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Poultry Manure as a Soil Amendment: Composition, Physicochemical and Biological Effects, Carbon Dynamics, Valorisation Pathways and Environmental Risks

Rolf Gäel Mabicka Obame[1], Neil-Yohan Musadji[2], Urlain Gael Yakouya-Moubamba[3], Elie Fosso Menkem[4], Maurice Ognalaga[2], Dieu-Donne Mouketou-Tarazewicz[5]

[1]Department of Phytotechnology, National Institute of Agronomy and Biotechnology University of Science and Technology of Masuku, Franceville, Gabon
[2]Department of Fundamental Engineering Sciences, National Institute of Agronomy and Biotechnology University of Science and Technology of Masuku, Franceville, Gabon
[3]Department of Geology, Faculty of Sciences, University of Science and Technology of Masuku, Franceville, Gabon
[4]Department of Geology, University of Buea, Buea, Cameroon
[5]Department of Geography, University Omar Bongo, Libreville, Gabon
Email: rolfgaelmabickaobame@gmail.com, neil.yohan.musadji@gmail.com, yurlaingael@yahoo.fr, fosso.menkem@gmail.com, dieudonne@expetrop.com

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Abstract

Escalating demand for food security has driven reliance on synthetic fertilizers, yet their high energy cost of manufacture and well-documented negative environmental externalities including soil acidification, waterway eutrophication, and greenhouse gas emissions make their long-term use unsustainable. Poultry manure (PM) is increasingly regarded as a cost-effective organic amendment capable of supplying the full spectrum of macro- and micronutrients required for crop production while simultaneously restoring soil physical, chemical, and biological integrity. Although numerous studies have investigated individual aspects of PM utilization, existing reviews generally address nutrient supply, composting technologies, or environmental impacts separately. This review provides an integrated systems-oriented synthesis linking manure composition, soil physicochemical and biological responses, soil organic carbon dynamics, greenhouse gas emissions, valorisation pathways, environmental risks, and management strategies within a single analytical framework. The review draws on experimental and meta-analytical evidence from tropical and subtropical agroecosystems, where degraded Acrisols and Ferralsols limit yields, and where PM represents the most accessible fertility input for smallholder farmers. While the agronomic benefits of PM are well established, optimising its use requires site-specific rate calibration, appropriate pre-treatment (composting, anaerobic digestion), and monitoring of contaminant accumulation. Integrating PM with biochar, judicious mineral fertilizer use, and precision nutrient management offers the greatest potential for sustainable soil restoration, circular bioeconomy development, and climate-smart agriculture.

Keywords

Poultry Manure, Soil Organic Matter, Soil Properties, Nutrient Cycling, Greenhouse Gas Emissions, Heavy Metals, Antibiotic Resistance, Circular Economy

1. Introduction

Global food security increasingly depends on sustained soil fertility while meeting the rising demand for agricultural production under increasing climatic and environmental pressures. However, the intensive application of synthetic fertilizers over recent decades has created a paradox: short-term yield gains are offset by the long-term degradation of the very resource base on which crop production depends. Chemical fertilizers are energy-intensive to manufacture and contribute to soil acidification, nutrient imbalances, declining soil biological activity and physical deterioration that accelerates erosion [1]-[3]. These challenges have renewed global interest in sustainable soil management practices that improve productivity while maintaining ecosystem functions.

In tropical regions, these pressures are compounded by highly weathered soils particularly Ferric Acrisols and Ferralsols which are characterized by low organic matter, weak aggregate stability, and limited cation exchange capacity, poor nutrient retention, and high susceptibility to nutrient depletion [4] [5]. Furthermore, the high cost and intermittent availability of mineral inputs further constrain their adoption by smallholder farmers across sub-Saharan Africa, where local organic resources remain the primary means of fertility management.

Among organic amendments, poultry manure (PM) occupies a distinct position because of its high nutrient density and relatively rapid mineralization. Comparative analyses consistently show that PM contains higher concentrations of nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg) and potassium (K), than most other livestock manures, and a significant fraction of these nutrients is rapidly available for plant uptake [6]-[9]. In addition to supplying essential nutrients, PM improves soil physical structure, stimulates microbial activity, and promotes soil organic carbon (SOC) sequestration [3] [10] [11]. These multifunctional properties make PM an attractive cornerstone of integrated soil fertility management (ISFM) and climate-smart agricultural systems.

Concurrently, the rapid expansion of global poultry production is generating increasing volumes of manure that may exceed local land-application capacity in intensive production regions. This biomass represents an important renewable nutrient resource, but it also poses significant environmental management challenges when poorly handled or indiscriminately applied [8] [12]. Uncontrolled land disposal of PM may introduce heavy metals, human pathogens, veterinary antibiotic residues, and antibiotic resistance genes (ARGs) into agricultural soils and waterways [8] [13] [14]. Furthermore, inadequate storage and handling may generate methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3), contributing to both climate change and local air quality degradation.

Existing reviews generally focus on nutrient supply, composting technologies, or environmental pollution separately, whereas few integrate manure composition, soil physicochemical and biological responses, carbon sequestration, greenhouse gas emissions, valorisation pathways, and environmental risks within a single systems-oriented framework. Such an integrated perspective is increasingly needed to support sustainable nutrient management and evidence-based decision-making across agricultural systems. Sustainable management of poultry manure also contributes to several Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land), through improved food security, resource efficiency, climate change mitigation, and land restoration.

This review therefore structures its synthesis around the key decision nodes that a researcher, agronomist, or policy-maker must navigate:

i) understanding the composition and variability of PM;

ii) quantifying its effects on the physical, chemical, and biological dimensions of soil functioning;

iii) characterising the balance between SOC sequestration potential and greenhouse gas trade-offs;

iv) evaluating bio-energy and circular-economy valorisation alternatives;

v) identifying and managing environmental and health risks; and

vi) integrated management strategies that maximize agronomic benefits while minimizing environmental impacts.

By synthesizing evidence across these interconnected themes, this review aims to provide a comprehensive scientific basis for the sustainable management of poultry manure in both tropical and temperate agroecosystems, with particular emphasis on tropical and subtropical regions where soil fertility constraints are most severe and research needs remain greatest.

2. Review Framework and Literature Selection

This manuscript follows a structured narrative review methodology. Peer-reviewed literature was identified through major scientific databases, including Web of Science, Scopus, PubMed, and Google Scholar. Search terms combined "poultry manure" with sub-topics including "soil physical properties", "soil chemical properties", "microbial community", "soil organic carbon", "greenhouse gas emissions", "biogas", "heavy metals", "antibiotic resistance genes", and "pathogen contamination". Priority was given to studies published within the last decade; seminal earlier studies were included where they established mechanistic or conceptual foundations.

Review articles and high-quality laboratory, greenhouse, and experimental field studies were integrated to ensure both breadth and depth. Additional relevant publications were identified through citation tracking of key review papers and highly cited original research articles to improve the comprehensiveness of the review. Studies from tropical and subtropical agroecosystems were given greater emphasis, reflecting the focus on contexts where degraded soils and resource-constrained farmers represent the primary target audience.

3. Poultry Manure Typology and Nutrient Composition

The poultry manure (PM) used here as a generic term for excreta-derived poultry waste, whereas poultry litter refers specifically to excreta mixed with bedding material, feathers, spilled feed and other residues generated during poultry production [8] [15]. Broiler is generally bedding-rich and may contain variable amounts of feed residues and feathers; cage-layer manure is dominated by excreta and usually contains little or no bedding; high-rise manure accumulates beneath caged birds; and poultry slurry refers to manure mixed with water. Distinguishing these forms is essential because nutrient concentration, moisture content, mineralisation rate, salt load and contaminant risk differ substantially among manure types and production systems [5] [16]. Unless otherwise specified, the composition values discussed below are reported on a dry-matter basis and as elemental nutrients, not oxide equivalents.

Poultry litter typically contains approximately 2.9% - 4.4% N, 3.2% - 5.5% P, 3.2% - 5.5%, and 2.2% - 3.8% K on a dry-matter basis although these ranges vary substantially with production system, bedding material, diet, manure age and storage history [8] [15] [17] [18]. It also supplies calcium (Ca), magnesium (Mg), sulfur (S) and trace elements such as copper (Cu), iron (Fe), manganese (Mn), chlorine (Cl), boron (B), molybdenum (Mo), cobalt (Co), and zinc (Zn), which may contribute to crop nutrition but may also create contaminant-loading risks when manure is repeatedly applied at high rates [2] [3] [11] [17]-[19]. Broiler litter typically contains higher bedding-derived organic matter, while layer manure generally contains higher Ca because of eggshell production. The C:N ratio of PM is generally low (6 - 15), promoting rapid microbial mineralisation, accelerated nutrient cycling, and early nutrient release compared with crop residues or compost.

Compositional variability is substantial and must be acknowledged in any management recommendation (**Figure 1**). The concentrations of macro- and micronutrients in PM are governed by the breeding system (cage, deep litter, free range), bird species and age, feed formulation, moisture content, manure age, bedding type and quantity, and storage and handling practices [8]. This variability is agronomically significant: N availability in the first growing season can range from as little as 25% to over 70% of total N, depending on manure management history and soil conditions. Variability in heavy metal content notably Zn, Cu, and As also depends on feed additives and management practices, creating site-specific environmental risks that require local assessment and continuous monitoring [19].

Overall, the high nutrient density, relatively low C:N ratio, and variable physicochemical composition of poultry manure highlight both its agronomic value and the importance of site-specific management strategies to optimize nutrient use efficiency while minimizing environmental risks.

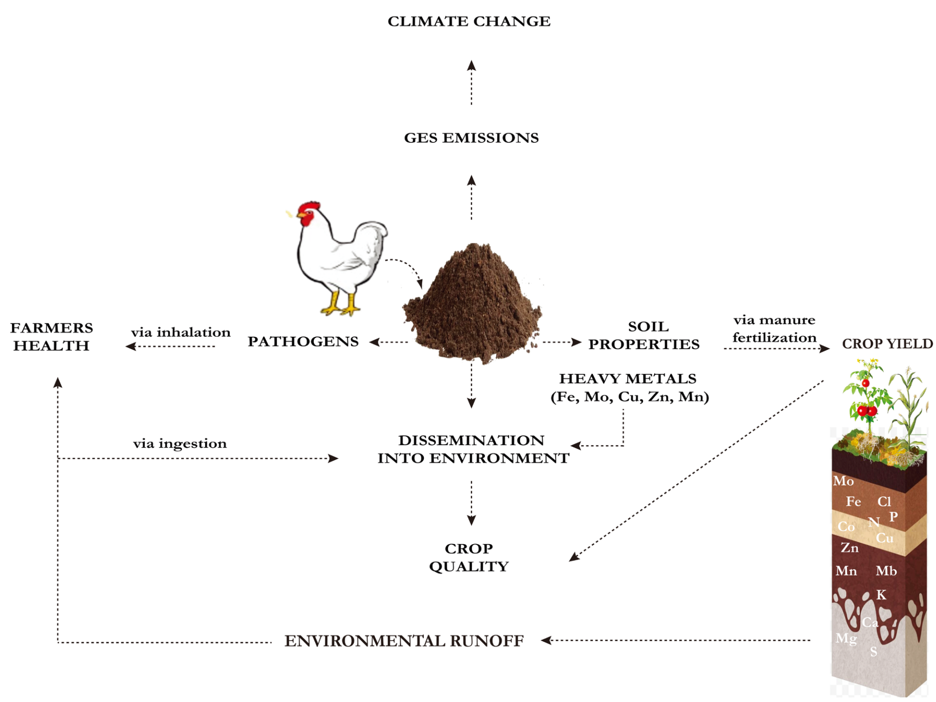

Figure 1. Agronomic benefits and environmental risk pathways associated with poultry manure recycling.

Conceptual framework illustrating of poultry manure (PM) as both a nutrient-rich organic amendment and a potential source of environmental and health risks. The diagram links PM application to improved soil properties, enhanced nutrient availability, increased soil organic carbon sequestration and crop yield, while highlighting parallel pathways of greenhouse-gas emissions, pathogen exposure, heavy-metal dissemination, crop-quality risks, runoff losses and farmer-health concerns. This dual agronomic environmental framework underscores the need for appropriate application rates, manure pre-treatment (e.g., composting or anaerobic digestion), and continuous environmental monitoring to maximize agronomic benefits while minimizing environmental impacts.

4. Effects of Poultry Manure on Soil Physical Functioning

PM application can improve these physical constraints through organic matter inputs that promote aggregation and increase the proportion of mesopores and macropores available for water storage and gas exchange (**Figure 2**). However, the magnitude and persistence of the response depend on manure type and maturity, application rate and duration, soil texture and mineralogy, antecedent degradation status, climate, tillage and crop management. These improvements may enhance soil physical quality and crop production when PM is applied within a site-specific nutrient-management framework.

4.1. Bulk Density and Soil Structure

Field evidence generally indicates that PM can reduce soil bulk density where soils are compacted or organic-matter depleted, but the response is not universal and depends on texture, amendment rate, manure maturity and management history. In sandy loam soils from Ibadan, Nigeria, poultry manure was consistently associated with lower bulk density. Are *et al.* [10] documented an 8.1% decrease in bulk density following PM application. Comparable reductions in compactness have also been reported for PM-amended tropical soils and related organic-amendment systems [2] [3] [20]. Mechanistically, manure-derived organic matter promotes the formation of stable organo-mineral aggregates, improves pore connectivity and creates a more open soil structure. Application rates near 10 $t \cdot ha^{-1}$ should therefore be interpreted as context-specific examples from individual field studies rather than general recommendations. Some biochar-amended treatments at very high rates (50 $t \cdot ha^{-1}$) have produced marginal bulk density increases in a sandy clay loam-textured soil [21], underscoring the importance of amendment-specific and site-specific management rather than direct comparison between biochar and poultry manure.

4.2. Total Porosity and Water Retention

PM application can increase total porosity by improving soil aggregate stability and organic matter content, although the strength of the response depends on soil texture, initial compaction, amendment quality and duration of application. Across contrasting tropical soil and crop-management contexts, [3] [22] [23] reported improved porosity or pore-related physical conditions after organic-amendment or PM application. Increased porosity is mechanistically linked to the formation of organo-mineral aggregates. As soil organic matter content (SOM) content rises, soil particles coalesce into larger structural units, reducing bulk density and increasing inter-aggregate pore space. Improved pore connectivity facilitates infiltration, aeration, root development, and water movement throughout the soil profile.

Soil moisture retention often improves after PM or related organic-amendment addition, particularly where low organic matter limits water-holding capacity [2] [10] [24]-[26]. Higher SOM acts l as a water-retention reservoir, increasing the water-holding capacity of light-textured soils while improving pore continuity and hydraulic regulation in clay-rich soils. The gradual decomposition of organic matter further supports stable soil structure, thereby improving both water infiltration and water storage.

Collectively, these physical improvements reduce erosion risk, improve water-use efficiency, and buffer crops against short-term drought stress making poultry manure particularly valuable in rain-fed tropical and subtropical agroecosystems where rainfall is often intense, erratic, and highly seasonal.

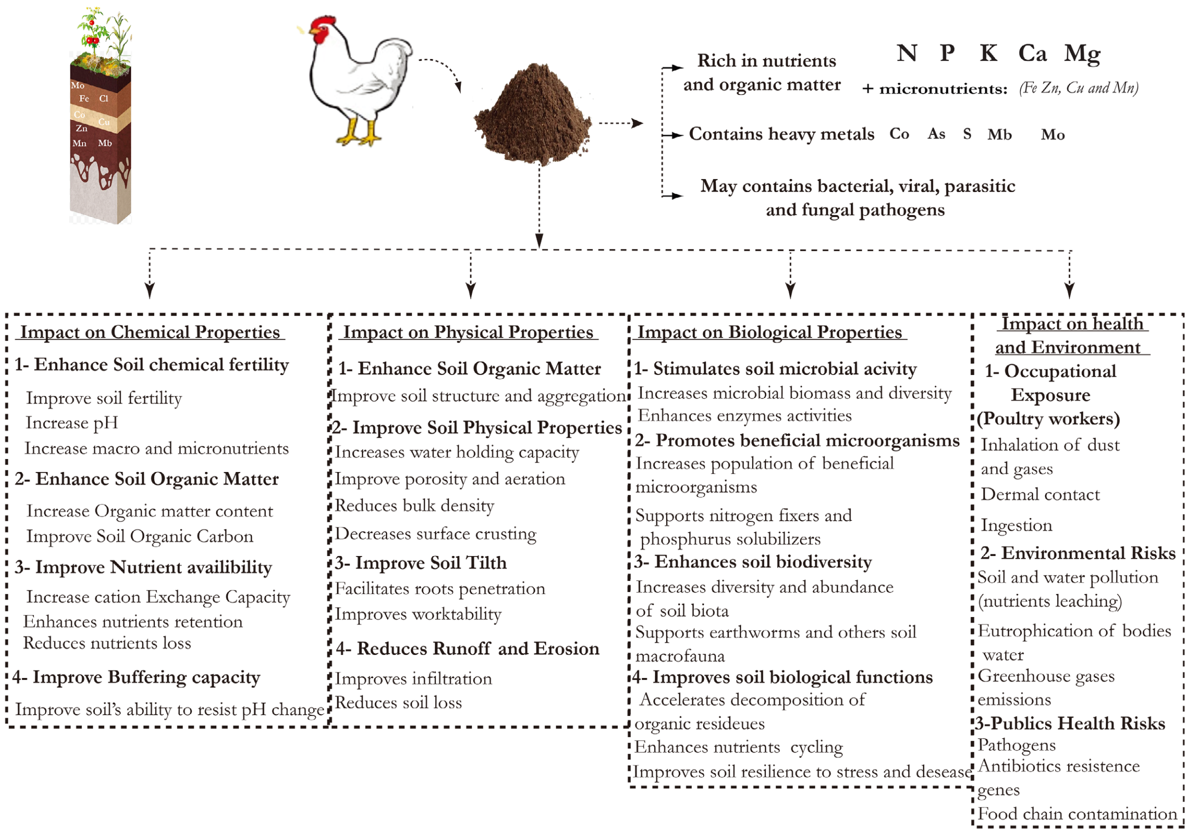

Figure 2. Integrated effects of poultry manure on soil chemical, physical and biological functioning.

Conceptual framework illustrating the major functional pathways through which poultry manure modifies soil systems. Poultry manure supplies macro- and micronutrients and organic matter, thereby improving soil aggregation, bulk density, porosity, water-holding capacity, pH buffering, nutrient availability, cation exchange capacity, and microbial activity. The figure also identifies potential risk vectors, including heavy metals, pathogens and occupational or environmental exposure, highlighting that sustainable poultry manure management requires balancing soil restoration and productivity with environmental protection, biosafety, and contaminant control.

5. Effects of Poultry Manure on Soil Chemical Fertility

5.1. Soil pH

The effect of PM on soil pH is often liming-like in acid tropical soils, but the response is modulated by initial pH, soil buffering capacity, texture, mineralogy, and manure maturity and application rate. Studies across Alfisols and Ferralsols in Nigeria, Cameroon, and Cuba report pH increases following PM application [1]-[3] [27] [28]. This increase may improve nutrient availability, reduce aluminium toxicity, and create more favorable conditions for root growth and microbial activity. Two mechanisms operate in concert. First, PM contains base-forming cations such Ca^{2+}, Mg^{2+} and K^+ that can displace exchangeable acidity from the cation exchange complex. Second, organic anions produced during PM decomposition, including malate, citrate and tartrate, can interact with Fe and Al oxide surfaces and moderate proton release [1]. However, results are not universal. Joseph *et al.* [29] found that PM did not significantly alter pH in coarse-textured Nigerian soils over the study period, suggesting that texture and buffering capacity strongly constrain the pH response.

5.2. Soil Organic Matter and Organic Carbon

PM addition generally increase SOM content where repeated organic inputs exceed decomposition losses, but the magnitude of accumulation depends on manure quality, application frequency, incorporation depth, soil texture, mineralogy and climate [2] [3] [10] [27]-[31]. Decomposing PM adds carbonaceous residues to the soil that may be stabilised as SOM through microbial biomass processing and association with mineral surfaces. Because SOM is the principal reservoir of soil organic carbon (SOC), repeated PM application can enhance carbon storage, but only where manure-derived C inputs exceed mineralisation and gaseous losses. PM quality, especially its C:N ratio and degree of decomposition, together with temperature and moisture regimes, determines whether added C is rapidly mineralised or retained in more persistent organic-matter pools.

5.3. Nitrogen, Phosphorus, and Exchangeable Cations

Total nitrogen often increases with PM application, particularly when manure-N inputs are synchronised with crop demand and losses through leaching, volatilisation or denitrification are limited [3] [16] [27] [29] [31]. The nitrogen in PM includes inorganic forms, mainly ammonium-N, that are rapidly available for plant uptake, and organic forms that are released progressively through microbial mineralisation. Available phosphorus (P) can also increase after PM application because added P and pH modification can enhance the release of previously adsorbed or occluded phosphate from Fe- and Al-bearing minerals [16] [27] [28]. However, in sandy soils with low P-retention capacity, the same process may increase P mobility and leaching risk rather than nutrient accumulation [29].

Exchangeable cations (Ca^{2+}, Mg^{2+}, and K^+) all increase with PM application, reflecting the direct contribution of these cations from manure decomposition, [2] [3], [27]-[31] (**Figure 3**). The enrichment of exchangeable base cations contributes to improved base saturation, nutrient availability, and overall soil fertility, particularly in highly weathered tropical soils characterized by low native nutrient reserves. Responses of cation exchange capacity (CEC) are less consistent. Toluwase Oreoluwa *et al.* [32] found no significant CEC change in some treatments, suggesting that CEC responses depend not only on manure application rate but also on the formation of stable humic substances during organic matter decomposition. Because humified organic matter contributes substantially to soil surface charge, the extent of CEC improvement is strongly influenced by PM composition, decomposition dynamics, soil mineralogy, and the duration of repeated manure application.

Overall, poultry manure enhances soil chemical fertility through complementary improvements in soil pH, organic matter accumulation, nutrient availability, and exchangeable base cations. However, the magnitude of these responses depends on manure characteristics, application strategy, and inherent soil properties, highlighting the importance of site-specific nutrient management.

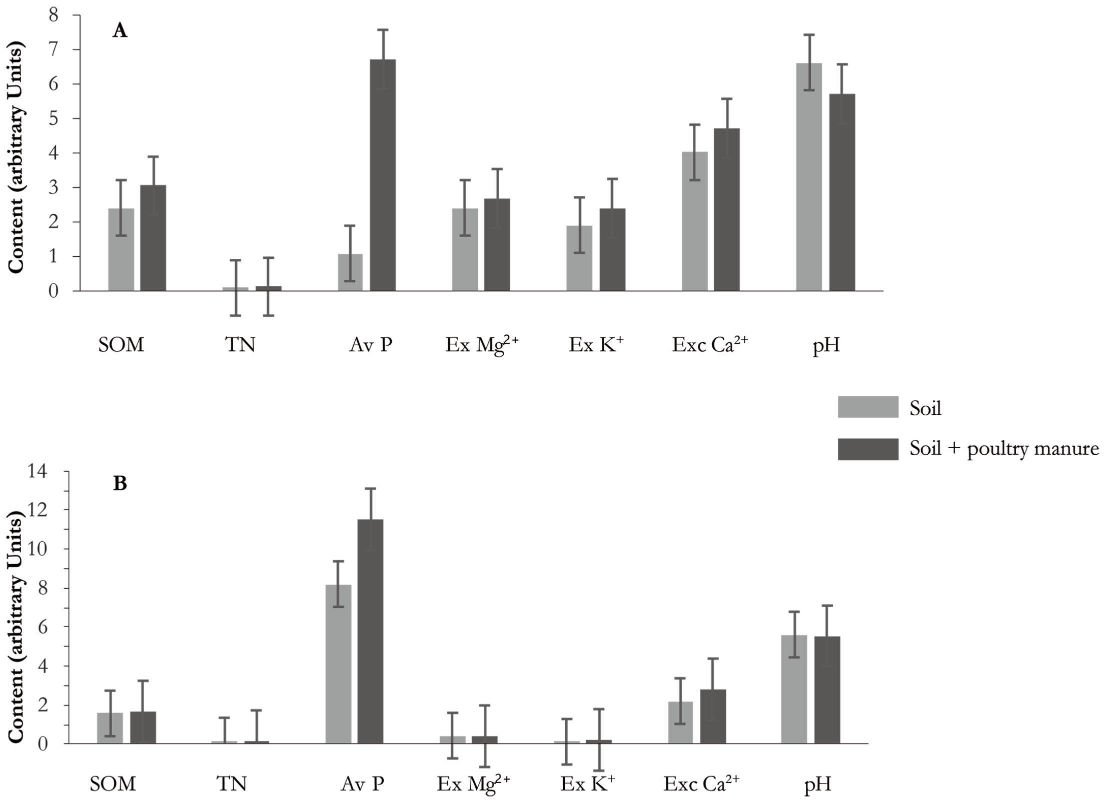

Figure 3. Soil fertility responses to poultry manure addition across contrasting soil contexts.

Mean values of selected soil fertility indicators under unamended soil and soil amended with poultry manure. Figure 3(A), Figure 3(B) illustrate treatment responses for soil organic matter (SOM), total nitrogen (TN), available phosphorus (Av. P), exchangeable Mg^{2+}, K^{+} and Ca^{2+}, and pH. Error bars indicate variability around mean values. The figure shows that PM addition generally enhances nutrient availability and exchangeable-base status, although the magnitude of response differs among soil properties and between panels, reflecting soil-specific buffering capacity and nutrient-retention mechanisms.

6. Effects of Poultry Manure on Soil Biological Activity

Soil biological activity mediates a wide range of nutrient transformation and cycling processes; it is therefore both a target and an indicator of soil health. PM provides readily available carbon and nitrogen substrates, organic compounds, micronutrients, vitamins, and enzyme precursors that stimulate microbial biomass production and enzymatic activity.

The addition of poultry manure modifies soil microbial communities through both direct and indirect mechanisms. Direct effects result from the supply of organic substrates and nutrients, whereas indirect effects occur through improvements in soil pH, moisture availability, aggregation, and nutrient status. Incorporation of poultry litter into soil induces marked changes in bacterial community composition as well as soil chemical properties [11]. These findings are in agreement with long-term fertilisation studies showing that repeated PM application restructures edaphic microbial communities through modifications of soil chemical attributes [33] [34]. A meta-analysis by [35] documented significant increases in microbial carbon and nitrogen following manure application across diverse soil types, attributing the effect to improved substrate availability and physical soil conditions created by PM-induced structural improvements. Increased microbial biomass following PM addition reflects enhanced microbial growth potential and greater nutrient turnover capacity, particularly in nutrient-depleted soils. Similar trends have been reported by [36], who noted that the composition of the microbial community also shifts qualitatively, with changes in microbial diversity, functional groups, and ecological interactions that may influence nutrient cycling, pathogen suppression and soil disease dynamics.

The stimulation of microbial activity by PM has important dual significance: it accelerates nutrient cycling beneficial to crops, but it may also temporarily increase CO_2 efflux and, under anaerobic microsites, methane and nitrous oxide production (**Section 7**). These responses depend strongly on manure application rate, moisture conditions, soil aeration status, temperature, and manure decomposition stage. Managing the balance between these outcomes maximising nutrient availability while limiting net greenhouse gas (GHG) emissions is a central challenge in PM-based soil fertility management. Overall, poultry manure acts as a biological catalyst that enhances microbial activity, nutrient cycling, and soil functional capacity. However, its effects are context-dependent and require integrated management approaches that consider both agronomic benefits and potential environmental consequences.

7. Soil Organic Carbon Sequestration and Greenhouse Gas Trade-Offs

7.1. Carbon Sequestration Potential

Livestock manure management represents an important component of sustainable agricultural systems because manure can function simultaneously as a nutrient source, soil amendment, and carbon input, while also representing a potential source of greenhouse gas (GHG) and air pollutant emissions. The main greenhouse gases associated with manure management are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which contribute to global warming and climate change. Consequently, improved manure management strategies are required to maximize carbon retention and nutrient recycling while minimizing emissions and environmental impacts [37].

The capacity of PM to promote SOC accumulation has been reported in field studies, but SOC gains should not be interpreted as evidence of net climate mitigation unless emissions during manure storage, treatment, and transport and field application are also considered [10] [38]-[41]. Adeleye *et al*. [40] found a 37.8% increase in SOC following PM application, while Are *et al*. [10] reported a 43.8% increase relative to untreated soils. These findings indicate that PM can increase soil carbon stocks under appropriate agronomic conditions, but the magnitude of PM-induced carbon storage depends on manure characteristics, application rate, frequency of application, decomposition dynamics, soil texture, mineralogy.

Recent long-term and meta-analytical evidence indicates that manure-based organic amendments, including poultry manure, generally promote greater SOC accumulation than mineral fertilisers alone, although the stabilisation pathway is not uniform across soils and climates. A global meta-analysis showed that manure application increased SOC stocks by 35.4% on average, with responses controlled by soil texture, climate, initial SOC content, manure type, application amount, tillage and the use of complementary mineral fertilisation [42]. Mechanistically, long-term manure inputs can increase net SOC by raising carbon inputs while reducing native SOC mineralisation when combined with mineral fertilisers, partly through lower priming effects and improved nitrogen availability [43]. More recent fractionation studies further show that organic fertilisation contributes to both particulate organic matter and mineral-associated organic matter (MAOM) pools, but that long-term sequestration depends strongly on soil texture, organic fertilisation intensity and the degree of MAOM saturation [44] [45]. These findings indicate that the long-term carbon-sequestration potential of PM depends on the balance between carbon inputs, decomposition losses, mineral protection, soil texture, climate conditions and management practices rather than on manure addition alone.

7.2. Greenhouse Gas Emissions from Poultry Production and Manure Management

For climate accounting, the assessment boundary must be explicitly separated into: i) emissions associated with poultry production and feed supply; ii) emissions from manure storage and treatment; iii) emissions after field application; iv) avoided emissions from fertilizer substitution or energy recovery; and v) measured soil-carbon change. Poultry production contributes to agricultural greenhouse gas emissions through feed production, energy consumption, manure storage, manure treatment, transportation, and field application of manure-derived nutrients. The livestock sector accounts for approximately 14.5% of global anthropogenic greenhouse gas emissions, with poultry representing an increasing contribution due to rising global production and consumption [46]-[48]. The three primary GHGs from poultry systems are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (**Figure 4**).

Carbon dioxide emissions originate primarily from energy consumption, fossil fuel combustion, electricity use, and upstream agricultural activities associated with feed production, particularly maize and soybean [48] [49]. Life-cycle assessments estimate that chicken meat production generates approximately 4.08 kg CO_2-eq per kilogram of live weight gain [50]. In the United States, manure management in poultry systems contributes approximately 5.2 million metric tonnes CO_2-eq annually [51].

Methane emissions from PM arise predominantly from anaerobic decomposition during storage. Because poultry are monogastric, enteric CH_4 is negligible; storage conditions notably temperature, moisture, and oxygen availability govern CH_4 production potential. Several factors including species, age, housing type, and feed composition modulate manure methane potential [52] [53].

Nitrous oxide represents the most climatically significant GHG from PM application to land. N_2O emissions results from nitrification and denitrification of organic and inorganic N in applied manure, and from the nitrogen-intensive cultivation of poultry feed [54]. Poultry manure is notably high protein and amino acids, yielding a significant organic N load that can be transformed into NH_3, NO_3^-, and N_2O, depending on soil conditions and managements [15] [55]. Ammonia (NH_3), although not classified as a greenhouse gas, represents an important nitrogen loss pathway and a major air-quality concern in poultry production systems. Total ammonia volatilisation losses from poultry housing range from 2% - 20% of total N in layer operations to 13% - 20% in broiler systems, contributing to atmospheric nitrogen deposition, soil acidification, and eutrophication.

Improved poultry manure management can reduce air quality impacts, recover nutrients and contribute to climate mitigation, but the outcome depends on the full management chain rather than on any single process. Recent mitigation studies have evaluated ammonia reduction after slurry or digestate application [56] [57], GHG emissions from broiler-manure treatment options [58], and environmental burdens of chicken-manure composting or compost valorisation [59] [60]. However, most existing studies still evaluate individual gases, isolated treatment technologies, or specific management stages rather than the complete manure life cycle. Comprehensive frameworks integrating emission reductions, carbon sequestration, nutrient recycling, fertilizer substitution, crop uptake, and soil carbon stabilization remain limited.

Recent studies have advanced the quantification of greenhouse-gas emissions and environmental burdens for specific manure-management pathways, including broiler manure treatment options such as composting, anaerobic digestion and biochar production [58], chicken manure composting with organic or biochar additives [60], and poultry manure valorisation as organic composts [59]. Broader reviews have also emphasized the environmental relevance of carbon, nitrogen and phosphorus cycling during poultry manure management [16], as well as the mitigation potential of manure-based strategies in livestock and poultry systems [53]. However, most existing assessments remain focused on individual gases, treatment technologies, production sectors or regional case studies. Although integrated cradle-to-field approaches are emerging, for example, in regional assessments of livestock and poultry manure management [61], a unified framework linking nutrient recycling, emission abatement, crop uptake and soil carbon stabilization remains insufficiently developed. This gap is particularly relevant for poultry systems, where manure management must be evaluated not only as a waste-treatment problem, but also as a soil-carbon, nutrient-recycling and climate-mitigation pathway [62].

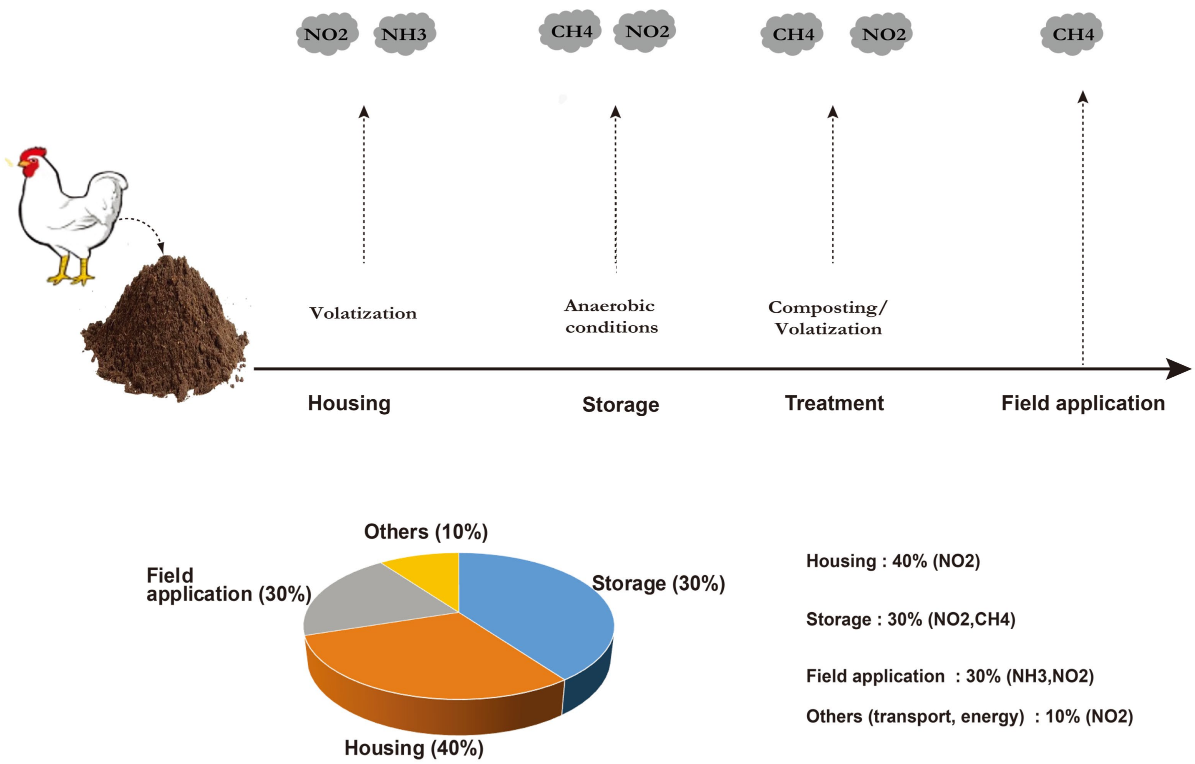

Figure 4. Greenhouse-gas emission hotspots along the poultry manure management chain.

Conceptual framework showing the main stages at which poultry manure can generate gaseous emissions, from housing and storage to treatment and field application. The diagram highlights volatilisation and anaerobic decomposition pathways associated with NH_3, CH_4 and N_2O emissions, while linking manure management to the broader climate footprint of poultry production. By locating emission hotspots along the manure chain, the figure supports integrated mitigation strategies combining improved storage, composting, anaerobic digestion, controlled field application and nutrient recycling.

8. Valorisation Pathways: From Waste to Resource

The rapid expansion of the global poultry sector has generated large biomass that in some intensive production regions exceed local soil nutrient demand and land application capacity. This accumulation creates environmental challenges related to nutrient losses, greenhouse gas emissions, pathogen dissemination, and odour generation. Consequently, alternative valorisation strategies based on circular economy principles are increasingly being explored to transform poultry manure from an agricultural waste stream into a source of renewable energy, recovered nutrients, and value-added soil amendments.

8.1. Anaerobic Digestion and Biogas Production

Anaerobic digestion (AD) of PM converts its organic fraction into biogas (predominantly CH_4 and CO_2) and digestate, the latter retaining most of the original nutrient value and being suitable for land application. Anaerobic digestion provides a dual benefit by reducing uncontrolled methane emissions from manure storage while recovering renewable energy. One cubic metre of biogas is equivalent in energy to approximately 0.7 kg of standard coal, with a net emission reduction of 11.50 kg of CO_2-equivalent [63]. Poultry-derived biogas constitutes 34.22% of China's national biogas production potential [12], while in Iran, poultry contributes 23% of total animal biogas production potential [64]. Projections for Türkiye suggest that PM-based capacity grew by 40% between 2003 and 2021, from 2472 GWh to 3469 GWh [65].

Beyond biogas production, anaerobic digestion generates nutrient-rich digestate that can partially substitute mineral fertilizers, thereby closing nutrient cycles within agricultural systems, thereby closing nutrient cycles within agricultural systems. However, digestate management remains essential because nitrogen losses, ammonia volatilization, and nutrient imbalances may occur if application is not properly controlled. Other thermal energy recovery approaches, such as fluidized bed combustion (FBC), can also utilize poultry litter as a low-grade fuel source for heat and electricity generation, either alone or blended with other agricultural, domestic, or industrial residues. Although PM is increasingly recognized as a promising renewable bioenergy feedstock, describing it as entirely "carbon neutral" requires caution because complete life-cycle assessments must account for emissions from manure collection, transportation, processing, and nutrient replacement effects. Nevertheless, integration of PM valorisation technologies into decentralized energy systems can contribute to fossil fuel substitution and improved waste management in rural agroecosystems [12] [66].

8.2. Composting and Thermochemical Processing

Composting transforms raw PM into a stabilised, pathogen-reduced, slow-release organic fertiliser with improved handling properties. The composting process reduces moisture content, mineralises a fraction of organic N (improving synchrony between N release and crop demand), and eliminates most pathogenic organisms through thermal phases (55˚C - 70˚C). The resulting compost is easier to store and transport and carries a lower risk of odour emissions and pathogen transfer than raw manure.

Thermochemical approaches pyrolysis, gasification, and fluidised bed combustion (FBC) convert PM into energy (heat, electricity, syngas) and/or biochar. Pyrolysis of PM co-amended with Ca-bentonite has been shown to produce a biochar-based fertiliser with sustained P and K release characteristics [30]. FBC is particularly well adapted to PM because it can process low-calorific-value fuels, either alone or co-fired with industrial or domestic wastes [17] [47]. [8] provides a comprehensive overview of PM thermochemical energy recovery in the context of European waste management frameworks.

However, thermochemical conversion pathways require careful evaluation of ash management, nutrient recovery efficiency, heavy metal concentration in residual products, and overall life-cycle environmental performance.

9. Environmental and Human Health Risks

9.1. Heavy Metal Accumulation

Continuous high-rate PM application progressively elevates soil concentrations of potentially toxic elements (PTEs), including Cd, Zn, Cr, and Cu, and to a lesser extent Pb, Ni, and As, particularly under long-term intensive manure management systems [35] [67]. Heavy metal inputs originate mainly from poultry feed additives, as elements such as zinc (Zn) and copper (Cu) are commonly supplemented beyond nutritional requirements for growth performance, enzyme function, and disease prevention. A substantial proportion of these elements is subsequently excreted and transferred into manure (**Figure 2**). The extent of accumulation depends on annual application rates, cumulative loading history, background soil concentrations, soil pH, organic matter content, texture, and mineralogical properties controlling metal adsorption and mobility [19] [68]. Because heavy metal accumulation is progressive and largely irreversible over agricultural time scales, long-term land application programmes should incorporate periodic soil testing, nutrient budgeting, contaminant monitoring, and application-rate optimization.

9.2. Pathogen Contamination

Raw PM can harbour a suite of human pathogens including Listeria monocytogenes, Salmonella enteritidis, Salmonella typhimurium, Staphylococcus aureus, Streptococcus spp., Campylobacter and Actinobacillus, all of which pose direct risks to human health via soil, water, and food chain contamination [8] [13]. Fungal communities associated with poultry manure may also include potentially harmful species, including Aspergillus (A. niger, A. nidulans, A. ochraceus), Penicilliums spp., Cladosporium spp., Alternaria spp., Candida albicans—may also be present [8] [69]. These pathogens can enter surface and groundwater through drainage systems and irrigation water reuse, particularly in Mediterranean and tropical countries where wastewater agriculture is common [70] [71].

Appropriate treatment strategies, including controlled composting, anaerobic digestion, and thermal processing, can substantially reduce pathogen loads and improve the sanitary safety of manure-derived products. However, treatment efficiency depends on temperature control, residence time, moisture conditions, and process management.

9.3. Antibiotic Residues and Resistance Gene Dissemination

Veterinary antimicrobials administered to poultry flocks are excreted largely intact in faeces. Manure application therefore introduces antibiotic residues into agricultural soils, where they exert selective pressure on soil microbial communities, promoting the proliferation and transfer of antibiotic resistance genes (ARGs) [14] [72] [73]. The long-term consequences for agricultural ecosystems and human medicine are significant: ARGs can persist in soils for months to years, transfer to crop plants, and enter the food chain. Although the extent to which manure-derived ARGs transfer directly into edible crops remains under investigation, agricultural soils receiving untreated or poorly managed manure represent potential reservoirs of antimicrobial resistance.

This risk highlights the importance of responsible veterinary antibiotic use, improved manure treatment, and monitoring strategies within integrated One Health frameworks linking animal production, environmental protection, and human health.

9.4. Pesticide Residues and Occupational Health

Chemical residues originating from poultry production systems may also represent additional environmental concerns. Insecticides and disinfectants used in poultry housing management can accumulate in manure and persist following land application, depending on their chemical properties and degradation rates [74]-[76]. Similarly, fipronil contamination has identified as a potential concern in poultry manure management systems, including anaerobic digestion pathways where residues may persist depending on treatment conditions. Workers involved in intensive poultry production may experience occupational exposure to PM-associated hazards, including dust particles, microbial aerosols, ammonia (NH_3), and volatile organic compounds (VOCs). Odorous compounds such as ammonium, dimethylamine, trimethylamine, butyric acid, phenol, and indole ranges from mild olfactory fatigue to chronic respiratory diseases including asthma and chronic obstructive pulmonary disease [77] [78]. Integrated ventilation management and exposure monitoring are therefore essential components of occupational health protection on PM-producing farms.

Therefore, effective ventilation systems, personal protective equipment, exposure monitoring, and improved manure-handling practices are essential components of occupational health protection in poultry production environments.

Overall, environmental and health risks associated with poultry manure are not inherent to the material itself but primarily result from inappropriate management, excessive application rates, and insufficient treatment. Integrating contaminant monitoring, controlled processing technologies, and precision nutrient management can substantially reduce these risks while preserving the agronomic and circular-economy benefits of PM recycling.

10. Management Implications and Research Priorities

The evidence reviewed above supports a coherent set of management recommendations for integrating PM into sustainable soil fertility systems, while also identifying research gaps that still constrain confident implementation across contrasting agroecological contexts.

Nutrient-budgeting, rather than a fixed application rate, should be the primary management lever for PM use. Application rates of around 10 $t \cdot ha^{-1}$ have h improve in soil physical condition, nutrient availability and crop performance in tropical and subtropical field studies [79] [80], but these values should be treated only as examples from specific soil-crop contexts. Operational recommendations should instead be based on crop nutrient demand, manure nutrient analysis, soil-test phosphorus, background salinity, soil texture and mineralogy, and cumulative contaminant loading. Site-specific calibration is essential because PM composition varies strongly with bird type, feed formulation, bedding material, manure age, storage conditions and farm-management practices [5] [16]. Farmers, researchers and extension services would therefore benefit from rapid, low-cost analytical tools for PM characterisation at the point of use. Near-infrared spectroscopy has shown promise for rapid manure nutrient assessment, but operational reliability still depends on calibration quality, sample preparation and locally representative manure databases [81].

Pre-treatment, particularly composting and anaerobic digestion, should be considered a central component of safe PM recycling rather than an optional step. Composting can stabilise organic matter, improve nutrient handling and reduce the bioavailability of some contaminants, whereas anaerobic digestion converts manure into biogas and digestate while reducing odour, pathogen pressure and greenhouse-gas risks associated with unmanaged manure storage or direct application [16] [53] [82]. Nevertheless, the successful implementation of these technologies depends on technical expertise, financial investment, infrastructure availability, and institutional support. These requirements may exceed the capacity of many individual smallholder farmers in sub-Saharan Africa and other resource-constrained regions. Consequently, policy incentives supporting cooperative composting facilities, community-scale anaerobic digesters, and locally adapted co-digestion systems could substantially improve technology adoption while reducing environmental pollution [83] [84].

Complementary amendment strategies also show promise. Combining PM with biochar or converting PM into biochar-based fertilisers can enhance nutrient retention, improve soil physical and chemical functioning, and potentially increase the persistence of manure-derived carbon in soil [30] [85]. Similarly, integrated nutrient management strategies that combine PM with reduced or targeted mineral fertiliser inputs can improve nutrient synchrony with crop demand, maintain productivity and reduce dependence on mineral fertilisers alone [86]. These integrated approaches also contribute to improved nutrient-use efficiency while reducing cumulative loading of phosphorus, soluble salts, heavy metals, and other potential contaminants, particularly in regions where repeated manure application is common.

Monitoring protocols for heavy metals, veterinary antibiotics, pathogens and antibiotic-resistance genes (ARGs) should be institutionalised for any land-application programme involving repeated or high-rate PM inputs. Recent evidence shows that manure application can enrich soil resistomes, increase the abundance of ARG subtypes and interact with heavy-metal contamination through co-selection processes [36] [87]-[89]. This is particularly important in intensively managed poultry landscapes where repeated manure use may generate cumulative contaminant and resistance pressures. Regulatory guidance comparable to European and North American frameworks could be adapted to tropical contexts, but such adaptation must account for differences in soil texture, rainfall intensity, organic-matter turnover, crop systems and monitoring capacity.

On the research agenda, three priority gaps stand out. First, integrated life-cycle assessments spanning manure generation, storage, processing, field application, crop response, fertiliser substitution and soil carbon dynamics remain limited for tropical agroecosystems. Existing assessments increasingly quantify individual pathways such as broiler-manure treatment, composted or pelletised poultry litter, and manure-derived organic composts, but they rarely close the full manure–soil–crop–carbon accounting boundary [58] [59] [61] [90]. The integration of contaminant monitoring within a One Health framework would strengthen links between agricultural productivity, environmental quality, animal health, and human health.

Regulatory guidance comparable to European and North American frameworks could be adapted for tropical regions; however, such adaptations should account for local differences in soil properties, rainfall regimes, climate, cropping systems, nutrient-use practices, and institutional monitoring capacity.

11. Conclusions

Poultry manure is a nutrient-dense and widely available organic amendment whose relevance extends beyond simple fertiliser substitution. Its value lies in the simultaneous supply of nitrogen, phosphorus, potassium, calcium, magnesium and organic carbon, together with a low C:N ratio that favours rapid mineralisation and early nutrient release. Yet poultry manure is not a uniform input. Its chemical composition, nutrient-release dynamics and contaminant load vary strongly with bird type, feed formulation, bedding material, moisture content, manure age, storage conditions and handling practices. Recognizing and managing this variability is fundamental to maximizing agronomic benefits while minimizing environmental risks.

The evidence reviewed throughout this study demonstrates that poultry manure can improve multiple dimensions of soil functioning. Physically, it reduces bulk density, promotes aggregation, enhances porosity and increases water-retention capacity, particularly in structurally degraded tropical soils. Chemically, it contributes to pH amelioration, organic-matter enrichment, nutrient replenishment and increased exchangeable-base availability. Biologically, it stimulates microbial biomass, enzymatic activity and nutrient-cycling processes, thereby strengthening the coupling between organic inputs, microbial transformation and plant nutrient supply. Collectively, these improvements enhance soil health, increase nutrient-use efficiency, and contribute to more resilient and productive agroecosystems. These interacting effects position poultry manure as a relevant component of integrated soil fertility management, especially in smallholder systems where mineral fertilisers are costly, intermittently available or environmentally problematic.

The role of poultry manure in carbon cycling is equally important but more ambivalent. Through the addition of carbonaceous residues and the formation of organo-mineral associations, poultry manure can contribute to soil organic carbon accumulation and the recovery of degraded soils. However, its carbon-sequestration potential cannot be evaluated independently from greenhouse-gas emissions generated during manure storage, treatment and field application. Methane, nitrous oxide, ammonia and carbon dioxide emissions depend on moisture, aeration, temperature, nitrogen availability and the management pathway adopted. Consequently, the net climate benefit of poultry manure depends not only on its capacity to build soil carbon but also on the effectiveness of management practices that minimize greenhouse-gas emissions throughout the manure management chain.

Valorisation pathways offer a means of shifting poultry manure from a waste-management constraint toward a circular bioresource. Composting stabilises organic matter, reduces pathogen pressure, improves handling and produces a slower-release amendment. Anaerobic digestion generates biogas while retaining much of the nutrient value in the digestate. Thermochemical conversion, including pyrolysis, gasification and fluidised-bed combustion, can produce renewable energy and biochar-based fertilisers with potential benefits for nutrient retention and long-term carbon stabilization. These technologies demonstrate that appropriately managed poultry manure can simultaneously contribute to renewable energy generation, nutrient recycling, waste reduction, and climate-change mitigation.

Nevertheless, the sustainable recycling of poultry manure depends on rigorous management of environmental and human-health risks. Repeated or high-rate applications may lead to the accumulation of heavy metals, salts, veterinary antibiotic residues, pathogens and antibiotic-resistance genes in soil–plant–water systems. These risks define the boundary between beneficial nutrient recycling and environmental contamination. Safe use therefore requires site-specific rate calibration, appropriate pre-treatment, monitoring of contaminant and pathogen loads, and regulatory guidance adapted to soil texture, rainfall regime, crop system, organic-matter turnover and local analytical capacity. Adopting a One Health perspective that integrates soil, environmental, animal, and human health considerations will further strengthen the sustainability of poultry manure management.

Overall, poultry manure should be managed not as a simple organic fertiliser, but as a multifunctional resource embedded in a manure–soil–crop–climate continuum. Its successful integration into sustainable soil fertility strategies requires a shift from opportunistic disposal to evidence-based recycling. Priority should be given to rapid manure characterisation, locally calibrated application rates, cooperative composting or anaerobic-digestion facilities, combined use with biochar or targeted mineral fertilisers, and long-term monitoring of nutrients, carbon and contaminants. Future research should move beyond short-term agronomic trials toward integrated life-cycle assessments that link manure generation, storage, processing, field application, crop response, greenhouse-gas emissions, soil organic carbon stabilisation and socioeconomic feasibility. Such an integrated framework is essential for poultry manure to contribute simultaneously to soil restoration, food security, waste valorisation and climate-smart agriculture.

Future research should increasingly adopt multidisciplinary approaches integrating agronomy, soil science, microbiology, environmental chemistry, climate science, engineering, economics, and policy analysis. Comprehensive life-cycle assessments linking manure generation, storage, processing, field application, crop productivity, greenhouse-gas emissions, soil carbon stabilization, and socioeconomic performance remain particularly needed, especially in tropical and subtropical agroecosystems.

Ultimately, the sustainable management of poultry manure represents far more than an agricultural practice; it constitutes an important pathway toward regenerative agriculture, circular bioeconomy development, climate-smart food production, and long-term soil restoration. By integrating scientific knowledge, technological innovation, and evidence-based policies, poultry manure can become a strategic resource for enhancing food security while simultaneously advancing environmental sustainability and supporting the achievement of Sustainable Development Goals, particularly SDGs 2 (Zero Hunger), 12 (Responsible Consumption and Production), 13 (Climate Action), and 15 (Life on Land).

Author Contributions

Mabicka Obame Rolf Gael: Conception design and drafting the full paper; Neil-Yohan Musadji data cleaning and analysis, Urlain Gael Yakouya-moubamba: formal analysis, Elie Fosso Menkem methodology: Maurice Ognalaga: project administration, Dieu-Donne Mouketou-Tarazewicz5 revising the paper critically for intellectual content. All authors consent to publish.

Conflicts of Interest

The authors report that there are no competing interests to declare.

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