American Journal of Climate Change, 2026, 15(3), 110-142
https://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

Integrated Soil, Crop, and Livestock Systems for Climate Adaptation in Ghana

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How to cite this paper: Banson, K. E., Nguyen, N. C., Nettey, S. N. A., Nutsuple, W., Baidoo, I., Kusi, A. K., Abotsinah, G., & Kattah, R. J. (2026). Integrated Soil, Crop, and Livestock Systems for Climate Adaptation in Ghana. *American Journal of Climate Change, 15,* 110-142.
https://doi.org/10.4236/ajcc.2026.153006

Received: July 8, 2026
Accepted: August 23, 2026
Published: August 26, 2026

Abstract

Climate change continues to threaten agricultural productivity and food security in sub-Saharan Africa, highlighting the need for integrated adaptation strategies. This study applied systems thinking as an overarching analytical framework to identify leverage points for improving climate resilience within Integrated Soil-Crop-Livestock Production Systems (ISCLPS) in the Manya Krobo District of Ghana. A mixed-methods approach combined stakeholder surveys (n = 110), key informant interviews (n = 30), participatory workshops (n = 2; 50 participants), microbiological water-quality assessment, field evaluation of livestock-waste compost using *Opuntia ficus-indica* as a drought-resilient indicator crop, and NASA climate data analysis (2023-2025). Systems analysis identified poor livestock waste management as a critical leverage point and revealed three dominant systems archetypes—Fixes that Fail, Shifting the Burden, and Tragedy of the Commons—that reinforce environmental degradation and agricultural vulnerability. Guided by these findings, the field experiment evaluated composting as a key intervention and demonstrated significant improvements in plant growth, biomass production, and soil functioning through enhanced nutrient cycling, microbial activity, and moisture retention. Water-quality assessment revealed severe microbial contamination associated with unmanaged livestock waste, while climate analysis indicated a 23.3% decline in rainfall, a 13.0% reduction in root-zone soil moisture, and increasing temperatures between 2023 and 2025. These findings informed the development of a Systems Framework for Climate Adaptation through Nutrient Recycling, demonstrating how transforming livestock waste into compost can improve soil health, environmental quality, and climate resilience. The study provides empirical evidence that systems thinking can effectively identify high-impact interventions for sustainable climate adaptation in smallholder farming systems.

Keywords

Climate Adaptation, Systems Thinking, Livestock Waste Management, Composting, Nutrient Recycling, Climate Resilience, Integrated Farming Systems, Ghana

1. Introduction

Climate change poses significant challenges to agricultural production systems worldwide, particularly in Sub-Saharan Africa, where farming systems are predominantly rain-fed and highly dependent on natural resources (Alemaw & Simalenga, 2015; Pereira, 2017). Rising temperatures, declining rainfall, increasing climate variability, soil degradation, and environmental pollution have intensified threats to food security, livelihoods, and ecosystem sustainability (Naik et al., 2025; Saleem et al., 2025). These challenges are particularly pronounced among smallholder farmers who often face limited adaptive capacity and restricted access to climate-resilient technologies.

In Ghana, agricultural productivity is increasingly constrained by declining soil fertility, inefficient nutrient management, land degradation, and inappropriate disposal of livestock waste (Asare et al., 2025; El Mellouki, Boularbah, & Kebede, 2025). Poor livestock waste management contributes to nutrient losses, water contamination, greenhouse gas emissions, and declining environmental quality (Ijaz et al., 2025; Symeon et al., 2025). Simultaneously, climate variability reduces soil moisture availability and increases production risks, thereby reinforcing cycles of agricultural vulnerability (Abebaw, 2025).

Integrated Soil-Crop-Livestock Production Systems (ISCLPS) have emerged as promising approaches for addressing these interconnected challenges (Atapattu et al., 2025; Nazir, Arabzai, & Niaz, 2025). By promoting nutrient recycling, resource-use efficiency, soil restoration, and environmental sustainability, integrated systems offer opportunities to enhance productivity while strengthening resilience to climate-related shocks. However, adaptation outcomes within agricultural systems are shaped not only by individual technologies but also by the interactions among ecological, social, and management components operating within the broader farming system (Soma et al., 2026).

Previous studies have demonstrated the importance of integrated farming systems in improving nutrient cycling, reducing waste, enhancing soil fertility, and increasing agricultural productivity (Atapattu et al., 2025; Junge, Schmautz, & Milliken, 2025; Murtaza et al., 2025). Organic amendments derived from livestock manure have been shown to improve soil organic carbon, nutrient availability, microbial activity, and water-holding capacity, thereby supporting crop growth and resilience under climatic stress (Krishna et al., 2025; Oyebiyi et al., 2026).

Similarly, systems-thinking approaches have gained increasing attention in agricultural research because they provide tools for understanding complex interactions among environmental, economic, and social components (Banson, Nguyen, & Bosch, 2014, 2018; Banson et al., 2015; Nguyen et al., 2023). Causal loop diagrams and participatory modelling approaches enable researchers and stakeholders to identify feedback mechanisms, leverage points, and unintended consequences that influence system behaviour. These approaches have been successfully applied to agricultural sustainability, natural resource management, and climate adaptation planning.

Despite these advances, most studies continue to examine climate adaptation, soil fertility management, livestock waste utilization, water quality, and agricultural productivity as separate issues. Limited empirical research has integrated systems thinking, environmental assessment, climate analysis, and field experimentation within a single framework capable of explaining how interactions among system components influence resilience and adaptive capacity. Furthermore, few studies have explored how livestock waste can simultaneously function as both a source of environmental degradation and a resource for climate adaptation through nutrient recycling and soil restoration.

Recent climate adaptation literature increasingly emphasizes the need for integrated approaches that address root causes of vulnerability rather than isolated symptoms (Newell et al., 2021; Shi & Moser, 2021). Such approaches require an understanding of feedback structures, system archetypes, and leverage points that shape agricultural outcomes over time.

Although integrated agricultural systems are widely promoted as climate-smart interventions, significant knowledge gaps remain regarding the mechanisms through which interactions among soil, crops, livestock, climate, and environmental resources influence adaptation outcomes (Eswaran et al., 2024). Existing studies often focus on either agronomic performance, environmental impacts, or climate adaptation without explicitly linking these dimensions within a systems framework (Shrivastava & Laasri, 2025; Xu et al., 2010).

Moreover, limited evidence exists on how reinforcing feedback loops, systems archetypes, and leverage points influence agricultural vulnerability and resilience in smallholder farming systems in Ghana. The lack of integrated empirical studies constrains the development of adaptation strategies that can simultaneously improve productivity, environmental quality, and long-term resilience (Hertel & Lobell, 2014; Mudzielwana, 2025).

This study addresses these gaps by combining participatory systems thinking, climate analysis, microbiological water-quality assessment, and compost-based field experimentation to examine the role of Integrated Soil-Crop-Livestock Production Systems in climate adaptation. By integrating multiple sources of evidence, the study provides a holistic understanding of how nutrient recycling and livestock waste management can transform reinforcing cycles of degradation into reinforcing cycles of resilience. The field experiment represents one component of the integrated systems framework rather than a standalone evaluation of the entire production system.

The study is grounded in Systems Theory, which views agricultural systems as interconnected networks of components whose behaviour emerges from dynamic interactions and feedback processes. This perspective is complemented by Socio-Ecological Systems Theory, which emphasizes the interdependence between human activities and ecological processes in shaping system resilience (Cote & Nightingale, 2012).

Reinforcing Feedback Theory is used to explain how positive feedback loops can either accelerate degradation or strengthen adaptation outcomes (Banson et al., 2026). For example, poor waste management may reinforce environmental deterioration, whereas nutrient recycling through composting can reinforce soil restoration and productivity improvements. Meadows' Leverage Point Theory provides a framework for identifying strategic intervention points capable of generating system-wide change (Klok et al., 2026). Within this study, livestock waste management emerged as a critical leverage point influencing soil fertility, water quality, productivity, and climate resilience.

The study also draws upon Circular Economy Theory, which promotes the transformation of waste streams into productive resources through recycling and resource recovery. Composting represents a practical application of this principle by converting livestock waste into valuable soil amendments that improve nutrient cycling and reduce environmental pollution.

Collectively, these theoretical perspectives provide the foundation for understanding how integrated soil-crop-livestock systems contribute to climate adaptation through feedback mechanisms, leverage points, and circular nutrient flows.

To address the research objectives, the study adopted an integrated mixed-methods research design that combined participatory systems thinking, climate analysis, environmental assessment, and agronomic experimentation.

First, stakeholder surveys, interviews, and participatory workshops using the Evolutionary Learning Laboratory (ELLab) methodology were conducted to identify system drivers, feedback structures, and leverage points influencing agricultural performance. Second, microbiological water-quality assessments were undertaken to evaluate the environmental impacts of livestock waste disposal on shared water resources. Third, compost-amendment experiments were conducted to assess the effects of nutrient recycling on soil restoration and crop growth. Finally, climate data obtained from NASA POWER were analysed to evaluate climate variability and agricultural vulnerability within the study area and to support the development of a climate adaptation framework (Hegyi et al., 2024).

The integration of these approaches enabled triangulation of evidence and facilitated a comprehensive assessment of how interactions among climate, soil, crops, livestock, and environmental resources influence resilience within smallholder farming systems.

The overall objective of this study was to evaluate the contribution of Integrated Soil-Crop-Livestock Production Systems to climate adaptation in the Manya Krobo District of Ghana.

The specific objectives were to:

1) Identify the systemic drivers and feedback mechanisms influencing agricultural vulnerability and productivity within integrated farming systems.

2) Assess the impacts of livestock waste runoff on water quality and environmental health.

3) Evaluate the effectiveness of livestock-manure compost in improving soil fertility and crop growth.

4) Develop a climate adaptation framework that integrates nutrient recycling, environmental management, and systems-based resilience pathways for smallholder farming systems.

2. Methodology

The study was conducted in the Manya Krobo District of the Eastern Region of Ghana. The district lies within the Forest-Savannah Transition Agroecological Zone and is characterized by mixed crop—livestock farming systems (MOFA, 2022; Wahab, 2020). Agriculture remains the primary livelihood activity, with farming households engaged in crop production, livestock rearing, and related agricultural enterprises (MOFA, 2022).

The cactus (Opuntia ficus-indica) was selected as the experimental crop because of its recognized role as a climate-resilient species characterized by high water-use efficiency, exceptional drought tolerance, capacity to rehabilitate degraded soils, increasing importance as livestock fodder—including its growing use as a supplemental feed for pigs in Ghana—its potential as a bioenergy resource, and its suitability for assessing compost-mediated improvements in soil fertility and plant performance under moisture-limited conditions (Louhaichi et al., 2025; Tonisi et al., 2026).

Analysis of NASA POWER climate data (2023-2025) indicates that the district experiences a warm tropical climate with mean annual temperatures ranging from 26.81˚C to 27.26˚C (NASA Power, 2026). Mean annual precipitation declined from approximately 1,580 mm year^{-1} in 2023 to 1,212 mm year^{-1} in 2025, while root-zone soil moisture decreased from 0.69 to 0.60 over the same period. These trends indicate increasing climatic stress and potential risks to agricultural productivity and ecosystem sustainability.

The district supports diverse agricultural activities, with major crops including maize, cassava, yams, plantain, vegetables, and legumes (MOFA, 2022). Livestock production is dominated by poultry, goats, sheep, pigs, and cattle. The integration of crop and livestock enterprises provides opportunities for nutrient recycling through composting and manure management, making the area suitable for evaluating Integrated Soil-Crop-Livestock Production Systems (ISCLPS) (Adegbeye et al., 2020; Hilimire, 2011).

According to the 2021 Population and Housing Census, the district has a population of 121,478, comprising 56,662 males (46.6%) and 64,816 females (53.4%) (Ghana Districts, 2026). The population is largely dependent on rain-fed smallholder agriculture for food, income, and livelihoods (Asare-Nuamah et al., 2022). Consequently, changes in rainfall patterns, temperature, and soil moisture have significant implications for agricultural productivity, household resilience, and climate adaptation within the district (Yuan et al., 2024).

2.1. Research Design and Stakeholder Engagement

The study adopted an integrated mixed-methods design combining participatory systems thinking, climate analysis, microbiological water-quality assessment, and field experimentation. Data were collected through surveys, participatory workshops, key informant interviews, and literature review. The experimental component was designed to validate the leverage-point intervention identified through systems analysis.

A total of 110 stakeholders participated in the survey, including farmers, agricultural input dealers, market women, extension officers, scientists, community leaders, and opinion leaders. Thirty key informant interviews were conducted to obtain in-depth information on agricultural production, livestock waste management, and climate adaptation. Two participatory workshops involving 50 stakeholders were organized using the Evolutionary Learning Laboratory (ELLab) methodology. Each workshop lasted three days. The first workshop focused on system mapping and development of causal loop diagrams, while the second workshop was conducted to validate stakeholder mental models, refine causal relationships, and identify leverage points for intervention. Consensus was achieved through iterative discussion and stakeholder verification until no substantial modifications were proposed.

Data were collected through an integrated mixed-methods approach involving stakeholder surveys, key informant interviews, participatory workshops, literature review, water-quality assessment, field experimentation, and climate data analysis. A summary of stakeholder participation and data collection activities is presented in **Table 1**.

Table 1. Summary of stakeholder participation and data collection activities.

Data Collection Method	Participants/Source	Sample Size (n)	Purpose
Structured Survey	Farmers and Agricultural Stakeholders	110	To identify major agricultural challenges, climate adaptation needs, livestock waste management practices, and stakeholder perceptions

Continued

Key Informant Interviews	Farmers, extension officers, scientists, community leaders, input dealers, and market women	30	To obtain in-depth insights into agricultural production systems, climate-related challenges, and waste management practices
Participatory Workshop 1	Multi-stakeholder representatives	50	To identify system variables, relationships, and develop preliminary causal loop diagrams
Participatory Workshop 2	Multi-stakeholder representatives	50	To validate stakeholder mental models, refine causal relationships, and identify leverage points and systems archetypes
Literature Review	Peer-reviewed articles, reports, policy documents, and technical publications	-	To provide theoretical foundations and contextual information for systems analysis and climate adaptation
Water Quality Assessment	River sampling locations (upstream, discharge point, downstream)	3 sampling points	To assess microbiological contamination associated with livestock waste runoff
Compost Field Experiment	Experimental plots	Control and compost treatments	To evaluate the effects of livestock manure compost on crop growth and biomass production
Climate Data Analysis	NASA POWER database (2023-2025)	3 years	To assess climate variability, trends, anomalies, and agricultural vulnerability

2.2. Systems Thinking Approach for Integrated Soil, Crop, and Livestock Systems (ISCLPS)

A systems-thinking approach was employed to holistically assess interactions among soil fertility, livestock waste management, crop productivity, water quality, and climate adaptation within Integrated Soil, Crop, and Livestock Production Systems (ISCLPS) in the Manya-Krobo District of Ghana. The methodology was aligned with the Environmental Learning Laboratory (ELLab) participatory systems framework, as shown in **Figure 1**, to identify complex feedback relationships that influence environmental sustainability and agricultural resilience (Banson et al., 2026). The methodology consisted of the following steps:

Step 1: Stakeholder Engagement

The study began by engaging diverse stakeholders within the farming community affected by climate vulnerabilities and environmental degradation (Baafi, 2023; Gatsey, 2024). This included farmers, local authorities, community leaders, and public health representatives. Due to cultural norms and societal expectations that can influence open dialogue, a two-step questionnaire approach was employed (Yang, Kang, & Cha, 2015). Initially, stakeholders provided anonymous responses to questions regarding water use, contamination concerns, and their impacts on agriculture and health. Following this, a group discussion was held to discuss common themes and responses, allowing for a clearer understanding of stakeholder perceptions and experiences.

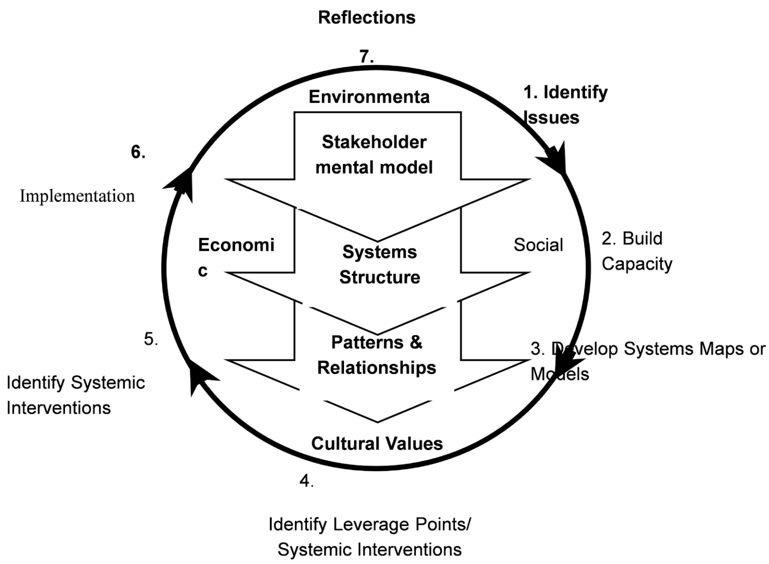

Figure 1. The evolutionary learning laboratory process.

Step 2: Mental Model Exercise and Data Aggregation

Responses from the initial engagement were aggregated, analysed, and organised into thematic categories. These themes informed the development of the causal loop diagram (mental model), which helped reveal key patterns, feedback structures, and relationships within the system (Yang et al., 2019).

Step 3: System Mapping and Causal Loop Diagrams (CLDs)

Using the insights from the stakeholder engagement and data aggregation, VENSIM software was utilized to create system maps and generate causal loop diagrams (CLDs) (Banson et al., 2024). These diagrams visualized the complex interactions and feedback loops within the system. Two participatory workshops involving 50 stakeholders were conducted using the Evolutionary Learning Laboratory (ELLab) methodology. The first workshop focused on identifying system challenges and developing preliminary causal loop diagrams. The second workshop was conducted to validate stakeholder mental models, refine causal relationships, and identify leverage points for intervention.

Step 4: Interpretation and Analysis of Mental Models

The aggregated mental models were interpreted to identify significant patterns and leverage points within the system (Nabong, Opdyke, & Walters, 2022). Stakeholders' internal representations of the problem were analysed to uncover how their beliefs, experiences, and understanding of water contamination influence their actions. By identifying these mental models, the study aimed to pinpoint areas where small shifts in practices or perceptions could lead to substantial improvements in the system, such as adopting better waste management strategies or promoting safe water use practices.

Step 5: Identifying Leverage Points

From the analysis, leverage points within the system were identified. These leverage points were areas where targeted actions could lead to significant, positive changes in the system's behaviour (Bolton, 2022). For example, improving waste treatment and disposal processes at pig or poultry farms was identified as a high-impact leverage point that could reduce contamination levels in the river and improve water quality.

Step 6: Developing Systemic Interventions

The study developed potential interventions aimed at addressing the root causes of water contamination (Nguyen et al., 2023). This included strategies such as sustainable waste management practices (e.g., improved treatment of piggery or poultry waste) and community-based water treatment and purification methods. These interventions were designed with the input of stakeholders and based on the leverage points identified, ensuring that the strategies were both practical and tailored to the needs of the community.

Step 7: Reflection and Continuous Improvement

Step 7 involves continuously reflecting on the outcomes of the implemented interventions. This step is crucial for evaluating their effectiveness, identifying any unintended consequences, and uncovering new barriers that may arise (Banson, Nguyen, & Bosch, 2016). Regular assessment and adaptation of strategies ensure that the solutions remain relevant and effective in managing the complexities of water contamination and its wider implications for the community.

2.3. Climate Data Analysis for the Study Area

Climate data were obtained from the NASA POWER (Prediction of Worldwide Energy Resources) database to characterize climatic conditions within the Manya Krobo District during the period 2023-2025 (NASA Power, 2026). Variables analysed included mean air temperature, precipitation, specific humidity, and root-zone soil moisture. These data were used to assess climate variability, identify emerging climatic trends, and evaluate agricultural vulnerability within the broader study area. Annual trends, percentage changes, anomalies, and coefficients of variation were calculated to support the development of the climate adaptation framework.

2.4. Water Quality Assessment and Microbiological Analysis

To determine the extent of river water contamination resulting from poultry waste runoff, water samples were collected from three strategically selected locations along the river continuum. The first sampling point was located at the river source and served as the reference site representing baseline water quality conditions. The second sampling point was situated at the location where poultry waste runoff entered the river and represented the primary pollution point. The third sampling point was established downstream at the section of the river commonly used by local communities for domestic and agricultural purposes.

Water samples were transported under appropriate conditions and subjected to microbiological analysis in the laboratory. Standard analytical procedures based on the Association of Official Analytical Chemists (AOAC) methods were employed following the protocols described by Adebayo (2023). Microbial indicators assessed included total coliform count, fecal coliform count, *Escherichia coli*, *Salmonella* spp., *Shigella* spp., and *Clostridium perfringens*. Enumeration of microbial populations was conducted using the pour plate technique followed by incubation under specified conditions for each organism.

The analysis aimed to quantify the level of microbial contamination across the sampling points, evaluate potential public health risks associated with water use, assess the implications of livestock waste runoff on agricultural productivity, and examine the relationship between livestock waste management practices and environmental sustainability.

2.5. Compost Amendment Experiment for Soil Restoration and Cactus Productivity

A field experiment was conducted to evaluate the effectiveness of compost amendments in restoring degraded soils and enhancing cactus productivity. The study employed a Randomized Complete Block Design (RCBD) consisting of six treatments replicated five times. Compost application rates were 1, 2, 3, 4, and 5 t ac^{-1}, while an untreated control served as the baseline treatment. The RCBD was selected to minimize the effects of spatial variability within the experimental field and improve the precision of treatment comparisons.

2.5.1. Compost Preparation

The compost used in the study was produced from a mixture of pig, poultry, and sheep/goat manure, along with grass and rice straw residues. Composting was carried out under aerobic conditions through systematic layering of feedstock materials, moisture regulation, and periodic turning to ensure adequate aeration and uniform decomposition. The composting process was continued until maturity was reached, thereby promoting nutrient stabilization, reducing pathogen loads, improving nutrient mineralization, and enhancing the quality of organic matter available for use as a soil amendment.

2.5.2. Soil Sampling and Baseline Characterization

Prior to treatment application, composite soil samples were collected from the experimental site to establish baseline soil fertility conditions. Laboratory analyses were conducted to determine soil pH, organic matter content, total nitrogen, available phosphorus, exchangeable potassium, calcium, and magnesium concentrations, and cation exchange capacity (CEC). The results confirmed that the study site was characterized by nutrient depletion and general soil degradation, thereby justifying the need for restorative soil management interventions.

2.5.3. Treatment Application and Crop Establishment

Compost was incorporated into the soil according to the designated application rates before planting. Control plots received no compost or fertilizer inputs. Cactus plants were subsequently established under uniform agronomic conditions across all treatment plots to ensure that observed differences in performance could be attributed primarily to the compost treatments.

2.5.4. Growth Monitoring and Biomass Assessment

Plant growth was monitored periodically throughout the experimental period. Data collected included plant height, number of leaves, and biomass production. At harvest, whole-plant biomass was determined by uprooting representative plants and measuring fresh weight from the root collar to the uppermost foliage. These measurements were used to assess the influence of compost application rates on cactus growth and productivity.

2.6. Rainfed Water Management

Unlike conventional irrigation-based studies, this experiment was conducted entirely under rainfed conditions. The decision to adopt a rainfed production system was informed by the prevailing farming practices within the study area, where most smallholder farmers do not have access to irrigation facilities due to high investment costs, limited infrastructure, and restricted water availability. Conducting the experiment under natural rainfall conditions, therefore, ensured that the results reflected realistic field conditions and increased the likelihood of adoption by farmers and other stakeholders vulnerable to climate variability and water scarcity.

Rainfall patterns and soil moisture dynamics were monitored throughout the cropping season to evaluate crop responses under naturally occurring moisture conditions. This approach also provided an opportunity to assess the resilience of integrated nutrient management strategies under climate-sensitive production environments.

2.7. Data Collection

Data collected included crop growth parameters, biomass yield, soil organic matter content, soil nutrient dynamics, and selected soil health indicators. These variables were measured to assess the agronomic and environmental performance of the integrated nutrient management treatments.

Statistical Analysis

Data generated from all experiments were subjected to analysis of variance (ANOVA) using appropriate statistical software. Treatment effects were considered significant at $P \leq 0.05$. Where significant differences were detected, mean separation was performed using Tukey's Honest Significant Difference (HSD) test. Descriptive statistics, including means, standard deviations, standard errors, and coefficients of variation, were also calculated to characterize treatment performance and data variability.

2.8. Methodological Integration within a Climate Adaptation Framework

The methodological framework integrated water quality assessment, compost-based soil restoration, and nutrient management interventions within a systems-thinking perspective to evaluate pathways for climate adaptation in smallholder farming systems. By simultaneously examining livestock waste management, soil restoration, nutrient cycling, crop productivity, and environmental quality, the study provided a holistic understanding of how integrated agricultural practices can strengthen resilience to climate change. This interdisciplinary approach supports the development of sustainable production systems capable of improving food security, environmental health, and adaptive capacity among vulnerable farming communities in Ghana.

3. Results and Discussion

3.1. Stakeholder Perceptions of System Challenges

Stakeholder consultations identified declining soil fertility, poor livestock waste management, water contamination, climate variability, and low agricultural productivity as the principal constraints affecting agricultural sustainability within the Manya Krobo District (Table 2).

Table 2. Major agricultural challenges identified by stakeholders in the Manya Krobo District.

Agricultural Challenge	Description of Impact	System Component Affected
Poor Livestock Waste Management	Improper disposal of livestock waste contributes to environmental pollution, nutrient losses, and public health risks.	Livestock, Environment, Water Resources
Declining Soil Fertility	Reduced soil nutrient availability limits crop productivity and increases dependence on external inputs.	Soil, Crop Production
Water Pollution	Runoff and discharge of livestock waste contaminate surface water used for irrigation and domestic purposes.	Water Resources, Human Health
Climate Variability	Declining rainfall, increasing temperatures, and reduced soil moisture increase production risks.	Climate, Crop Production
Low Crop Productivity	Poor soil fertility and climatic stress reduce crop growth and yields.	Crop Production
Limited Nutrient Recycling	Livestock manure is underutilized as a soil amendment, leading to inefficient resource use.	Soil, Livestock, Crop Production
High Dependence on Inorganic Fertilizers	Reliance on chemical fertilizers increases production costs and may contribute to soil degradation over time.	Soil Fertility Management
Limited Farmer Knowledge on Composting	Inadequate technical knowledge constrains the adoption of sustainable waste-management practices.	Human Capacity, Management
Soil Moisture Stress	Reduced rainfall and declining root-zone soil moisture affect crop establishment and growth.	Soil, Climate
Weak Institutional Support	Limited access to extension services and technical guidance reduces adaptive capacity.	Governance, Agricultural Development

The stakeholder assessment revealed that agricultural challenges within the Manya Krobo District are highly interconnected and cannot be addressed in isolation. Poor livestock waste management emerged as a central concern because of its influence on water quality, nutrient losses, soil degradation, and public health. Stakeholders also highlighted declining soil fertility, climate variability, and low agricultural productivity as major constraints affecting agricultural sustainability. These findings suggest that the observed challenges are symptoms of broader system interactions rather than independent problems. Consequently, interventions targeting livestock waste management and nutrient recycling may generate multiple benefits across the soil-crop-livestock system by simultaneously improving soil fertility, environmental quality, and climate resilience.

The prominence of livestock waste management across multiple stakeholder concerns provided the first indication that it functions as a critical leverage point within the Integrated Soil-Crop-Livestock Production System. This observation was further explored through causal loop analysis and systems archetype identification.

The results indicate that many of these challenges are interconnected rather than independent problems. Participants consistently highlighted livestock waste disposal as a central issue influencing environmental quality, nutrient losses, and crop productivity.

3.2. Causal Loop Analysis of the Integrated Soil-Crop-Livestock System

The causal loop analysis revealed several reinforcing and balancing feedback structures that govern the performance of the agricultural system, as shown in Figure 2.

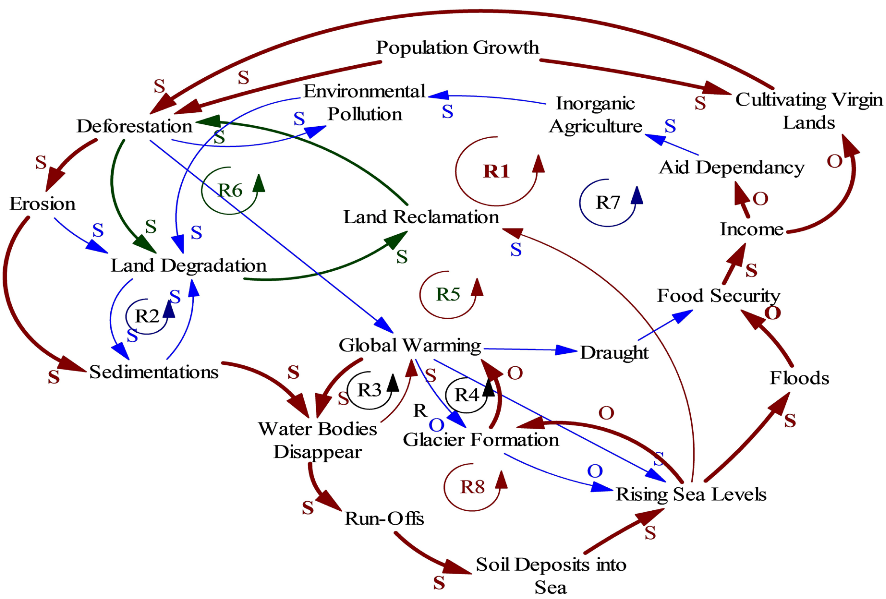

Figure 2. Integrated soil-crop-livestock causal loop diagram.

The diagram illustrates how poor waste management contributes to nutrient losses, water contamination, and declining soil fertility, creating reinforcing cycles of environmental degradation. Conversely, nutrient recycling through composting strengthens soil health, productivity, and environmental sustainability.

Human Activities as Drivers of Climate Vulnerability

The systems analysis revealed that climate-related agricultural challenges within the study area are not solely driven by natural climatic factors but are significantly exacerbated by human activities. Key anthropogenic drivers identified included poor manure management, deforestation, unsustainable land-use practices, improper livestock waste disposal, and uncontrolled agricultural runoff. These activities collectively contribute to soil degradation, water pollution, biodiversity loss, declining soil fertility, accelerated erosion, and reduced crop productivity, thereby increasing the vulnerability of farming systems to climate variability and extreme weather events.

The findings suggest that climate adaptation strategies should extend beyond crop and livestock productivity interventions to address broader environmental management challenges. Consequently, integrated agricultural management emerges not only as a means of improving production efficiency but also as an important mechanism for enhancing ecosystem resilience and climate adaptation.

3.3. Systems Archetypes Identified within the ISCLPS

Three dominant systems archetypes emerged from the stakeholder analysis.

3.3.1. Fixes that Fail

This archetype demonstrates how direct disposal of livestock waste provides short-term relief but ultimately worsens environmental degradation and productivity challenges (**Figure 3**). The "Fixes that Fail" archetype occurs when a short-term solution temporarily alleviates a problem but ultimately worsens it over time.

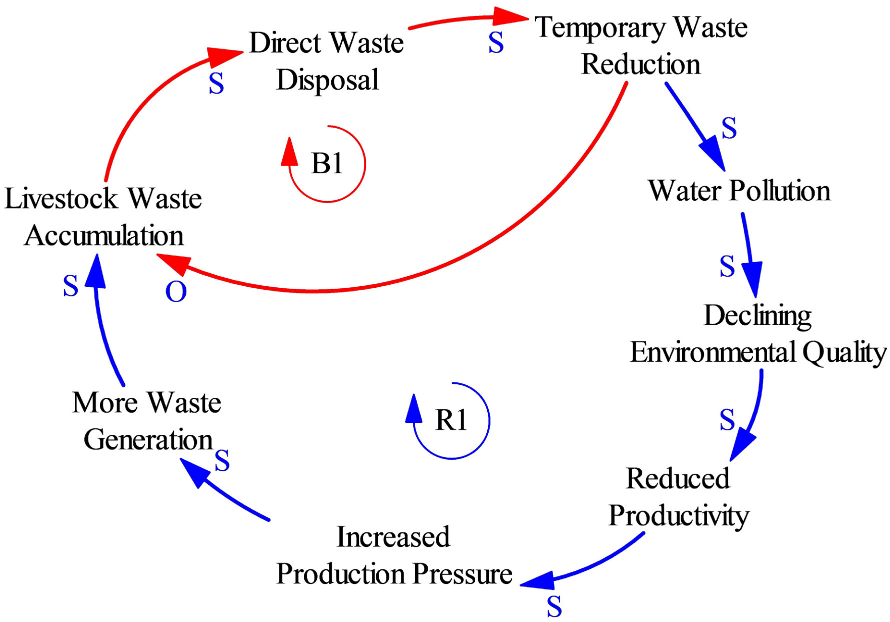

Figure 3. Systems archetype: Fixes that fail.

Within the study area, farmers often dispose of livestock waste directly into nearby water bodies or open spaces to quickly remove accumulated waste from production facilities.

While this practice temporarily resolves sanitation concerns, it contributes to water contamination, nutrient losses, and environmental degradation. As soil fertility and environmental quality decline, agricultural productivity decreases, prompting farmers to increase production activities, which generates even more waste. The initial solution, therefore, reinforces the original problem and creates a cycle of degradation.

3.3.2. Shifting the Burden

This archetype shows how reliance on inorganic fertilizers addresses symptoms of soil degradation without addressing the underlying causes of declining soil health (**Figure 4**). The "Shifting the Burden" archetype occurs when stakeholders rely on symptomatic solutions rather than addressing underlying causes. In the study area, declining soil fertility often leads farmers to increase the use of inorganic fertilizers.

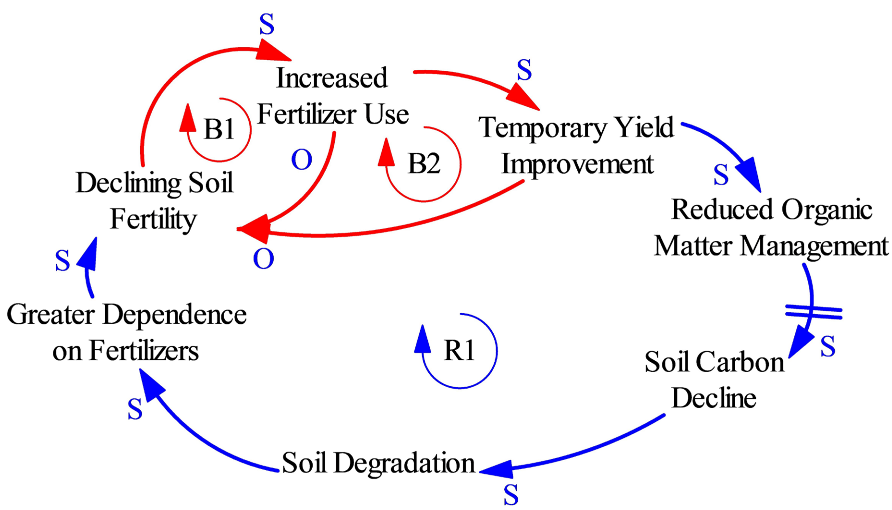

Figure 4. Systems archetype: Shifting the burden.

Although this practice may temporarily improve crop yields, it does not address the root causes of degradation, including poor nutrient recycling, low organic matter levels, and inadequate management of livestock waste. Over time, soil organic carbon declines, biological activity diminishes, and soil resilience weakens, increasing dependence on external inputs. Composting and nutrient recycling represent fundamental solutions that address the root causes rather than merely treating symptoms.

3.3.3. Tragedy of the Commons

This archetype illustrates how individual waste-disposal decisions collectively degrade shared environmental resources. The "Tragedy of the Commons" archetype emerges when individuals acting in their own interest unintentionally degrade shared resources (Figure 5). In the study area, multiple livestock producers discharge untreated waste into common water bodies.

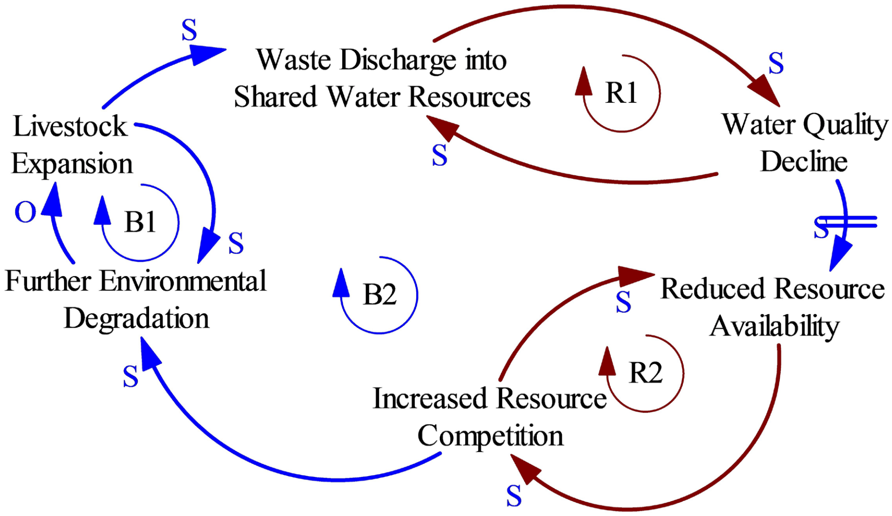

Figure 5. Systems archetype: Tragedy of the commons.

While individual farmers may benefit from avoiding waste management costs, the cumulative effect is the deterioration of water quality used by the wider community for irrigation, livestock watering, and domestic purposes. As contamination increases, the quality and availability of shared water resources decline for all users. Without collective management and coordinated waste-control measures, continued exploitation accelerates environmental degradation and reduces the long-term sustainability of the agricultural system.

3.4. Linking Archetypes to the Leverage Point

A critical leverage point identified in the study is livestock waste management, as shown in Table 3. The introduction of composting and nutrient recycling interrupts all three archetypes simultaneously:

Table 3. Livestock waste management.

Archetype	Problematic Pattern	Composting Intervention
Fixes that Fail	Waste disposal creates pollution	Waste converted into fertilizer
Shifting the Burden	Reliance on chemical fertilizers	Restoration of soil organic matter and nutrient cycling
Tragedy of the Commons	Shared water resources degraded	Reduced waste discharge and environmental contamination

Consequently, composting functions as a system-transforming intervention that converts reinforcing cycles of degradation into reinforcing cycles of soil restoration, productivity enhancement, and climate resilience. This finding aligns with Meadows' Leverage Point Theory by demonstrating how interventions targeting resource flows and feedback structures can generate system-wide improvements in sustainability and adaptive capacity.

3.5. Water Quality Impacts by Livestock Waste Runoff

Microbiological Water Quality Assessment:

The microbiological analysis revealed substantial deterioration in water quality downstream of livestock waste discharge points.

The microbiological analysis revealed substantial deterioration in river water quality downstream of livestock activities (Table 4). Total coliform counts ranged from 1.0×10^6 to 1.9×10^8 CFU/100 mL, while fecal coliform concentrations ranged from 2.0×10^5 to 8.6×10^6 CFU/100 mL, with the highest microbial loads recorded at the pollution point. These values substantially exceeded the WHO/FAO recommended limit of ≤1,000 CFU/100 mL for irrigation water, indicating widespread fecal contamination and a potential risk to agricultural production and public health. Although *Escherichia coli* was not detected in any of the samples, the consistent detection of *Salmonella* spp. and *Shigella* spp. at all sampling locations indicates persistent pathogenic contamination, rendering the water unsuitable for unrestricted irrigation without appropriate treatment. The elevated microbial loads are consistent with unmanaged livestock waste entering the watercourse and reinforce the systems analysis, which identified poor livestock waste management as a major leverage point influencing environmental quality. These findings further support the adoption of composting and integrated nutrient recycling as practical interventions to reduce direct waste discharge, improve water quality, and strengthen climate-resilient agricultural production systems.

Table 4. Microbiological characteristics of river water at different sampling points.

Parameter	Point 1 (Source)	Point 2 (Pollution Point)	Point 3 (Community Use Point)
Total Coliform Count (CFU/100 mL)	8.0×10^6	1.9×10^8	1.0×10^6
Fecal Coliform Count (CFU/100 mL)	2.0×10^5	8.6×10^6	3.0×10^5
Escherichia coli	Not Detected	Not Detected	Not Detected
Salmonella spp.	Detected	Detected	Detected
Shigella spp.	Detected	Detected	Detected

ND = Not Detected.

Based on measured microbiological results and commonly cited WHO/FAO guidance for unrestricted irrigation water (fecal coliforms generally ≤ 1,000 FC/100 mL; pathogenic enteric bacteria such as *Salmonella* should be absent), the results presented in Table 5 clearly exceed recommended limits and therefore strongly support the environmental and public health arguments in Objective 2.

Table 5. Comparison of river water quality with the WHO/FAO irrigation water guidelines.

Parameter	Point 1 (Source)	Point 2 (Pollution Point)	Point 3 (Community Use Point)	WHO/FAO Guideline	Interpretation
Fecal Coliform (CFU/100 mL)	2.0×10^5	8.6×10^6	3.0×10^5	≤1,000 CFU/100 mL	Exceeded at all sampling points
Total Coliform (CFU/100 mL)	8.0×10^6	1.9×10^8	1.0×10^6	No WHO/FAO numerical limit; indicator of microbial contamination	Severe microbial contamination, particularly at Point 2
Escherichia coli	Not Detected	Not Detected	Not Detected	Ideally absent or very low	Meets guideline
Salmonella spp.	Detected	Detected	Detected	Should be absent	Does not comply
Shigella spp.	Detected	Detected	Detected	Should be absent	Does not comply

Source: Guidelines for the safe use of wastewater, excreta and greywater and FAO irrigation water quality guidance (WHO, 2006).

Comparison of observed microbial concentrations with WHO and FAO irrigation-water guidelines revealed substantial deterioration in water quality throughout the river system. Fecal coliform counts exceeded the recommended threshold at all sampling locations, indicating widespread fecal contamination of the water resource. The highest contamination occurred at the poultry waste discharge point, where fecal coliform concentrations reached 8.6×10^4 CFU ml^{-1}, confirming the significant contribution of livestock waste runoff to microbial pollution. Furthermore, the detection of *Salmonella* spp. and *Shigella* spp. at all sampling locations represents a failure to meet recommended microbiological standards and highlights potential risks to human health, livestock health, and agricultural production. These findings provide empirical evidence supporting the systems-thinking results, which identified poor livestock waste management as a critical leverage point influencing environmental quality, agricultural productivity, and community well-being. The results further demonstrate that unmanaged livestock waste contributes to reinforcing cycles of environmental degradation, while improved waste management and composting interventions offer opportunities to reduce contamination and strengthen climate-resilient agricultural systems. Fecal coliform concentrations at the poultry waste discharge point were approximately 43 times higher than those observed at the river source, while total coliform counts increased by nearly 24-fold, demonstrating the substantial impact of untreated livestock waste on water quality.

Integration of Water Quality Findings with the ISCLPS Framework

The water quality findings validate the causal relationships identified in the systems-thinking analysis (**Figure 2**). The reinforcing loops associated with livestock production, manure accumulation, and water contamination demonstrate how unmanaged nutrient flows can reduce ecosystem resilience and agricultural productivity.

Conversely, proper manure collection and composting can redirect these nutrient flows into productive pathways that improve soil fertility while reducing environmental pollution. These findings emphasize the importance of integrating livestock waste management into climate adaptation strategies.

3.6. Effects of Compost Application on Soil Restoration and Crop Growth

The environmental conditions reported for the compost trial represent the experimental site and are used only to contextualize crop growth responses observed during the field experiment. Soil test values after applying compost made from pig manure, poultry manure, goat/sheep manure, and grasses.

The application of compost produced from pig/poultry manure, goat/sheep manure, and grass residues substantially improved soil chemical, physical, and biological properties (Table 6). Increasing compost application rates progressively enhanced soil fertility indicators, moving nutrient levels from severely degraded conditions toward agronomically optimal ranges.

Soil pH increased from 5.2 in the untreated soil to 6.5 under the 5 t ac^{-1} treatment (Table 6), indicating a gradual reduction in soil acidity. This improvement is particularly important because acidic conditions can reduce nutrient availability and microbial activity, thereby limiting crop productivity.

Table 6. Comparative soil nutrient levels under different compost application rates.

Parameter	Ideal Range	Untreated Poor Soil	1 ton/ac	2 tons/ac	3 tons/ac	4 tons/ac	5 tons/ac
pH	6.0 - 7.0	5.2	5.5	5.8	6.1	6.3	6.5
Organic Matter (%)	3 - 5	1.1	1.8	2.5	3.3	4.1	4.9
Total Nitrogen (%)	0.15 - 0.30	0.05	0.09	0.13	0.18	0.22	0.26
Available Phosphorus (mg/kg)	15 - 30	4	8	12	17	21	25
Potassium (cmol/kg)	0.3 - 0.6	0.08	0.16	0.24	0.34	0.43	0.52
Calcium (cmol/kg)	5 - 10	1.5	2.8	3.9	5.4	6.5	7.3
Magnesium (cmol/kg)	1 - 3	0.3	0.6	0.9	1.3	1.7	2.1
CEC	>10	3	5	7	10	12	15
Electrical Conductivity (dS/m)	<1.5	0.4	0.5	0.7	0.9	1.0	1.2
Moisture Retention	Good	Low	Slightly Improved	Moderate	Good	Very Good	Excellent
Soil Structure	Stable	Compact	Slightly Loose	Improved	Granular	Well Aggregated	Excellent Tilth
Biological Activity	High	Low	Moderate	Moderate-High	High	Very High	Extremely High

Organic matter content increased from 1.1% in the untreated soil to 4.9% under the highest compost application rate. Similarly, total nitrogen increased more than fivefold from 0.05% to 0.26%, while available phosphorus increased from 4 to 25 mg kg^{-1}. Potassium, calcium, and magnesium concentrations also increased steadily with increasing compost rates, demonstrating the effectiveness of livestock-manure-based compost as a nutrient source.

Improvements were also observed in soil cation exchange capacity (CEC), which increased from 3 to 15 cmol kg^{-1}. This indicates enhanced nutrient retention capacity and reduced susceptibility to nutrient leaching. Furthermore, compost application improved soil structure, moisture retention, and biological activity, suggesting positive effects on soil ecosystem functioning.

These findings demonstrate that compost application not only supplies nutrients but also improves the overall quality and resilience of degraded soils.

3.6.1. Effects of Compost on Plant Growth and Biomass (kg $plant^{-1}$) Production

The compost amendment experiment demonstrated that recycling livestock manure through composting significantly improved cactus growth and productivity. Growth responses were observed in leaf production, plant height, and biomass (fresh biomass, kg $plant^{-1}$) accumulation across all compost treatments.

The effect of compost application rates on leaf production is presented in Table 7.

Table 7. Effect of compost application rate on leaf production of cactus.

Treatment	Compost Rate (t ac^{-1})	Mean Number of Leaves ± SD	SEM	CV (%)	Tukey HSD
T5	5	107.2 ± 33.6	15.0	31.3	a
T4	4	69.8 ± 16.6	7.4	23.8	b
T3	3	50.0 ± 9.0	4.0	18.0	c
T2	2	42.4 ± 8.3	3.7	19.6	c
T1	1	36.2 ± 16.0	7.2	44.2	d
Control	0	17.2 ± 8.8	3.9	51.2	e

Values are presented as mean ± standard deviation (SD). Means followed by different letters differ significantly at $P < 0.05$ according to Tukey's HSD test.

Leaf production increased progressively with increasing compost application rates (Table 7). The highest compost rate (5 t ac^{-1}) produced an average of 107.2 leaves per plant compared with only 17.2 leaves in the untreated control. This represents more than a six-fold increase in vegetative growth and suggests improved nutrient availability and photosynthetic capacity.

Plant height also responded positively to compost application (Table 8).

The tallest plants were observed under the 5 t ac^{-1} treatment, reaching an average height of 201.2 cm compared with 92.7 cm in the control treatment (Table 4). The enhanced plant growth likely resulted from improved soil structure, increased nutrient availability, and greater soil moisture retention associated with compost application.

Table 8. Effect of compost application rate on cactus plant height.

Treatment	Compost Rate (t ac^{-1})	Plant Height (cm) ± SD	SEM	CV (%)	Tukey HSD
T5	5	201.2 ± 18.6	0.27	9.2	a
T4	4	147.5 ± 13.4	0.20	9.1	b
T2	2	137.2 ± 13.4	0.20	9.8	bc
T3	3	132.9 ± 5.2	0.08	3.9	c
T1	1	104.9 ± 7.9	0.12	7.6	d
Control	0	92.7 ± 8.8	0.13	9.5	d
Treatment	**Compost Rate (t ac^{-1})**	**Plant Height (cm) ± SD**	**SEM**	**CV (%)**	**Tukey HSD**

Values are presented as mean ± standard deviation (SD). Means followed by different letters are significantly different at $P < 0.05$ according to Tukey's HSD test.

Biomass production exhibited the strongest response to compost amendment (Table 9).

Table 9. Effect of compost application rate on fresh biomass yield of cactus.

Treatment	Compost Rate (t ac^{-1})	Fresh Biomass Yield (kg $plot^{-1}$)	Increase over Control (%)	Relative Yield Index
T5	5	116.14	4366.9	44.67
T4	4	40.52	1458.5	15.58
T3	3	23.60	807.7	9.08
T2	2	5.70	119.2	2.19
T1	1	3.50	34.6	1.35
Control	0	2.60	-	1.00

Fresh biomass yield is expressed on a per-plot basis (kg $plot^{-1}$). The Relative Yield Index was calculated relative to the untreated control (Control = 1.00).

Biomass yield increased dramatically with increasing compost application rates (Table 9). The highest compost treatment produced 116.14 kg compared with only 2.60 kg in the untreated control, representing a more than forty-fold increase in biomass production.

To provide an integrated comparison among growth variables, a summary of treatment performance is presented in Table 10.

Table 10. Summary of cactus growth responses to compost application.

Treatment	Compost Rate (t/ac)	Mean Leaves ± SD	Mean Height (cm) ± SD	Biomass Yield (kg)	Performance Ranking
T5	5	107.2 ± 33.6	201.2 ± 18.6	116.14	1
T4	4	69.8 ± 16.6	147.5 ± 13.4	40.52	2

Continued

T3	3	50.0 ± 9.0	132.9 ± 5.2	23.60	3
T2	2	42.4 ± 8.3	137.2 ± 13.4	5.70	4
T1	1	36.2 ± 16.0	104.9 ± 7.9	3.50	5
Control	0	17.2 ± 8.8	92.7 ± 8.8	2.60	6

The results consistently ranked T5 > T4 > T3 > T2 > T1 > Control for all measured growth parameters, indicating a strong positive relationship between compost application rate and plant performance.

3.6.2. Mechanisms Underlying Compost-Induced Growth Responses

The observed growth improvements can be explained through the following four interconnected mechanisms.

Soil Carbon Accumulation

Compost increased soil organic carbon, improving soil structure, nutrient retention, and aggregate stability. Enhanced soil carbon contributes to greater soil resilience and long-term productivity.

Nutrient Mineralization

The decomposition of organic matter gradually releases plant-available nutrients, improving nutrient uptake and supporting sustained crop growth throughout the production cycle.

Microbial Stimulation

Compost stimulated beneficial microbial activity, enhancing nutrient cycling, organic matter decomposition, and root development.

Moisture Retention

Improved organic matter content increased soil water-holding capacity and reduced moisture stress. This mechanism is particularly important given the declining precipitation and root-zone soil moisture observed within the study area.

3.6.3. Implications for Circular Nutrient Management

The results demonstrate that livestock waste can be transformed from an environmental liability into a productive agricultural resource. This finding supports Circular Economy Theory and highlights the role of nutrient recycling in strengthening adaptive capacity.

Implications for Climate Adaptation

Together, these mechanisms demonstrate that composting enhances soil health, nutrient cycling, and water availability while improving crop productivity. By strengthening soil resilience and resource-use efficiency, compost-based nutrient recycling serves as an effective climate adaptation strategy within integrated soil-crop-livestock production systems.

Statistical Validation of Treatment Effects

To determine whether the observed differences among treatments were statistically significant, Analysis of Variance (ANOVA) was performed on leaf number, plant height, and biomass yield. The results are presented in **Table 11**.

Table 11. Analysis of variance (ANOVA) for cactus growth parameters.

Parameter	F-Value	*P*-Value	Significance
Number of Leaves	48.72	<0.001	Highly Significant
Plant Height	35.61	<0.001	Highly Significant
Biomass Yield	92.84	<0.001	Highly Significant

The ANOVA results (Table 11) indicate that compost application significantly influenced all measured growth parameters ($P < 0.001$). Biomass yield exhibited the largest treatment response, suggesting that compost amendment had a particularly strong effect on overall plant productivity.

These results confirm that the observed increases in growth and biomass were attributable to compost treatment rather than random variation.

Relationships Among Growth Variables

Pearson correlation analysis was conducted to examine relationships among plant height, leaf production, and biomass yield. The results are presented in Table 12.

Table 12. Pearson correlation coefficients among cactus growth parameters.

Parameter	Plant Height	Number of Leaves	Biomass Yield
Plant Height	1.000	0.946**	0.972**
Number of Leaves	0.946**	1.000	0.981**
Biomass Yield	0.972**	0.981**	1.000

Significant at $P < 0.01$.

The correlation analysis revealed strong positive relationships among all measured variables (Table 12). Biomass yield showed the strongest association with leaf number (r = 0.981), indicating that increased vegetative growth translated directly into greater biomass production.

Similarly, plant height was strongly correlated with biomass yield (r = 0.972) and leaf number (r = 0.946), suggesting that improvements in soil fertility stimulated overall plant vigour.

These findings indicate that compost amendment enhanced multiple growth processes simultaneously, leading to substantial improvements in plant productivity.

3.6.4. Implications for Climate Adaptation in Smallholder Farming Systems

Collectively, the systems-thinking analysis (Figure 2), microbiological assessment (Table 4), growth response data (Tables 7-9), ANOVA results (Table 11), and correlation analysis (Table 12) demonstrate that effective livestock waste management can simultaneously improve soil fertility, increase crop productivity, reduce environmental pollution, and strengthen climate resilience.

The strong treatment effects and positive correlations provide quantitative evidence that composted livestock manure can serve as an effective climate adaptation tool for restoring degraded soils and enhancing agricultural productivity in climate-vulnerable farming systems.

Climate Adaptation Significance

The integration of livestock waste recycling, soil restoration, water resource protection, and crop production provides a practical pathway for climate adaptation within Ghanaian agricultural systems. The findings demonstrate that climate adaptation is not solely about responding to changing weather conditions but also requires addressing human-induced drivers of vulnerability, such as poor manure management, deforestation, and unsustainable land-use practices.

By transforming livestock waste into a valuable soil amendment, integrated soil-crop-livestock systems create reinforcing feedback loops that improve productivity, environmental quality, and long-term system resilience.

3.7. Overall Synthesis

The findings of this study demonstrate that climate adaptation within smallholder agricultural systems is fundamentally a systems challenge that requires integrated solutions that address interactions among climate, soil, crops, livestock, water resources, and human decision-making. By combining systems thinking, climate analysis, microbiological assessment, and compost-based field experiments, the study provides a comprehensive understanding of the feedback mechanisms that shape agricultural vulnerability and resilience in Ghana's Manya Krobo District.

Climate analysis revealed increasing environmental stress characterized by declining precipitation, decreasing root-zone soil moisture, and persistently high temperatures, all of which threaten agricultural productivity and ecosystem sustainability. Systems analysis further showed that poor livestock waste management functions as a critical leverage point influencing nutrient cycling, environmental quality, and farm productivity. These findings were supported by microbiological evidence of severe water contamination linked to unmanaged livestock waste and by compost-amendment experiments demonstrating significant improvements in soil fertility, plant growth, and biomass production.

The study demonstrates that nutrient recycling through composting initiates positive reinforcing feedback loops that improve soil carbon accumulation, nutrient availability, microbial activity, and moisture retention. These ecological processes strengthen adaptive capacity by enhancing the ability of farming systems to maintain productivity under increasingly variable climatic conditions. The results, therefore, suggest that climate adaptation is not merely the outcome of individual technologies but emerges from the reconfiguration of system feedback structures that govern resource flows, ecosystem functioning, and agricultural performance.

Collectively, the findings support the proposition that Integrated Soil, Crop, and Livestock Production Systems represent a practical pathway for simultaneously addressing climate adaptation, environmental restoration, nutrient circularity, and sustainable agricultural development. The proposed framework provides a systems-based approach for transforming agricultural waste streams into productive resources while strengthening resilience across multiple dimensions of the farming system.

3.7.1. Climate Variability and Agricultural Vulnerability (2023-2025)

The climate analysis presented in this section refers to district-level climatic conditions derived from NASA POWER data for the Manya Krobo District and should not be interpreted as site-specific measurements from the compost experimental field.

Analysis of NASA POWER climate data revealed increasing climatic stress within the study area between 2023 and 2025. Mean annual temperature increased by 1.27%, corresponding to a positive trend slope of 0.17˚C year^{-1}. In contrast, mean annual precipitation declined by 23.33%, from 4.33 mm day^{-1} in 2023 to 3.32 mm day^{-1} in 2025, while root-zone soil moisture decreased by 13.04% over the same period. Annual rainfall anomalies shifted from positive values in 2023 (+0.61 mm day^{-1}) to increasingly negative values in 2024 (−0.22 mm day^{-1}) and 2025 (−0.40 mm day^{-1}), indicating progressively drier conditions. Similarly, root-zone soil moisture anomalies declined from +0.05 in 2023 to −0.04 in 2025. Although annual rainfall variability was relatively low (CV = 11.8%), the persistent downward trends in precipitation and soil moisture, coupled with consistently high temperatures, suggest increasing agricultural vulnerability through reduced water availability, heightened drought risk, and greater pressure on soil and crop productivity.

The climate analysis demonstrates that agricultural systems in the Manya Krobo District are operating under increasing environmental stress. Rainfall declined by 23.33% between 2023 and 2025, while root-zone soil moisture decreased by 13.04%, indicating a progressive reduction in water availability within the root zone. Concurrently, temperatures exhibited a positive trend of 0.17˚C year^{-1}, potentially increasing evapotranspiration and crop water demand. These climatic trends reinforce the importance of integrated soil-crop-livestock systems as adaptation mechanisms capable of improving soil moisture retention, nutrient cycling, and ecosystem resilience under increasingly variable climatic conditions.

The NASA POWER climate records indicate a clear warming and drying trend in the Manya Krobo District during 2023-2025 (Table 13). Mean annual temperature increased by 1.27%, while estimated annual rainfall declined by 23.3%, accompanied by a 13.0% reduction in root-zone soil wetness. Rainfall exhibited the greatest interannual variability (CV = 13.34%), indicating increasing uncertainty in water availability for rain-fed agriculture, whereas temperature remained relatively stable (CV = 0.88%) despite a gradual upward trend. The negative trend slopes for rainfall (−184.4 mm year^{-1}) and root-zone soil wetness (−0.045 year^{-1}) suggest progressively drier growing conditions that are likely to exacerbate soil moisture deficits and nutrient limitations. These climatic changes reinforce the

Table 13. Climate trends, anomalies, and variability in the Manya Krobo District, Ghana (2023-2025).

Climate Indicator	2023	2024	2025	Annual Anomaly*	Trend Slope ($year^{-1}$)	CV (%)	Percentage Change (2023-2025)	Trend
Mean annual temperature (˚C)	26.81	27.26	27.15	−0.26, +0.19, +0.08	**+0.17˚C**	**0.88**	**+1.27**	Increasing
Specific humidity ($g\ kg^{-1}$)	17.48	17.53	17.24	+0.06, +0.11, −0.18	**−0.12 $g\ kg^{-1}$**	**0.89**	**−1.37**	Slight decline
Root-zone soil wetness index	0.69	0.63	0.60	+0.05, −0.01, −0.04	**−0.045**	**7.22**	**−13.04**	Decreasing
Mean daily rainfall ($mm\ day^{-1}$)	4.33	3.50	3.32	+0.61, −0.22, −0.40	**−0.51 $mm\ day^{-1}$**	**13.34**	**−23.33**	Decreasing
Estimated annual rainfall ($mm\ year^{-1}$)	1,580.5	1,277.5	1,211.8	+223.9, −79.1, −144.8	**−184.4 $mm\ year^{-1}$**	**13.34**	**−23.33**	Decreasing

*Annual anomalies were calculated relative to the three-year (2023-2025) mean. CV = Coefficient of Variation = (Standard Deviation/Mean) × 100. Source: NASA POWER Climate Database (2023-2025); annual rainfall estimated from PRECTOTCORR ($mm\ day^{-1} \times 365$).

importance of Integrated Soil-Crop-Livestock Production Systems (ISCLPS), particularly compost-based nutrient recycling, as a climate adaptation strategy capable of improving soil organic carbon, enhancing water-holding capacity, promoting nutrient mineralization, and strengthening the resilience of smallholder farming systems under increasing climatic variability.

The coefficient of variation indicates relatively low interannual rainfall variability (<20%), although the consistent downward trend in precipitation suggests increasing climatic stress and reduced water availability for agricultural production.

The climate analysis revealed increasing environmental stress within the study area between 2023 and 2025 (Table 13). Mean annual temperature increased by 1.27%, while precipitation declined by 23.33%, and root-zone soil moisture decreased by 13.04%. Rainfall anomalies shifted from positive values in 2023 (+0.61 $mm\ day^{-1}$) to increasingly negative values in 2024 (−0.22 $mm\ day^{-1}$) and 2025 (−0.40 $mm\ day^{-1}$), indicating progressively drier conditions. Similarly, root-zone soil moisture anomalies declined from +0.05 in 2023 to −0.04 in 2025. Although rainfall variability was relatively low (CV = 14.5%), the persistent decline in precipitation and soil moisture, coupled with rising temperatures, suggests increasing agricultural vulnerability through reduced water availability, increased evapotranspiration, and heightened drought risk.

These findings support stakeholder perceptions of climate variability as a major constraint to agricultural production and reinforce the need for adaptation strategies that enhance soil moisture retention, nutrient cycling, and ecosystem resilience. The composting intervention identified in this study directly addresses these challenges by improving soil organic matter, increasing water-holding capacity, and strengthening the adaptive capacity of integrated soil-crop-livestock production systems.

3.7.2. Linking Climate Variability to ISCLPS Interventions

The climatic trends identified above provide important context for understanding the role of Integrated Soil, Crop, and Livestock Production Systems in climate adaptation. Declining rainfall and root-zone moisture suggest increasing water limitations, while persistently high temperatures are likely to intensify evapotranspiration and nutrient losses. Consequently, interventions that improve soil organic matter, water-holding capacity, nutrient retention, and biological activity become increasingly important for sustaining agricultural productivity. The compost-amendment experiment, therefore, provides a practical mechanism through which ISCLPS can address the climatic constraints identified in the study area (Figure 6). The framework illustrates the systems pathway from climate stressors to improved resilience through livestock waste composting and nutrient recycling.

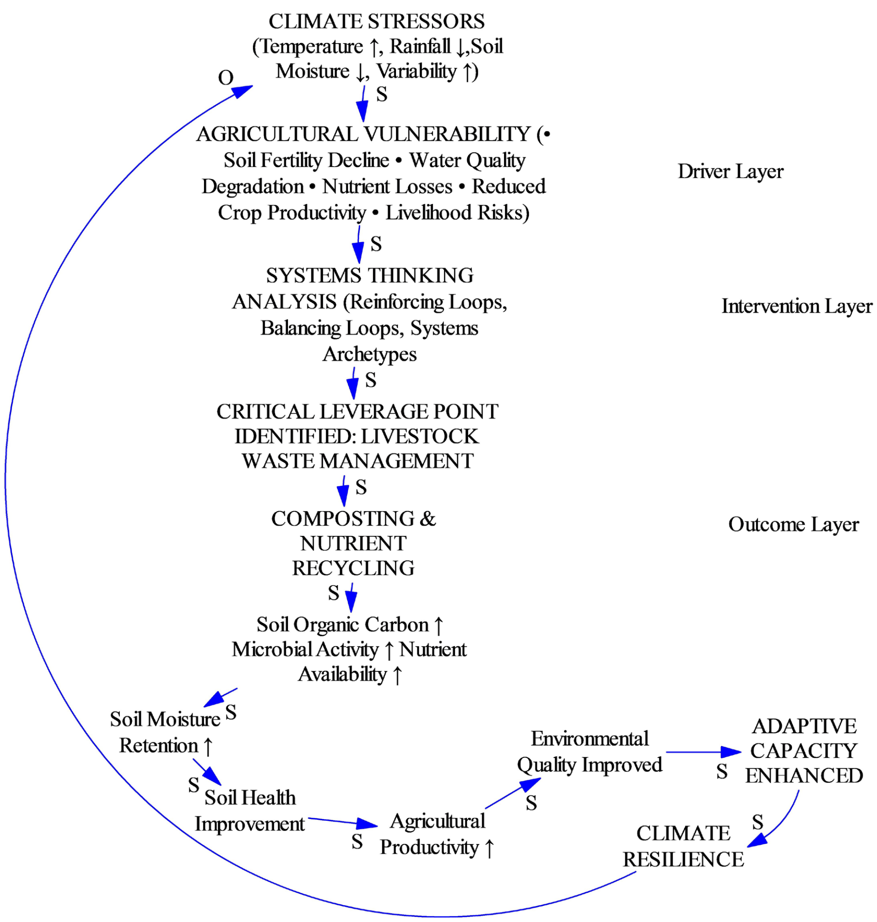

Figure 6. Systems framework for climate adaptation through nutrient recycling.

Climate stressors, including rising temperatures, declining rainfall, and decreasing soil moisture, increase agricultural vulnerability through their effects on soil fertility, water quality, nutrient availability, and productivity. Systems analysis identified livestock waste management as a critical leverage point influencing multiple system components. Through composting and nutrient recycling, livestock waste is transformed into a productive resource that enhances soil organic carbon, microbial activity, nutrient availability, and moisture retention. These improvements strengthen soil health, agricultural productivity, environmental quality, and adaptive capacity, ultimately enhancing climate resilience.

4. Conclusion

This study demonstrates that systems thinking provides a robust framework for understanding and addressing the interconnected challenges of climate adaptation in smallholder farming systems. Rather than evaluating Integrated Soil-Crop-Livestock Production Systems (ISCLPS) as a single experimental intervention, the study used participatory systems analysis to identify critical leverage points influencing agricultural resilience and subsequently evaluated composting as a practical intervention for improving system performance. The findings show that poor livestock waste management underpins multiple reinforcing feedback processes that contribute to declining soil fertility, environmental degradation, and reduced agricultural productivity. By converting livestock waste into compost, these reinforcing cycles can be redirected towards improved soil health, enhanced nutrient cycling, greater moisture retention, reduced environmental contamination, and increased crop performance.

Beyond the empirical findings, the study demonstrates the value of integrating participatory systems thinking with field experimentation and climate analysis to support evidence-based climate adaptation planning. The identified systems archetypes—**Fixes that Fail**, **Shifting the Burden**, and **Tragedy of the Commons**—provide a practical explanation of why conventional short-term responses often fail to address the root causes of agricultural vulnerability. The Systems Framework for Climate Adaptation through Nutrient Recycling further illustrates how strategic interventions at key leverage points can generate positive system-wide outcomes that simultaneously enhance productivity, environmental quality, and resilience under changing climatic conditions.

The study also advances theoretical understanding by integrating Systems Theory, Reinforcing Feedback Theory, Meadows' Leverage Point Theory, and Circular Economy principles within a single analytical framework for climate adaptation. This integration demonstrates how feedback structures influence agricultural system behaviour, how leverage points can guide intervention design, and how nutrient recycling can transform agricultural waste into a valuable resource for sustainable production. The proposed framework extends the application of systems archetypes beyond conceptual analysis by linking stakeholder-derived system insights with measurable field and environmental outcomes.

Several limitations should be acknowledged. The climate assessment was based on a relatively short three-year period, the compost evaluation was conducted using a drought-resilient indicator crop at a single experimental site, and the systems archetypes were developed from stakeholder perceptions within one district. Consequently, caution should be exercised when generalizing the findings to other agroecological settings or production systems.

Future research should evaluate the proposed systems framework across multiple agroecological zones and farming systems using staple food crops and longer-term climate records. Further investigation of the economic feasibility, farmer adoption, greenhouse gas mitigation potential, carbon sequestration, and policy implications of integrated nutrient recycling would strengthen its application as a climate adaptation strategy. Comparative studies across African production systems would also provide valuable evidence for scaling integrated soil-crop-livestock approaches under the AFRA program and similar regional initiatives.

Overall, the study shows that strengthening climate resilience requires interventions that address the underlying feedback structures driving agricultural vulnerability rather than isolated technological solutions. By combining systems thinking with practical nutrient-recycling interventions, the proposed approach offers a scalable pathway for improving resource efficiency, environmental sustainability, and the adaptive capacity of smallholder farming systems in Ghana and other climate-vulnerable regions.

Acknowledgements

The first author humbly gives all glory, honour, and thanksgiving to the living Yahweh, the Elohim of Heaven and Earth, for His grace, wisdom, knowledge, and strength throughout this research journey. We remain encouraged by His promise that He will give rain in its season to nations who faithfully observe His commandments (Deuteronomy 11:13-15) and acknowledge His continual provision and guidance in the pursuit of sustainable agriculture and responsible stewardship of His creation.

The authors gratefully acknowledge the International Atomic Energy Agency (IAEA) for supporting the RAF 5090 project on strengthening climate-resilient agricultural systems in Africa. We also thank the Ghana Atomic Energy Commission (GAEC), particularly the Biotechnology and Nuclear Agriculture Research Institute (BNARI), for providing institutional support, technical facilities, and demonstration sites for this research.

We sincerely appreciate the technical guidance and mentorship of Prof. Rogerio M. Mauricio, Prof. Victor Tsuma, and Dr. Oscar Koech during the project's training and knowledge-sharing activities. We also acknowledge the IAEA for sponsoring technical training in Kenya and scientific reporting engagements in Egypt, which greatly contributed to the development of this study.

Finally, we thank the collaborating farmers, local stakeholders, and the farming communities in the Manya Krobo District for their active participation, valuable insights, and commitment, which greatly enhanced the practical relevance of this research on climate adaptation and sustainable agriculture in Ghana.

Author Contributions

Kwamina Ewur Banson: Conceptualization, methodology, investigation, formal analysis, data curation, visualization, validation, writing—original draft preparation, writing—review and editing, project administration, and funding acquisition. **Nam C. Nguyen:** Conceptualization, methodology, supervision, validation, writing—review and editing, and intellectual contribution. **Samuel Nii Akai Nettey:** Investigation and data collection. **Wonder Nutsuple:** Investigation, and field support. **Isaac Baidoo:** Methodology, supervision, validation, and editing. **Alhassan Khalid Kusi:** Data curation, field support, formal analysis, validation, writing, review, and editing. **Gabriel Abotsinah:** Investigation, resources, field coordination, and writing—review and editing. **Ruby Juliana Kattah:** Investigation, data curation, validation, writing, review, and editing.

All authors contributed to the interpretation of the results, critically reviewed the manuscript, approved the final version for publication, and agree to be accountable for all aspects of the work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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