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Advances in organic resources utilization for agriculture: A comprehensive review

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Abstract

The sustainable advancement of agriculture necessitates the efficient utilization of organic resources to improve soil quality, increase crop performance, and minimize reliance on chemical-based inputs. Organic materials - including compost, Farmyard Manure (FYM), crop residues, biochar, biofertilizers, and green manures - have long been recognized for their contributions to soil fertility and ecosystem functioning. Technological developments such as enriched organic manures, organo-mineral fertilizers, and integrated nutrient management approaches have considerably enhanced nutrient-use efficiency and soil carbon sequestration. Emerging innovations, including pyrolysis-derived biochar, precision-based application systems, and digital monitoring tools, are further advancing environmentally sound agricultural practices. At the governance level, policy frameworks, circular economy approaches, and enhanced stakeholder awareness are facilitating broader adoption. Despite these advances, critical constraints persist concerning input safety, nutrient standardization, and large-scale infrastructure for organic resource management. This review synthesizes interdisciplinary evidence across emission mitigation, water quality, soil health, monitoring technologies, and policy to present a unified perspective on organic resource management for sustainable agricultural intensification.

Keywords: Organic resource management, soil carbon sequestration, sustainable agriculture, biochar, nutrient cycling, greenhouse gas mitigation, soil health, circular bioeconomy

1. Introduction

Global agriculture faces the dual imperative of meeting rising food demands while simultaneously curtailing its environmental footprint. Mounting concerns over declining soil fertility, escalating Greenhouse Gas (GHG) concentrations, and the ecological costs of synthetic fertilizer dependency have brought the sustainable management of organic resources to the forefront of agricultural science (Lal, 2004; Reganold and Wachter 2016) [16, 29]. Organic materials - encompassing compost, farmyard manure, crop residues, biofertilizers, and animal wastes - have historically been valued for their capacity to improve soil fertility and support plant growth. In recent years, however, scientific and technological progress has substantially transformed the processing, application, and integration of these resources within modern farming systems (Gattinger *et al.* 2012; Bünemann *et al.* 2018) [11, 7].

The agricultural sector is under continuous pressure to satisfy rising food demands while simultaneously reducing environmental impacts. Among the most promising yet insufficiently deployed strategies is the sustainable management of organic resources such as livestock manure, composts, biosolids, and recycled organic matter. These materials are rich in essential nutrients and organic matter that, when appropriately managed, improve soil fertility, reduce dependence on synthetic fertilizers, and strengthen ecosystem services (Mäder *et al.* 2002; Lal 2015) [21, 17]. Conversely, mismanagement of organic inputs is associated with significant environmental concerns, including gaseous emissions of ammonia (NH₃), nitrogen oxides (NO_x), and nitrous oxide (N₂O), as well as nutrient leaching into water bodies and microbial contamination of aquatic ecosystems (Reay *et al.* 2012) [28].

Unlike previous reviews that primarily focused on nutrient management or organic farming systems in isolation, the present review integrates emission mitigation, water quality protection,

soil restoration, advanced monitoring technologies, and policy frameworks within a unified perspective on organic resource management. A particular emphasis is placed on multiscale integration - spanning field trials, watershed-level assessments, and continental modelling - and climate-smart approaches designed to support sustainable agricultural intensification.

1.1 Scope and rationale

The utilization of organic resources in agriculture is a cross-disciplinary subject that intersects agronomy, environmental science, soil microbiology, hydrology, and agricultural policy. To comprehensively evaluate the agronomic and environmental consequences of organic resource use, research must integrate data across both spatial and temporal dimensions. Farm and watershed-level investigations facilitate assessment of cumulative impacts on water quality and GHG emissions, while modelling approaches and remote sensing technologies at regional and continental scales help extrapolate findings, evaluate scalability, and support policy formulation (Kalogeris *et al.* 2025; Bhattacharyya *et al.* 2018) [15, 5]. The integration of multiscale datasets and methodologies is therefore crucial for addressing environmental trade-offs and developing adaptive, science-based regulatory frameworks.

1.2 Objectives

This review compiles interdisciplinary research and synthesis efforts focused on improving knowledge related to the sustainable use of organic resources in agroecosystems. The primary objectives are:

- 1) To investigate mechanisms and mitigation measures for gaseous emissions from organic resource use, including emission factors under diverse climates, soil conditions, and application techniques;
- 2) To evaluate novel measurement and monitoring techniques - sensor-based technologies, micrometeorological systems, isotopic tracing, and remote sensing - for quantifying gaseous emissions and nutrient flows;
- 3) To assess the impacts of organic resource management on water quality and soil health, with emphasis on nutrient cycling, carbon sequestration, and microbial activity; and
- 4) To analyse relevant policy and regulatory frameworks,

identifying opportunities for harmonization and governance improvements across regions.

2. Measurement and monitoring techniques

Accurate quantification of gaseous emissions, nutrient losses, and environmental impacts associated with organic resource use is essential for designing effective mitigation strategies and supporting evidence-based policymaking. During the past two decades, major advances have been achieved in measurement technologies, analytical instruments, and modelling tools that enable detailed monitoring of emission behaviour and nutrient dynamics across various spatial and temporal scales (Bhattacharyya *et al.* 2018; Lal, 2015) [5, 17].

2.1 Emission monitoring

The release of nitrogen-related gases from organic amendments creates both environmental and regulatory challenges. Monitoring these emissions requires highly sensitive, reliable, and scalable techniques capable of operating under variable field conditions. High-resolution spectroscopic methods - including Photoacoustic Spectroscopy, Fourier-Transform Infrared (FTIR) Spectroscopy, and Cavity Ring-Down Spectroscopy (CRDS) - have become the standard for laboratory and semi-field investigations, offering real-time quantification of NH_3 , NO_x , and N_2O at sub-part-per-billion concentrations. Open-path laser systems extend these capabilities to large-scale spatial monitoring with minimal ecosystem disturbance, while portable electrochemical sensors have made in situ assessment feasible in remote and resource-limited locations (Bhattacharyya *et al.* 2018) [5]. Environmental integration is equally important: weather stations and soil probes recording soil temperature, moisture, wind patterns, and air pressure are routinely deployed alongside gas-measurement systems to capture the environmental drivers of emission variability. Despite these advances, emission factors remain highly context-dependent, scaling from plot to landscape continues to be methodologically challenging, and the need for cost-effective and reliable monitoring technologies persists. Table 1 summarizes the principal emission monitoring techniques, their target gases, advantages, and limitations with supporting references.

Table 1: Summary of key emission monitoring techniques for nitrogen-based gases from organic resource applications

Technique	Target Gas(es)	Key advantages	Limitations	References
Photoacoustic spectroscopy	NH_3 , N_2O	ppb-level real-time quantification; high selectivity	Cost; requires laser calibration	Bhattacharyya <i>et al.</i> , (2018) [5]
FTIR spectroscopy	NH_3 , NO_x , N_2O , CH_4	Multi-gas simultaneous detection; no consumables	Expensive; large instrument footprint	Reay <i>et al.</i> , (2012) [28]
Cavity Ring-Down Spectroscopy (CRDS)	N_2O , CH_4 , CO_2	Sub-ppb precision; stable over long deployments	High capital cost	Bhattacharyya <i>et al.</i> , (2018) [5]
Open-path laser systems	NH_3 , N_2O , CH_4	Large-area non-invasive spatial monitoring	Complex calibration; weather-sensitive	Kalogeris <i>et al.</i> , (2025) [15]
Electrochemical sensors	NH_3 , NO_x	Low-cost; portable; field-deployable	Lower accuracy; sensor drift	Bhattacharyya <i>et al.</i> , (2018) [5]
Micrometeorological methods	Multiple GHGs	Landscape-scale flux; minimal disturbance	Requires steady atmospheric conditions	Pretty <i>et al.</i> , (2018) [27]
Chamber-based methods	N_2O , CH_4	Simple; widely applicable; low cost	Small spatial footprint; disturbs soil	Gattinger <i>et al.</i> , (2012) [11]

NH_3 = ammonia; NO_x = nitrogen oxides; N_2O = nitrous oxide; CH_4 = methane; ppb = parts per billion; FTIR = Fourier-Transform Infrared; CRDS = Cavity Ring-Down Spectroscopy

2.2 Water-soil monitoring

In addition to atmospheric emissions, organic resource application strongly influences soil quality and water contamination risks, particularly through nutrient leaching and surface runoff (Lal, 2015; Hansen *et al.* 2001) ^[17, 13]. Suction lysimeters and ceramic-cup samplers are extensively utilized for collecting soil solutions and quantifying nitrate and ammonium leaching, whereas runoff plots and flow-weighted samplers directly measure nutrient transport in surface water. Event-oriented monitoring, which captures pollutant movement during high-risk episodes such as rainfall immediately following amendment application, has proven especially informative for targeting management interventions. Soil hydrological monitoring relies on Time-Domain Reflectometry (TDR) and Frequency-Domain Reflectometry (FDR) for continuous soil moisture assessment, complemented by double-ring and mini-disk infiltrometers to evaluate water infiltration rates. Penetrometers, aggregate stability analyses, and bulk density probes are further employed to characterize structural modifications caused by organic inputs (Glab and Kulig, 2008) ^[12]. At the microbial level, advanced molecular techniques - including quantitative PCR (qPCR) and metagenomics - facilitate the tracking of microbial contaminants and antibiotic resistance genes, while isotopic tracer studies using ¹⁵N and ¹⁸O help differentiate nitrogen loss pathways (Lori *et al.* 2017) ^[20].

2.3 Remote sensing and modelling

Although in situ measurements provide high precision, their spatial coverage is inherently limited. Remote sensing technologies and process-oriented models are increasingly employed to extend field-level observations to broader geographic scales. Satellite platforms such as Sentinel-2 and Landsat 8 deliver high-resolution imagery for monitoring crop growth, soil moisture, and crop residue cover (Kalogeris *et al.* 2025) ^[15], while Unmanned Aerial Vehicles (UAVs) equipped with multispectral and thermal sensors offer finer spatial and temporal resolution. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and Soil-Adjusted Vegetation Index (SAVI) are used to estimate nutrient status and field variability, and thermal imaging supports identification of moisture stress and zones vulnerable to leaching (Bhattacharyya *et al.* 2018) ^[5]. Process-based models - including DNDC, DayCent, and APSIM - simulate emissions, nutrient leaching, and crop productivity using site-specific environmental and management data, whereas hydrological models such as SWAT and HYPE evaluate water quality impacts at watershed and basin scales. Integration of remote sensing outputs with Geographic Information Systems (GIS) enables spatial visualization and hotspot mapping, and Bayesian inference methods are increasingly used to reduce uncertainty in model predictions. Collectively, these approaches support scenario-driven simulations under varying climate, soil, and policy conditions, which are invaluable for strategic planning and adaptive governance (Pretty *et al.* 2018) ^[27].

3. Emission mitigation from organic resource use

The sustainable use of organic resources in agriculture - including Farmyard Manure (FYM), compost, biochar, and green manure - offers dual benefits by enhancing soil productivity and contributing to climate change mitigation. However, improper management may increase emissions of GHGs, including methane (CH₄), N₂O, and NH₃ (Awasthi *et al.* 2020; Reay *et al.* 2012) ^[1, 28]. Strategic management practices are therefore required to minimize these emissions while maintaining soil fertility and crop productivity.

3.1 Agronomic mitigation strategies

Agronomic approaches modify the soil-plant-atmosphere interactions that regulate GHG formation and nutrient cycling, primarily aiming to reduce emission hotspots, optimize microbial processes, and enhance soil carbon storage. Conservation agriculture - combining reduced tillage, residue retention, and crop diversification - represents one of the most widely studied and effective frameworks. No-till or reduced tillage conserves soil aggregates, minimizes oxidation of Soil Organic Carbon (SOC), and lowers fuel-related emissions from tillage operations (Lal, 2004; Gattinger *et al.* 2012) ^[16, 11]. Crop rotation involving legumes or deep-rooted species increases biological nitrogen fixation and improves nutrient balance, thereby reducing dependency on synthetic fertilizers (Blanco-Canqui *et al.* 2015) ^[6]. Mulching through surface residue application enhances soil cover, regulates soil temperature and moisture, and creates microbial conditions that suppress N₂O emissions (Glab and Kulig, 2008) ^[12]. In paddy systems, Alternate Wetting and Drying (AWD) management has demonstrated CH₄ emission reductions of up to 85% compared to continuous flooding (Reay *et al.* 2012) ^[28]. Biochar - produced through biomass pyrolysis under low-oxygen conditions - is increasingly recognized for its capacity to mitigate GHG emissions when co-applied with organic amendments. A global meta-analysis by Zhong *et al.* (2025) ^[38] demonstrated an average reduction of approximately 54% in N₂O emissions when biochar was combined with manure or compost.

3.2 Organic amendments

Long-term application of FYM improves soil structure, nutrient retention, and emission mitigation when managed effectively (Smith *et al.* 2020; Lal, 2015) ^[31, 17]. Composting converts raw organic materials into stabilized humic substances with substantially lower emission potential during field application (Awasthi *et al.* 2020) ^[1]. Compost application has been shown to increase SOM by up to 30% over multiple growing seasons, while concurrently enhancing microbial diversity and enzymatic activity. Green manuring - the cultivation and incorporation of cover crops, particularly legumes - increases in situ organic inputs, promotes biological nitrogen fixation, and reduces denitrification losses through balanced C:N ratios (Blanco-Canqui *et al.* 2015) ^[6]. Table 2 provides a comparative overview of key organic amendments, their soil benefits, GHG implications, and recommended best management practices.

Table 2: Comparative summary of major organic amendments: Soil benefits, GHG implications, and best management practices

Amendment type	Soil benefits	GHG implications	Best management practice	References
Farmyard Manure (FYM)	Soil structure; SOC; WHC	N ₂ O ↓ when timing-optimized; NH ₃ ↑ if surface-applied	Cool, moist conditions; soil incorporation	Smith <i>et al.</i> , (2020) ^[31] ; Lal (2015) ^[17]
Compost	SOM +20-30%; microbial diversity	N ₂ O ↓ via N immobilization; lower CH ₄ potential	Ensure C:N > 20; avoid over-application	Awasthi <i>et al.</i> , (2020) ^[1] ; Gattinger <i>et al.</i> , (2012) ^[11]

Biochar	SOC; CEC; water retention	N ₂ O ↓ ~54% (meta-analysis); CH ₄ ↓	Site-specific rates; feedstock selection	Zhong <i>et al.</i> , (2025) ^[38] ; Awasthi <i>et al.</i> , (2020) ^[1]
Green manure / cover crops	BNF; erosion control; SOM	N ₂ O ↓ via balanced C:N; NH ₃ ↓	Timely incorporation; residue management	Blanco-Canqui <i>et al.</i> , (2015) ^[6]
Crop Residues (Mulch)	WHC; temperature regulation; SOC	N ₂ O ↓; CH ₄ variable (soil moisture)	Avoid anaerobic decomposition	Glab & Kulig (2008) ^[12] ; West & Post (2002) ^[37]
Biosolids / sewage sludge	Macro/micronutrients; organic matter	N ₂ O risk if N-rich; pathogen concerns	Composting or anaerobic treatment first	Reay <i>et al.</i> , (2012) ^[28]

SOM = soil organic matter; SOC = soil organic carbon; WHC = water-holding capacity; BNF = biological nitrogen fixation; CEC = cation exchange capacity; C:N = carbon-to-nitrogen ratio; DOC = dissolved organic carbon; N₂O = nitrous oxide; CH₄ = methane; NH₃ = ammonia

4. Effects on water quality

Water quality deterioration remains a major environmental concern, particularly in regions dominated by intensive agriculture. Excessive leaching of nutrients - especially nitrogen and phosphorus - into groundwater and surface waters has resulted in widespread eutrophication, hypoxic zones, and contamination of drinking water resources (Hansen *et al.* 2001; Sharpley *et al.* 1994) ^[13, 30]. Organic resource management practices, when implemented efficiently, can reduce nutrient runoff, improve soil water retention, and decrease irrigation dependence, thereby offering significant hydrological co-benefits in addition to their agronomic value (Pretty *et al.* 2006) ^[26].

4.1 Soil structure and water retention

One of the principal hydrological advantages of organic farming is the long-term enhancement of soil physical properties, which directly governs water movement and nutrient transport. Continuous incorporation of organic matter - including compost, crop residues, and green manure - improves soil aggregation and porosity (Lal, 2004; Bünemann *et al.* 2018) ^[16, 7]. Well-aggregated soils exhibit higher infiltration capacity, thereby reducing runoff volume and limiting nutrient transport to adjacent water bodies. Organic matter also enhances soil water-

holding capacity, which is particularly beneficial in semi-arid and arid environments (Glab and Kulig, 2008) ^[12].

4.2 Reduction of nutrient leaching and chemical contamination

The exclusion of synthetic agrochemicals is a defining characteristic of organic farming systems and significantly contributes to reduced water contamination risks. Avoidance of synthetic nitrogen fertilizers reduces nitrate leaching, a major source of groundwater contamination (Hansen *et al.* 2001) ^[13]. Lower phosphorus loading helps reduce eutrophication risks in freshwater environments (Sharpley *et al.* 1994) ^[30]. Organic systems further encourage closed-loop nutrient cycling through composting, green manuring, and on-farm recycling. Enhanced microbial activity and symbiotic associations - including mycorrhizal networks and nitrogen-fixing bacteria - improve biological nutrient uptake and further diminish leaching losses. Studies consistently report lower pesticide residues and synthetic contaminants in runoff from organically managed farms compared to conventional systems (Bengtsson *et al.* 2005) ^[4]. Table 3 summarizes the major organic management practices, their water quality benefits, potential risks, and recommended mitigation strategies.

Table 3: Organic resource management practices and their effects on water quality: Benefits, risks, and mitigation strategies

Management practice	Water quality benefit	Potential risks	Mitigation strategy	References
Compost / FYM application	Reduced nitrate leaching; enhanced soil structure	Pathogen & heavy metal contamination risk if un-composted	Proper composting; rate calibration to crop demand	Hansen <i>et al.</i> , (2001) ^[13] ; Mäder <i>et al.</i> , (2002) ^[21]
Cover cropping	Captures residual N; reduces off-season leaching	Minimal - cover crops can increase NO ₃ if poorly managed	Timely termination; species selection for C:N	Snapp <i>et al.</i> , (2005); Blanco-Canqui <i>et al.</i> , (2015) ^[6]
Mulching	Reduces surface runoff and erosion; retains soil moisture	Low risk; may increase DOC in leachate	Maintain adequate mulch thickness	Teasdale & Mohler (2000); Glab & Kulig (2008) ^[12]
Reduced / no-till	Improved aggregation; reduced sediment and P loss	Potential herbicide accumulation if used transitionally	Combine with cover crops and organic inputs	Lal (2004) ^[16] ; West & Post (2002) ^[37]
Contour farming / buffer strips	Intercepts runoff; traps sediment and P	Low risk; high biodiversity co-benefit	Site topography planning; maintain strip vegetation	Pretty <i>et al.</i> , (2006) ^[26]
Biochar amendment	Reduces P leaching; improves soil structure	Very low risk; may adsorb contaminants	Application rate and depth management	Zhong <i>et al.</i> , (2025) ^[38] ; Awasthi <i>et al.</i> , (2020) ^[1]

NO₃ = nitrate; P = phosphorus; N = nitrogen; DOC = dissolved organic carbon; C:N = carbon-to-nitrogen ratio

5 Impacts on soil quality

Soil is a dynamic living system that underpins agricultural productivity and environmental sustainability. Decades of intensive conventional farming - characterized by excessive synthetic inputs, repeated tillage, and monocropping - have caused severe soil degradation manifested as reductions in SOM, biological activity, and ecosystem services including water retention, nutrient cycling, and carbon sequestration (Lal 2004;

Tsiafouli *et al.* 2015) ^[15, 34]. The application of organic resources offers an effective strategy for restoring degraded soils by improving their biological, physical, and chemical properties (Gattinger *et al.* 2012; Reganold and Wachter 2016) ^[11, 29].

5.1 Enhancement of soil organic matter and carbon sequestration

Soil organic matter forms the foundation of soil health by

regulating nutrient retention, microbial activity, and physical stability. Long-term field studies have demonstrated SOM increases of up to 30% under organic management compared to conventional farming (Leifeld and Fuhrer, 2010; Gattinger *et al.* 2012) ^[19, 11]. Organic amendments provide carbon-rich substrates that decompose gradually and form stable humic compounds, contributing to both short-term fertility and long-term carbon sequestration. Practices such as mulching, no-till farming, and cover cropping reduce decomposition rates and protect organic matter from oxidative loss (West and Post, 2002; Poeplau and Don, 2015) ^[37, 25].

5.2 Stimulation of microbial biomass and biological activity

Healthy soils rely on active and diverse microbial communities

that regulate nutrient cycling, suppress soil-borne diseases, and drive organic matter decomposition. Organically managed soils generally contain 25-50% higher microbial biomass than conventionally managed soils (Lori *et al.* 2017; Banerjee *et al.* 2016) ^[20, 2]. Continuous addition of organic substrates stimulates microbial metabolism and reproduction, creating a positive feedback between organic matter inputs and biological activity. The absence of synthetic fungicides, herbicides, and insecticides further minimizes negative impacts on beneficial microbial populations, preserving the biological integrity of the soil ecosystem (Tuck *et al.* 2014; Bünemann *et al.* 2018) ^[35, 7]. Table 4 provides a quantified summary of soil quality improvements reported across long-term studies of organic management systems.

Table 4: Quantified soil quality improvements under organic resource management: Parameters, observed changes, drivers, and functional significance

Soil quality parameter	Observed change	Key driver practice	Functional significance	References
Soil Organic Matter (SOM)	+20-30% over 5-10 years	Compost, FYM, crop residues, green manure	Nutrient retention, structural stability, microbial substrate	Leifeld & Fuhrer (2010) ^[19] ; Gattinger <i>et al.</i> , (2012) ^[11]
Microbial biomass	+25-50% vs. conventional	Continuous organic substrate addition	Nutrient cycling, disease suppression, enzyme activity	Lori <i>et al.</i> , (2017) ^[20] ; Banerjee <i>et al.</i> , (2016) ^[2]
Carbon sequestration	+0.1-0.4 Mg C ha ⁻¹ yr ⁻¹	No-till, mulch, cover crops, biochar	Climate mitigation, long-term fertility, soil structure	West & Post (2002) ^[37] ; Poeplau & Don (2015) ^[25]
Water-Holding Capacity (WHC)	+10-25%	Organic matter addition; mulching	Drought resilience; reduced irrigation demand	Glab & Kulig (2008) ^[12] ; Basche & DeLonge (2019) ^[3]
Aggregate Stability	Significantly improved	FYM, compost, reduced tillage	Reduced erosion, better aeration, root growth	Bhattacharyya <i>et al.</i> , (2018) ^[5] ; Lal (2004) ^[16]
Enzyme activity (e.g., phosphatase, urease)	+30-60% vs. conventional	Diverse organic inputs; no synthetic biocides	Mineralization of P and N; improved plant nutrition	Lori <i>et al.</i> , (2017) ^[20] ; Bünemann <i>et al.</i> , (2018) ^[7]
Soil biodiversity (macro/meso)	Greater species richness	Absence of pesticides; diverse crop rotations	Ecosystem resilience; pest and disease regulation	Tsiafouli <i>et al.</i> , (2015) ^[34] ; Tuck <i>et al.</i> , (2014) ^[35]

SOM = soil organic matter; SOC = soil organic carbon; WHC = water-holding capacity; CEC = cation exchange capacity; BNF = biological nitrogen fixation; Mg C ha⁻¹ yr⁻¹ = megagrams carbon per hectare per year

6. Policy, regulation, and governance

The transition toward organic farming systems and the sustainable utilization of organic resources represents not only an agricultural challenge but also a fundamental governance and policy imperative. Widespread adoption requires supportive policies, economic incentives, and institutional assistance (Pretty *et al.* 2018; Lampkin *et al.* 2015) ^[27, 18].

6.1 Policy frameworks

The utilization of organic resources in agriculture is strongly shaped by regional and national regulations that must balance agricultural sustainability with environmental protection. Key frameworks include the European Union Nitrates Directive and the United States Clean Water Act, which establish standards for nutrient application rates and regulate runoff from organic

fertilizers to prevent water pollution (European Commission 1991; U.S. EPA 2004) ^[8, 36]. Certification standards such as EU Organic and USDA Organic regulate the sourcing, processing, and application of organic materials (IFOAM, 2020) ^[14]. Nutrient Management Plans (NMPs), mandatory in many jurisdictions, ensure that manure application aligns with crop nutrient requirements and minimizes nitrogen and phosphorus losses to the environment (OECD, 2021) ^[24]. Emerging carbon footprint policies are beginning to incentivize carbon sequestration and GHG reduction through the use of biochar, compost, and manure (FAO, 2021) ^[10]. Table 5 presents a comparative overview of major global policy frameworks relevant to organic resource management, including their key provisions and regulatory significance.

Table 5: Global policy frameworks governing organic resource utilization in agriculture: Provisions, scope, and management relevance

Policy / regulation	Region / scope	Key provisions	Relevance to organic resource management	References
EU Nitrates Directive (91/676/EEC)	European Union	Limits N application to 170 kg ha ⁻¹ yr ⁻¹ ; designates Nitrate Vulnerable Zones (NVZs)	Reduces NO ₃ leaching to groundwater; mandates NMPs	European Commission (1991) ^[8]
U.S. Clean Water Act	United States	Regulates point and non-point source agricultural runoff; CAFO permits required	Protects surface and groundwater from nutrient pollution	U.S. EPA (2004) ^[36]
EU Farm to Fork Strategy (2020)	European Union	Target: 25% organic farmland by 2030; 50% reduction in synthetic pesticide use	Accelerates organic transition; incentivizes organic amendments	European Commission (2020) ^[9]

USDA Organic Regulations (NOP)	United States	Prohibits synthetic fertilizers/pesticides; mandates organic matter management	Encourages compost, manure, and crop residue use	IFOAM (2020) ^[14]
FAO agroecology framework	Global	Promotes nutrient recycling, biodiversity, and climate-smart practices	Reduces synthetic input dependency globally	FAO (2021) ^[10]
OECD nutrient management plans	OECD countries	Mandatory NMPs for large farms; training for smallholders	Aligns organic input rates with crop demand; reduces losses	OECD (2021) ^[24]
India national policy on biofertilizers	India	Subsidizes biofertilizer production; mandates quality standards	Promotes microbial inoculants with organic amendments	Banerjee <i>et al.</i> , (2016) ^[2]

NMP = Nutrient Management Plan; NVZ = Nitrate Vulnerable Zone; CAFO = Concentrated Animal Feeding Operation; F2F = Farm to Fork Strategy; NOP = National Organic Program; BNF = biological nitrogen fixation

6.2 Risk and adoption barriers

Although organic farming and organic resource utilization offer substantial environmental and agronomic advantages, several barriers continue to restrict widespread adoption. During the transition from conventional to organic farming, producers frequently experience lower crop yields due to the absence of synthetic fertilizers and pesticides; technical guidance, pilot programmes, and transitional grants are therefore critical to reducing financial risk (Migliorini and Wezel, 2017) ^[22].

Inconsistent and fragmented policies related to organic farming and waste management create regulatory uncertainty that hinders long-term planning by farmers and agribusinesses (Lampkin *et al.* 2015) ^[18]. A persistent shortage of trained extension officers and technical expertise at the farm level further constrains adoption, underscoring the need for sustained investment in education, training, and knowledge-transfer systems (Pretty *et al.* 2018) ^[27].

Table 6: Integrated synthesis of organic resource management outcomes across key agronomic and environmental domains

Domain	Key practices	Quantified outcomes	Caveats / limitations	References
Emission mitigation	Biochar + manure; AWD; cover crops	N ₂ O ↓ ~54%; CH ₄ ↓ up to 85%; NH ₃ ↓	Highly effective when site-calibrated	Zhong <i>et al.</i> , (2025) ^[38] ; Reay <i>et al.</i> , (2012) ^[28]
Water quality protection	Cover crops; contour farming; compost	NO ₃ leaching ↓; P runoff ↓; pesticide residue ↓	Dependent on application rates and soil type	Hansen <i>et al.</i> , (2001) ^[13] ; Sharpley <i>et al.</i> , (1994) ^[30]
Soil carbon sequestration	No-till; compost; biochar; green manure	SOM +20-30%; SOC +0.1-0.4 Mg C ha ⁻¹ yr ⁻¹	Long-term; requires continued organic inputs	Gattinger <i>et al.</i> , (2012) ^[11] ; West & Post (2002) ^[37]
Soil biological activity	Diverse organic amendments; no biocides	Microbial biomass +25-50%; enzyme activity +30-60%	Sustained only with ongoing organic input diversity	Lori <i>et al.</i> , (2017) ^[20] ; Banerjee <i>et al.</i> , (2016) ^[2]
Crop productivity	Integrated organic + biofertilizer systems	Comparable to conventional in long-term; lower synthetic inputs	Transition period (2-5 years) yield gap possible	Mäder <i>et al.</i> , (2002) ^[21] ; Reganold & Wachter (2016) ^[29]
Climate resilience	Diversified rotations; biochar; mulch	Improved WHC; reduced heat/drought stress; stable yields	Requires policy support and farmer capacity building	Pretty <i>et al.</i> , (2018) ^[27] ; FAO (2021) ^[10]
Policy compliance	NMPs; EU F2F; USDA NOP	Regulatory alignment; market access; certification	Fragmented global frameworks; need harmonization	OECD (2021) ^[24] ; IFOAM (2020) ^[14]

WHC = Water-Holding Capacity; SOC = Soil Organic Carbon; SOM = Soil Organic Matter; NMP = Nutrient Management Plan; F2F = Farm to Fork Strategy; NOP = National Organic Program; GHG = Greenhouse Gas; N₂O = Nitrous Oxide; CH₄ = Methane; NH₃ = Ammonia; ↓ = Reduction; ↑ = Increase

7. Conclusion

The sustainable utilization of organic resources in agriculture has advanced considerably over the past decade, driven by the urgent need to restore soil health, minimize dependence on synthetic inputs, and reduce environmental degradation. Organic amendments - including compost, green manures, biochar, animal manures, and plant-derived residues - have demonstrated significant potential for improving soil fertility, enhancing microbial processes, and increasing crop productivity. The integration of organic inputs with bio-stimulants, Plant Growth-Promoting Rhizobacteria (PGPR), and precision-based application systems has further enhanced the efficiency and agronomic value of organic resources (Lori *et al.* 2017; Banerjee *et al.* 2016) ^[20, 2]. Meta-analyses and long-term field experiments have consistently confirmed the role of organic amendments in strengthening nutrient cycling, reducing greenhouse gas emissions, and improving the resilience of agricultural systems under changing climatic conditions (Zhong *et al.* 2025; Gattinger *et al.* 2012) ^[28, 11].

Despite these achievements, critical challenges remain regarding

the standardization of organic resource quality, maintenance of nutrient balance, and scaling of technologies across diverse agroecological regions. Strong policy support, enhanced farmer awareness, and sustained scientific research are necessary to fully realize the potential of organic resources within a circular and climate-smart agricultural framework. The present review underscores that the utilization of organic resources represents a fundamental pillar of sustainable agriculture and that continued progress - supported by scientific innovation, integrated nutrient management, and effective multi-level governance - will be essential for achieving long-term soil health, food security, and environmental sustainability. As evidenced by the quantitative summaries presented across Tables 1-6, the interdisciplinary evidence base for organic resource management is robust and expanding, providing a sound scientific foundation for policy action and agronomic innovation.

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