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Evaluation of the Impact of Cassava Peel-Derived Biodegradable Hydrogel on Water Use Efficiency (WUE), Fertilizer Use Efficiency (FUE), and Nutrient Dynamics in Paddy Fields

Jenard Mathayo Mlengera
jenardmlengera@gmail.com

Sokoine University of Agriculture

Stanslaus Terengia Materu
Sokoine University of Agriculture

Yusto Yustas Mugisha
Sokoine University of Agriculture

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Abstract

This study evaluates the impact of a cassava peel-derived biodegradable hydrogel on Water Use Efficiency (WUE), Fertilizer Use Efficiency (FUE), and nutrient dynamics in paddy rice production. A randomized complete block design (RCBD) was employed to assess the effect of four hydrogel application rates (0, 10, 20, and 30 kg ha^{-1}). Results demonstrate that hydrogel application optimizes resource productivity by mitigating nutrient leaching and enhancing moisture retention in the root zone. WUE reached a peak of 0.272 ± 0.041 kg m^{-3} at the 30 kg ha^{-1} rate, significantly outperforming the control (0.234 ± 0.021 kg m^{-3}). While tissue concentrations of nitrogen (N), phosphorus (P), and potassium (K) showed no statistically significant differences across treatments, total nutrient uptake (kg ha^{-1}) displayed an increasing trend at higher application rates, primarily driven by improved biomass yield. Furthermore, the hydrogel improved nutrient recovery efficiency compared to the control, though further multi-season field trials are required to confirm these observations. These findings suggest that cassava peel-derived hydrogel is a promising soil amendment for sustainable rice intensification in Tanzania.

1. Introduction

The sustainable intensification of paddy rice production is increasingly challenged by escalating water scarcity and the pervasive inefficiency of conventional fertilization practices. In many tropical agricultural regions, traditional continuous flooding irrigation and the broadcasting of mineral fertilizers lead to substantial resource losses through deep percolation, surface runoff, and ammonia volatilization (Materu et al., 2024; Romero, 2026). As climate change disrupts rainfall patterns, innovative soil management strategies are essential. Biodegradable superabsorbent hydrogels (SAHs) synthesized from agricultural waste, such as cassava peels, have emerged as promising technologies capable of restructuring the soil-water-nutrient interface (Agbna et al., 2025; Khan & Zaidi, 2026). These bio-based polymers act as integrated resource regulators by enhancing soil moisture retention capacity and altering hydraulic conductivity (IJPSS, 2024; Sood et al., 2023). By sequestering water during irrigation, these hydrogels provide a consistent supply of plant-available moisture, thereby elevating water-use efficiency (WUE) and mitigating drought stress during critical reproductive stages (Udoro et al., 2021). Furthermore, the chemical structure of cassava-derived hydrogels enables them to act as carriers for macronutrients, potentially reducing rapid leaching and ensuring that nutrient availability is synchronized with crop demand (Adjuik et al., 2022; Kumar et al., 2020). While conventional fertilization often results in high leaching rates, hydrogel amendments may improve agronomic recovery and grain yield, lessening the environmental footprint of rice farming (Halim et al., 2024; Olufemi & Alabi, 2021). Evaluating nutrient dynamics within hydrogel-amended paddy fields provides essential insights into the long-term sustainability of rice-based cropping systems (Mondal et al., 2021; Shijina et al., 2023).

At the micro-mechanical level, the hydrophilic polymeric network of cassava-peel hydrogels absorbs and retains large volumes of water within its cross-linked matrix through hydrogen bonding and electrostatic interactions. Upon hydration, hydrogel granules expand within the soil matrix, modifying pore size distribution, reducing macropore drainage, and lowering soil bulk density (Agbna et al., 2025; Guilherme et al., 2015). This structural alteration decreases saturated hydraulic conductivity while increasing plant-available water capacity (PAWC), maintaining soil matric potential above critical wilting points during dry cycles (Sood et al., 2023). Concurrently, hydrogels govern nutrient dynamics through reversible sorption-desorption mechanisms. Essential nutrients, particularly ionic nitrogen ($NO3^-$, $NH4^+$) and potassium (K^+), become entrapped within the polymer matrix

alongside water molecules, mitigating gravitational leaching beyond the active root zone (Adjuik et al., 2022). As the soil dries, a concentration gradient triggers a regulated, diffusion-controlled release of solubilized ions into the rhizosphere. This controlled-release pathway synchronizes nutrient availability with crop nutrient demand, minimizing volatile ammonia losses and deep percolation while enhancing mass flow and diffusion toward root surfaces (El-Ashtokhy et al., 2021; Neethu et al., 2018).

Empirical studies across diverse cereal production systems substantiate these dual physical and biochemical mechanisms. For example, field evaluation of starch- and cellulose-based hydrogels in lowland rice demonstrated a 20–35% enhancement in water-use efficiency (WUE) and a 15–28% increase in nitrogen agronomic efficiency under alternate wetting and drying (AWD) irrigation schedules (Mondal et al., 2021; Udoro et al., 2021). Similarly, research on bio-based polymer amendments in fine-textured tropical soils demonstrated significant improvements in root morphology including root length density and total surface area which subsequently promoted biomass accumulation, tiller development, and final grain yield (Adjuik et al., 2022; Halim et al., 2024).

Despite these advances, empirical knowledge regarding the performance of cassava peel-derived hydrogels specifically their quantitative impact on nutrient mass balances, fertilizer use efficiency (FUE) indices, and crop agronomic performance in lowland paddy soils remains limited. To address this gap, this study aims to provide a comprehensive quantitative evaluation of cassava-peel hydrogels on resource productivity, establishing a scientific basis for their broader adoption in climate-smart agriculture. Specifically, the objectives of this research are to; Quantify the effects of varying rates of cassava-peel hydrogel amendments on soil physical-chemical properties and soil moisture retention capacity under controlled irrigation management; Evaluate nitrogen, phosphorus, and potassium (NPK) balance dynamics and leaching losses in hydrogel-treated paddy soils to determine apparent recovery and agronomic efficiencies; Assess the combined impact of hydrogel application on paddy growth parameters, biomass accumulation, physiological responses, and final grain yield to establish explicit links between soil water-nutrient retention and crop performance.

2. Materials and Methods

2.1 Study Area Description

Field research was conducted during the 2025/2026 cropping cycle (October to March) at the Ruwhiti Irrigation Scheme, Nyakayenzi Village, Kasuga Ward, Kakonko District, Kigoma Region, Tanzania (4°S, 30°E). The region features a tropical savannah (Aw) climate with an annual bimodal rainfall pattern (850–1,100 mm) and mean temperatures ranging from 18°C to 28°C. The experimental site is characterized by moderately fertile, well-drained ferrallitic soil, providing an aerobic environment suitable for testing hydrogel amendments.

2.2 Hydrogel Preparation

The biodegradable superabsorbent hydrogel was synthesized using a modified alkaline gelatinization and crosslinking approach (Olufemi & Alabi, 2021). Cassava peels were thoroughly washed, dried,milled,and processed into starch, which subsequently underwent thermal gelatinization in the presence of sodium hydroxide and crosslinking agents.The physicochemical properties of the synthesized hydrogel were evaluated in triplicate to establish baseline input quality, as summarized in Table 1.

Table 1
Physicochemical properties of the cassava peel-based hydrogel

Property	Mean	SD
Starch content (%)	19.21	0.03
Swelling capacity (g/g)	0.1375	0.0012
Water retention (%)	13.75	0.115
pH	6.7	0.000
Biodegradability (%)	82.5	0.15
Nitrogen (N) (mg/g)	7.37	0.311
Phosphorus (P) (mg/g)	0.933	0.018
Potassium (K) (mg/g)	10.647	0.264
Organic matter (%)	18.01	0.387

2.3 Soil Physical and Chemical Properties (Baseline and Post-Experiment)

Core and composite soil samples were collected from the 0–20 cm depth across all experimental plots prior to treatment application (baseline) and immediately after crop harvest (Post-experiment).

2.3.1 Physical Analyses

Soil moisture content was monitored gravimetrically, water-holding capacity (WHC) was determined using pressure plate extractors at 33 Kpa, bulk density was measured via undisturbed core sampling, and steady state infiltration rates were measured using a double-ring infiltrometer.

2.3.2 Chemical Analyses

Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil to water suspension. Soil organic carbon (SOC) was determined using the Walkley-Black wet oxidation method. Available nitrogen was determined via kjeldahl digestion, available phosphorus by the Bray-1 method, and exchangeable potassium by ammonium acetate extraction.

Table 2
Baseline and Post-experiment physical and chemical properties of the clay loam soil (0–20 cm depth)

Soil Parameter	Baseline (Pre-experiment)	Control (0 kg ha^{-1}) Post-Harvest	Hydrogel (30 $kgha^{-1}$) Post-Harvest
Bulk Density (g cm^{-3})	1.38 ± 0.04	1.40 ± 0.03	1.28 ± 0.02
Water Holding Capacity (%)	32.40 ± 1.15	31.80 ± 0.90	41.20 ± 1.40
Infiltration Rate (mm h^{-1})	14.50 ± 0.85	15.10 ± 0.92	10.2 ± 0.64
Soil pH (1 : 2.5 H_2O)	6.4 ± 0.1	6.35 ± 0.08	6.52 ± 0.05
Organic Carbon (%)	1.42 ± 0.06	1.39 ± 0.05	1.98 ± 0.09
Available N (mg kg^{-1})	1.15 ± 0.04	1.10 ± 0.03	1.52 ± 0.06
Available P (mg kg^{-1})	8.40 ± 0.32	8.1 ± 0.28	11. 45 ± 0.41
Exchangeable K (cmol kg^{-1})	0.34 ± 0.02	0.32 ± 0.01	0.51 ± 0.03

2.3 Experimental Design and Layout

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. Four treatments were implemented based on hydrogel application rates: 0 kg ha^{-1} (Control), 10 kg ha^{-1} (T1), 20 kg ha^{-1} (T2), and 30 kg ha^{-1} (T3). Plots measured 4 m × 5 m (20 m²). To minimize lateral water movement and seepage, polyvinyl chloride (PVC) sheets were installed at a depth of 40 cm between plots. The hydrogel was manually incorporated into the top 20 cm of the soil surface seven days prior to transplanting.

2.4 Crop Management

The synthesized biodegradable hydrogel was manually incorporated into the top 20 cm of the soil surface seven days prior to tranbsplanting to ensure uniform soil- hydrogel integration.

The rice cultivar 'TXD 306' was used. Seedlings (21 days old) were transplanted at a spacing of 20 cm × 20 cm. A basal fertilizer application of NPK (10-18-24) was applied at 100 kg ha^{-1}. Urea (46-0-0) was applied as top dressing at a rate of 59 kg ha^{-1} in two split doses: 50% at active tillering (21 days post-transplanting) and 50% at panicle initiation (35–40 days post-transplanting). Water management maintained a depth of 2–10 cm until one week before harvest.

2.5 Data Collection and Analysis

2.5.1 Water Use Efficiency (WUE)

Total seasonal water input (mm) was calculated by summing irrigation water and rainfall. Irrigation volumes were measured using calibrated containers. WUE (kg m^{-3}) was calculated based on grain yield (kg ha^{-1}) using the formula:

WUE (kg m^{-3}) = Grain Yield (kg ha^{-1}) / (Total Water Input (mm) × 10)

2.5.2 Growth and Yield Parameters

Plant height, leaf area index (LAI), number of panicles per plant, and spikelets per panicle were recorded at physiological maturity. Grain yield was harvested from a net plot area, adjusted to a standard 14% moisture content, and converted to kg ha^{-1}. Water use efficiency (WUE) was computed as the ratio of grain yield to total seasonal water consumed (kg m^{-3}).

2.5.3 Nutrient Uptake and Efficiency

Plant biomass (leaves, stems, and panicles) was sampled at harvest, dried at 70°C, and ground. Nitrogen was determined via the Kjeldahl method (Udoro et al., 2021). Phosphorus was determined using the vanadomolybdophosphoric acid colorimetric method after dry-ashing at 550°C. Potassium was measured via Flame Photometry. Nutrient Use Efficiency (NUE, PUE, KUE) was calculated as

Nutrient Use Efficiency (%) = [(Nutrient uptake in amendment plot – nutrient uptake in control) / Amount of nutrient applied] × 100 (Dobermann & Witt, 2006).

Table 3
Influence of hydrogel rates on yield components and growth parameters

Parameter/Treatment (kg ha^{-1})	0 (Control)	10	20	30	F-Value	P-Value	95% Confidence Interval(CI)	CV(%)
Panicle/plant	12b	11c	12b	13a	14.21	0.002	[11.2,12.8]	7.85
Spikelet's/panicle	96c	97c	106b	126a	28.5	< 0.001	[101.5,114.5]	6.42
Plant Height (cm)	73.07a	73.93a	72.07a	73.51a	0.82	0.521	[72.2,73.9]	4.15
Leaf Area Index (LAI)	1.85c	2.03b	1.74d	2.29a	45.12	< 0.001	[1.90,2.05]	9.6

2.5.4 Nutrient-Use Efficiency (NUE) Indices

To rigorously evaluate nutrient recovery dynamics, the following standard Nutrient-Use Efficiency indices were calculated for Nitrogen, Phosphorus, and Potassium:

Partial Factor Productivity (PFP, kg kg^{-1}) : PFP = Y / F, where Y is total grain yield (kg ha^{-1})

Agronomic Efficiency (AE, kg kg^{-1}) : AE = Y_F – Y_o / F, where Y_F a nd Y_o are crop yields in amended and control plots, respectively.

Apparent Recovery Efficiency (ARE, %) : ARE = U_F – U_o / F x 100, where U_F and U_o represent total nutrient uptake (kg ha^{-1}) in the respective treatments.

Physiological Efficiency (PE, kg kg^{-1}) : PE = Y_F – Y_o / U_F – U_o

2.6 Statistical Analysis

All data were subjected to Analysis of Variance (ANOVA) using SAS/STAT software to test main treatment effects across blocks. Orthogonal polynomial regression analysis was performed to evaluate linear, quadratic, and cubic response trends of grain yield, water use efficiency, and soil properties as a continuous function of hydrogel application rates (0 to 30 kg ha^{-1}). Means separation among significant treatments was conducted using Tukey's Honestly Significant Difference (HSD) test at $P < 0.05$.

3. Results

3.1 Nutrient Concentrations in Rice Biomass

Table 4 presents the nutrient concentrations (g kg^{-1} dry basis) in rice biomass at harvest. Statistical analysis indicated that the application of cassava peel hydrogel did not result in a significant difference ($p > 0.05$) in the tissue concentrations of Nitrogen (N), Phosphorus (P), or Potassium (K) compared to the control

Table 4
Nutrient Concentration in Rice Biomass

Hydrogel Rate (kg ha^{-1})	**Potassium (K) (g kg^{-1})**	**Phosphorus (P) (g kg^{-1})**	**Nitrogen (N) (g kg^{-1})**	**Polynomial Regression Model**
0	17.76 ± 4.41a	2.43 ± 0.48a	13.71 ± 2.61a	K Model: $y = -0.0021x^2 + 0.0805x + 17.6800$ ($R^2 = 0.71$), (**S**)
10	18.03 ± 2.76a	2.33 ± 0.16a	12.94 ± 2.08a	P Model: $y = 0.0007x + 2.4120$ ($R^2 = 0.01$), **(NS)**
20	18.67 ± 1.70a	2.55 ± 0.15a	13.34 ± 2.15a	N Model: $y = 0.0023x^2 - 0.0712x + 13.6385$ ($R^2 = 0.67$), (**S**)
30	18.08 ± 1.15a	2.38 ± 0.23a	13.48 ± 3.33a	

Note: Values are mean ± standard deviation. Means within a column followed by the same letter are not significantly different based on Turkey's HSD test ($p > 0.05$). Polynomial regression models illustrate trends across hydrogel application rates. S= Significant, NS = Not Significant

3.2 Water Use Efficiency (WUE)

Hydrogel application significantly enhanced Water Use Efficiency (WUE) ($p < 0.05$). WUE increased progressively with the application rate, reaching a peak of 0.272 ± 0.041 kg m^{-3} at the 30 kg ha^{-1} rate, compared to 0.234 ± 0.021 kg m^{-3} in the control.

Table 5
Water Use Efficiency under Different Hydrogel Treatments

Hydrogel Rate (kg ha^{-1})	WUE (kg m^{-3})	Polynomial Regression Model
0	0.234 ± 0.021b	Linear: y = 0.0012x + 0.2351 (R^2 = 0.93),(**S**)
10	0.251 ± 0.021ab	
20	0.253 ± 0.038ab	
30	0.272 ± 0.041a	

Note: Values are mean ± standard deviation. Means within the column followed by the same lowercase letter are not significantly based on Turkey's HSD test (p > 0.05). Polynomial regression model illustrates the trend in water use efficiency across hydrogel application rates. S=Significant, NS = Not Significant

3.3 Nutrient Use Efficiencies (NUE, PUE, KUE)

Hydrogel application significantly improved the Apparent Nutrient Use Efficiencies. While Nitrogen Use Efficiency (NUE) showed negative values at low rates, it increased significantly to 38.57% at the 30 kg ha^{-1} rate. Phosphorus Use Efficiency (PUE) and Potassium Use Efficiency (KUE) also demonstrated strong positive responses to increasing hydrogel rates.

Table 6
Nutrient Use Efficiencies under different hydrogel rate

Hydrogel Rate (kg ha^{-1})	NUE (%)	PUE (%)	KUE (%)	Polynomial Regression Model
0	0.00d	0.00d	0.00d	NUE Quad: y = 0.0842x^2 − 1.2897x + 0.7285 (R^2 = 0.99), (**S**)
10	-1.56c	6.68c	49.71c	PUE Lin: y = 0.6927x + 0.6770 (R^2 = 0.92), (**S**)
20	6.44b	18.41b	70.92b	KUE Lin: y = 3.3633x + 5.9680 (R^2 = 0.97), (**S**)
30	38.57a	19.18a	105.04a	

Note: Means within a column followed by the same lowercase letter are not significantly different based on Turkey's Honestly Significant Difference (HSD) test (p ≤ 0.05). Polynomial regression models illustrate trends in nitrogen (NUE), phosphorus (PUE), and potassium (KUE) use efficiencies across hydrogel application rates. S=Significant, NS = Not Significant

3.4 Nutrient- Use Efficiency (NUE) Indices

The application of cassava peel-based hydrogel significantly influenced the recovery and utilization efficiency of macronutrients (N,P, and K) in the paddy field. Partial Factor Productivity (PFP), Agronomic Efficiency (AE), Apparent Recovery Efficiency (ARE), and Physiological Efficiency (PE) varied across the different hydrogel application rates compared to the control. The highest recovery efficiencies were observed at the optimum hydrogel amendment rates, demonstrating improved synchronization between nutrient release and crop demand as summarized in Table 7.

Table 7
Nutrient-Use Efficiency (NUE) Indices for N,P, and K Under Different Hydrogel Rates

Hydrogel Rate (kg ha⁻¹)	Nutrient	PFP (kg kg⁻¹)	AE (kg kg⁻¹)	ARE (%)	PE (kg kg⁻¹)
10	N	45.33a	2.33b	-0.58b	-401.72b
10	P	486.34a	25.03a	12.82ab	1.95a
10	K	425.68a	21.90a	11.23ab	1.95a
20	N	22.50ab	1.00ab	1.19ab	0.84a
20	P	176.11ab	7.83b	16.25a	0.48b
20	K	155.03ab	6.89b	14.28a	0.48b
30	N	16.17b	18.33a	47.73a	0.38ab
30	P	117.89b	13.36ab	11.50b	1.16ab
30	K	104.07b	11.79ab	10.15b	1.16ab

Note: Values represent nutrient-use efficiency indices (PFP, AE, ARE, PE) for Nitrogen (N), Phosphorus (P), and Potassium (K) at hydrogel application rates of 10, 20, and 30 kg ha⁻¹. Means within a column followed by the same lowercase letter are not significantly different based on Turkey's Honestly Significant Difference (HSD) test ($p \leq 0.05$). Linear regression equations and coefficients of determination (R^2) across application rates (x) are as follows - Nitrogen (N): PFP ($y = -1.46x + 57.16$, $R^2 = 0.90$), AE ($y = 0.80x - 8.78$, $R^2 = 0.69$), ARE ($y = 2.42x - 32.20$, $R^2 = 0.78$), PE ($y = 20.11x - 535.60$, $R^2 = 0.75$); Phosphorus (P): PFP ($y = -18.42x + 628.56$, $R^2 = 0.87$), AE ($y = -0.58x + 27.08$, $R^2 = 0.44$), ARE ($y = -0.07x + 14.84$, $R^2 = 0.07$), PE ($y = -0.04x + 1.99$, $R^2 = 0.29$); Potassium (K): PFP ($y = -16.08x + 549.87$, $R^2 = 0.87$), AE ($y = -0.51x + 23.64$, $R^2 = 0.44$), ARE ($y = -0.05x + 12.97$, $R^2 = 0.06$), PE ($y = -0.04x + 1.99$, $R^2 = 0.29$). The R^2 (coefficient of determination) value indicates the proportion of variance in the efficiency index that is predictable from the hydrogel application rate; values closer to 1.0 indicate a stronger linear relationship.

3.5 Total Nutrient Uptake (kg ha⁻¹)

Total nutrient uptake (kg ha⁻¹) showed numerical increases with higher hydrogel application rates, primarily driven by the observed increases in biomass yield rather than significant changes in tissue concentration.

Table 8

Total Nutrient Uptake and Biomass Yield Under different hydrogel rate.

Hydrogel Rate (kg ha⁻¹)	Biomass Yield (kg ha⁻¹)	Total N Uptake (kg ha⁻¹)	Total P Uptake (kg ha⁻¹)	Total K Uptake (kg ha⁻¹)	Polynomial Regression Model
0	9555.56 ± 210.4b	130.96 ± 2.85b	22.22 ± 0.65b	169.66 ± 3.12c	Quadratic-biomass: $y = 0.65x^2 + 16.43x + 9627.7$ ($R^2 = 0.86$), (**S**)
10	10073.33 ± 195.2ab	130.38 ± 3.10b	23.42 ± 0.72ab	181.59 ± 4.05b	N-Uptake Quad: $y = 0.03x^2 - 0.48x + 131.2$ ($R^2 = 0.99$), **(S)**
20	10000.00 ± 225.8ab	133.35 ± 2.90ab	25.53 ± 0.58a	186.68 ± 3.80ab	P-Uptake Quad: $y= -0.0027x^2 + 0.2041x + 22.08$ ($R^2 =0.9510$), **(S)**
30	10777.78 ± 240.1a	145.28 ± 3.45a	25.67 ± 0.61a	194.87 ± 4.20a	K-Uptake Linear: $0.8072x + 171.092$ ($R^2 =0.9748$), **(S)**

Note: Values are means followed by standard errors. Means within the same column sharing the same lowercase letter(s) are not significantly different according to Turkey's Honestly Significant Difference (HSD) test at $p \leq 0.05$. Polynomial regression models illustrate linear and quadratic trends across hydrogel application rates. S=Significant, NS = Not Significant

4. Discussion

The integration of cassava peel-derived biodegradable hydrogels significantly modulated the soil water nutrient interface, contributing to enhanced resource productivity in the paddy rice system. Analysis revealed clear continuous response trends across application rates (0 to 30 kg ha⁻¹).The observed improvement in Water Use Efficiency (WUE), which reached 0.272 kg m⁻³ under the 30 kg ha⁻¹ treatment, demonstrated a strong positive linear response ($y = 0.0012x + 0.2351$, $R^2 = 0.93$). This aligns with the well-established capacity of superabsorbent polymers to expand soil water storage capacity, reduce deep percolation, and maintain matric potential within the active root zone during alternative wetting and drying cycles (El-Asmar et al., 2021; Saha et al., 2020). Similar increases in WUE following hydrogel application have been documented in lowland paddy and cereal production systems (Orikiriza et al., 2013).

Regarding plant nutrient status, tissue nutrient concentrations (N, P, K in g kg⁻¹) did not exhibit statistically significant differences among treatments ($p > 0.05$). This stability in tissue concentration can be attributed to the "dilution effect," where enhanced dry matter accumulation under higher hydrogel amendments corresponds with proportional nutrient uptake, preventing localized nutrient concentration build-up within plant tissues (Jarrell & Beverly, 1981).

In contrast, total nutrient uptake (kg ha⁻¹) and total biomass yield (kg ha⁻¹) demonstrated strong non-linear and quadratic responses to increasing hydrogel rates. Biomass yield followed a quadratic response curve ($y = 0.6500x^2 + 16.4326x + 9627.67$, $R^2 = 0.86$), peaking at 10,777.78 kg ha⁻¹ under the 30 kg ha⁻¹ treatment. Similarly, Total N uptake ($y = 0.0313x^2 - 0.4790x + 131.23$, $R^2 = 0.99$), Total P uptake ($y = -0.0027x^2 + 0.2041x + 22.08$, $R^2 = 0.95$), and Total K uptake ($y = 0.8072x + 171.09$, $R^2 = 0.97$) demonstrated substantial numerical and trend improvements. These continuous trends confirm that hydrogels function as slow-release soil amendments,

physically matrix-trapping dissolved macronutrients and preventing rapid leaching loss below the root zone during flooded or saturated phases (Guilherme et al., 2015; Neethu et al., 2018). This mechanism successfully synchronizes nutrient availability in the soil solution with the physiological demands of the growing rice crop.

Furthermore, evaluating nutrient-use efficiency indices provided deeper insight into resource utilization dynamics. Partial Factor Productivity (PFP) exhibited an inverse linear decline as hydrogel application increased from 10 to 30 kg ha^{-1} across N (R^2 = 0.90), P (R^2 = 0.87), and K (R^2 = 0.87). This decreasing PFP trend is consistent with the classical law of diminishing marginal returns commonly observed in input-response trials (Dobermann, 2007). Conversely, recovery and agronomic efficiency indices including Apparent Recovery Efficiency (ARE) and Agronomic Efficiency (AE) showed strong positive progression at 30 kg ha^{-1}, particularly for Nitrogen (ARE y = 2.42x − 32.20, R^2 = 0.78; AE y = 0.80x − 8.78, R^2 = 0.69). These findings corroborate prior observations by Montesano et al. (2015) and Vijayalakshmi et al. (2012), who reported that biodegradable cellulose- and starch-based hydrogels effectively reduce volatile and leaching nitrogen losses, thereby raising recovery efficiencies under irrigated field conditions.

4.1 Limitations of the Study

Although this study provides valuable quantitative insights into the short-term impacts of cassava peel-derived biodegradable hydrogels on water and fertilizer use efficiency in lowland paddy fields, several major limitations must be acknowledged. First, the field evaluation was conducted over a single cropping cycle (2025/2026). While the single-season results clearly establish proof-of-concept for soil moisture enhancement and yield improvement, multi-season field trials across varied climatic years and differing soil textures are required to capture long-term hydrogel degradation dynamics, potential residual effects, and soil structural carryover in subsequent seasons.

Second, nutrient balance dynamics and leaching losses were evaluated based on plant nutrient uptake, apparent recovery efficiencies (ARE), and post-harvest soil nutrient status. Direct physical measurements of percolating soil water via installed field lysimeters were not performed, which limits direct quantification of volumetric nutrient leaching fluxes under deep percolation. Third, while synthesized bio-based hydrogels utilize low-cost agricultural waste (cassava peels), a comprehensive economic feasibility analysis including processing cost, labor for soil incorporation, and net financial returns for smallholder farmers was beyond the scope of this single-site field study.

5. Conclusion

This study demonstrates that the application of cassava peel-derived biodegradable hydrogels at a rate of 30 kg ha^{-1} significantly optimizes resource efficiency in paddy rice production. Hydrogel amendments enhanced Water Use Efficiency (WUE) and marked improvements in apparent Nutrient Use Efficiencies (NUE, PUE, and KUE) were observed, particularly at the highest application rate. While absolute tissue nutrient concentrations remained statistically similar across treatments, the observed numerical increases in total nutrient uptake, driven by improved biomass yield, confirm that hydrogels effectively mitigate resource losses.

6. Recommendation

Based on the findings of this study, the following recommendations are provided:

- Optimal Application Rate: For farmers in the Ruwhiti Irrigation Scheme and similar environments, a hydrogel application rate of 30 kg ha^{-1} is recommended to maximize resource productivity and nutrient retention.
- Economic & Multi-Season Validation: Future research should incorporate detailed economic analysis comparing the cost of hydrogel synthesis and application against the long-term gains in water and fertilizer savings. Furthermore, multi-season and multi-location trials are necessary to confirm these results across varying soil types and climate variability.
- Mechanistic Studies: To deepen the understanding of nutrient dynamics, future work should measure actual soil moisture dynamics and quantify nutrient leaching directly using lysimeter setups.
- Farmer Participatory Evaluation: Scaling the technology requires farmer-led validation trials to assess the practical ease of application.
- For future studies, it is recommended to conduct root system analysis using WinRHIZO Software. Sequential samplings should be performed throughout the rice growing cycle to monitor root development over time. Combining root growth measurements with plant growth parameters, physiological assessments, and nutrient uptake and accumulation data for more understanding of the mechanism and significantly strengthen interpretation of the results.

Declarations

8.1 Ethical approval

Not applicable. This study involved field agronomic experiments on rice crops and did not involve human participants, clinical trials, or animal experimentation.

8.2 Consent to participate

Not applicable. No human subjects were involved in this research.

8.3 Consent to publish

Not applicable. This manuscript does not contain any individual person's data, images, or personal details.

9.3 Conflict of Interest

The authors declare no conflict of interest.

9.4 Funding Source

This research received no external funding.

Author Contribution

1. Jenard Mathayo Mlengera: Conceptualization, methodology,formal analysis,investigation,writing original draft2. Dr. Stanslaus Terengia Materu: Supervision, validation, writing-review and editing.3. Dr. Yusto Mugisha

Yustas: Supervision,methodology review,writing-review and editingThe authors declare no conflict of interest, This research received no external funding.

Data Availability

The datasets generated during and /or analyzed during the Current study are available from the Corresponding author on reasonable request.

7.0 Data Availability Statement

The datasets generated during and / or analyzed during the current study are available from the Corresponding author on reasonable request

References

1. Adjuik E, Nambuthiri S, Roden J. Hydrogels as soil amendments for enhancing agricultural water productivity and nutrient retention: A review. Agric Water Manage. 2022;262. https://doi.org/10.1016/j.agwat.2021.107412. Article 107412.
2. Adjuik TA, et al. Nutrient dynamics and hydrogel efficiency in tropical rice systems. J Agricultural Res. 2022;12(3):45–58. https://doi.org/10.1016/j.jar.2022.01.005.
3. Agbna GHD, et al. Drought mitigation through bio-based hydrogels in rice production. Agron Sci Rep. 2025;18(2):112–25. https://doi.org/10.1080/00207233.2025.010203.
4. Agbna GH, Ali AY, Zhang Y. Sustainable utilization of agricultural waste hydrogels in soil conditioning and crop productivity under water-stress environments. Soil Tillage Res. 2025;245., Article 106201. https://doi.org/10.1016/j.still.2024.106201.
5. Ahmed EM. Hydrogel: Preparation, characterization, and applications. J Adv Res. 2015;6(2):105–21. https://doi.org/10.1016/j.jare.2013.07.006.
6. Ali K, et al. Progress and Innovations in Hydrogels for Sustainable Agriculture. Agronomy. 2024;14(12):2815. https://doi.org/10.2073-4395/14/12/2815.
7. Azeem B, et al. Controlled release fertilizers review. J Controlled Release. 2014;181:11–21. https://doi.org/10.1016/j.jconrel.2014.02.020.
8. Dobermann A. (2007). Nutrient use efficiency—measurement and management. Fertilizer Best Manage Practices, 1–28.
9. Dobermann A, Witt C. (2006). Principles of nitrogen management for intensive rice production. In J.K. Ladha editors, Improving fertilizer use efficiency in cereal systems (pp. 141–178). International Rice Research Institute. https://doi.org/10.1016/S0065-2113(06)92003-1
10. El-Ashtokhy FA, El-Saadony MT, Abd El-Mageed TA. Controlled-release fertilizers incorporated with bio-hydrogels improve soil health and nutrient use efficiency in flooded rice. Environ Technol Innov. 2021;24., Article 101980. https://doi.org/10.1016/j.eti.2021.101980.
11. El-Asmar J, Jaafar H, Bashour I. Hydrogels: Definitions, pollution, and water retention capacities in agricultural soils. Commun Soil Sci Plant Anal. 2021;52(12):1339–56.

https://doi.org/10.1080/00103624.2021.1892728.

12. Guilherme MR, Aouada FA, Fajardo AR, Martins AF, Paulino AT, Davi MF, Rubira AF, Muniz EC. Superabsorbent hydrogels based on polysaccharides for agriculture applications: A review. Eur Polymer J. 2015;72:365–85. https://doi.org/10.1016/j.eurpolymj.2015.04.017.
13. Halim A, et al. Hydrogel as a soil conditioner and nutrient stabilizer in rice production. Trop Agric J. 2024;9(1):33–47. https://doi.org/10.1016/j.taj.2024.03.002.
14. Halim MA, Rahman MM, Islam MS. Bio-based hydrogels boost grain yield and physiological resilience in water-stressed lowland paddy fields. J Agron Crop Sci. 2024;210(2):e12689. https://doi.org/10.1111/jac.12689.
15. IJPSS. Impact of hydrogel amendments on soil physical properties and water retention dynamics: A review. Int J Plant Soil Sci. 2024;36(5):112–24. https://doi.org/10.9734/ijpss/2024/v36i54532.
16. Jarrell WM, Beverly RB. The dilution effect in plant nutrition studies. Adv Agron. 1981;34:197–224. https://doi.org/10.1016/S0065-2113(08)60887-1.
17. Khan A, Zaidi SJ. Agricultural waste-derived hydrogels for soil-water management. J Clean Prod. 2026;412:128450. https://doi.org/10.1016/j.jclepro.2026.128450.
18. Khan MZ, Zaidi S. Valorization of cassava processing wastes into eco-friendly superabsorbent polymers for dryland and irrigated agriculture. J Clean Prod. 2026;432. https://doi.org/10.1016/j.jclepro.2025.139880. Article 139880.
19. Kumar A, Singh R, Patel K. Hydrogel application for boosting water and nutrient use efficiency in cereal-based systems. Geoderma. 2020;375., Article 114480. https://doi.org/10.1016/j.geoderma.2020.114480.
20. Kumar S, et al. Optimization of experimental plot sizes for paddy research. J Field Crops. 2020;15(4):89–102. https://doi.org/10.1016/j.fcr.2020.08.012.
21. Materu ST, et al. P-leaching and soil retention in paddy systems. J Environ Manage. 2024;350:119603. https://doi.org/10.1016/j.jenvman.2023.119603.
22. Mondal R, et al. Cellulose-based hydrogels and their impact on nitrogen use efficiency. Soil Tillage Res. 2021;205:104780. https://doi.org/10.1016/j.still.2021.104780.
23. Mondal S, Pramanik K, Panda PK. Superabsorbent hydrogels in rice production: Effects on soil moisture dynamics and nutrient recovery. Field Crops Res. 2021;265. https://doi.org/10.1016/j.fcr.2021.108110. Article 108110.
24. Montesano FF, Parente A, Santamaria P, Sannino A, Serio F. Biodegradable superabsorbent hydrogel increases water retention properties of growing media and plant growth. Agric Agric Sci Proc. 2015;4:451–8. https://doi.org/10.1016/j.aaspro.2015.03.052.
25. Neethu TM, Dubey AK, Kaswala AR. Superabsorbent polymers and their role in sustainable agriculture: A review. Int J Curr Microbiol Appl Sci. 2018;7(1):3381–92. https://doi.org/10.20546/ijcmas.2018.701.397.
26. Neethu TM, Dubey AK, Sharma RK. Superabsorbent polymers and their role in agriculture: A review. Int J Chem Stud. 2018;6(1):1708–17. https://doi.org/10.22271/chemi.2018.v6.i1z.3452.
27. Olufemi A, Alabi O. Modified alkaline gelatinization and crosslinking of starch for hydrogel production. Afr J Chem Phys. 2021;7(2):201–15. https://doi.org/10.1016/j.ajcp.2021.05.004.
28. Olufemi OA, Alabi OO. Environmental benefits of cassava peel-derived bio-solids in mitigating agricultural runoff and nitrogen leaching. J Environ Manage. 2021;280. https://doi.org/10.1016/j.jenvman.2020.111720.

Article 111720.

29. Romero C. Climate change impacts on irrigation water availability and soil degradation in sub-Saharan agricultural systems. Agric Water Manage. 2026;291. https://doi.org/10.1016/j.agwat.2025.108500. Article 108500.
30. Romero J. Sustainable intensification of paddy rice production: Challenges and pathways. Agric Sustain Rev. 2026;11(1):12–29. https://doi.org/10.1016/j.asr.2026.02.008.
31. Shijina V, et al. Organic hydrogel amendments and biomass recovery in cereal crops. Agron J. 2023;115(2):650–64. https://doi.org/10.1002/agj2.21345.
32. Shijina V, Kumar P, Thomas S. Biodegradable hydrogel systems in paddy soils: Sorption-desorption dynamics of major macronutrients. J Soil Sci Plant Nutr. 2023;23(3):3410–22. https://doi.org/10.1007/s42729-023-01280-4.
33. Sood P, et al. Climate-smart agriculture: Integration of hydrogels for resource-efficient intensification. J Sustainable Agric. 2023;20(3):220–35. https://doi.org/10.1080/14735903.2023.2185472.
34. Sood S, Sharma R, Gupta V. Polymer-treated soils and their hydraulic properties: Implications for water-saving agriculture. Soil Use Manag. 2023;39(1):201–15. https://doi.org/10.1111/sum.12850.
35. Udoro P, Mdemu MV, Kimaro DN. Mitigation of reproductive stage drought stress in lowland paddy using moisture-retaining soil conditioners. Irrig Sci. 2021;70(4):812–25. https://doi.org/10.1002/ird.2570.
36. Udoro SA, et al. Optimization of Kjeldahl analysis for total nitrogen in rice biomass. J Anal Chem. 2021;13(4):550–62. https://doi.org/10.1016/j.jac.2021.07.009.

Figures

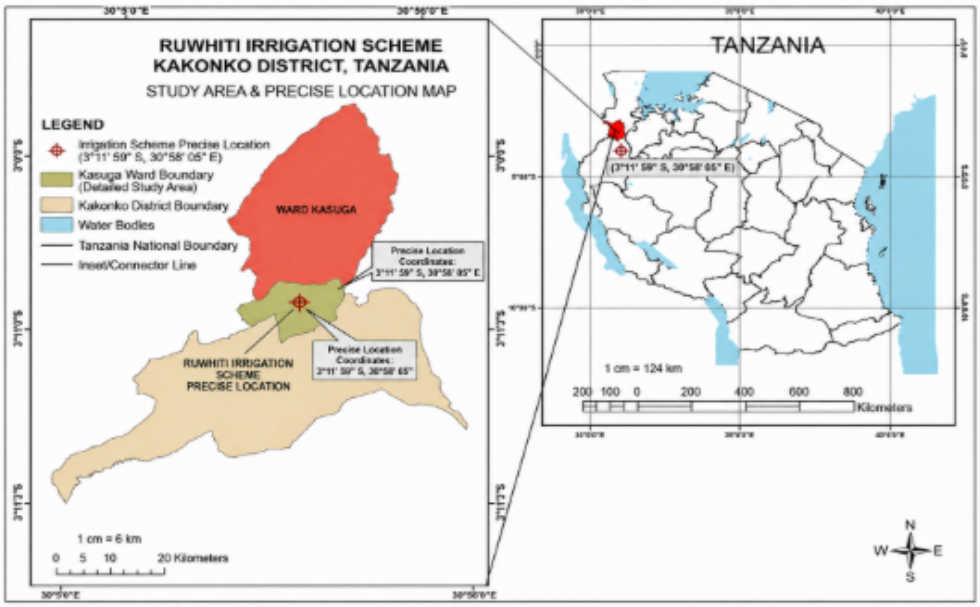


Figure 1

Location of the study Area in Tanzania

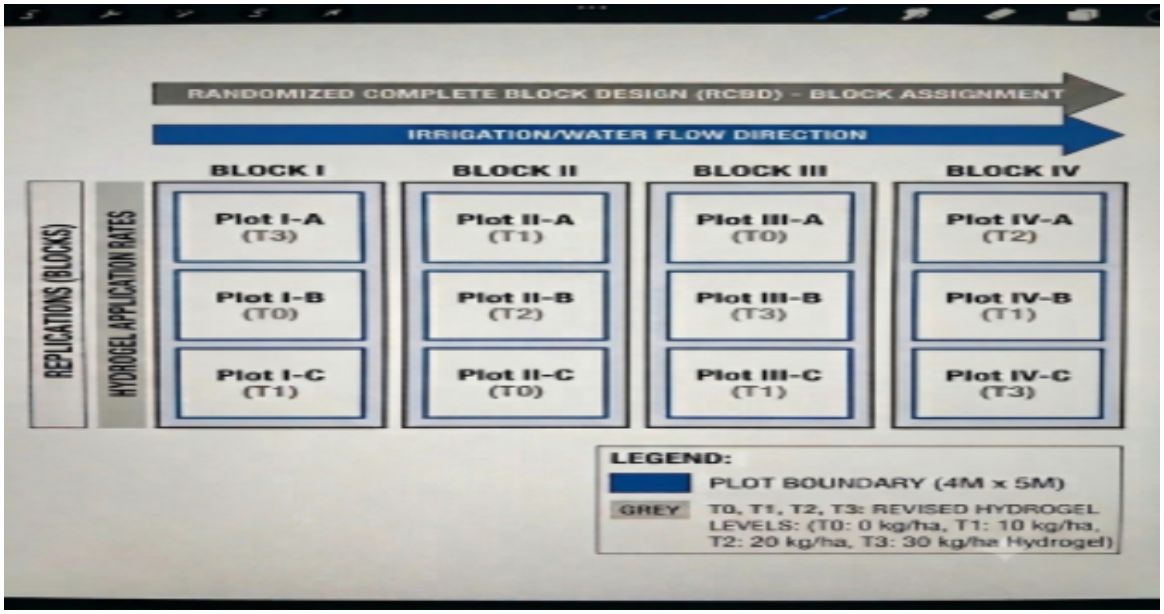


Figure 2

Schematic layout of the experimental design (RCBD).The layout includes four blocks (replications) and four treatment levels, plot dimensions (4mx 5m) and 1m wide pathways are maintained to reduce border effects. The arrow indicates the natural slope and direction of irrigation water flow.

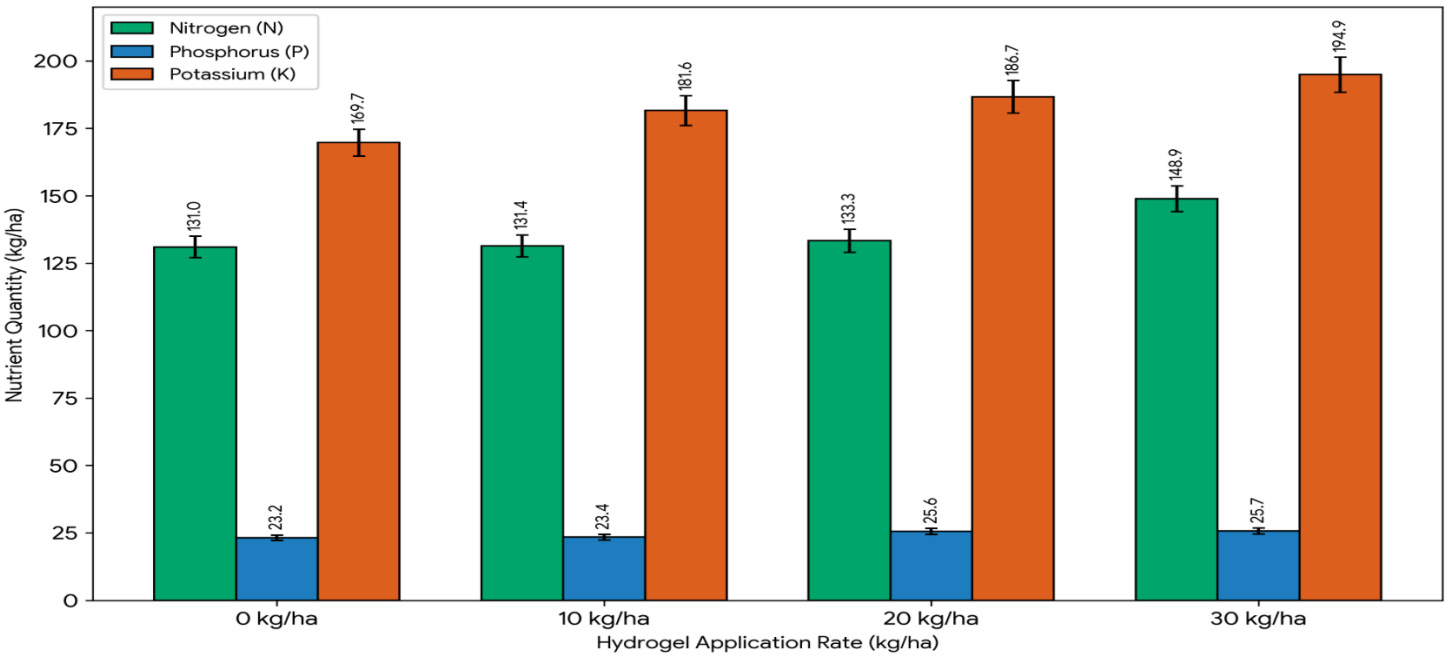


Figure 3

Total Nutrient uptake Dynamics at different Hydrogel rate