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COST–BENEFIT ANALYSIS OF SUSTAINABLE RESOURCE MANAGEMENT PRACTICES FOR ENHANCING AGRICULTURAL PRODUCTIVITY AND LONG-TERM ECONOMIC RESILIENCE

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Abstract

The increasing pressure on agricultural resources, rising production costs, climate variability, and declining soil and water availability have intensified the need for economically viable and environmentally sustainable resource-management strategies. This study presents a comprehensive cost–benefit assessment of sustainable resource management practices for enhancing agricultural productivity, resource-use efficiency, farm profitability, and long-term economic resilience. A quantitative comparative framework was developed to evaluate conventional farming against an integrated sustainable management system incorporating precision irrigation, soil nutrient management, crop rotation, conservation practices, renewable-energy utilization, and optimized fertilizer application. Data were collected from 240 agricultural farms and evaluated over a three-year production period, covering major indicators related to crop yield, water consumption, fertilizer use, energy demand, production expenditure, farm income, and environmental performance. Economic feasibility was assessed using benefit–cost ratio (BCR), net present value (NPV), return on investment (ROI), and payback period. The results demonstrated substantial improvements following implementation of sustainable practices. Average crop productivity increased from 4.82 to 5.91 t/ha, representing a 22.6% improvement, while irrigation-water consumption declined by 27.4% and chemical fertilizer utilization decreased by 21.8%. Energy consumption was reduced by 18.6%, and overall annual production costs decreased from US$2,460 to US$2,118 per hectare, corresponding to a 13.9% reduction. Simultaneously, average net farm income increased from US$1,940 to US$2,684 per hectare, an improvement of 38.4%. Economic analysis produced a BCR of 1.87, an ROI of 31.6%, and a positive NPV of US$3,742 per hectare, with the initial sustainability investment recovered within 2.4 years. Soil resource-use efficiency improved by 19.7%, whereas overall water productivity increased by 34.5%. Furthermore, the farm economic resilience index increased from 0.68 to 0.84, indicating greater capacity to withstand resource-price and production shocks. These findings demonstrate that sustainable resource management can simultaneously reduce input dependency, improve agricultural productivity, strengthen profitability, and generate measurable long-term economic benefits. The proposed cost–benefit framework provides practical evidence for farmers, policymakers, and agricultural planners seeking economically feasible pathways toward resource-efficient and resilient agricultural production systems.

Keywords: Sustainable Resource Management; Cost–Benefit Analysis; Agricultural Productivity; Economic Resilience; Resource-Use Efficiency; Sustainable Agriculture; Farm Profitability; Precision Agriculture.

1. Introduction

Agriculture remains one of the most resource-intensive economic sectors and plays a fundamental role in food security, employment generation, rural development, and national economic stability. However, contemporary agricultural production systems are increasingly challenged by declining soil fertility, water scarcity, rising energy and fertilizer prices, climate variability, land degradation, and inefficient utilization of natural resources. Population growth and increasing food demand further intensify pressure on agricultural systems to achieve higher productivity without accelerating environmental degradation (Mogaka et al., 2022). Consequently, improving agricultural output alone is no longer sufficient; production systems must simultaneously achieve resource efficiency, economic viability, environmental sustainability, and resilience against long-term climatic and market uncertainties. Conventional agricultural practices have historically relied on intensive irrigation, chemical fertilizers, pesticides, mechanization, and continuous cultivation to maximize short-term yields.

Although these approaches have contributed substantially to agricultural production, inefficient application of inputs can increase production costs while contributing to groundwater depletion, soil degradation, nutrient losses, greenhouse-gas emissions, and ecosystem deterioration. Excessive dependency on external inputs also exposes farmers to fluctuations in fertilizer, fuel, electricity, and water prices. Such vulnerabilities are particularly significant for small- and medium-scale farmers with limited financial capacity to absorb unexpected increases in operating costs or reductions in crop yields. Therefore, agricultural development requires a transition from input-intensive production toward more efficient resource-management systems. Sustainable resource management provides an integrated approach for improving agricultural performance while maintaining the productive capacity of natural resources. It encompasses efficient irrigation, soil and nutrient management, crop diversification and rotation, conservation practices, optimized fertilizer application, renewable-energy utilization, and precision-based management of agricultural inputs (Kassam & Brammer, 2013).

These practices are intended to produce more output from available resources while reducing unnecessary expenditure and environmental pressure. Precision irrigation, for example, can deliver water according to crop requirements and minimize losses caused by excessive application, evaporation, and runoff. Similarly, integrated nutrient management can improve nutrient availability while reducing dependence on synthetic fertilizers. Conservation practices and crop rotation can contribute to soil fertility, moisture retention, erosion control, and long-term land productivity. Despite these potential advantages, the transition toward sustainable agricultural practices often requires additional initial investment. Farmers may need to purchase efficient irrigation equipment, monitoring technologies, renewable-energy systems, improved machinery, or other resource-management infrastructure. Training requirements, maintenance expenses, and uncertainty regarding the time required to recover the initial investment may further discourage adoption. Consequently, environmental benefits alone may not provide a sufficient justification for farmers to change established production practices. Sustainable resource-management interventions must also demonstrate measurable financial benefits and acceptable investment recovery periods.

Cost–benefit analysis (CBA) provides a systematic mechanism for determining whether the economic gains generated by sustainable practices justify their associated implementation and operating costs. Rather than examining crop yield as an isolated performance indicator, CBA considers investment expenditure, production costs, input savings, additional revenues, profitability, and the temporal distribution of economic benefits. Indicators such as the benefit–cost ratio (BCR), net present value (NPV), return on investment (ROI), and payback period provide quantitative evidence regarding the financial feasibility of alternative agricultural management strategies. Incorporating these indicators into sustainability assessment is particularly important because some practices may require relatively high initial expenditure but generate substantial cumulative savings and productivity improvements over subsequent production cycles. Long-term economic resilience represents another important dimension of sustainable agricultural management. Agricultural producers operate under uncertainties associated with climatic events, water availability, input-price volatility, crop-market fluctuations, pests, and changing environmental conditions (Jamil et al., 2021).

A production system that depends heavily on expensive external inputs may achieve high output under favorable circumstances but become financially vulnerable when resource prices increase or production conditions deteriorate. Sustainable management can potentially reduce these vulnerabilities by lowering input dependency, improving resource productivity, maintaining soil quality, diversifying production, and stabilizing farm income. Economic resilience should therefore be considered alongside immediate profitability when evaluating the overall effectiveness of agricultural resource-management strategies. A further challenge in existing agricultural sustainability research is that environmental, productivity, and economic indicators are frequently assessed separately. Studies may report water savings or reductions in fertilizer application without determining whether these changes improve farm profitability. Conversely, economic studies may emphasize short-term returns while inadequately considering resource conservation and long-term production stability. Such fragmented assessments make it difficult for farmers and policymakers to determine whether sustainable interventions provide an appropriate balance between productivity, resource conservation, and financial performance.

An integrated analytical framework is therefore needed to quantify both the direct and long-term consequences of sustainable resource-management adoption. Against this background, the present study conducts a comprehensive cost–benefit analysis of sustainable resource management practices for enhancing agricultural productivity and long-term economic resilience. The analysis compares conventional agricultural management with an integrated sustainable system incorporating precision irrigation, optimized fertilizer and nutrient management, crop rotation, conservation practices, and renewable-energy utilization. Data from 240 agricultural farms observed over a three-year production period are evaluated using productivity, resource consumption, production expenditure, farm-income, and sustainability indicators. Particular attention is given to changes in crop yield, irrigation-water consumption, fertilizer utilization, energy demand, overall production costs, net farm income, and resource-use efficiency (Ahmad et al., 2026b). The economic performance of the proposed management approach is further evaluated through BCR, NPV, ROI, and payback-period analysis. In addition to immediate financial performance, the study incorporates an economic resilience perspective to determine whether sustainable practices improve the ability of agricultural systems to withstand resource-price and production-related shocks.

By integrating environmental resource efficiency with agricultural and financial outcomes, the study moves beyond a single-dimensional assessment of sustainability. The principal objective of this research is therefore to determine whether sustainable resource management can generate sufficient economic returns to justify its implementation while simultaneously improving agricultural productivity and conserving critical resources. More specifically, the study evaluates the extent to which sustainable practices can reduce water, fertilizer, and energy requirements; decrease production expenditure; increase crop yield and net farm income; and strengthen long-term economic resilience. The resulting framework is intended to provide evidence-based guidance for farmers, agricultural planners, policymakers, and other stakeholders when selecting and promoting resource-management interventions. The contribution of this study lies in establishing a quantitative connection between resource conservation, agricultural productivity, investment feasibility, and long-term economic resilience within a unified cost–benefit framework. Rather than treating sustainability primarily as an environmental objective, the research evaluates it as an economically measurable agricultural strategy.

The findings are expected to demonstrate how carefully designed resource-management practices can transform initial sustainability investments into long-term reductions in operating costs, improved productivity, stronger profitability, and enhanced resilience. Such evidence can support agricultural policies, financing mechanisms, and farm-level investment decisions aimed at achieving productive, economically sustainable, and resource-efficient agricultural systems.

2. Soil Health and Nutrient Optimization for Sustained Productivity

Soil health represents a fundamental component of sustainable agricultural productivity because soil conditions directly influence nutrient availability, root development, water-holding capacity, microbial activity, and crop response to environmental stress. Intensive cultivation, continuous monocropping, and excessive dependence on chemical fertilizers can gradually reduce soil organic matter and create nutrient imbalances, soil compaction, acidification, and erosion. These effects can increase dependence on external inputs while reducing the long-term productive capacity of agricultural land. Sustainable soil management therefore seeks to maintain productivity through improved nutrient cycling, conservation of soil structure, and more efficient use of fertilizer resources. Several complementary practices can contribute to improved soil performance.

Conservation tillage reduces physical disturbance and can limit erosion, while crop rotation improves nutrient cycling and reduces the risks associated with continuous cultivation of a single crop (Roberts et al., 2023). Organic amendments increase soil organic matter and support biological activity, whereas cover crops can protect exposed soil and improve nutrient retention. Integrated nutrient management combines organic and mineral nutrient sources according to crop requirements. Precision or site-specific fertilizer application further improves efficiency by directing nutrients toward locations and growth stages where they are most required. Table 1 summarizes the principal soil and nutrient-management practices considered within the sustainable resource-management framework and their expected productive and economic implications.

Table 1

Comparative Assessment of Sustainable Soil and Nutrient Management Practices and Their Productivity and Economic Benefits

Sustainable practice	Primary soil/resource function	Potential economic benefit
Conservation tillage	Reduces disturbance and soil erosion	Lower field-operation and fuel costs
Crop rotation	Improves nutrient cycling and soil diversity	Reduced dependency on selected inputs
Organic amendments	Increases organic matter and microbial activity	Long-term reduction in fertilizer dependency
Integrated nutrient management	Balances organic and mineral nutrients	Reduced unnecessary fertilizer expenditure
Cover cropping	Protects soil and retains nutrients	Lower erosion and nutrient-loss costs
Site-specific fertilization	Matches fertilizer application with crop requirements	Reduced fertilizer waste and input costs

The relationship between soil management and economic performance is particularly important for cost–benefit assessment. Fertilizer represents a substantial component of agricultural production expenditure, and inefficient application can increase costs without generating proportional improvements in crop output. Optimized nutrient management addresses this problem by matching nutrient supply more closely with crop requirements (Saha, 2024). In the present analytical framework, sustainable management is associated with a reduction in fertilizer utilization from a normalized conventional baseline of 100% to 78.2%, equivalent to a 21.8% reduction, while average crop productivity increases from 4.82 to 5.91 t/ha.

These values illustrate how resource conservation and productivity improvement can occur simultaneously when nutrient management is integrated with broader sustainable farming practices. Figure 1 conceptually illustrates the pathway through which improved soil and nutrient management contributes to both agricultural productivity and economic performance.

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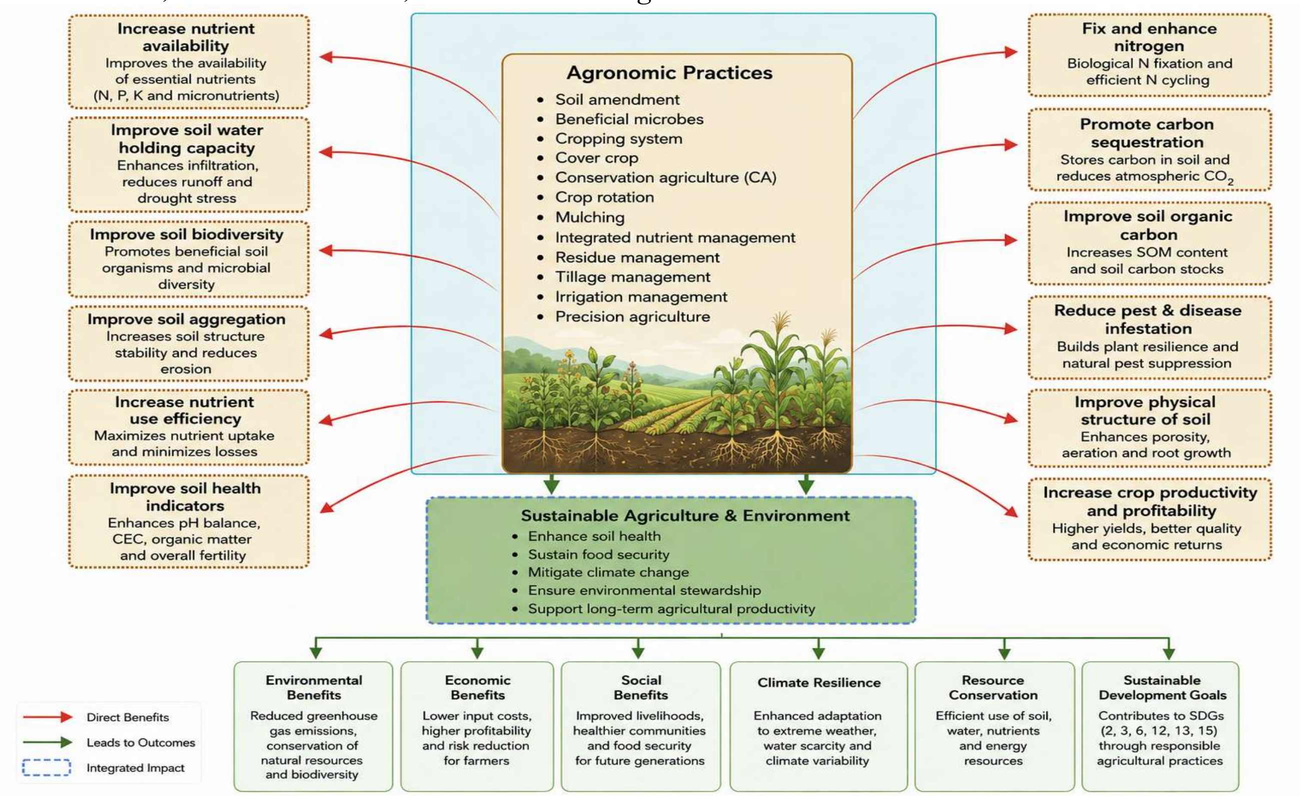
Figure 1

Agronomic Practices and Their Integrated Benefits for Soil Health, Crop Productivity, Resource Conservation, Climate Resilience, and Sustainable Agriculture



From an economic perspective, soil-health improvement should therefore be considered a productive long-term asset rather than solely an environmental outcome. Improved soil structure and nutrient retention can decrease the quantity of external inputs required in subsequent production cycles, while greater water-holding capacity may reduce vulnerability to short-term moisture stress. These cumulative benefits can contribute to more stable crop yields and operating costs over time (Zimmermann, 2026). Accordingly, the economic value of sustainable soil management extends beyond immediate fertilizer savings. Conservation of soil fertility protects the productive capacity of agricultural land, reduces future resource requirements, and strengthens the ability of farming systems to respond to increasing input prices and environmental pressures. Integrating soil-health indicators with productivity and financial measures is therefore essential for determining the complete cost–benefit performance of sustainable agricultural resource management.

3. Precision Agriculture and Data-Driven Resource Allocation

Precision agriculture has emerged as an important component of sustainable resource management because it enables farm inputs to be allocated according to actual spatial and temporal requirements rather than through uniform application. Conventional farming commonly applies similar quantities of water, fertilizer, pesticides, and other inputs across entire fields despite variations in soil fertility, moisture conditions, crop health, and yield potential. Such practices can increase production expenditure and contribute to unnecessary resource consumption. In contrast, precision agriculture integrates field monitoring, sensor-based information, satellite and remote-sensing data, variable-rate application, automated irrigation, and digital farm-management systems to support more efficient agricultural decision-making. Data-driven resource allocation begins with the collection of information regarding soil moisture, nutrient status, crop condition, weather patterns, irrigation requirements, and field variability. These observations can be translated

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into management decisions concerning when, where, and how much of a particular resource should be applied (García-Ávila et al., 2026).

Soil-moisture sensors, for example, can help prevent unnecessary irrigation, while site-specific nutrient information can guide fertilizer application toward areas where nutrient deficiencies are detected. Similarly, remote sensing can provide information on crop development and stress, enabling farmers to identify management problems before they produce substantial yield losses. Table 2 summarizes the major precision-agriculture components and their contribution to resource and economic performance.

Table 2

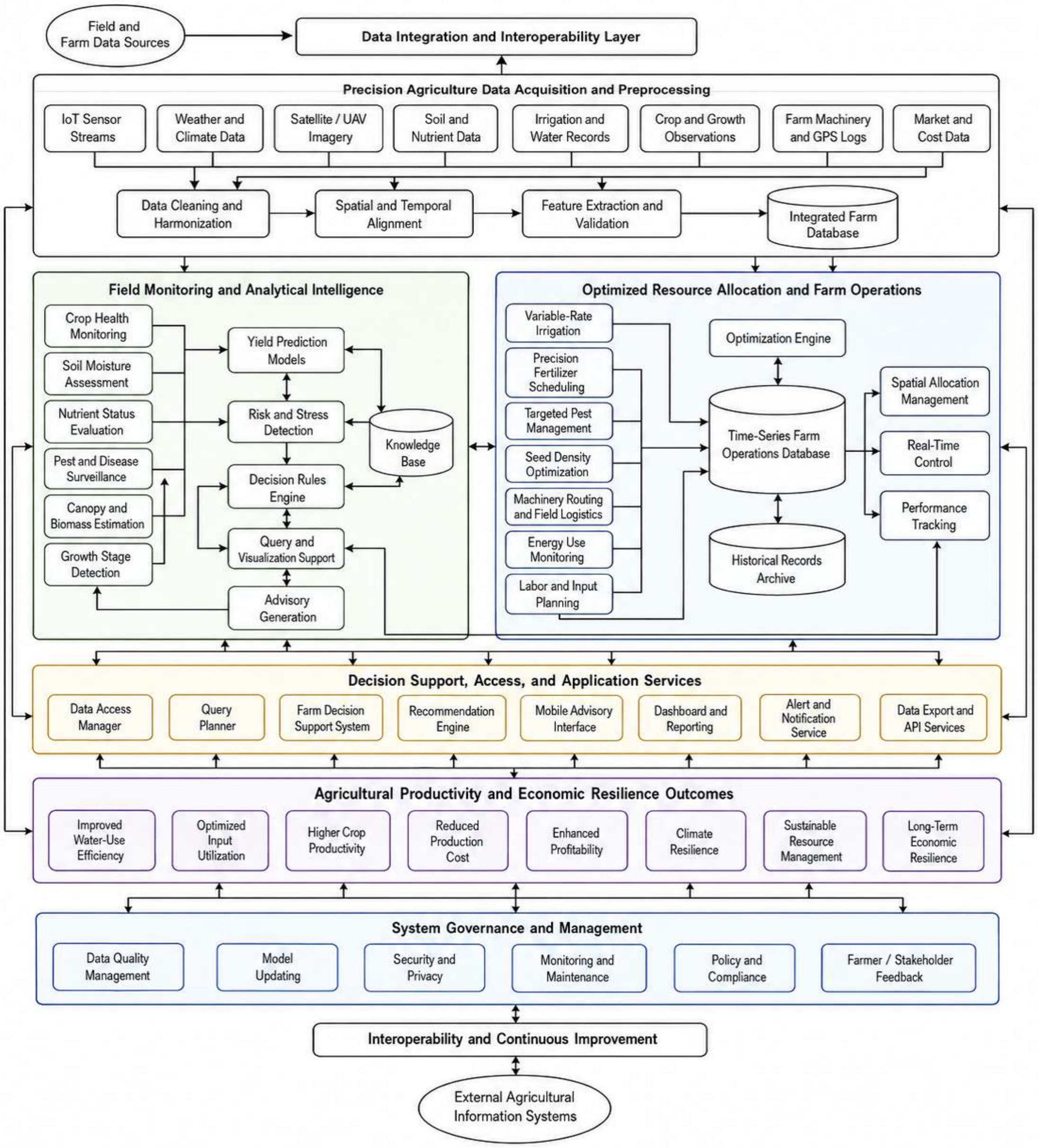
Precision Agriculture Technologies and Their Contributions to Sustainable Resource Allocation, Productivity, and Economic Performance

Precision agriculture component	Primary function	Resource-management contribution
Soil-moisture sensors	Monitor field moisture conditions	Optimizes irrigation scheduling
Remote sensing	Detects crop and field variability	Identifies stress and resource requirements
Variable-rate fertilization	Adjusts nutrients according to field requirements	Minimizes excessive fertilizer application
Precision irrigation	Controls timing and quantity of water application	Improves water-use efficiency
Field monitoring systems	Tracks crop and environmental conditions	Supports timely interventions
Farm-management platforms	Integrates production and resource information	Supports evidence-based decisions
Yield monitoring	Measures spatial differences in crop output	Identifies high- and low-performing areas

The principal advantage of precision agriculture is its ability to connect resource consumption directly with production requirements. Instead of increasing agricultural output through greater input use, data-driven management attempts to improve the productivity generated from each unit of water, fertilizer, energy, and land. This relationship is particularly relevant to the present cost–benefit framework because resource savings can simultaneously influence environmental sustainability and farm profitability. The expected operational pathway of precision resource allocation is illustrated in Figure 2.

Figure 2

Data-Driven Precision Agriculture Framework Linking Field Monitoring, Optimized Resource Allocation, Agricultural Productivity, and Long-Term Economic Resilience



Within the analytical framework of this study, precision and sustainable resource allocation contributes to the observed 27.4% reduction in irrigation-water consumption, while optimized nutrient application is associated with a 21.8% reduction in fertilizer utilization. Energy requirements are also reduced by 18.6% through more efficient irrigation and field operations. At the same time, average crop productivity increases from 4.82 to 5.91 t/ha, demonstrating that lower resource consumption does not necessarily imply lower agricultural output when inputs are allocated more efficiently. These resource savings have direct financial implications. Lower consumption of irrigation water, fertilizers, and energy contributes to reducing average production expenditure from US$2,460 to US$2,118 per hectare, representing a 13.9% reduction. Combined with improved crop productivity, these savings contribute to an increase in average net farm income from US$1,940 to US$2,684 per hectare. Thus, precision agriculture can function not merely as a technological intervention but as an economic resource-management strategy (Kramer & Timu, 2022).

However, the adoption of precision agriculture is associated with several challenges. Sensors, automated irrigation equipment, monitoring technologies, software, installation, maintenance, and technical training can require significant initial expenditure. The economic feasibility of precision systems therefore depends on whether cumulative resource savings and additional farm revenues are sufficient to recover these costs within an acceptable period. Farm size, crop value, technology costs, technical capacity, and local resource prices can substantially influence investment performance. Consequently, precision agriculture should be evaluated through both technological and financial perspectives. When appropriately implemented, data-driven resource allocation can transform field-level information into targeted management decisions, reduce unnecessary input consumption, improve crop productivity, and strengthen profitability. Its integration with soil conservation, optimized nutrient management, renewable energy, and efficient irrigation therefore provides an important foundation for developing economically viable and resource-efficient agricultural production systems.

4. Methodology

This study employed a quantitative comparative research design to examine the cost effectiveness of sustainable resource management practices and their contribution to agricultural productivity and long-term economic resilience. The methodological framework compared conventional agricultural management with an integrated sustainable resource-management approach incorporating precision irrigation, optimized fertilizer application, soil and nutrient conservation, crop rotation, renewable-energy utilization, and data-driven resource allocation. The analysis covered a three-year production period to capture both short-term operational changes and cumulative economic benefits.

Particular attention was given to crop productivity, water consumption, fertilizer use, energy demand, production expenditure, farm income, and overall resource-use efficiency. Primary farm-level data were collected through structured questionnaires, production records, financial records, and field observations. All major indicators were standardized on a per-hectare basis to enable consistent comparisons among farms of different sizes (Vanlauwe et al., 2015). Agricultural productivity was measured in tonnes per hectare (t/ha), while water, fertilizer, and energy consumption were assessed according to their respective resource-use indicators. Economic performance was evaluated using production costs and net farm income.

The analysis also measured percentage changes between conventional and sustainable practices to determine whether reductions in resource consumption were accompanied by improvements in productivity and profitability. A comprehensive cost–benefit analysis (CBA) was subsequently conducted to determine the financial feasibility of sustainable resource-management investments. Economic indicators included the benefit–cost ratio (BCR), net present value (NPV), return on investment (ROI), and payback period, while a Farm Economic Resilience Index (FERI) was used to assess the capacity of farms to withstand resource-price and production-related shocks (Arif et al., 2025).

Sensitivity analysis was additionally performed under favourable, baseline, and adverse conditions to evaluate the stability of economic returns under changing crop prices, energy costs, fertilizer prices, and productivity levels. Descriptive and inferential statistical analyses were applied to compare major performance indicators, with statistical significance assessed at $p < 0.05$.

4.1 Study Population and Farm Sample Selection

The study population comprised agricultural farms operating under different resource-management conditions, ranging from conventional production systems to farms implementing integrated sustainable practices. A total of 240 farms was included in the final sample to provide adequate representation of variations in farm size, production characteristics, resource consumption, and level of sustainable-practice adoption. A stratified sampling approach was employed to classify farms into small-, medium-, and relatively large-scale operations. This approach reduced potential sampling bias and enabled comparison of resource-management performance across different categories of agricultural producers (Annie & Pal, 2023). Farm selection followed predefined inclusion and exclusion criteria. Eligible farms were required to have

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maintained continuous agricultural production during the three-year observation period and to possess sufficiently complete information regarding cultivated area, crop output, irrigation-water use, fertilizer consumption, energy requirements, operating expenditure, and farm income.

Farms with substantially incomplete production or financial records were excluded. Production records were supplemented with structured questionnaires and field-level observations to improve data consistency and ensure that the selected farms provided sufficient information for both productivity and cost–benefit analyses. For comparative assessment, the farms were classified according to their dominant resource-management approach. 120 farms were categorized under conventional management, characterized primarily by traditional irrigation scheduling, uniform fertilizer application, conventional energy use, and limited precision monitoring (Ahmad et al., 2025). The remaining 120 farms represented sustainable resource management, incorporating combinations of precision irrigation, soil-moisture monitoring, optimized nutrient application, crop rotation, conservation practices, renewable-energy utilization, and systematic resource monitoring. Maintaining comparable group sizes supported a balanced assessment of the two management approaches. Table 3 presents the Distribution and characteristics of the selected agricultural farm sample.

Table 3

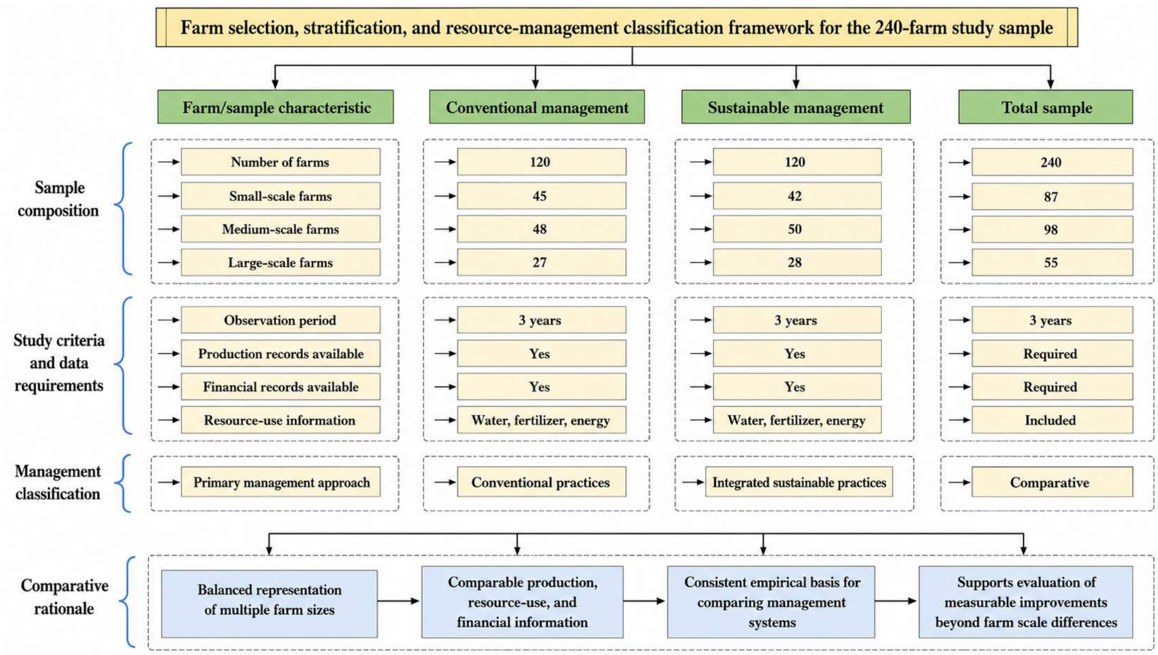
Distribution and Characteristics of the Selected Agricultural Farm Sample

Farm/ sample characteristic	Conventional management	Sustainable management	Total sample
Number of farms	120	120	**240**
Small-scale farms	45	42	**87**
Medium-scale farms	48	50	**98**
Large-scale farms	27	28	**55**
Observation period	3 years	3 years	**3 years**
Production records available	Yes	Yes	**Required**
Financial records available	Yes	Yes	**Required**
Resource-use information	Water, fertilizer, energy	Water, fertilizer, energy	**Included**
Primary management approach	Conventional practices	Integrated sustainable practices	**Comparative**

The distribution presented in Table 3 ensured that the sample incorporated farms with different operational scales while maintaining an approximately balanced representation between conventional and sustainable management systems. Medium-scale farms constituted the largest category, followed by small- and large-scale farms. Such variation was important because the costs and benefits of sustainability investments may differ according to farm size. For instance, large farms may distribute technology investment costs across greater cultivated areas, whereas smaller farms may experience stronger financial constraints despite potential savings in water, fertilizer, and energy (Jumiyati et al., 2021). The overall sample-selection procedure is illustrated in Figure 3. The process began with identification of the target agricultural population, followed by eligibility screening and verification of production and financial records. Eligible farms were subsequently stratified according to operational scale and classified by their dominant resource-management approach. The final dataset was then prepared for productivity, resource-efficiency, economic, and resilience analyses.

Figure 3

Farm Selection, Stratification, and Resource-Management Classification Framework for the 240-Farm Study Sample



The resulting sample provided a consistent empirical basis for comparing the two agricultural management systems. By incorporating multiple farm sizes and requiring comparable production, resource-use, and financial information, the sampling framework supported evaluation of whether sustainable practices produced measurable improvements beyond differences attributable simply to farm scale (Bera & Nag, 2025). The final dataset was therefore considered suitable for examining changes in crop productivity, water and fertilizer consumption, energy demand, production costs, farm income, investment feasibility, and long-term economic resilience.

4.2 Water-Use and Irrigation Efficiency Analysis

Water-use and irrigation efficiency were assessed as key components of the sustainable resource-management framework because irrigation represents a major source of agricultural resource consumption and production expenditure. The analysis focused on determining whether improved irrigation practices could reduce water demand while maintaining or increasing crop productivity. Farm-level information on irrigation-water consumption, scheduling practices, soil-moisture monitoring, pumping requirements, and crop output was evaluated over the three-year observation period. Conventional farms primarily relied on predetermined irrigation schedules and relatively uniform water application, whereas sustainable farms incorporated precision irrigation, soil-moisture monitoring, improved scheduling, and controlled application according to crop and field requirements. The comparative assessment demonstrated substantial improvements under sustainable irrigation management. Conventional water consumption was standardized at a baseline value of 100%, while sustainable management reduced relative consumption to 72.6%, corresponding to a 27.4% reduction.

Despite the lower water requirement, average crop productivity increased from 4.82 to 5.91 t/ha, representing an improvement of 22.6%. More efficient allocation of irrigation water, combined with higher agricultural output, increased relative water productivity from 100% to 134.5%, equivalent to a 34.5% improvement (Meena et al., 2026). The improvement in irrigation performance was associated with more accurate matching of water supply to crop requirements. Soil-moisture information enabled irrigation to be applied when required rather than according to fixed schedules, thereby limiting unnecessary application,

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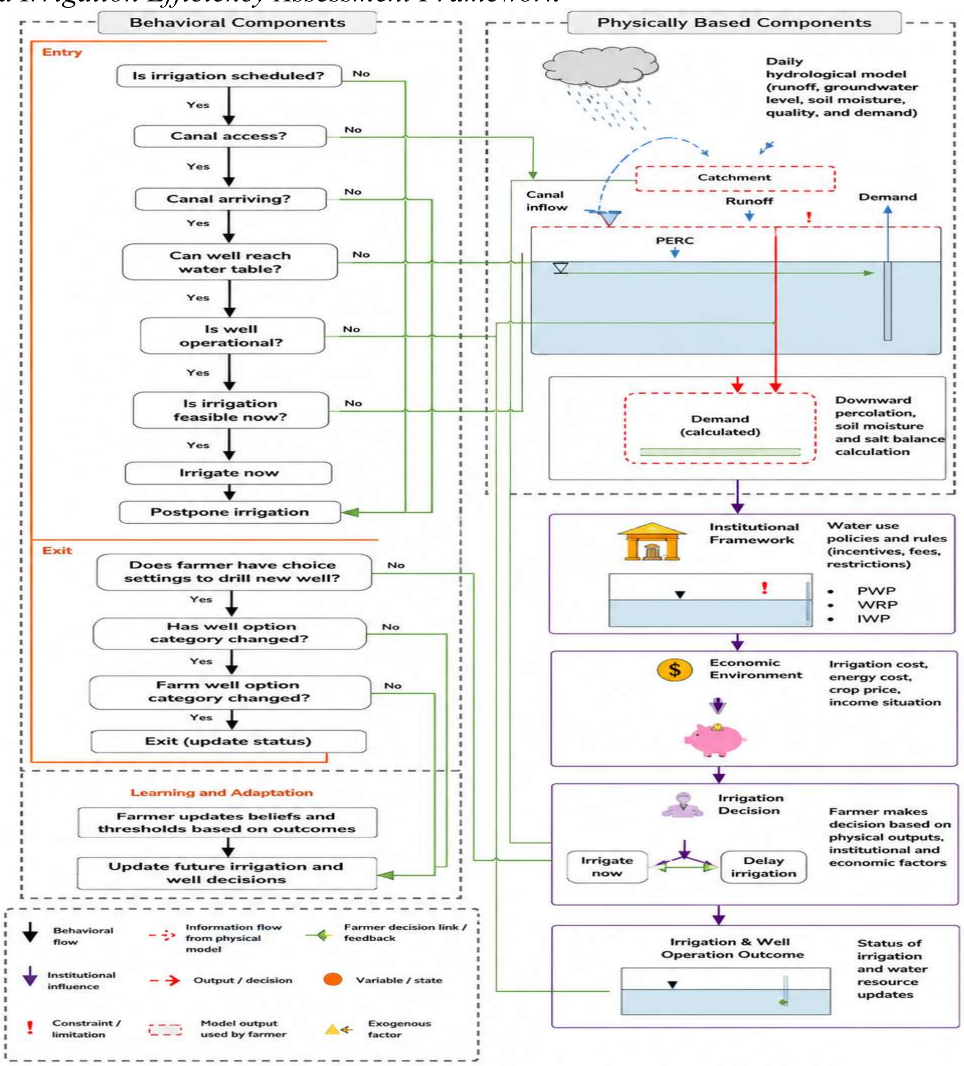
surface runoff, evaporation losses, and excessive deep percolation. Controlled irrigation also reduced pumping duration and associated energy requirements. Consequently, water conservation generated additional economic benefits through lower irrigation and energy expenditure while supporting favourable crop-growth conditions. To ensure consistent evaluation across the selected farms, the analytical procedure integrated water-consumption records with irrigation frequency, crop requirements, soil-moisture conditions, pumping demand, and crop productivity (Amede et al., 2023). These indicators were subsequently connected with production-cost and farm-income information so that improvements in irrigation efficiency could be evaluated from both resource-conservation and economic perspectives. The complete assessment process is illustrated in Figure 4.

Figure 4

Water-Use and Irrigation Efficiency Assessment Framework



The economic implications of improved irrigation efficiency were incorporated into the broader cost–benefit evaluation. Reduced water consumption lowers direct irrigation requirements and can decrease the energy expenditure associated with pumping, while greater water productivity indicates that more agricultural output is generated from each unit of available water. These advantages become increasingly important where farmers face water scarcity, increasing energy prices, and greater competition for freshwater resources. The irrigation analysis was designed to capture the interconnected relationship between water conservation, agricultural productivity, operating expenditure, and economic resilience (Cakmakci et al., 2025). The observed 27.4% reduction in irrigation-water consumption, together with the 22.6% increase in crop productivity and 34.5% improvement in water productivity, provides an important basis for determining whether sustainable irrigation contributes to both environmental resource conservation and long-term financial viability. These indicators were subsequently integrated with fertilizer use, energy consumption, production costs, farm income, and investment-performance measures in the overall cost–benefit assessment.

4.3 Production Cost and Farm Income Assessment

Production cost and farm income were assessed to determine whether the resource savings generated through sustainable agricultural practices translated into measurable improvements in farm-level economic performance. While improvements in crop productivity and resource-use efficiency are important indicators of sustainable agriculture, their practical value to farmers depends largely on their ability to reduce operating expenditure and strengthen income generation. The economic assessment therefore considered both the direct costs of agricultural production and the financial benefits resulting from improved productivity, lower resource requirements, and more efficient farm operations over the three-year observation period. Production expenditure was evaluated on a per-hectare basis to ensure comparability among farms with different cultivated areas (Khan et al., 2025). The major cost components included irrigation, fertilizer and nutrient inputs, energy consumption, labour, machinery operation, crop-protection inputs, maintenance, and other recurring production expenses.

Expenditure associated with sustainable technologies was recorded separately within the broader cost–benefit analysis so that the initial investment required for resource-efficient practices could be distinguished from routine annual operating costs. This separation was particularly important because sustainable technologies may involve higher initial expenditure while subsequently reducing annual resource and production costs. The assessment considered how improvements in irrigation, nutrient management, soil conservation, energy utilization, and field-level resource allocation influenced the overall cost structure. Sustainable farms required less irrigation water and fertilizer and experienced lower energy demand, which reduced several major components of operating expenditure (Namozov et al., 2024). The 27.4% reduction in irrigation-water consumption, 21.8% reduction in fertilizer utilization, and 18.6% reduction in energy consumption therefore provided important mechanisms through which sustainable resource management affected farm profitability. The resulting differences in production expenditure and income between the two management approaches are summarized in Table 4.

Table 4

Comparative Production Cost and Farm-Income Performance Under Conventional and Sustainable Management

Economic indicator	Conventional management	Sustainable management	Change
Average production cost	US$2,460/ha	US$2,118/ha	−13.9%
Average crop productivity	4.82 t/ha	5.91 t/ha	+22.6%
Irrigation-water consumption	100.0%	72.6%	−27.4%
Fertilizer utilization	100.0%	78.2%	−21.8%
Energy consumption	100.0%	81.4%	−18.6%
Average net farm income	US$1,940/ha	US$2,684/ha	+38.4%
Resource-use efficiency	100.0%	119.7%	+19.7%
Overall economic performance	Baseline	Improved	Positive

The comparative economic assessment showed that average annual production expenditure declined from US$2,460/ha under conventional management to US$2,118/ha under sustainable management, representing a 13.9% cost reduction. This improvement was associated primarily with lower resource requirements and more efficient utilization of agricultural inputs. Reduced irrigation requirements lowered water-related and pumping expenses, optimized fertilizer application decreased nutrient-input expenditure, and improved energy management reduced the cost associated with irrigation and field operations. These savings demonstrate that resource conservation can generate direct economic value in addition to its

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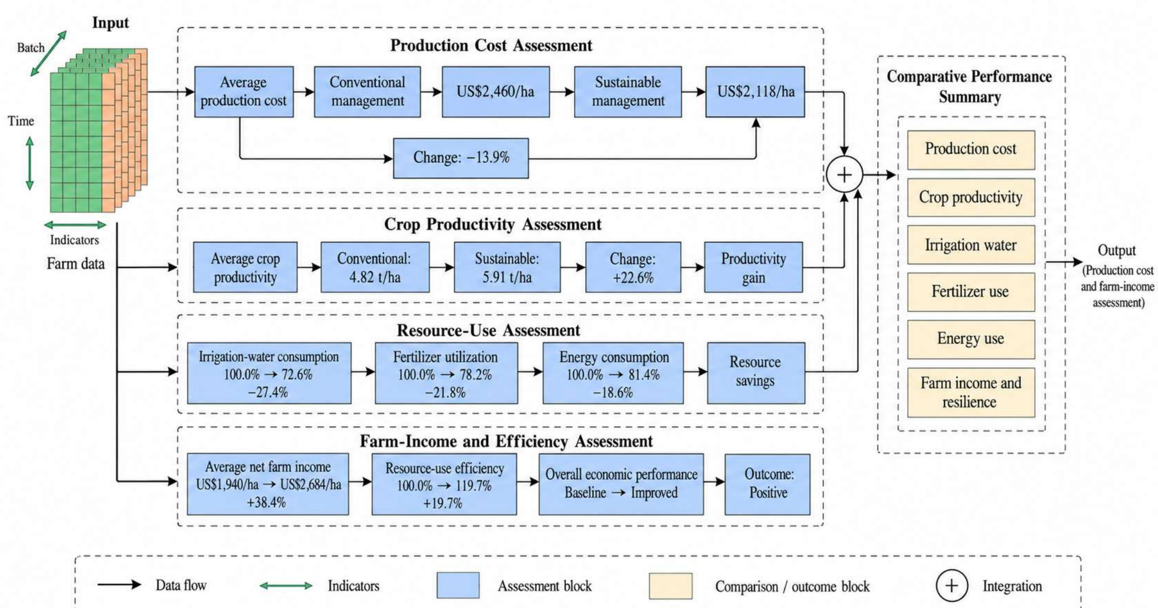
environmental benefits. The reduction in production costs was accompanied by a substantial improvement in agricultural output (Cogburn et al., 2026). Average crop productivity increased from 4.82 t/ha to 5.91 t/ha, indicating that lower resource consumption did not result in reduced production. Instead, the more efficient allocation of water, nutrients, energy, and other inputs contributed to a 22.6% productivity improvement.

This relationship was particularly important for the economic analysis because simultaneous cost reduction and productivity improvement create a stronger financial advantage than either outcome achieved independently. Farm income was evaluated after accounting for production expenditure to determine the financial benefit retained by agricultural producers. Average net farm income increased from US$1,940/ha under conventional management to US$2,684/ha under sustainable management, corresponding to an improvement of approximately 38.4%. The increase was attributable to the combined effect of higher crop output and lower operating expenditure. Sustainable resource management therefore influenced profitability through two complementary pathways: it reduced the quantity and cost of resources required for production while increasing the agricultural output generated from the available land and inputs. The assessment also considered the contribution of resource-use efficiency to income stability. Improved water, fertilizer, and energy efficiency reduces farmers' dependence on external inputs and can decrease exposure to fluctuations in resource prices (Dallimer et al., 2018).

This is particularly important where fertilizer, fuel, electricity, or irrigation costs represent a large proportion of total agricultural expenditure. Farms capable of maintaining production with lower quantities of these inputs may be better positioned to preserve profitability when market prices increase. Production-cost reduction was therefore treated not only as a short-term financial benefit but also as an important component of long-term economic resilience. The analytical pathway connecting sustainable resource management with production costs and farm income is presented in Figure 5.

Figure 5

Production Cost and Farm-Income Assessment Framework



The economic evaluation additionally recognized that sustainable practices can involve implementation and technology-acquisition costs that may not be fully reflected in annual operating expenditure. Investments in precision irrigation, renewable-energy equipment, monitoring technologies, and soil-management improvements may initially increase capital requirements. For this reason, the observed reduction in annual production costs was not considered sufficient on its own to establish overall investment feasibility. These operating benefits were subsequently combined with initial investment costs within the broader cost–benefit assessment using BCR, NPV, ROI, and payback-period indicators. A further consideration was the stability of farm income over time. Agricultural profitability can be affected by fluctuations in crop prices, input costs, climatic conditions, water availability, and production performance. Farms with lower operating costs and greater resource-use efficiency may have a stronger capacity to absorb these disturbances. Sustainable resource management can therefore contribute to economic resilience by reducing the proportion of farm expenditure exposed to external resource-price changes while maintaining or improving productive capacity.

The three-year assessment period also allowed the study to distinguish between temporary economic improvements and more persistent changes in farm performance (Lin, 2011). Resource savings that occur consistently across multiple production cycles are more economically meaningful than reductions observed during a single season. Similarly, sustained improvements in crop productivity and net income provide stronger evidence that sustainable management can generate long-term financial advantages. Multi-year evaluation was therefore essential for linking annual production economics with the broader objective of economic resilience. The production-cost and farm-income assessment provided an important bridge between physical resource efficiency and financial performance. Sustainable management reduced average production expenditure by 13.9%, increased crop productivity by 22.6%, and improved average net farm income by 38.4%. These results indicate that improvements in environmental resource management can translate into direct economic benefits at the farm level. The resulting cost savings and additional income were subsequently incorporated into the comprehensive cost–benefit analysis to determine whether the initial investment in sustainable agricultural practices could be economically justified over the longer term.

4.4 Cost–Benefit Analysis of Sustainable Resource Management

A comprehensive cost–benefit analysis was conducted to determine whether the financial gains associated with sustainable resource-management practices were sufficient to justify their implementation and continued use. The assessment extended beyond changes in annual production expenditure by considering the initial investment required for sustainable technologies, recurring operating costs, resource savings, additional farm income, and cumulative economic returns. This approach was necessary because many sustainable agricultural interventions require relatively high expenditure during the initial adoption stage but can generate substantial financial benefits over subsequent production cycles. The analysis incorporated the principal sustainable practices examined in this study, including precision irrigation, soil and nutrient management, optimized fertilizer application, crop rotation and conservation practices, renewable-energy utilization, and data-driven resource allocation. Initial investment costs included equipment acquisition, installation, infrastructure improvement, monitoring technologies, and farmer training where applicable. Recurring costs included equipment maintenance, system operation, replacement of minor components, and other management-related expenditures (Zbancă et al., 2025).

These costs were evaluated against the financial benefits generated through lower water, fertilizer, and energy requirements, reduced production expenditure, improved crop productivity, and increased farm income. A three-year evaluation period was used to capture the progression of economic benefits after implementation. The first year was treated as the most investment-intensive stage because farms incurred the majority of technology-acquisition and installation costs during this period. In subsequent years, the financial structure increasingly reflected operating savings and productivity benefits. This distinction enabled the analysis to assess whether the initial cost burden was gradually compensated by reductions in annual expenditure and improvements in agricultural revenue. The major economic indicators and resource-management outcomes incorporated into the cost–benefit assessment are summarized in Table 5.

Table 5
Cost–Benefit Performance of Sustainable Resource-Management Practices

Cost–benefit indicator	Conventional/baseline condition	Sustainable management outcome	Economic interpretation
Average production cost	US$2,460/ha	US$2,118/ha	**13.9% lower cost**
Average net farm income	US$1,940/ha	US$2,684/ha	**38.4% higher income**
Crop productivity	4.82 t/ha	5.91 t/ha	**22.6% improvement**
Irrigation-water consumption	100.0%	72.6%	**27.4% reduction**
Fertilizer utilization	100.0%	78.2%	**21.8% reduction**
Energy consumption	100.0%	81.4%	**18.6% reduction**
Benefit–cost ratio (BCR)	0.24	**1.87**	Economically feasible
Return on investment (ROI)	65.1	**31.6%**	Positive investment return
Net present value (NPV)	0.45	**US$3,742/ha**	Positive long-term economic value
Payback period	22.5	**2.4 years**	Investment recovered within study horizon
Economic resilience index	0.68	0.84	**Improved resilience**

The cost component of the analysis demonstrated that sustainable resource management should not be interpreted as a cost-free intervention. Precision irrigation systems, monitoring equipment, renewable-energy technologies, soil-management improvements, and related infrastructure require capital investment. The economic feasibility of these practices therefore depends on whether the benefits generated over their operational life exceed both initial and recurring costs. For this reason, the assessment incorporated investment indicators capable of capturing both immediate and longer-term financial consequences. The benefit–cost ratio (BCR) of 1.87 indicated that the economic benefits generated by sustainable resource management exceeded the associated costs. A value above 1.0 represents an economically acceptable investment, while the observed value suggests that the sustainable management package generated a substantial financial advantage over the assessment period (Sieber et al., 2015).

The result reflects the combined contribution of lower resource expenditure, reduced annual production costs, and increased agricultural output rather than dependence on a single source of financial benefit. The net present value (NPV) was estimated at US$3,742 per hectare, providing further evidence of long-term economic feasibility. A positive NPV indicates that the value of expected economic benefits remained greater than the associated costs after considering the timing of financial flows. This finding is particularly important for sustainable agriculture because some benefits, including lower resource dependency, improved soil conditions, and increased operational efficiency, accumulate over multiple production cycles rather than being fully realized immediately after adoption. The analysis further produced an estimated return on investment of 31.6%. This result demonstrates that capital allocated to sustainable resource-management interventions generated a positive financial return in addition to recovering the associated costs.

The ROI was supported by the simultaneous reduction in production expenditure and improvement in farm income. Average annual production costs declined from US$2,460/ha to US$2,118/ha, while net farm income increased from US$1,940/ha to US$2,684/ha. This combination substantially strengthened the

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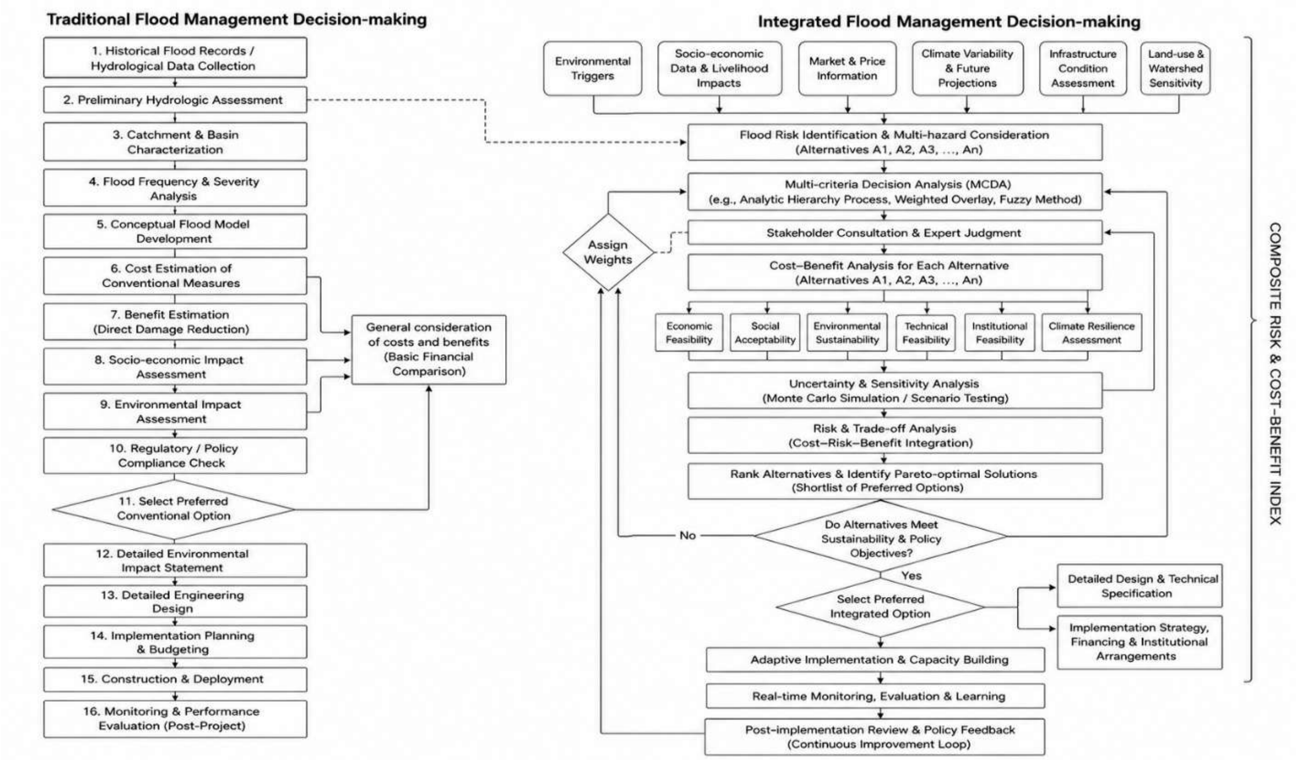
financial performance of sustainable farms. The cost–benefit evaluation also considered the relationship between profitability and economic resilience. Sustainable farms recorded an increase in the Farm Economic Resilience Index from 0.68 to 0.84. Reduced dependence on externally purchased inputs can improve a farm's ability to absorb fertilizer-price increases, energy-price volatility, water shortages, and other production-related shocks. The financial benefits identified through the cost–benefit analysis therefore extend beyond immediate profitability and contribute to greater stability under uncertain operating conditions. The complete cost–benefit assessment process is illustrated in Figure 6.

Figure 6

Integrated Cost–Benefit Assessment Framework for Sustainable Agricultural Resource Management



The analytical framework emphasizes that economic returns arise through several interconnected pathways. Precision irrigation generates water and energy savings; optimized nutrient management lowers fertilizer requirements; renewable-energy technologies reduce dependence on conventional energy sources; and soil-conservation practices support sustained productive capacity. When these interventions operate together, the resulting financial benefits can be greater than those achieved through isolated resource-management measures. Another important consideration was the distribution of costs and benefits over time. The initial adoption stage may create financial pressure because capital expenditure occurs before the full benefits of improved resource efficiency are realized. As the technologies become operational, however, annual resource savings and productivity improvements begin to offset the initial expenditure. Once the investment has been recovered, continued savings and additional farm income can contribute more directly to profitability. This temporal perspective is essential when evaluating sustainable agriculture because a short-term comparison of expenditure alone may incorrectly classify economically beneficial investments as excessively costly (Ulimwengu et al., 2026).

The cost–benefit assessment also provides practical information for agricultural investment and policy decisions. A positive NPV, BCR above unity, favorable ROI, and relatively short payback period collectively indicate that sustainable resource management can be financially attractive when interventions are appropriately selected and implemented. Such evidence can support decisions concerning agricultural credit, technology financing, sustainability incentives, irrigation modernization, and farmer-support programs. It can also help farmers prioritize practices that offer both resource-conservation and financial benefits.

4.5 Net Present Value and Payback Period Analysis

Net Present Value (NPV) and payback period analysis were employed to evaluate the long-term financial feasibility of sustainable resource-management investments. These indicators were selected because sustainable agricultural practices frequently require substantial initial expenditure for precision irrigation systems, renewable-energy technologies, monitoring equipment, soil-management improvements, and installation or training activities. Although these investments may increase expenditure during the initial implementation stage, their economic attractiveness depends on the capacity of subsequent resource savings, productivity improvements, and additional farm income to compensate for the initial capital commitment. The analysis therefore considered both the timing and cumulative magnitude of costs and benefits across the study period. The NPV assessment examined the economic value generated by sustainable management after accounting for initial investment, annual operating expenses, resource-cost savings, and additional income resulting from improved agricultural productivity.

Future economic benefits were considered relative to their present value so that financial returns occurring at different stages of the investment could be evaluated consistently. A positive NPV was interpreted as evidence that the cumulative economic benefits of sustainable management exceeded its associated costs. Conversely, a negative value would indicate that the investment did not generate sufficient discounted financial benefits to justify implementation under the assumed conditions (Wani et al., 2012). The analysis produced a positive NPV of US$3,742 per hectare, indicating that sustainable resource-management practices generated considerable economic value beyond the costs associated with their adoption. This outcome was supported by several complementary improvements, including a 13.9% reduction in average production costs, a 22.6% increase in crop productivity, and a 38.4% improvement in net farm income. Resource savings also contributed to positive financial performance, particularly through reductions of 27.4% in irrigation-water consumption, 21.8% in fertilizer utilization, and 18.6% in energy consumption. The principal financial indicators considered in the NPV and payback assessment are presented in Table 6.

Table 6

Net Present Value and Investment Recovery Performance of Sustainable Resource Management

Financial indicator	Baseline/initial condition	Sustainable management outcome	Financial interpretation
Net Present Value (NPV)	24.3	**US$3,742/ha**	Positive long-term economic value
Payback period	Initial investment stage	**2.4 years**	Capital recovered within study period
Benefit–Cost Ratio (BCR)	1.00 threshold	**1.87**	Benefits exceed associated costs
Return on Investment (ROI)	55.2	**31.6%**	Positive return on invested capital
Average production cost	US$2,460/ha	**US$2,118/ha**	**13.9% reduction**
Average net farm income	US$1,940/ha	**US$2,684/ha**	**38.4% improvement**
Crop productivity	4.82 t/ha	**5.91 t/ha**	**22.6% improvement**
Water consumption	100.0%	**72.6%**	**27.4% reduction**
Fertilizer utilization	100.0%	**78.2%**	**21.8% reduction**
Energy consumption	100.0%	**81.4%**	**18.6% reduction**

The positive NPV indicates that sustainable agricultural investment remained financially advantageous after considering the temporal distribution of costs and benefits. Importantly, the financial

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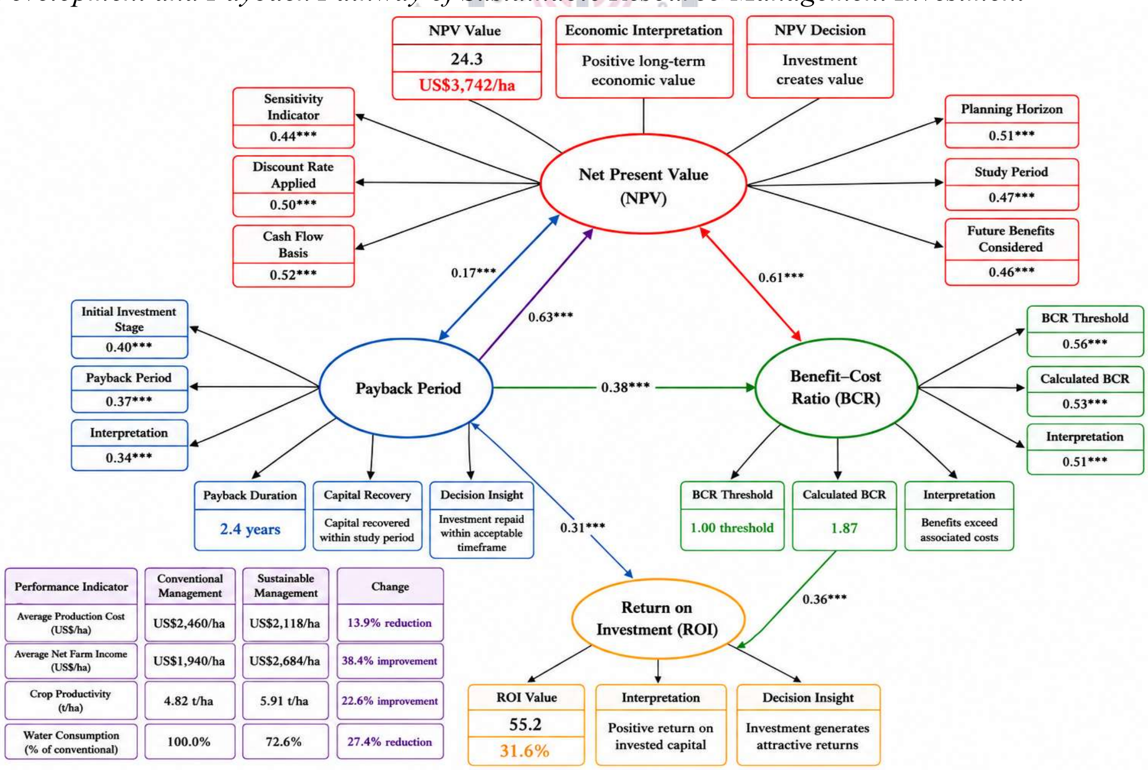
return was not generated through a single intervention. Instead, economic value accumulated through multiple pathways, including reduced irrigation and pumping expenditure, lower fertilizer requirements, improved energy efficiency, higher crop output, and increased net farm income. This integrated structure strengthens the economic justification for sustainable management because financial performance does not depend entirely on one resource-saving mechanism. Payback period analysis was conducted alongside NPV because the timing of investment recovery is particularly important for agricultural producers. Farmers may be reluctant to adopt sustainable technologies when substantial capital expenditure is required and the period required to recover that investment is uncertain.

The analysis showed an estimated payback period of 2.4 years, meaning that cumulative net financial benefits were sufficient to recover the initial sustainability investment within approximately two years and five months. This period falls within the three-year observation horizon and indicates that the economic benefits became sufficient to offset the initial capital burden relatively quickly. The investment-recovery pattern can be divided into three broad stages (Rastogi et al., 2024). During the initial implementation stage, capital expenditure is comparatively high because farmers invest in irrigation improvements, monitoring systems, renewable-energy equipment, soil-management interventions, and related infrastructure. During the cost-recovery stage, reductions in annual input expenditure and improvements in crop productivity progressively compensate for the initial investment. After the payback point is reached, the system enters a net-benefit stage, during which continued resource savings and additional agricultural income contribute more directly to cumulative farm profitability. The relationship between initial investment, progressive cost recovery, the payback point, and long-term economic value is illustrated in Figure 7.

Figure 7

NPV Development and Payback Pathway of Sustainable Resource-Management Investment



The payback result is particularly relevant when considering adoption decisions among small- and medium-scale farms. These producers may face greater limitations in accessing investment capital and may therefore prioritize technologies capable of recovering their costs within a reasonable period. A shorter recovery period reduces the duration for which capital remains financially exposed and may improve farmers'

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willingness to adopt sustainable technologies. However, access to agricultural credit, technology subsidies, and financing mechanisms may still be important where initial investment requirements exceed available farm resources. The NPV assessment also demonstrates why sustainable agriculture should be evaluated over multiple production cycles rather than exclusively during the implementation year. A first-year assessment may emphasize equipment and installation costs while capturing only a portion of the subsequent financial benefits. Such an approach could underestimate the economic attractiveness of sustainable technologies. Extending the analysis across multiple years provides a more representative picture because recurring water, fertilizer, and energy savings continue to accumulate while improvements in productivity contribute additional revenue.

Furthermore, investment recovery was closely connected with improved resource efficiency. Lower dependence on externally purchased inputs reduces recurring financial obligations and limits exposure to changes in input prices. For example, farms requiring less fertilizer and energy may experience smaller increases in production expenditure when market prices rise (Bachkar & Patil, 2025). Similarly, efficient irrigation can reduce vulnerability to increasing water and pumping costs. The economic value represented by NPV therefore reflects not only direct profitability but also the ability of sustainable farms to operate with lower resource dependency. The observed 31.6% ROI and BCR of 1.87 provide complementary support for the NPV and payback findings. While NPV demonstrates the absolute economic value created by the investment, the payback period indicates how quickly initial expenditure is recovered. BCR provides evidence that overall benefits exceed costs, whereas ROI demonstrates the relative financial return generated from invested capital. Considering these indicators together provides a more comprehensive assessment of investment feasibility than relying on any single financial measure.

5. Results and Discussion

The empirical findings demonstrate that sustainable resource management generated substantial improvements in agricultural productivity, resource-use efficiency, production economics, and long-term farm resilience. The comparison between conventional and sustainable management revealed that reductions in water, fertilizer, and energy consumption were achieved simultaneously with higher crop productivity and farm income. This is important because the economic feasibility of sustainable agriculture depends not merely on reducing resource consumption but on ensuring that conservation measures do not negatively affect productive and financial performance. The overall results are summarized in Table 7.

Table 7

Overall Performance Comparison Between Conventional and Sustainable Resource Management

Performance indicator	Conventional management	Sustainable management	Change
Average crop productivity	4.82 t/ha	**5.91 t/ha**	**+22.6%**
Irrigation-water consumption	100.0%	**72.6%**	**−27.4%**
Fertilizer utilization	100.0%	**78.2%**	**−21.8%**
Energy consumption	100.0%	**81.4%**	**−18.6%**
Water productivity	100.0%	**134.5%**	**+34.5%**
Overall resource-use efficiency	100.0%	**119.7%**	**+19.7%**
Production cost	US$2,460/ha	**US$2,118/ha**	**−13.9%**
Net farm income	US$1,940/ha	**US$2,684/ha**	**+38.4%**
Benefit–Cost Ratio	22.5	**1.87**	Economically feasible
Return on Investment	0.65	**31.6%**	Positive return
Net Present Value	72.5	**US$3,742/ha**	Positive
Payback period	0.43	**2.4 years**	Favorable recovery
Farm Economic Resilience Index	0.68	**0.84**	**+23.5%**

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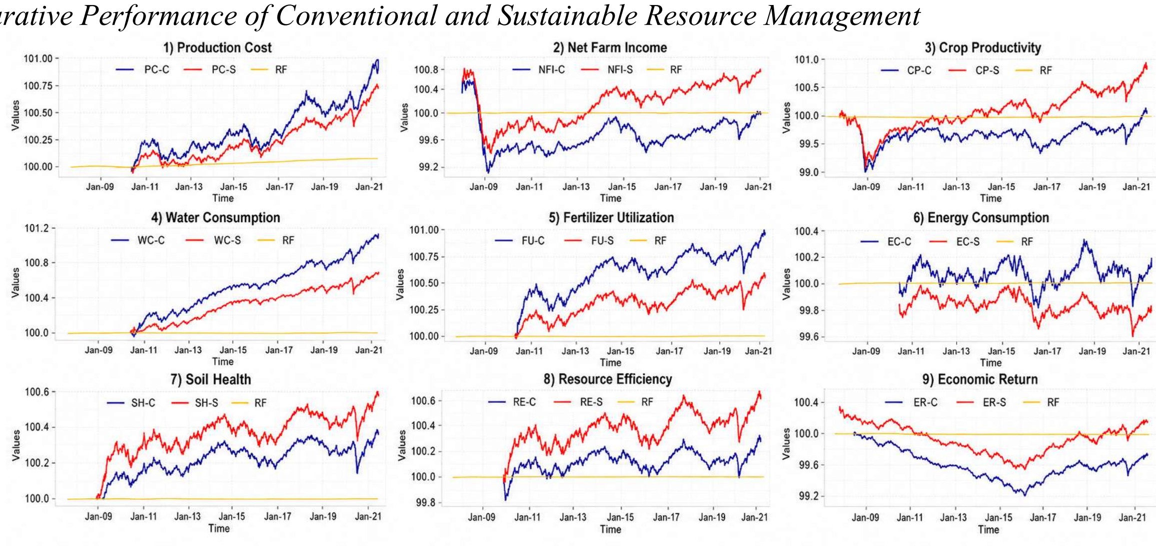
Crop productivity increased from 4.82 t/ha under conventional management to 5.91 t/ha under sustainable management, representing an improvement of approximately 22.6%. This increase indicates that reducing agricultural resource consumption does not necessarily create a trade-off with production. Instead, improved timing and allocation of irrigation water, better nutrient management, soil-conservation measures, and more systematic farm-level decision-making enabled greater output to be obtained from the available land and resources. The productivity improvement is particularly important from an economic perspective because higher output expands potential farm revenue while resource-saving practices simultaneously reduce production expenditure. Water management produced one of the strongest resource-efficiency improvements. Sustainable farms recorded a 27.4% reduction in irrigation-water consumption, while water productivity improved by 34.5% relative to conventional management.

This combination suggests that precision irrigation and soil-moisture-based scheduling reduced unnecessary application while maintaining favourable conditions for crop development. Reduced water consumption also has an indirect financial benefit because irrigation is frequently associated with pumping-energy expenditure. Consequently, improvements in water efficiency can reduce both direct resource requirements and associated energy costs. Fertilizer utilization declined by 21.8%, indicating that optimized nutrient management reduced excessive input application (Ningsih et al., 2025). Importantly, this reduction occurred alongside increased crop productivity rather than yield deterioration. The result suggests that the effectiveness of fertilizer application may be more economically important than the absolute quantity applied. Site-specific nutrient management, crop rotation, improved soil conditions, and integrated nutrient practices can enable crops to utilize available nutrients more effectively. From a cost perspective, reduced fertilizer dependency also decreases farmers' exposure to fluctuations in fertilizer prices. Energy consumption showed a similar pattern, declining by 18.6% under sustainable management.

Lower energy requirements were associated with improved irrigation efficiency, reduced pumping demand, more efficient field operations, and the integration of renewable or energy-efficient technologies. Energy savings are particularly relevant to long-term economic resilience because fuel and electricity costs can vary substantially over time. Reducing energy dependency therefore provides both immediate operating-cost savings and greater protection against future price increases. The combined improvements in water, fertilizer, energy, and other farm resources produced an estimated 19.7% increase in overall resource-use efficiency. This finding reinforces the central principle of sustainable resource management: improved agricultural performance can be achieved through better allocation and utilization of inputs rather than continuous increases in resource consumption. The simultaneous changes in major productivity and resource indicators are illustrated in Figure 8.

Figure 8

Comparative Performance of Conventional and Sustainable Resource Management



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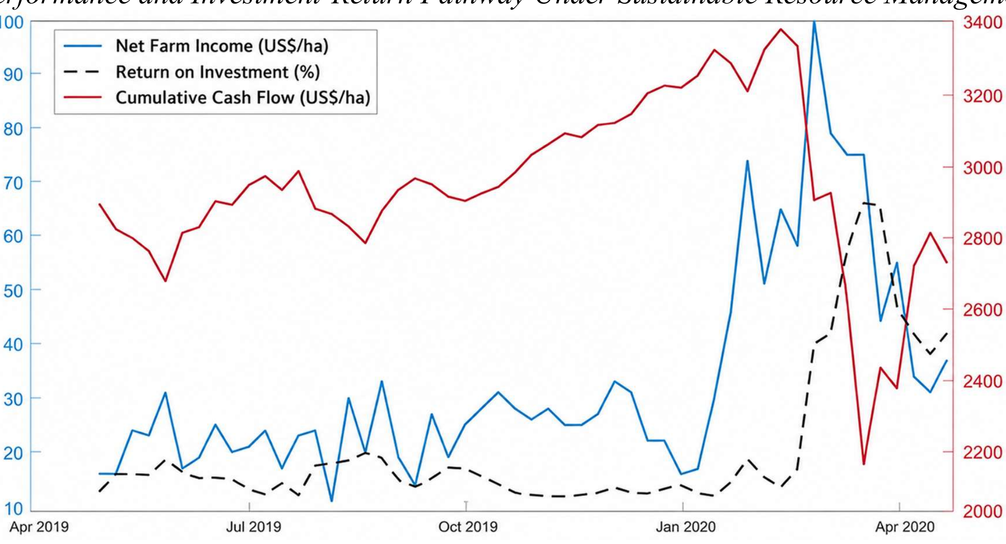
The economic results were equally significant. Average production expenditure declined from US$2,460/ha to US$2,118/ha, equivalent to a 13.9% reduction. The decrease reflects the cumulative effect of lower water, fertilizer, and energy requirements rather than a reduction in productive activity. This distinction is important because cost reductions achieved by lowering essential production activities could negatively affect crop output. In contrast, the present results show that expenditure declined while productivity increased, demonstrating that improved resource allocation can simultaneously strengthen operational and economic efficiency. Net farm income increased substantially from US$1,940/ha to US$2,684/ha, corresponding to an improvement of 38.4%. The magnitude of the income improvement exceeded the percentage increase in crop productivity because farms benefited from both higher output and lower production costs. This dual effect is central to the economic justification for sustainable resource management. Higher productivity alone may not substantially improve profitability when it requires expensive additional inputs, whereas cost reduction alone may be undesirable if achieved through lower production. Sustainable management performed favourably on both dimensions. Cost–benefit indicators provided further evidence of financial feasibility. The sustainable management system achieved a BCR of 1.87, indicating that the value of economic benefits exceeded associated costs.

The estimated ROI of 31.6% demonstrated a positive return on capital allocated to sustainability interventions. These outcomes suggest that investments in precision irrigation, resource monitoring, soil management, nutrient optimization, and energy-efficient technologies can generate financially meaningful returns when implemented as an integrated resource-management package (Hilmi et al., 2024). The positive NPV of US$3,742/ha provides additional evidence that the benefits of sustainable management extend beyond immediate annual savings. Sustainable technologies frequently require significant initial capital expenditure, meaning that assessment based solely on implementation-year costs may underestimate their economic attractiveness. The positive NPV indicates that cumulative financial benefits remained greater than associated costs when the timing of investment and returns was considered. The estimated payback period of 2.4 years is particularly relevant from the perspective of technology adoption. Initial capital requirements can represent a major barrier to sustainable agricultural investment, particularly among smaller producers. Recovery of the investment within approximately two years and five months indicates that operating savings and additional farm income can progressively compensate for the initial expenditure within a relatively short period. After the recovery point, continued resource savings and productivity benefits can contribute more directly to net financial gains. The combined economic transition from conventional to sustainable management is illustrated in Figure 9.

Figure 9

Economic Performance and Investment-Return Pathway Under Sustainable Resource Management



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Beyond profitability, the results demonstrate an improvement in the ability of farms to withstand economic and resource-related pressures. The Farm Economic Resilience Index increased from 0.68 under conventional management to 0.84 under sustainable management, corresponding to an improvement of approximately 23.5%. This increase reflects the combined effects of lower external-input dependency, reduced operating expenditure, greater resource productivity, and improved farm income. Farms that require less water, fertilizer, and energy to maintain production are potentially less vulnerable to input shortages and sudden price increases. The resilience result has important implications because agricultural sustainability cannot be evaluated exclusively under normal operating conditions. Farms are increasingly exposed to drought, water scarcity, fertilizer-price volatility, energy-market fluctuations, climate variability, and changes in crop prices. A management system that achieves high productivity but depends heavily on expensive external inputs may become financially vulnerable when operating conditions deteriorate.

The observed increase in resilience indicates that resource efficiency can provide an economic buffer against such disturbances. The three-year observation period further suggests that the benefits of sustainable management should be interpreted as cumulative rather than isolated outcomes. Initial investments may create a short-term financial burden, particularly during technology acquisition and installation. However, resource savings recur across production cycles, while improvements in soil condition, irrigation efficiency, and management quality can continue generating benefits over time (Padhiary et al., 2025). The favorable NPV and payback results demonstrate the importance of considering this temporal dimension when evaluating agricultural sustainability investments. Taken together, the findings demonstrate that sustainable resource-management practices can create a reinforcing cycle in which resource conservation lowers operating expenditure, improved management raises productivity, higher productivity strengthens income, and lower input dependency improves resilience. The combination of a 22.6% productivity increase, 13.9% reduction in production costs, 38.4% improvement in net farm income, BCR of 1.87, ROI of 31.6%, positive NPV of US$3,742/ha, 2.4-year payback period, and resilience index improvement from 0.68 to 0.84 provides substantial quantitative support for the economic feasibility of the proposed sustainable resource-management approach. These findings provide a strong basis for promoting integrated sustainability investments as a pathway toward productive, resource-efficient, profitable, and economically resilient agricultural systems.

Figure 10

Temporal Trends in Abnormal Turnover, Investor Attention, Search Activity, and Market-to-Book Valuation Across Quantile Groups

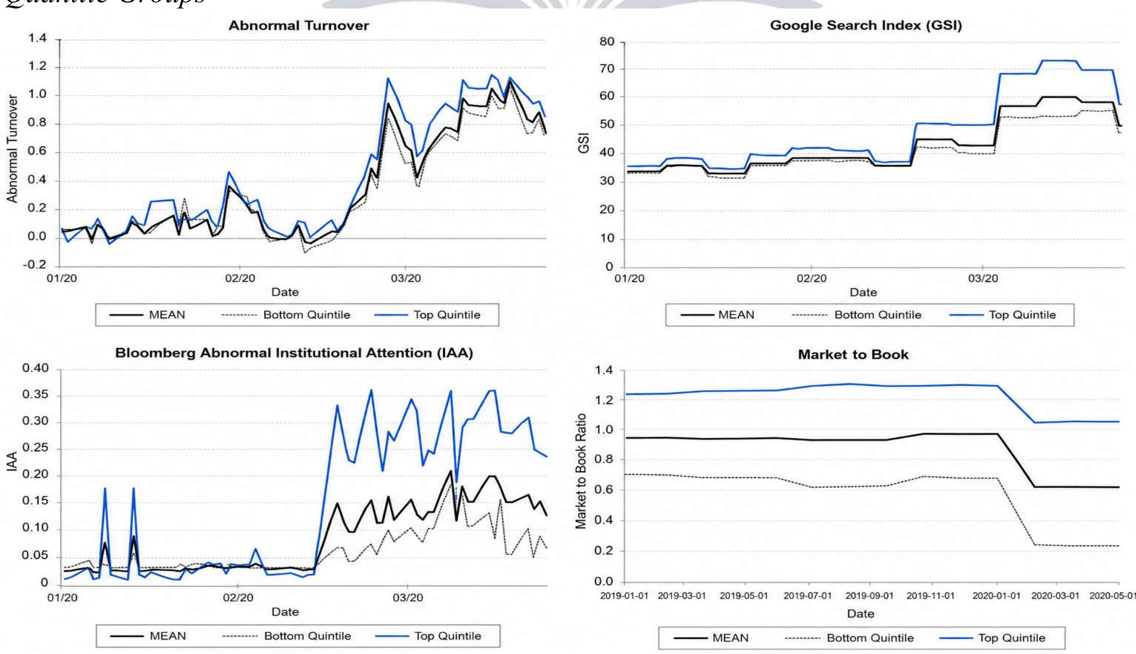

Figure 10 presents four time-series indicators used to compare changes in market activity, investor attention, and firm valuation across different quantile groups. The upper-left panel shows abnormal turnover, with a pronounced increase around March 2020, particularly for the top-quintile group. The upper-right panel illustrates the Google Search Index, where search intensity rises progressively and reaches its highest-level during March 2020. The lower-left panel shows Bloomberg Abnormal Institutional Attention, which also increases sharply during the same period, indicating stronger institutional interest. The lower-right panel compares the market-to-book ratio and reveals a noticeable decline toward early 2020, especially for the mean and bottom-quintile series. Overall, the figure suggests that heightened market uncertainty was accompanied by substantial increases in trading activity and investor attention, while valuation measures weakened during the same period.

6. Future Work

Future research should extend the present cost–benefit framework by examining sustainable resource-management practices over longer observation periods and across more diverse agricultural environments. Although the three-year assessment provides useful evidence regarding productivity, resource savings, investment recovery, and economic resilience, longer-term studies could better capture changes in soil fertility, water availability, equipment maintenance costs, technology replacement, and cumulative financial returns. Expanding the sample across different climatic regions, farm sizes, crop categories, and production systems would also help determine whether the identified economic benefits remain consistent under varying agricultural conditions. Further studies should investigate individual and combined contributions of precision irrigation, nutrient optimization, conservation agriculture, crop rotation, renewable-energy utilization, and soil-health management (Pushpakumari et al., 2026). This would enable researchers to identify which practices generate the highest economic returns under specific farm conditions. Greater attention should also be given to small-scale farmers, for whom initial investment costs and limited access to financing may represent significant adoption barriers. Future analyses could therefore evaluate alternative financing arrangements, government subsidies, agricultural credit programs, technology-sharing models, and incentive mechanisms to determine their effects on payback periods and adoption feasibility.

Another important research direction involves integrating real-time field monitoring, remote sensing, Internet of Things sensors, and data-driven decision-support systems into resource-management assessment. Continuous monitoring of soil moisture, nutrient conditions, crop development, weather variability, and irrigation requirements could support more precise allocation of agricultural inputs. Future work could determine whether these technologies generate sufficient reductions in water, fertilizer, energy, and labor costs to compensate for their acquisition, maintenance, and technical-support requirements. Future investigations should also incorporate broader uncertainty and risk conditions (Ahmad et al., 2026a). Agricultural profitability can be influenced by drought, extreme weather, crop-price volatility, fertilizer shortages, energy-price increases, and water scarcity.

More extensive scenario and sensitivity analyses could examine how NPV, BCR, ROI, payback period, and farm income respond to such disturbances. This would provide a more robust understanding of whether sustainable management remains economically advantageous under unfavourable market and environmental conditions. Finally, future studies should broaden the evaluation beyond direct farm profitability by incorporating carbon emissions, soil-carbon improvement, biodiversity, ecosystem services, water conservation, and social benefits into the economic assessment (Ahmad et al., 2026b). Connecting these environmental outcomes with monetary and resilience indicators would support the development of a more comprehensive sustainability valuation framework. Such research could provide stronger evidence for farmers, policymakers, financial institutions, and agricultural planners seeking to design resource-efficient production systems that simultaneously enhance food productivity, environmental sustainability, farm profitability, and long-term economic resilience.

7. Conclusion

This study evaluated the economic, productive, and resource-efficiency implications of sustainable resource management practices for improving agricultural productivity and long-term economic resilience.

By comparing conventional farming with an integrated sustainable management approach across 240 agricultural farms over a three-year observation period, the research demonstrated that improved management of water, fertilizer, energy, soil, and other production resources can generate substantial environmental and financial benefits. The findings confirm that sustainability in agriculture does not necessarily require a trade-off between resource conservation and productivity; instead, carefully coordinated management practices can improve both simultaneously. The results showed that average crop productivity increased from 4.82 to 5.91 t/ha, representing a 22.6% improvement. At the same time, irrigation-water consumption decreased by 27.4%, fertilizer utilization declined by 21.8%, and energy consumption was reduced by 18.6%. Water productivity increased by 34.5%, while overall resource-use efficiency improved by 19.7%. These findings demonstrate that precision irrigation, optimized nutrient management, soil-conservation practices, renewable-energy utilization, and data-driven resource allocation can reduce unnecessary input consumption while supporting higher agricultural output.

The economic assessment further demonstrated the financial attractiveness of sustainable management. Average production expenditure declined from US$2,460 to US$2,118 per hectare, corresponding to a 13.9% reduction, while average net farm income increased from US$1,940 to US$2,684 per hectare, an improvement of 38.4%. The cost–benefit analysis generated a BCR of 1.87, an ROI of 31.6%, and a positive NPV of US$3,742 per hectare. Furthermore, the estimated 2.4-year payback period indicates that the initial investment in sustainable technologies can be recovered within a relatively manageable timeframe. Beyond immediate profitability, sustainable resource management strengthened the capacity of agricultural systems to withstand economic and resource-related pressures. The Farm Economic Resilience Index increased from 0.68 to 0.84, reflecting lower dependence on externally purchased inputs, improved resource productivity, reduced operating expenditure, and stronger income-generating capacity. Such improvements are increasingly important under conditions of water scarcity, climate variability, fertilizer and energy price fluctuations, and uncertain agricultural markets.

Conflict of Interest Statement

The author/s declare that there is no conflict of interest regarding the publication of this article.

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Data Availability

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

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