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Regenerative Agriculture and Legume Covers: A Review of Degraded Soil Recovery and Soil Microbiota

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Abstract

Soil degradation is one of the greatest threats to food security and ecological balance. In response, regenerative agriculture offers a transformative alternative: restoring soil health through ecological intensification. This paper reviews the scientific evidence on how cover crops—primarily legumes—and their interaction with microorganisms accelerate the recovery of depleted soils. Legumes stand out as key allies in land restoration by fixing atmospheric nitrogen, supplying high-quality organic matter, and improving soil structure. These contributions stimulate microbial biomass, enhance subsoil diversity, and activate key enzymes to reactivate nutrient cycling. Likewise, symbiotic relationships in the rhizosphere strengthen plant resilience. Despite their proven benefits, the widespread adoption of these practices faces technical and socioeconomic barriers such as initial seed costs, water competition in arid zones, and lack of specialized machinery. Therefore, it is essential to design management strategies tailored to local contexts. In conclusion, enhancing soil microbiology through legumes is a decisive pillar for building sustainable and resilient agroecosystems in the long term.

Subject Areas

Earth & Environmental Sciences and Engineering

Keywords

Soil Degradation, Regenerative Agriculture, Cover Crops, Legumes, Soil Microbiome

1. Introduction

Regenerative agriculture has emerged as an innovative approach aimed at the functional restoration of agroecosystems by implementing practices that promote the recovery of soil health, increased biodiversity, and the reactivation of key ecological processes [1]. This approach prioritizes improving soil organic matter, reducing physical soil disturbance, and diversifying species, with the goal of improving resilience to adverse environmental conditions and reducing dependence on external inputs.

Agricultural soils are under constant pressure resulting from both intensive anthropogenic practices—such as conventional tillage, monoculture and the excessive use of agro-inputs—and environmental factors associated with climate change, leading to progressive degradation processes that affect productivity and long-term sustainability [2] [3]. These conditions favor nutrient loss, reduced soil organic carbon, and deterioration of soil biodiversity, thereby increasing the vulnerability of agricultural systems [4]. In this context, practices such as crop rotation, permanent soil cover, and minimum tillage have demonstrated positive effects on soil structure, fertility, and system stability, positioning regenerative agriculture as a relevant strategy to address global challenges related to sustainability and food security [5]-[11].

Comprehensive assessment of soil quality, considering its physical, chemical and biological properties, is a fundamental element in understanding the soil constraints that affect plant growth and agricultural productivity. In particular, biological indicators such as biomass and microbial activity have become increasingly important due to their sensitivity to changes in soil management and their role in regulating biogeochemical cycles. In this sense, the integrated analysis of these attributes allows for the design of more efficient and sustainable management strategies aimed at optimizing the functioning of the agroecosystem [12] [13].

Within these strategies, legumes used as live cover crops play a critical role in soil regeneration due to their ability to fix atmospheric nitrogen through symbiosis with rhizobial bacteria [14]. These species contribute significantly to the incorporation of organic carbon, the enhancement of functional biodiversity, and the optimization of nutrient cycles through the addition of high-quality organic residues and radical exudates [15]. Their adaptability to various soil and climatic conditions and their ability to establish symbiotic associations with specialized bacterial genera make them key components in sustainable soil management systems [16].

Consequently, the integration of legumes into crop rotations and covers promotes significant increases in the yield of major crops, reinforcing their role as an effective alternative to reduce dependence on synthetic fertilizers (evaluating direct green manure legume rotation yield responses) [17]-[19]. These systems also improve moisture retention, optimize the physical properties of the soil, and suppress weeds.

In this context, the present study aims to analyze the available scientific evi-

dence on the use of legume-based live cover crops within regenerative agriculture systems, evaluating their effects on the recovery of degraded soils, biomass dynamics and soil microbial activity, as well as identifying the socioeconomic and technical barriers to their adoption.

2. Methodology

2.1. Review Design and Approach

A structured narrative review of the scientific literature was carried out aimed at identifying, analyzing, and synthesizing the available evidence on the effect of legume living covers on degraded soil recovery and agroecosystem sustainability. The review aimed to answer the following research question: "How do legume living covers contribute to the recovery of degraded agricultural soils through modifications of their physical, chemical, and biological properties, particularly through changes in microbiota, nutrient cycling, soil carbon, and crop productivity?" The process included an explicit strategy of searching, selecting, evaluating evidence, and synthesizing information, taking as a reference the quality criteria for narrative reviews proposed by SANRA [20].

The eligibility criteria were previously defined considering the condition of the soil, the cropping system, the type of cover and the response variables. Studies carried out on degraded, eroded soils or soils with loss of organic matter, fertility or biological functionality, developed in agricultural agroecosystems and evaluating legumes used as cover crops, green manures or living covers, were considered eligible. The main response variables were considered the physical, chemical and biological properties of the soil, microbiota and microbial biomass, nutrient cycling, productivity, organic matter, pollution and carbon storage or sequestration.

2.2. Literature Search and Selection Strategy

The literature search was carried out in Scopus, Web of Science, PubMed, and Google Scholar, considering publications between 2000 and 2026. Keywords were used in Spanish and English related to legume cover crops, soil degradation and recovery, microbiota, nutrient cycling, productivity, and carbon sequestration, combined using the Boolean operators AND and OR. The main equation was: ("legume cover crops" OR "leguminous cover crops" OR "living cover crops" OR "legume green manure") AND ("soil degradation" OR "degraded soil" OR "soil restoration" OR "soil health") AND ("soil microbiota" OR "microbial biomass" OR "microbial diversity" OR "nutrient cycling" OR "carbon sequestration"). This was adapted to the syntax of each database and complemented with specific thematic searches.

Original articles and academic reviews in Spanish and English that addressed the effects of legume covers on soil physical, chemical, and biological properties, microbiota, nutrient cycling, productivity, pollution, and carbon were included. Duplicates, documents without full text, editorials, opinions, and studies without sufficient methodology or thematic relevance were excluded.

The search identified 11,527 records, distributed in Scopus (31), Web of Science (906), PubMed (10,000) and Google Scholar (590), which were organized in a matrix to eliminate duplicates and screen titles, abstracts and full texts. Two reviewers participated in the selection, resolving discrepancies by consensus. Finally, the selected studies were systematized according to authors, year, country, type of cover, cropping system, soil condition, variables evaluated, methodology and main results.

2.3. Systematization and Analysis of Information

To identify patterns of conceptual similarity between the types and processes of land degradation documented in the literature, a Hierarchical Cluster Analysis (HCA) was performed from 18 thematic categories identified in the reviewed studies. The data matrix was constructed using binary coding (presence = 1; absence = 0) of attributes related to degradation processes, their causes, impacts, and affected soil properties. Subsequently, a dissimilarity matrix was calculated using the Jaccard index and an agglomerative hierarchical clustering method with average link (UPGMA) was applied.

The hierarchical classification groups the 18 categories into five clusters: Cluster I, related to nitrogen processes and pollution, includes nitrogen fixation and pollution; Cluster II, associated with erosion and water processes, includes erosion, water infiltration and moisture; Cluster III, focused on the physicochemical and biological properties of the soil, integrates physical and structural properties, chemical and biological properties, and nutrient cycling; Cluster IV, linked to agronomic productivity, functionality and organic matter, brings together agricultural agroecosystems, legumes, cover crops and manures, soil degradation and restoration, soil health, quality and fertility, microbial communities and microbiota, biomass and microbial diversity, organic carbon and soil organic matter, as well as productivity, yield and sustainability; finally, Cluster V exclusively comprises the enzymatic activity of the soil, as an indicator of its biochemical processes. The structure obtained is presented in **Figure 1** and was used as an organizational framework for the thematic synthesis and structuring of the development sections of the review [3] [6] [21]-[38].

2.4. Synthesis of the Evidence

The selected evidence was synthesized qualitatively using a thematic approach, guided by the mechanisms and outcomes associated with legume cover crops in the recovery of degraded agricultural soils. The synthesis focused on five complementary dimensions: 1) soil physical, chemical, and biological properties; 2) soil microbiota and nutrient cycling; 3) crop productivity and stability; 4) ecosystem restoration and soil carbon sequestration; and 5) soil contamination and carbon stocks within the soil-plant system.

The findings were subsequently interpreted alongside the hierarchical cluster analysis (HCA), which provided a conceptual framework for organizing the

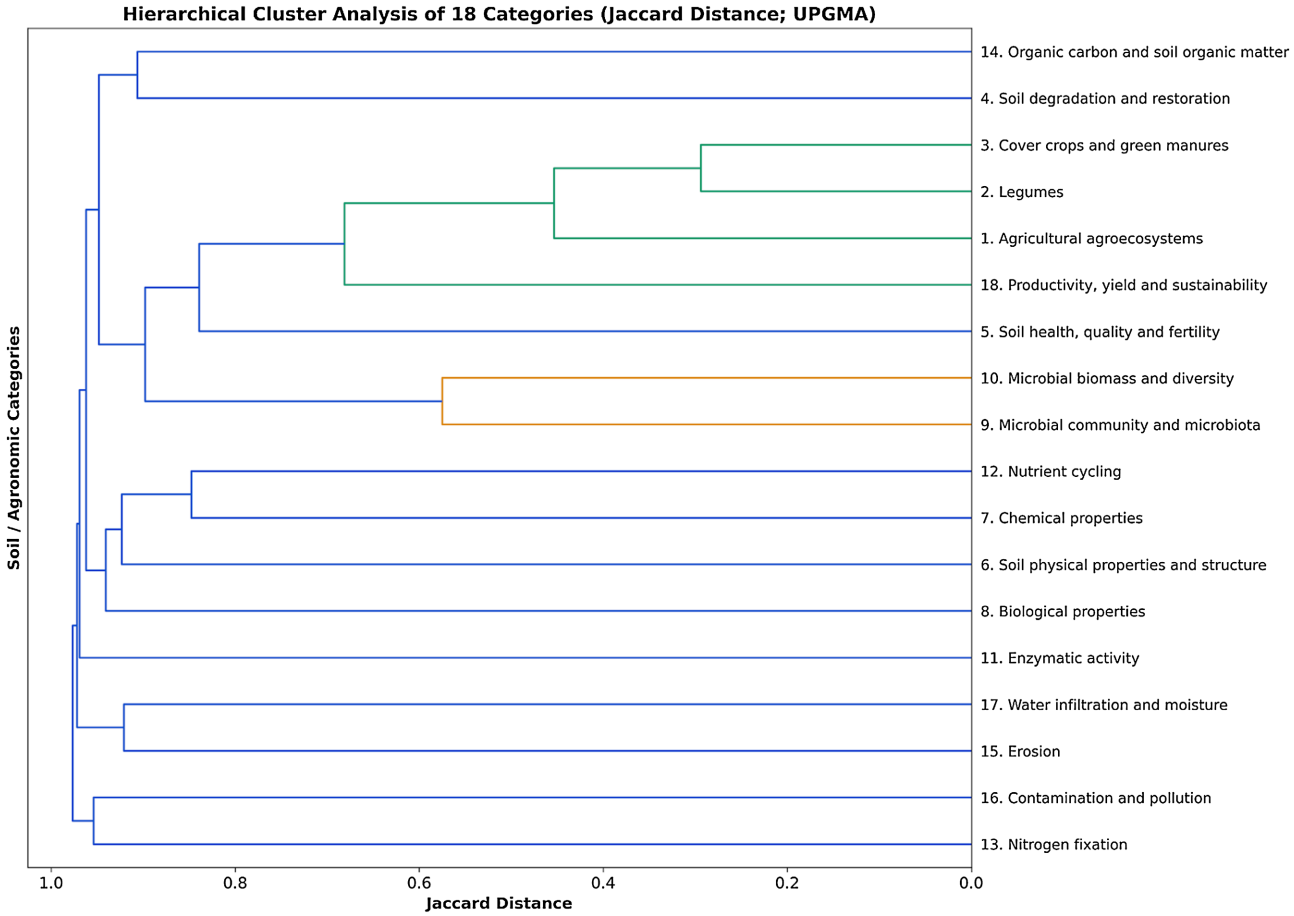

Figure 1. Hierarchical dendrogram of cluster analysis (HCA) on soil degradation categories identified in the scientific literature.

degradation processes identified in the literature. This integration supported the examination of convergent and divergent findings, relationships among soil degradation processes and regeneration mechanisms, and remaining knowledge gaps concerning the contribution of legume covers to soil functional recovery and agroecosystem resilience.

3. Development

3.1. Degraded Soils: Current State and Systemic Dynamics

Soils are one of the most critical natural resources for the functioning of terrestrial ecosystems, as they sustain agricultural production, regulate carbon and water cycles, and maintain biodiversity [10]. Soil degradation, understood as the loss of its ecological, productive and regulatory functions, has intensified in recent decades due to the interaction between climatic factors and anthropogenic activities [22] [39].

On a global scale, approximately 40% of the earth's surface shows some degree of degradation, directly affecting billions of people and significantly reducing agricultural productivity [30] [40]. It also generates substantial economic losses and contributes to climate change through the release of carbon stored in the soil [22]. In Latin America and the Caribbean (LAC), the problem is especially critical: be-

tween 60% and 75% of soils have degradation associated with agricultural expansion, deforestation and intensive management [39] [41], which compromises water regulation and multiple ecosystem services [42].

The causes include extreme weather events such as prolonged droughts and intensification of rainfall [26], in addition to human activities such as overgrazing, deforestation, and inadequate tillage [43]. Its manifestations include erosion, compaction, salinization, acidification, loss of organic matter, and decrease in soil biodiversity [25] [30]. Therefore, degradation should be understood as a systemic phenomenon driven by socioeconomic factors such as population pressure, land tenure insecurity, and lack of technical assistance [22] [32].

Faced with this problem, the literature highlights the need to move towards sustainable management and land degradation neutrality (LDN) promoted by international organizations [40]. In this area, the incorporation of legumes as mulches and green manures has been widely documented as an effective alternative to restore soil fertility and reactivate soil biology [43]-[45].

3.2. Principles of Regenerative Agriculture and Functional Restoration

Regenerative agriculture is consolidated as a comprehensive operational framework aimed at restoring ecological functionality, improving soil health, and strengthening climate resilience through the intensification of biological processes [1] [46]. **Figure 2** illustrates the interconnected principles that articulate this approach.

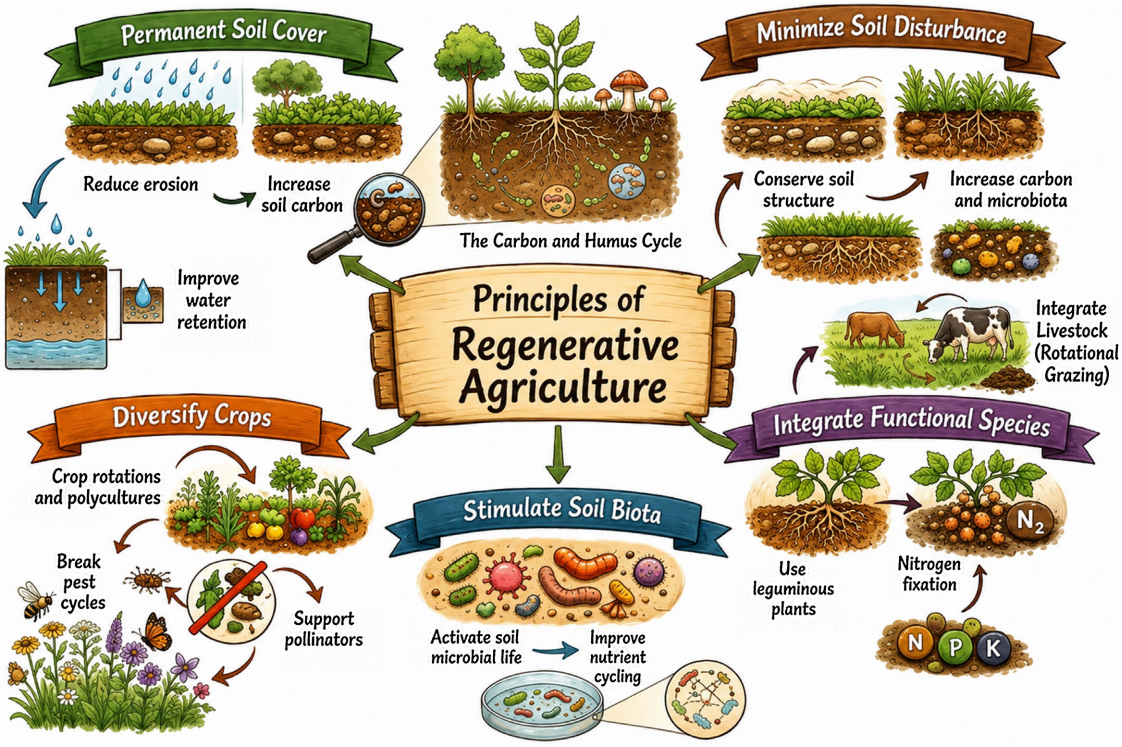

Figure 2. Principles of regenerative agriculture and conceptual framework linking legume cover crops, soil microbiota, and soil restoration.

The core principles that articulate this approach include:

1) *Permanent ground cover:* It constitutes a regulating and protective pillar. Physically, it attenuates the direct impact of raindrops and wind, while biogeochemically it increases soil organic carbon (SOC) by between 10% and 30% compared specifically to bare fallow baselines in temperate and humid tropical cropping systems under multi-year management (>3 - 5 years) [47] [48]. However, these carbon gains are highly context-dependent and diminish in dryland systems with low biomass accumulation. In addition, it buffers extreme soil surface temperatures, protecting the microbial community [25].

2) *Reduction or elimination of tillage:* Conventional tillage destroys aggregates and accelerates the oxidation of organic matter. On the contrary, no-tillage promotes the reorganization of macroaggregates through fungal hyphae and roots, improving porosity and hydraulic conductivity [49]. Its combination with plant covers maximizes carbon accumulation in surface strata and enzymatic activity [50].

3) *Crop diversification:* Overcome the functional homogeneity of monocultures through rotations and polycultures. Greater plant diversity generates a more varied range of root exudates, diversifying the structure and function of soil microbial communities [51] [52]. It also breaks pest cycles and optimizes the use of soil profile resources [4] [53].

4) *Integration of functional species* (*Legumes*) *and Biological Nitrogen Fixation* (*FBN*)*:* Legumes stand out for their symbiosis with rhizobial bacteria (Rhizobium, Bradyrhizobium, Mesorhizobium). Root infection is a regulated process initiated by chemical signals and the emission of Nod factors by bacteria [54]. This induces deformation of the root hair, the formation of infection threads, and the development of nodular primordia in the root cortex [55] [56]. In symbiosomes, bacteria differentiate into bacteroides that convert atmospheric N_2 into assimilable forms. Although factors such as salinity or drought exert pressure, various adapted strains maintain FBN under adverse conditions [57]. Additionally, its organic acid-rich exudates promote the solubilization of inorganic phosphorus [58].

5) *Stimulation of soil microbiota:* Soil biota (bacteria, mycorrhizal fungi, microfauna) drives nutrient cycling and natural pathogen suppression [59] [60]. Regenerative agriculture enhances microbial biomass and food webs, favoring the formation of stable glomalin and aggregates [46] [61].

3.3. Legume Live Covers: Ecological and Agronomic Functions

Living legume covers play a multifunctional role in the agroecosystem. In the physical and hydraulic spheres, temperature reductions of 5˚C - 10˚C in maximum soil surface temperatures under living legume covers are observed primarily under hot, semi-arid, or tropical summer conditions relative to unshaded, bare soil baselines [62] [63]. In temperate regions during spring, living covers can conversely maintain cooler soil temperatures that slightly delay cash crop germination. Infiltration increases of 30% to 50% occur predominantly after long-term

adoption (>4 years) in fine-textured or compacted soils subjected to continuous live cover, compared to conventional tilled fallow baselines. Furthermore, global meta-analyses confirm that reductions in runoff and water erosion of 40% to 80% are achieved on sloped agricultural lands (>5% - 10% slope) under high canopy-density legume covers compared to bare soil control treatments [64] [65]. However, non-legume grass covers often outperform legumes in rapid slope stabilization due to their denser fibrous root architecture.

The effects of legume cover crops on soil carbon dynamics, thermal conditions, water infiltration, erosion control, and crop productivity vary according to environmental and management conditions. A global meta-analysis of 85 publications on legume-incorporated cropping systems reported increases of 21.4% in microbial biomass carbon, 9.1% in particulate organic carbon, and 7.9% in the recalcitrant carbon fraction compared with systems without legumes. The magnitude of these responses varied with climatic conditions, soil properties, and nitrogen management [66]. Evidence on soil temperature is also context-dependent. A review of legume cover crops reported an experimental reduction of approximately 5˚C in maximum soil temperature at a depth of 5 cm under living mulch compared with dead mulch, although this result should not be generalized across species, seasons, or climates without considering the original experimental conditions [67]-[69].

Regarding soil hydrology, a meta-analysis of 89 studies found that cover crops increased infiltration rates by an average of 34.8% (95% confidence interval: 19.8%-50.0%) relative to the reference management used in the included studies. In experiments maintaining cover crops for more than four years, the mean increase was 30.0% (95% confidence interval: 1.7% - 51.3%) [62]. These estimates represent cover crops collectively rather than leguminous species alone. In tree-crop systems, a separate meta-analysis of 85 publications found mean reductions of 48.5% in runoff and 70.5% in soil loss underground-cover management; however, effectiveness varied with cover type, slope, and climate, and legume covers were less effective than non-legume covers in the overall comparison [70].

Yield responses likewise depend on the cropping system, climate, management duration, and reference baseline. A meta-analysis of 315 field-trial datasets from China reported that legume green manure increased wheat, maize, and rice yields by 9.49%, 16.70%, and 19.22%, respectively, compared with treatments without legume green manure. Grain yield gains of up to 30% in following cereal crops (e.g., maize, wheat) are specifically reported in nitrogen-limited soils following a full-season legume green manure baseline-compared to unfertilized bare fallows [71] [72]. In well-fertilized systems or under water-limited dryland conditions, yield responses may be neutral or slightly negative due to soil moisture depletion. Significant gains were observed in rotations with grain crops, whereas the effects were not significant in the intercropping systems assessed [73]. Therefore, reported percentages must be interpreted as context-dependent averages rather than universal outcomes.

In the biological and agronomic field, the rapid decomposition of legume biomass—characterized by a low C/N ratio—releases mineralizable nitrogen that benefits subsequent crops in rotation and can increase the yield of cereals such as wheat or corn by up to 30% [71] [72]. Likewise, species such as *Crotalaria juncea* or *Canavalia ensiformis* release allelopathic compounds that effectively suppress weed germination and competition, reducing the need for synthetic herbicides [74] [75].

3.4. Key Legume Species as Cover and Their Soil Inputs

Table 1 then summarizes the agronomic characteristics; range of nitrogen inputs and ecological functions of the main legume species used in regenerative systems.

Table 1. Legume species used in regenerative systems.

Species	Climate and adaptation	Fixed N_2 contribution ($kg \cdot ha^{-1}$)	Biomass contribution (t $DM \cdot ha^{-1}$)	Main ecological and edaphic functions
Crotalaria juncea (Sunn hemp)	Tropical/SubtropicalD rought tolerant	80 - 150	5.0 - 9.0	High biomass production, natural nematicide, deep soil decompaction.
Vigna unguiculata (Cowpea/Coastal bean)	Warm tropical/Arid poor/acidic soils	50 - 110	3.0 - 6.0	Excellent fast coverage, tolerance to water stress, and solubilization of rhizospheric phosphorus.
Canavalia ensiformis (Jack bean)	Tropical/Subtropical shade and drought tolerant	70 - 130	4.0 - 8.0	Control of weeds due to allelopathy, high accumulation of nitrogen and labile carbon.
Medicago sativa (Alfalfa)	Temperate/Subtropical deep and neutral soils	100 - 200	4.0 - 10.0	Very deep pivotal root system, edaphic restructuring, sustained N fixation.

3.5. Interaction between Legumes and Soil Microbiome: Direct Microbial Responses vs. Systemic Associations

Direct Legume-Driven Microbial Changes: The continuous release of root exudates (sugars, amino acids, and flavonoids) creates a metabolic hotspot in the rhizosphere that recruits plant growth-promoting bacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) [76] [77]. This direct stimulation significantly increases microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN), as well as the immediate activity of hydrolytic enzymes (such as β-glucosidase, urease, phosphatases, and dehydrogenases) directly involved in residue breakdown [78] [79].

Systemic Agroecosystem Associations (Drought Resilience, Nutrient Cycling, and Pathogen Suppression): In contrast to direct rhizosphere recruitment, broader ecological outcomes such as drought resilience, long-term nutrient cycling, and soil-borne pathogen suppression represent systemic agroecosystem associations rather than direct single-factor effects of legume covers. Drought resilience is mediated indirectly through cumulative macroaggregate stabilization, glomalin production, and organic matter build-up over time [33] [80]. Similarly,

biological pathogen suppression typically stems from broader competitive microbial community structures fostered by plant diversity rather than direct legume exudates, with exceptions in specific biofumigant species (e.g., Crotalaria juncea). Disentangling direct biochemical inputs from these indirect network effects is critical for accurate ecological modeling [81] [82].

3.6. Technical Barriers, Agronomic Trade-Offs, and Challenges to Mass Adoption

a. Critical Agronomic Trade-Offs: 1) *Cover-crop termination timing vs. water competition:* Delaying legume cover termination maximizes biological nitrogen fixation and biomass production; however, in semi-arid environments or dry spring seasons, late termination severely depletes stored soil water required for subsequent cash crop establishment; 2) *Nitrogen mineralization dynamics vs. losses:* Legume residues decompose rapidly due to their low C:N ratio. If cash crop nitrogen demand is not temporally synchronized with residue mineralization, significant nitrate leaching (NO_3^-) or nitrous oxide (N_2O) emissions occur; 3) *Interactions with tillage and fertilizer management:* Under continuous no-till systems, legume covers build surface organic mulch and promote fungal networks; under conventional tillage, rapid residue incorporation triggers an abrupt burst of respiration and organic carbon oxidation. Furthermore, high synthetic N fertilizer applications suppress biological nitrogen fixation rates [83] [84].

b. Socio-Economic and Technical Barriers: Despite the scientific evidence supporting legume covers, large-scale implementation faces critical limitations: 1) Initial economic costs and availability of commercial seeds; 2) Specialized machinery requirements (direct seeders for dense stubble or roller-crimpers for mechanical termination); 3) Land tenure insecurity discouraging multi-year soil restoration investments; and 4) Cultural perceptions regarding bare soil maintenance [85] [86].

3.7. Future Perspectives and Knowledge Gaps

To consolidate regenerative legume-based agriculture, future research should prioritize the following knowledge gaps: 1) *Characterization of underutilized native legumes:* Despite the existence of thousands of species of Fabaceae, commercial agriculture depends on a small number of varieties. It is urgent to evaluate native species adapted to extreme conditions of acidity, salinity or aridity; 2) *Dynamics of the rhizospheric microbiome at the multi-omics scale:* It is necessary to deepen through metagenomics and metabolomics in the specific interactions between strains of rhizobia, mycorrhizae and nutrient solubilizing bacteria under conditions of combined abiotic stress; and, 3) *Long-term economic modeling and public policies:* It is necessary to generate long-term economic-financial models that quantify the monetary value of ecosystem services (carbon sequestration, water regulation) in order to design incentives or payment schemes for environmental services that facilitate adoption.

4. Conclusion

The evidence analyzed confirms that soil degradation can be effectively addressed through regenerative agricultural practices that integrate ecological and biological processes. Cover crops, especially legumes, play a central role in restoring soil functionality by improving organic matter inputs, nutrient cycling, and microbial activity. However, successful implementation requires managing key agronomic trade-offs through site-specific recommendations: 1) In water-limited or semi-arid environments, species selection must prioritize drought tolerance with strict, moisture-triggered termination rules to prevent cash crop yield penalties from water competition. 2) In high-rainfall or irrigated systems, termination timing and residue management must be synchronized with cash crop N uptake windows to prevent nitrate leaching and gaseous N_2O losses. 3) Under conservation tillage, living covers should be paired with mechanical crimping or specialized direct-seeding machinery to maximize soil organic carbon retention and aggregate stability. Future research should focus on site-specific management strategies, multi-location trials, and long-term economic-ecological modeling to support sustainable agricultural transitions.

Conflicts of Interest

The authors declare no conflicts of interest.

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