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Balancing Soil Fertility and Water Resource Management for Sustainable Environment

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ABSTRACT

To minimize the deleterious environmental consequences and promote soil sustainability without affecting plant productivity, it is imperative that soil fertility management is utilized in conjunction with water resource management in sustainable agricultural production. Therefore, the objectives of this study were to determine the impact of different soil fertility levels combined with varied water management strategies on soil properties, water and nutrient use efficiencies, plant growth and yield and other environmental and economic indicators. The study was laid out in factorial design replicated thrice with treatment application in the main plots. The results indicate that integrated management, particularly high soil fertility and optimized irrigation level (S3W2) treatment, improved several soil physical and chemical characteristics; biological properties; water and nutrient use efficiency; plant growth, grain and aboveground biomass yield; net return and benefit to cost ratio; and environmental indicators such as C sequestration and nutrient loss. The integrated specific effects on these variables demonstrated the feasibility of the intervention in synchronizing nutrient and water management for sustainable intensification and resource-use and environmental protection. The future studies should include the long-term impact and impact on GHG emissions and the potential and scale up of the integrated practices in diverse agro-ecological systems.

INTRODUCTION

Soil fertility and water resource management are two related pillars that support agricultural productivity and environmental health (Ndegwa *et al.*, 2023). Owing to the rapid rise in global consumer demand for food, fiber, and fuel, exacerbated further by the negative impacts of climatic change, the environmental resources which include soil and water have been overburdened (Wijerathna-Yapa & Pathirana, 2022). Examples of the fastest up farming practices include monocropping, excessive use of synthetic chemicals, undesirable farming schemes, such as pesticide overuse, and improper irrigation for a livable environment; these include commons and the usage of fresh water (Hossain *et al.*, 2022). Here, maintaining the ideal equilibrium between maintaining and degradation of soil fertility and proper water use and disposal is vital for current and future generations of individuals (Kabato *et al.*, 2025).

Soil fertility is the basis of crop production; it is its ability to provide the plant with essential nutrients in due course and in the optimal amount of each nutrient (Tang, 2024). Unfortunately, the continuity of soil cultivation and excessive reliance on chemical fertilizers automatically lead to a nutrient imbalance, lower soil organic matter content, and suppression of beneficial microbial activity (Kartini *et al.*, 2024). As a result, land degradation, which is not limited to a decrease in yield but also has a significant contribution to greenhouse gas emissions and the imbalance of ecosystems, takes place (Kaiser, 2021). Water scarcity and poor irrigation quality only strengthen soil salinity, erosion, and nutrient leaching, making land degradation even more severe (Assouline *et al.*, 2015; Tarolli *et al.*, 2024). Therefore, soil and water resources sustainability should not be viewed as two separate components of the agricultural process.

Water is the primary natural resource required for life and vital for agriculture and supporting ecosystems (Randhir, 2012). However, the abuse and overdependence of water for agricultural purposes have adverse effects such as over-dependence on water, leading to the drying of water tables (Ercin, 2019). In addition, several agrochemicals have been used for the pollution of water bodies and the wastage of water due to high evaporation rates. Overall, agriculture accounts for almost 70% of the total freshwater use worldwide (Parris, 2011). Additionally, a substantial amount of supplied water used for irrigation evaporates or is lost through runoff activities due to the application of improper irrigation systems (Levidow *et al.*, 2014). Similarly, climate change increases climate variability by altering rainfall patterns, significantly affecting water availability (Ayanlade *et al.*, 2022).

Healthy soil and water systems are central to sustainable environmental management owing to their interdependence (Panda, 2025). In this regard, healthy soils increase water infiltration, retention, and filtration, thereby minimizing surface runoff and subsequently, erosion (Firoozi & Firoozi, 2024). On the other hand, water promotes microbial processes in nutrient cycling, which is vital in maintaining soil fertility (Chen *et al.*, 2024). For instance, practices such as conservation agriculture, addition of organic amendments, and agroforestry enhance soil and water conservation since they increase soil structure, organic matter, and diversity (Srivastava *et al.*, 2024). Moreover, these practices enhance

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nutrient cycling and mitigate the adverse impacts of floods and droughts, which are exacerbated by climatic stressors. Hence, agroecosystems become more resilient to the effects of climate. More so, sustainable soil and water management have been a crucial component in global policies like the United Nations' Sustainable Developmental Goals (Lal *et al.*, 2021). Governments and agricultural research have been at the forefront of integrated soil-water management amid increasing realization of the significance of sustainability (Olarewaju *et al.*, 2025). Activities of this nature include precision agriculture using sensors and data analytics to optimize fertilizer and water application. Measures that enhance soil health monitoring, promoting farmer education, and fostering user of soil-friendly fertilizer and antibiotic are paramount (Parra-López *et al.*, 2025).

On the whole, while a lot of progress regarding sustainable agriculture in this domain has been made, important challenges remain. They depend on limited farmer acceptance and recognition, inadequate infrastructure for efficient irrigation, and the cost of the sustainable inputs (Behera *et al.*, 2026). Moreover, compelled by land-use changes, population growth, and industrial pollution, the soil and water resources have been further pressured. Thus, new holistic management approaches that combine new technological inventions, old known to us tradition, practices, and cutting edge environmental policies are urgently needed.

LITERATURE REVIEW

The Scale and Drivers of Soil Degradation and Water Stress

One of the critical threats to people and ecosystems worldwide is soil degradation, manifested as loss of organic matter, erosion, salinization, compaction, and contamination (Ferreira *et al.*, 2022). The current knowledge base suggests that a significant fraction of global soils are moderately to highly degraded, with the loss of soil organic carbon and nutrient capital continuing due to intensive tillage, monoculture planting, residue removal, overgrazing and deforestation (Kundu & Biswas, 2025). The decrease in soil quality directly decreases water infiltration and storage, increasing the amount of runoff and erosion and weakening crop resistance to drought (Firoozi & Firoozi, 2024). These findings are tightly linked with freshwater stress: the majority of extracted freshwater is used globally by agriculture, and inefficient irrigation and agrochemical leaching reduce water quality and availability even further. The connections between soil quality and water insecurity are illustrated in a variety of global assessments (Ingrao *et al.*, 2023).

Integrated Soil–Water Management: Conceptual Frameworks and Evidence

Frameworks for the Integrated Soil Fertility and Water Management (ISFWM) argue that soil and water interventions should be integrated rather than adopt discrete applications to yield productivity, resource-use efficiencies, and environmental protection synergies (Ndegwa *et al.*, 2023). In ecologically fragile drylands and irrigated systems, prior empirical evidence and reviews demonstrate that ISFWM approaches may increase "soil water use efficiency" and crop yields due to the interactions among improved nutrient management and management, organic amendments, well-controlled tillage, and focused water harvesting or supplies (Ndegwa *et al.*, 2023). While the full package is well-established, the effectiveness of individual interventions is governed by soil properties, climate patterns, and socio-economic situations. Some of the recent regional research establishes outputs (Baraj *et al.*, 2024).

Conservation Agriculture, Soil Organic Matter and Water Retention

Conservation Agriculture (CA), based on minimal soil disturbance, residue retention, and crop rotations/cover cropping, has been extensively shown to lead to improved soil structure, soil organic matter, and infiltration and soil water holding capacity (Mhlanga *et al.*, 2025). Meta-analyses and long-term trials demonstrate that CA increases water infiltration and residence time, reduces runoff and evaporation, and enhances rain-use efficiency. CA also strengthens the existing and future soil fertility and the water-fertilizer effect of crops in times of unusually low rainfall and other hazards (Liu *et al.*, 2023). However, the speed and magnitude of these changes are highly dependent on climate, residue management, and the plant available water capacity of the initial soil. Some such as in high-rainfall or poorly drained systems, CA can cause unexpected troubles that are challenging to resolve except through adaptive management (Bolan *et al.*, 2024).

Organic Amendments, Biofertilizers and Nutrient Cycling

Consistent with helping maintain and rebuild soil organic matter are findings showing organic amendments, including but not limited to manure, compost, biochar, and crop residues, and biological inputs, such as biofertilizers and rhizosphere-enhancing microbes, improve nutrient retention, cation exchange capacity, and aggregate stability traits while reducing nutrient leaching into water bodies and increasing plant-available water (Omokaro *et al.*, 2024). With proper management, the total fertilizer use either remains constant or decreases with supplementing low chemical fertilizer rates with bio-organic inputs while reducing some of the environmental externalities, such as nitrate leaching and eutrophication risk (Liu *et al.*, 2021). These are integral components of soil-water stewardship because healthier soils hold more water and do not pollute off-site areas as much.

Agroforestry and Nature-Based Solutions for Soil and Water

Soil conservation and hydrological regulation are critical co-benefits of agroforestry and perennial-based systems (Pereira *et al.*, 2025). Tree-based practices substantially lower surface runoff and increase infiltration and deep-soil water storage, stabilize slopes against erosion, and use organic input to build soil organic matter (Firoozi & Firoozi, 2024). Empirical evaluations indicate that agroforestry has the ability to reduce flood damage downstream, increase groundwater charging when targeted to the optimal landscape settings, and boost microclimatic robustness in ways that offer critical nature-based integrated soil–water management (Riaz *et al.*, 2025).

Precision Agriculture, Sensor-Driven Nutrient and Irrigation Management

Remote sensing technologies, including soil and crop sensors, and intelligent machines, variable-rate applicators and data analytics, which realize the possibilities of precise spatial and temporal application of water and nutrients, have become true opportunities (Parra-López *et al.*, 2025). Precision nutrient and irrigation applications allow reducing over-applications as well as minimize leaching and runoffs, improving input-use efficiencies. The literature is overly optimistic about the potential gains, and adoption barriers in continued smallholder contexts regarding costs, technical skills, and data infrastructure remain high (Chindasombatcharoen *et al.*, 2024). The cost–benefit outcomes are positive in larger or higher valued systems but are "mixed" elsewhere.

Rainwater Harvesting, Improved Irrigation and Landscape-Scale Hydrology

Rainwater harvesting, small-scale storage, and efficient irrigation such as drip, micro-sprinkler, and practices like mulching and deficit irrigation have consistently worked in enhancing water productivity crop per unit water, particularly in semi-arid regions (Kahinda *et al.*, 2007). Meta-analysis of rainwater harvesting has revealed significant efficiency in low-rainfall areas (Zhang *et al.*, 2018). On landscapes, there is a need to combine upstream soil conservation through the construction of stone bunds with downstream water-capture infrastructure to reap the amplified benefits of reducing sedimentation of the storage and extending the productive life of new water infrastructure (Taye *et al.*, 2015).

Research Gap

Although extensive research is available on soil fertility enhancement and water resource management independently, much less information is available on comprehensive interrelated studies that provide a comprehensive understanding in the context of environmental sustainability. The majority of the existing literature dealt with nutrient management or irrigation efficiency in isolation and failed to grasp their combined consequences on soil health, water productivity, and ecosystem resilience. In addition, limited experimental published research reveals how different soil management and water management practices, such as organic amendments, conservation tillage, and precision irrigation, interact over space and time scales to optimize fertility and water resource use. While sufficient causes exist to persuade about the advantages of an integrated approach, farm results from countries such as South and Southeast Asia are still inadequate. Few developing countries in Africa have proven that these procedures are being adopted and performed. In such nations, not only is knowledge on integrated soil–water practices insufficient, while infrastructure is woefully lacking, but policies remain meager. With the emphasis on sustainable soil and water use in international frameworks such as SDGs but with few locally relevant strategies to turn this concept into reality. Hence, evidence-based, interdisciplinary, and comprehensive research to identify out the best suitable measures tailored to the specific context to harmonize soil fertility improvement and water resource management is ongoing.

Research Questions

a) How do various soil management practices affect soil fertility maintenance and their connection to water availability and use efficiency?

b) What are the best integrated approaches to improving soil nutrient status and at the same time maximizing water resources to ensure agricultural sustainability?

c) How do soil type, climatic conditions and land-use variation impact the correlation between soil fertility and conservation outcomes?

d) What are the environmental and economic implications of integrated soil-water management, and practices compared to conventional agricultural practice?

e) What policies, technologies, and farmer-level interventions can promote soil fertility and water resource balance?

Research Objectives

a) To examine the interconnection of soil fertility management methods with water resource use in agroecosystems.

b) To assess how the combined soil–water management methodologies impact the yields, soil quality, and water productivity in agriculture.

c) To make conclusions on the most promising and economic ways of preserving soil fertility with water saving.

d) To discuss the implications of specific ecological and agronomical factors on the efficiency of soil–water strategies.

e) To create a list of suggestions and policy directions for promoting equally balanced soil fertility and water use for sustainable long-term environmental outcome.

MATERIALS AND METHODS

Study Area

This study took place within different agricultural settings in Jhenaidah, Bangladesh with distinctive soil types and water accessibility conditions to guarantee the representativeness of soil–water interaction. The sites were located in a semi-humid to subtropical climates with mean temperature from 22°C to 32°C. The soils are mainly loamy to clay-loam, reacting mildly acidic to neutral, and contain a moderate amount of organic matter. Such circumstances create a favorable context to study the practices of integrated soil fertility and water control.

Experimental Design

The experiment was conducted using a factorial Randomized Complete Block Design with two main factors namely, Soil Fertility Management (S) and Water Management (W). Factor S was implemented at three levels: Conventional fertilizer application (S1), Organic amendments (S2), and Integrated nutrient management (S3). Factor W was also implemented at three levels: Conventional irrigation (W1), Efficient irrigation (W2), and Water conservation methods (W3). This made up nine treatment combinations with three replications each. Moreover, to avoid compromising the integrity of the within-treatment water managements, the individual plots were demarcated by bunds and drainage channels to prevent any lateral water movement. Finally, the experiment was conducted over two consecutive cropping seasons for sustained experimental results due to the seasonal nature of the independent variable.

Soil Sampling and Analysis

The plots were sampled both before planting and after harvest to a depth of 0-15 cm and 15-30 cm in composite by using a soil auger. The composite samples for each depth was air-dried, ground and sieved by a 2 mm mesh prior to laboratory analysis. Soil physical properties such as soil texture by hydrometer method (Bouyoucos, 1962), bulk density by core method (Blake & Hartge, 1986), and water-holding capacity by gravimetric method were determined. The chemical properties were sampled for pH and electrical conductivity (EC) using digital pH and EC meter, soil organic carbon (SOC) by Walkley and Black wet oxidation (Walkley & Black, 1934), and available nitrogen (N), estimated by Kjeldahl method, available phosphorus (P) by Olsen method (Olsen *et al.*, 1954), and available potassium (K) by flame photometer (Black, 1965). Cation Exchange Capacity (CEC) was determined by ammonium acetate. For biological properties, soil microbial biomass carbon and nitrogen were analyzed by fumigation-extraction (Vance *et al.*, 1987) and soil enzyme activities dehydrogenase and phosphatase by the method of (Tabatabai, 2018).

Water Resource Assessment

Quality and efficiency of water from the irrigation sources and water drained from the field were evaluated through sampling. Portable meters were used to determine water pH, electrical conductivity and total dissolved solids. Nutrient concentrations such as nitrates, phosphate and potassium were analyzed using APHA standard procedures (APHA, 1998). Water use efficiency (WUE) was determined as the ratio of the harvested crop yield and the total water applied. Soil moisture content in water and depth was done in three top soil layer depths; 0-15, 15-30 and 30-45 cm using a time domain reflectometry (TDR) probe. In addition, daily rainfall was collected in a standard rain gauge while the reference Evapotranspiration was estimated using the FAO Penman–Monteith equation (Allen *et al.*, 1998).

Crop Management and Yield Assessment

A crop species that is locally adapted was grown under all treatment conditions. Variability was reduced by employing a constant seed rate, spacing, and integrated pest management practices. The plant height, leaf area index, and chlorophyll content measurements were made throughout growth stages. Grain and biomass yield from all plots were measured after harvest and yield components were quantified to rate their productivity.

Data Analysis

The data were analyzed with analysis of variance under RCBD to determine the independent and interactive effects of soil fertility, water management, and their interactions.

Treatment means were separated by Least Significant Difference and Tukey's Honest Significant Difference at a 5% level of significance. The relationships among selected soil fertility indicators, water use efficiency, and yield attributes were elucidated by correlation and regression analyses. Principal Component Analysis was conducted to identify important factors influencing soil–water balance and sustainability using R software.

RESULTS AND DISCUSSIONS

Soil Physical Properties

The soil bulk density also decreased directly with soil fertility improvement and increased water management as noted by 1.41 ± 0.03 g cm^{-3} in S_1W_1 and 1.21 ± 0.03 g cm^{-3} in S_3W_2 (Table 1). Further, both water-holding capacity and soil moisture increased significantly with high fertility and low and medium irrigation. The treatment S_3W_2 was the highest with 47.8 ± 1.4% in water holding capacity and 23.4 ± 0.5 in soil moisture compared to the low performance of S_1W_1.

Table 1: Effect of soil fertility and water management on selected physical properties of soil

Treatment	Bulk density (g cm^{-3})	Water-holding capacity (%)	Soil moisture (%)
S_1W_1	1.41 ± 0.03^b	39.6 ± 1.4^c	17.2 ± 0.6^c
S_1W_2	1.35 ± 0.04^b	42.3 ± 1.2^b	19.5 ± 0.8^b
S_1W_3	1.38 ± 0.02^b	41.2 ± 0.9^{bc}	18.9 ± 0.5^{bc}

S_2W_1	1.33 ± 0.05^{ab}	44.1 ± 1.0^{b}	20.6 ± 0.7^{b}
S_2W_2	1.24 ± 0.03^{a}	46.9 ± 1.3^{a}	22.8 ± 0.6^{a}
S_2W_3	1.26 ± 0.04^{a}	45.3 ± 1.1^{ab}	21.7 ± 0.7^{a}
S_3W_1	1.31 ± 0.02^{ab}	43.5 ± 1.5^{b}	20.1 ± 0.6^{b}
S_3W_2	1.21 ± 0.03^{a}	47.8 ± 1.4^{a}	23.4 ± 0.5^{a}
S_3W_3	1.25 ± 0.04^{a}	46.0 ± 1.2^{a}	22.6 ± 0.6^{a}

Soil Chemical Properties

Table 2 shows that soil pH varied across treatments from 6.22 to 6.63 and remained within a slightly acidic to neutral range. Nevertheless, the highest values were observed under S_2W_2 and S_3W_2. Organic carbon, total nitrogen, and available nutrients increased significantly from low to high fertility and moderate water. The highest organic carbon values 1.32 ± 0.04% were recorded for S_3W_2; for total nitrogen, these indices were 0.12 ± 0.01%. Furthermore, available phosphorus and potassium values under were also maximal for S_3W_2 22.4 ± 0.8 mg kg^{-1}, 130.7 ± 4.3 mg kg^{-1}, respectively. All of the measured values were lowest for treatment S_1W_1.

Table 2: Chemical characteristics of soil under different treatments

Treatment	pH	Organic C (%)	Total N (%)	Available P (mg kg^{-1})	Available K (mg kg^{-1})
S_1W_1	6.22 ± 0.03^{b}	0.78 ± 0.02^{c}	0.07 ± 0.01^{c}	12.4 ± 0.5^{c}	89.1 ± 2.8^{c}
S_1W_2	6.31 ± 0.04^{b}	0.81 ± 0.03^{c}	0.08 ± 0.01^{bc}	13.8 ± 0.6^{b}	94.3 ± 3.0^{b}
S_1W_3	6.28 ± 0.03^{b}	0.79 ± 0.02^{c}	0.07 ± 0.01^{c}	13.2 ± 0.5^{bc}	91.6 ± 2.5^{bc}
S_2W_1	6.45 ± 0.04^{ab}	1.05 ± 0.03^{b}	0.10 ± 0.01^{b}	17.5 ± 0.7^{b}	115.4 ± 4.0^{b}
S_2W_2	6.56 ± 0.05^{a}	1.18 ± 0.04^{a}	0.11 ± 0.01^{a}	19.1 ± 0.8^{a}	121.2 ± 4.2^{a}
S_2W_3	6.51 ± 0.04^{a}	1.12 ± 0.03^{ab}	0.10 ± 0.01^{ab}	18.6 ± 0.7^{ab}	118.5 ± 3.9^{ab}
S_3W_1	6.48 ± 0.03^{ab}	1.20 ± 0.03^{a}	0.11 ± 0.01^{a}	20.3 ± 0.9^{a}	124.1 ± 4.1^{a}
S_3W_2	6.63 ± 0.04^{a}	1.32 ± 0.04^{a}	0.12 ± 0.01^{a}	22.4 ± 0.8^{a}	130.7 ± 4.3^{a}
S_3W_3	6.57 ± 0.03^{a}	1.27 ± 0.03^{a}	0.11 ± 0.01^{a}	21.5 ± 0.7^{a}	127.9 ± 4.0^{a}

Soil Biological Properties

Application of soil fertility and well-managed water significantly enhanced soil microbial activities and enzymatic functions with a p-value less than 0.05 (Table 3). Microbial biomass of C and N showed a vast increment from the minimum fertility and water regime, varying from 214 ± 6 μg g^{-1} and 21.2 ± 0.8 μg g^{-1}, respectively in S_1W_1 to the maximum fertility and moderate irrigation, S_3W_2 with an average of 435 ± 10 μg g^{-1} and 42.7 ± 1.2 μg g^{-1}. Dehydrogenase and phosphatase activities depicted a comparable increment with modest under S_3W_2, at 36.4 ± 1.1 μg TPF g^{-1} h^{-1} and 65.9 ± 2.2 μg pNP g^{-1} h^{-1} respectively.

Table 3: Biological properties of soil under different treatments

Treatment	Microbial biomass C (μg g^{-1})	Microbial biomass N (μg g^{-1})	Dehydrogenase (μg TPF g^{-1} h^{-1})	Phosphatase (μg pNP g^{-1} h^{-1})
S_1W_1	214 ± 6^{c}	21.2 ± 0.8^{c}	18.5 ± 0.7^{c}	42.6 ± 1.4^{c}
S_1W_2	243 ± 7^{c}	24.6 ± 0.9^{c}	21.7 ± 0.8^{c}	46.3 ± 1.6^{c}
S_1W_3	231 ± 6^{c}	23.1 ± 0.7^{c}	20.8 ± 0.7^{c}	44.9 ± 1.5^{c}
S_2W_1	365 ± 8^{b}	35.4 ± 1.1^{b}	30.9 ± 1.0^{b}	58.2 ± 1.8^{b}
S_2W_2	401 ± 9^{a}	39.8 ± 1.2^{a}	33.2 ± 1.1^{a}	61.3 ± 2.0^{a}
S_2W_3	388 ± 8^{ab}	38.1 ± 1.1^{ab}	32.5 ± 1.0^{ab}	59.7 ± 1.9^{ab}
S_3W_1	416 ± 9^{a}	40.5 ± 1.2^{a}	34.2 ± 1.0^{a}	63.1 ± 2.1^{a}
S_3W_2	435 ± 10^{a}	42.7 ± 1.2^{a}	36.4 ± 1.1^{a}	65.9 ± 2.2^{a}
S_3W_3	428 ± 9^{a}	41.9 ± 1.1^{a}	35.7 ± 1.1^{a}	64.8 ± 2.1^{a}

Soil Moisture Dynamics

Table 4 shows that S_3W_2 also recorded the highest moisture levels of 25.8 ± 0.8%, 23.5 ± 0.7% and 21.2 ± 0.6% respectively in the 0–15, 15–30 and 30–45 cm while S_1W_1 recorded the lowest values of 18.4 ± 0.6%, 15.3 ± 0.5% and 13.8 ± 0.4%, respectively.

Table 4: Average volumetric soil moisture content (%) at different depths

Treatment	0–15 cm	15–30 cm	30–45 cm
S_1W_1	18.4 ± 0.6^{c}	15.3 ± 0.5^{c}	13.8 ± 0.4^{c}
S_1W_2	19.8 ± 0.7^{b}	16.6 ± 0.6^{b}	14.9 ± 0.5^{b}
S_1W_3	19.1 ± 0.6^{b}	16.0 ± 0.5^{bc}	14.4 ± 0.5^{bc}
S_2W_1	22.4 ± 0.7^{b}	19.5 ± 0.6^{b}	17.8 ± 0.6^{b}
S_2W_2	24.9 ± 0.8^{a}	22.6 ± 0.7^{a}	20.4 ± 0.6^{a}
S_2W_3	23.8 ± 0.7^{ab}	21.7 ± 0.6^{ab}	19.6 ± 0.6^{ab}
S_3W_1	23.0 ± 0.7^{ab}	20.9 ± 0.6^{b}	19.1 ± 0.5^{b}
S_3W_2	25.8 ± 0.8^{a}	23.5 ± 0.7^{a}	21.2 ± 0.6^{a}
S_3W_3	24.7 ± 0.7^{ab}	22.8 ± 0.6^{ab}	20.5 ± 0.6^{ab}

Irrigation Water Quality and Use Efficiency

These differences are slight but significant ($p < 0.05$), with pH increasing slightly with higher fertility and moderate irrigation (S_3W_2) compared to the other treatments and reaching 7.1 ± 0.1 (Table 5). EC is least in well-managed plots (S_3W_2: 698 ± 8 $\mu S\ cm^{-1}$). Nitrate and phosphate concentrations are highest in low-fertility scenarios and decrease with improved fertility and balanced water supply. Water use efficiency is significantly improved in the most fertile soil and most moderate water source with 3.72 ± 0.12 kg m^{-3} in S_3W_2 compared to 2.41 ± 0.08 kg m^{-3} in the least active condition.

Table 5: Water quality and water use efficiency under different management practices

Treatment	pH	EC ($\mu S\ cm^{-1}$)	NO_3^- ($mg\ L^{-1}$)	PO_4^{3-} ($mg\ L^{-1}$)	WUE ($kg\ m^{-3}$)
S_1W_1	6.9 ± 0.1^{b}	720 ± 12^{a}	11.2 ± 0.5^{a}	2.8 ± 0.1^{a}	2.41 ± 0.08^{c}
S_1W_2	7.0 ± 0.1^{b}	716 ± 11^{a}	10.7 ± 0.4^{ab}	2.6 ± 0.1^{b}	2.53 ± 0.09^{c}
S_1W_3	6.8 ± 0.1^{b}	729 ± 13^{a}	11.4 ± 0.5^{a}	2.9 ± 0.1^{a}	2.37 ± 0.07^{c}
S_2W_1	7.1 ± 0.1^{a}	710 ± 10^{b}	10.2 ± 0.4^{b}	2.4 ± 0.1^{c}	3.28 ± 0.10^{b}
S_2W_2	7.0 ± 0.1^{ab}	705 ± 9^{b}	9.6 ± 0.3^{b}	2.1 ± 0.1^{d}	3.55 ± 0.11^{a}
S_2W_3	7.2 ± 0.1^{a}	712 ± 10^{b}	10.0 ± 0.4^{b}	2.2 ± 0.1^{cd}	3.41 ± 0.10^{ab}
S_3W_1	7.1 ± 0.1^{a}	704 ± 9^{b}	9.8 ± 0.3^{b}	2.3 ± 0.1^{c}	3.62 ± 0.11^{a}
S_3W_2	7.1 ± 0.1^{a}	698 ± 8^{b}	9.1 ± 0.3^{b}	2.0 ± 0.1^{d}	3.72 ± 0.12^{a}
S_3W_3	7.2 ± 0.1^{a}	701 ± 9^{b}	9.4 ± 0.3^{b}	2.1 ± 0.1^{d}	3.64 ± 0.11^{a}

Crop Growth Characteristics

The plant height increased gradually from 118.4 ± 3.2 cm with S_1W_1 to a maximum of 142.6 ± 4.2 cm in S_3W_2. The leaf area index exhibited similar trends of increase, with a minimum of 3.2 ± 0.1 in S_1W_1 and a maximum of 4.9 ± 0.2 in S_3W_2. The chlorophyll content was highly elevated in the high fertility levels treatments, with a maximum of 45.3 ± 1.6 SPAD in S_3W_2 compared to 38.6 ± 1.2 SPAD under S_1W_1 (Table 6).

Table 6: Effect of treatments on crop growth parameters

Treatment	Plant height (cm)	Leaf area index	Chlorophyll (SPAD)
S_1W_1	118.4 ± 3.2^{c}	3.2 ± 0.1^{c}	38.6 ± 1.2^{c}
S_1W_2	122.7 ± 3.5^{bc}	3.4 ± 0.1^{b}	39.4 ± 1.3^{c}
S_1W_3	121.1 ± 3.3^{bc}	3.3 ± 0.1^{bc}	39.0 ± 1.2^{c}
S_2W_1	134.8 ± 3.8^{b}	4.3 ± 0.2^{b}	42.5 ± 1.4^{b}
S_2W_2	137.2 ± 4.0^{ab}	4.6 ± 0.2^{a}	43.9 ± 1.5^{a}
S_2W_3	136.0 ± 3.9^{ab}	4.5 ± 0.2^{a}	43.3 ± 1.5^{a}
S_3W_1	140.2 ± 4.1^{a}	4.7 ± 0.2^{a}	44.6 ± 1.6^{a}
S_3W_2	142.6 ± 4.2^{a}	4.9 ± 0.2^{a}	45.3 ± 1.6^{a}
S_3W_3	141.7 ± 4.1^{a}	4.8 ± 0.2^{a}	44.9 ± 1.5^{a}

Crop Yield and Productivity

While grain yield varied from 4.83 ± 0.12 t ha^{-1} in the lowest to 6.52 ± 0.17 t ha^{-1} in the optimal treatment S_1W_1 and S_3W_2, respectively (Table 7). The biomass yield showed an analogous trend with a decrease from 10.2 ± 0.3 to 12.9 ± 0.5 t ha^{-1} between S_1W_1 and S_3W_2 seemingly. The harvest index was improved with an increase from 47.4 ± 1.1% under S_1W_1 to 50.5 ± 1.2% under S_3W_2.

Table 7: Crop yield and productivity under different treatments

Treatment	Grain yield (t ha^{-1})	Biomass yield (t ha^{-1})	Harvest index (%)
S_1W_1	4.83 ± 0.12^{c}	10.2 ± 0.3^{c}	47.4 ± 1.1^{c}
S_1W_2	4.96 ± 0.13^{c}	10.4 ± 0.3^{c}	47.7 ± 1.1^{c}
S_1W_3	4.89 ± 0.12^{c}	10.3 ± 0.3^{c}	47.5 ± 1.1^{c}
S_2W_1	6.05 ± 0.15^{b}	12.1 ± 0.4^{b}	50.0 ± 1.2^{b}
S_2W_2	6.21 ± 0.16^{ab}	12.4 ± 0.4^{b}	50.0 ± 1.2^{b}
S_2W_3	6.14 ± 0.15^{b}	12.3 ± 0.4^{b}	49.9 ± 1.2^{b}
S_3W_1	6.38 ± 0.16^{a}	12.7 ± 0.4^{a}	50.2 ± 1.2^{a}
S_3W_2	6.52 ± 0.17^{a}	12.9 ± 0.5^{a}	50.5 ± 1.2^{a}
S_3W_3	6.47 ± 0.16^{a}	12.8 ± 0.4^{a}	50.4 ± 1.2^{a}

Nutrient Use Efficiency

Table 8 illustrates that nitrogen use efficiency varied from 31.2 ± 1.0% with the treatment of the lowest fertility and water level to 45.7 ± 1.5% with the treatment of the highest fertility level and water level. Likely, phosphorus use efficiency went down from 42.5 ± 1.2% to 59.3 ± 1.7% and potassium use efficiency increased from 58.1 ± 1.6% to 74.6 ± 2.1% with the treatments.

Table 8: Nutrient use efficiency as affected by different management practices

Treatment	N-use efficiency	P-use efficiency	K-use efficiency
S_1W_1	31.2 ± 1.0^{c}	42.5 ± 1.2^{c}	58.1 ± 1.6^{c}
S_1W_2	33.1 ± 1.1^{c}	44.8 ± 1.3^{c}	60.2 ± 1.7^{c}
S_1W_3	32.4 ± 1.0^{c}	43.7 ± 1.2^{c}	59.3 ± 1.6^{c}
S_2W_1	41.9 ± 1.3^{b}	54.9 ± 1.5^{b}	70.8 ± 1.9^{b}
S_2W_2	43.1 ± 1.4^{ab}	56.7 ± 1.6^{a}	72.2 ± 2.0^{a}
S_2W_3	42.6 ± 1.3^{b}	55.8 ± 1.5^{b}	71.5 ± 1.9^{b}
S_3W_1	44.8 ± 1.4^{a}	57.5 ± 1.6^{a}	73.4 ± 2.0^{a}
S_3W_2	45.7 ± 1.5^{a}	59.3 ± 1.7^{a}	74.6 ± 2.1^{a}
S_3W_3	45.1 ± 1.5^{a}	58.8 ± 1.7^{a}	73.9 ± 2.0^{a}

Environmental and Economic Indicators

Most treatments had carbon sequestration yields ranging from 0.18 ± 0.01 t C ha^{-1} yr^{-1} produced under the lowest fertility–water treatment condition S_1W_1 to 0.41 ± 0.02 t C ha^{-1} yr^{-1} under S_3W_2, as well as reduced in nutrient loss from 6 ± 1% under S_1W_2 to 26 ± 2% under S_3W_2. Although the input cost under S_3W_2 was a little higher at 1050 ± 15 USD ha^{-1}, the net return 3085 ± 38 USD ha^{-1} and B:C ratio 2.94 ± 0.05 were significantly better than most treatment (Table 9).

Table 9: Environmental and economic indicators of management strategies

Treatment	C sequestration (t C ha^{-1} yr^{-1})	Nutrient loss reduction (%)	Input cost (USD ha^{-1})	Net return (USD ha^{-1})	B:C ratio
S_1W_1	0.18 ± 0.01^{c}	–	920 ± 10^{c}	1325 ± 20^{c}	1.44 ± 0.03^{c}
S_1W_2	0.19 ± 0.01^{c}	6 ± 1^{c}	930 ± 10^{c}	1465 ± 22^{c}	1.57 ± 0.03^{c}
S_1W_3	0.18 ± 0.01^{c}	5 ± 1^{c}	925 ± 10^{c}	1420 ± 21^{c}	1.53 ± 0.03^{c}
S_2W_1	0.32 ± 0.02^{b}	18 ± 2^{b}	970 ± 12^{b}	2185 ± 30^{b}	2.25 ± 0.04^{b}
S_2W_2	0.35 ± 0.02^{ab}	22 ± 2^{a}	980 ± 12^{b}	2385 ± 32^{ab}	2.43 ± 0.05^{ab}
S_2W_3	0.34 ± 0.02^{ab}	20 ± 2^{b}	975 ± 12^{b}	2310 ± 31^{b}	2.37 ± 0.04^{b}
S_3W_1	0.38 ± 0.02^{a}	24 ± 2^{a}	1030 ± 15^{a}	2870 ± 35^{a}	2.78 ± 0.05^{a}

S_3W_2	0.41 ± 0.02^a	26 ± 2^a	1050 ± 15^a	3085 ± 38^a	2.94 ± 0.05^a
S_3W_3	0.39 ± 0.02^a	25 ± 2^a	1040 ± 15^a	2960 ± 36^a	2.85 ± 0.05^a

Principal Component Analysis

Principal components analysis results for major soil-water-crop variables are shown in Table 10. PC1 represented 58.9% of the total variance in the first four variables, which were soil organic carbon, microbial–biomass carbon, water use efficiency, and crop yield. Available phosphorus, potassium, and soil moisture were positively loaded on PC2, which contained an additional 25.7% of variance. The rest of the difference was made up by subsequent components; loadings on enzyme activity, pH, and bulk density were the most significant. PC5 corresponded to residual variation.

Table 10: Principal components of major soil–water–crop variables

Component	Eigenvalue	Variance (%)	Cumulative (%)	Major loadings
PC1	5.89	58.9	58.9	Soil organic carbon, Microbial biomass carbon, Water use efficiency, Crop yield
PC2	2.57	25.7	84.6	Phosphorus, Potassium, Soil moisture
PC3	0.79	7.9	92.5	Enzyme activity, pH
PC4	0.42	4.2	96.7	Bulk density, Harvest index
PC5	0.33	3.3	100.0	Residuals

Discussion

A crucial result of this study was improved soil structure under the integrated treatments, specifically lower bulk density and higher water-holding capacity under S_3W_2. This is especially the case because it is in line with previous results from properties conducted under conservation and integrated practices (Suzuki *et al.*, 2007). In such situations, minimal disturbance and organic amendment facilitated infiltration and water retention. In one review, these practices enhanced rainfall use efficiency under conservation agriculture (Pratibha *et al.*, 2025). Additionally, the improved moisture retention with the depths can be linked to similar work in dryland Kenya where the integrated soil-water-fertility practices increased soil moisture from conventional management by roughly 28–35%. Hence, the results affirm that the improvement of soil physical properties is a significant manner through which soil and water management interact (Oduor *et al.*, 2023).

The substantial enhance in organic carbon, total nitrogen, and accessible P and K under the integrated fertility interventions confirms the promise of combining organic and inorganic inputs, a premise cultivated by the "Integrated Soil Fertility Management" that supports the thought of combining various inputs for soil quality improvement. In this case, previous works in rice acknowledged the use of humic acid and gypsum with fertilizer to enhance soil CEC and nutrient retention (Hartina *et al.*, 2025). Moreover, the increase in microbial biomass and enzyme activities imply that the soil has more biological activity, promoting nutrient cycling and retention, aspects that are supported by the literature of integrated nutrient management across the world (Marzouk *et al.*, 2025). Evidently, since water and nutrient management work together, their effect universally seems to increase not only nutrient stocks but also the biological processes responsible for nutrient availability and water dynamics (Bilkis *et al.*, 2018; Wu & Ma, 2015).

This research's key aim was to reconcile soil fertility and water resource management, and the outcomes show that integrated treatments considerably enhanced both WUE and NUE. To illustrate, the most favorable treatment showed WUE of 3.72 kg m^{-3} and N-use efficiency of 45.7 kg grain per kg N, that are mostly comparable with prior studies that found integrated irrigation-nutrient management enhanced WUE and NUE (Zulfiqar *et al.*, 2023). In fact, an IAEA examine optimizing soil, water, and nutrient use efficiency in integrated cropping-livestock systems noted that synchronized interventions were more productive than single-factor treatments (IAEA, 2020).

Furthermore, the integrated treatments also led to higher growth parameters, grain and biomass yields and economic-environmental performance. Specifically, the 35% yield gain of S_3W_2, relative to the S_1W_1, matches the yield increments modeled in INM studies, specifically INM 8-150% relative to conventional fertilizer alone (Wu & Ma, 2015). The environmental indicators, higher soil C sequestration 0.41 t C ha^{-1} yr^{-1}; ~26% nutrient-loss reduction are also in agreement with the manure + fertilizers findings in Bangladesh and elsewhere, where integrated use of organic and inorganic inputs has improved fertility and sequestered more carbon (Bilkis *et al.*, 2018).

It is evident that many of the positive results observed are due to different mechanisms that interact. Mechanisms such as improved soil structure mediated by fertility + water management increase infiltration at the same time as decreasing runoff leading to further root-zone water availability (Manik *et al.*, 2019), similar with the soil moisture results discussed above. Further, the increase in soil organic matter and its associated microbial activity enhance the nutrient retention and decrease leachate synchronize nutrient supply with crop demand (Srivastava *et al.*, 2024). Irrigation efficiency and water use improve water stress ameliorate nutrient uptake and biomass, which is consistent with other water stress studies where deficits and optimal yields were achieved under moderate stress and plentiful nutrient supply (Dewangan *et al.*, 2017; Zulfiqar *et al.*, 2023).

Findings and Recommendations

Findings

i. Integrated soil fertility and water management (S_3W_2) facilitated soil physical properties: decreased bulk density, increased porosity, and higher water-holding capacity.

ii. Soil chemical properties and biological activity were improved in integrated treatments.

iii. S_3W_2 had the highest Water Use Efficiency and Nutrient Use Efficiency, illustrating the synchronization of water and nutrient supply with the level required by crops.

iv. The crop growth parameters and yield increased significantly in integrated management.

v. S_3W_2 resulted in the highest economic performance as indicated by the net returns and benefit-cost ratio.

vi. The highest yields for soil carbon sequestration and the lowest nutrient loss were obtained under integrated treatments.

vii. Principal component analysis indicated that intensive management of S_3W_2 and its variations, along with soil organic carbon sequestration, microbial activity, WUE and crop yield, influence sustainable productivity.

Recommendations

i. Promotion of sustainable crop production approach that involves integrated soil fertility and water management packages such as simultaneously use of organic-inorganic fertilizations and optimized irrigation.

ii. Promotion of regular soil testing and monitoring to customize nutrient application and prevent over-fertilization.

iii. Use of effective irrigation types that include drip, sprinkler, or regulated deficit irrigation to improve water use efficiency.

iv. Training of farmers on synchronization nutrient-water treatment to enhance yield, negligible nutrient loss, and water conservation.

v. Development of contextual policy incentives that include support for the "green" amendment organics and efficient irrigation facilities through subsidies.

vi. Long-term monitoring of soil health persistence, carbon storage, and related solar impact on the environment.

Limitations

i. The study covers a period of two cropping seasons which might not be enough to elucidate the long-term soil fertility and water dynamics Levels.

ii. Besides, results are relevant at the specific experimental site level and might impact differently in various soil types, climates and cropping systems.

iii. The economic analysis process assumes that opportunity costs shall endure constant with no fluctuating market process in a large-scale adoption perspective.

iv. Greenhouse gases emission and other environmental trade-offs off such as N_2O and CH_4 fluxes were not measured.

v. Integrated practices adoption might also be difficult due to practical constraints including labor, infrastructure issues and farmer awareness which were not thoroughly explored in this study.

CONCLUSION

The results of the current study reveal that integrating soil fertility management with efficient water resource strategies improves soil physical, chemical, and biological properties and increases water and nutrient use efficiency in addition to enabling crop growth, development and ultimately, economic productivity. S_3W_2 proved to be the most efficient system compared to the rest of the nine treatments tested under the experiment and suitable for joint effort and water using sustainability, environmental sustainability, and resource-use efficiency. Such synchronization of nutrient management and water usage is crucial in achieving nutrient losses and soil health. In conclusion, there is a need for further long-term studies evaluating the residual effects of soil fertility improvement, carbon sequestration, and GHG emissions under various agro-ecological zone and diverse soil types. Likewise, the ability to scale up integrated practices to different soils and diverse socio-economic conditions, evaluate barriers to the adoption of these practices, and site-specific optimization should be considered significant obstacles and opportunities for the successful uptake of these integrated practices.

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