mulch, and minimum tillage help protect the soil surface, conserve moisture, and reduce disturbances to soil structure.

Research Implications and Recommendations

The development of permaculture-based soil regeneration has implications for managing agricultural land, plantations, food gardens, and rehabilitating degraded soils.

1. From an environmental perspective, integrating regenerative practices can increase land cover and reduce soil loss due to erosion.
2. From an agronomic perspective, improved soil conditions can support root development, water-use efficiency, and nutrient availability.
3. From an economic perspective, using local biomass can reduce dependence on some external inputs, although labor, material processing, transportation, and maintenance costs still need to be considered.

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