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ABSTRACT

Water scarcity and soil degradation pose serious challenges to sustainable rice production. In this study, peels from the Mkombozi cassava variety were washed, sun-dried, milled, gelatinized, and dried to produce biodegradable hydrogel granules for evaluation as a sustainable soil amendment. Laboratory characterization revealed a mean starch content of $19.21 \pm 0.03\%$, organic matter of $18.01 \pm 0.39\%$, and a near-neutral pH of 6.7. The hydrogel contained macronutrients: 7.37mg/g nitrogen, 0.933mg/g phosphorus, and 10.647mg/g potassium. It exhibited a swelling capacity of 0.1375 ± 0.0012 g/g and released all absorbed water within 168 hours. A 30-day soil burial test demonstrated 82.5% weight loss. These results suggest that the cassava peel-derived hydrogel functions as a slow-release matrix for moisture and nutrients, establishing a scientific baseline for further field evaluation.

Keywords: *Biodegradable hydrogel, Cassava peels, Soil amendment, Water retention, Nutrient dynamics, Biodegradability, Sustainable agriculture, Starch-based hydrogel, slow release, Tanzania.*

1. Introduction

The global sector faces critical challenges due to water scarcity and declining soil fertility, which threaten long-term food security (Romero, 2026). Traditional irrigation practices often result in substantial water loss through deep percolation and evaporation, particularly in coarse-textured soils (Materu et al., 2024). Superabsorbent hydrogels (SAHs) have emerged as a transformative technology for improving moisture retention in soil matrices (Tariq et al., 2023). However, conventional synthetic hydrogels are often polyacrylamide-based and non-biodegradable, posing long-term environmental risks to paddy ecosystems (Tang et al., 2023)

Consequently, research is shifting toward bio-based hydrogels derived from agricultural wastes, such as cassava peels, which align with circular bio economy principles (Romero, 2026; Udoro et al., 2021). Despite this potential, there is limited empirical data on the baseline physicochemical characterization—specifically regarding nutrient dynamics and degradation behavior of hydrogels synthesized from indigenous varieties like the Mkombozi Cassava. This study aims to bridge this knowledge gap by synthesizing and characterizing the Mkombozi-derived hydrogel to determine its material properties, nutrient release kinetics, and structural stability prior to field application. These findings provide a necessary scientific baseline for field-scale application in Tanzania rice production systems.

2. Materials and Methods

2.1 Description of the Study Area

Research was conducted at the Ruwhiti Irrigation Scheme, located in Nyakayenzi Village, Kasuga Ward, Kakonko District, Kigoma Region, Tanzania (Figure 2.1). The area is characterized by a tropical savannah climate (Köppen-Geiger classification Aw) with bimodal rainfall, averaging 850–1,100 mm/year, occurring primarily between October and May. The mean annual temperature ranges from 18°C to 28°C, and the elevation is between 1100 to 1700 m above sea level. The soils are classified as ferrallitic, well-drained, and moderately fertile.

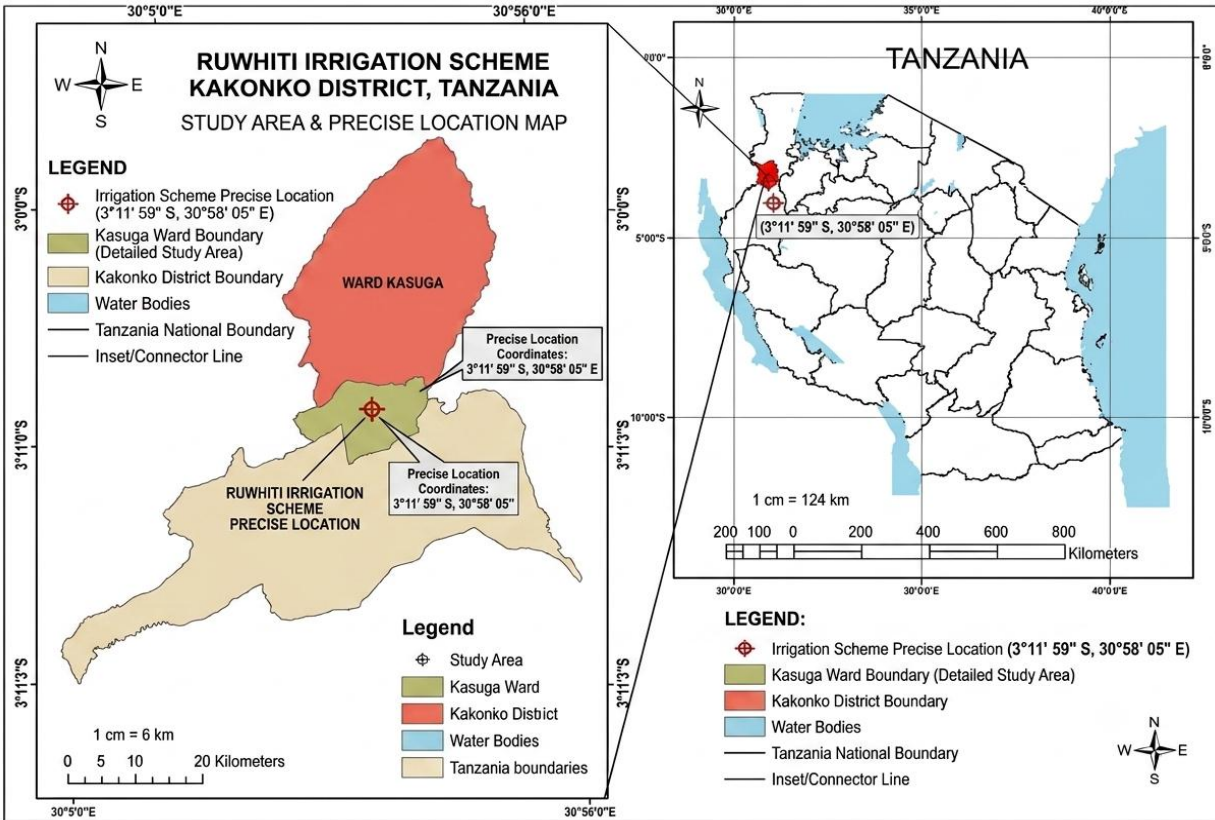


Figure 2.1: Location of the study Area in Tanzania

2.2 Hydrogel Preparation

Fresh Cassava peels from the Mkombozi variety (*Manihot esculenta* Crantz) were collected from cultivated cassava grown by farmers at Nyakayenzi village, Kasuga ward, Kakonko district, Kigoma region, Tanzania, via purposive sampling from local processing sites to ensure botanical consistency. Mature and healthy cassava roots processed for food consumption were selected, and the resulting peels were collected immediately after peeling. Forty kilograms (40 kg) of fresh peels were collected in clean, high-density polyethylene (HDPE) bags and transported to the laboratory at Sokoine University of Agriculture. The peels were thoroughly washed with distilled water to remove soil and extraneous impurities, then sun-dried for 7 days until a constant weight was achieved. The dried material was ground into fine powder using a locally fabricated electric hammer mill (2.2 kW, 3.0 hp motor) operating at 2,800 rpm.

To form the hydrogel matrix without synthetic chemical cross-linkers, a thermal gelatinization method was employed. A 1:10 (w/v) ratio of cassava peel flour (CPF) to distilled water was maintained. The slurry pH was adjusted to 7.0 using 0.1 M NaOH, monitored by a digital pH meter (precision ± 0.01). The slurry was heated to 70°C under continuous mechanical stirring using a magnetic stirrer with an integrated hot plate to ensure complete starch gelatinization. This process disrupts the intermolecular hydrogen bonds of native amylose and amylopectin, allowing for subsequent physical cross-linking via molecular realignment and retro gradation during cooling to 20°C (ambient temperature). The resulting hydrogel was oven-dried to a stable state and processed into granules for soil application.

2.3 Physicochemical Characterization

The physicochemical properties of the biodegradable hydrogel were determined using standard laboratory methods. All analyses were conducted in triplicate, and results are expressed as mean $\pm$ standard deviation (SD).

2.3.1 Starch Content

Starch is the primary functional component of cassava (*Manihot esculenta*) peels, providing the hydrophilic sites necessary for water absorption. To determine the starch content, 2.0 g of the pulverized hydrogel was treated with 80% ethanol to remove free sugars, isolating the structural starch. The sample was subjected to acid hydrolysis using 2.5 N HCL at 100°C, a process that cleaves the α -1,4 and α -1,6 glycosidic bonds within the starch matrix. The hydrolysate was neutralized with sodium hydroxide (NaOH), and reducing sugars were quantified using the Lane-Eynon titration method. The starch percentage was calculated by multiplying the glucose yield by a factor of 0.9.

2.3.2 Swelling Capacity

The swelling capacity (Q) was determined gravimetrically. Approximately 0.5 g (W_0) of dried hydrogel granules was accurately weighed (precision ± 0.0001 g) and placed in a fine-mesh nylon teabag of known dry weight. The teabag was submerged in 500 mL of distilled water at 25°C for 24 hours to reach equilibrium swelling. After 24 hours, the teabag was removed and suspended vertically for 10 minutes to allow excess surface water to drain under gravity. The final weight of the swollen hydrogel (W_s) was recorded, and Q (g/g) was calculated as:

$$Q = \frac{W_s - W_o}{W_o} \dots\dots\dots(1)$$

2.3.3 Water Retention and Release

To simulate drying cycles, a known mass of hydrogel was saturated with distilled water in a container (T = 0 hours). Samples were maintained in a controlled laboratory environment (25°C, 50% relative humidity). The total weight of the system was recorded periodically at 24, 48, 72, 120, 144, and 168 hours using an analytical balance. The percentage of water retained (WR) was calculated as:

$$WR (\%) = \frac{W_t}{W_i} \times 100 \dots\dots\dots(2)$$

Where W_t is the weight of water at time t and W_i is the initial weight of water at saturation.

2.3.4 pH Measurement

A digital glass electrode pH meter was calibrated with buffer solutions (pH 4.0, 7.0, and 10.0) at 25°C. A 1.0 g sample of the hydrogel was dispersed in 100 mL of deionized water (1:100 w/v) and stirred continuously for 30 minutes to equilibrate the polymer network. The pH was recorded once the reading stabilized.

2.3.5 Biodegradability Test

The soil burial method was used to assess degradation under environmental conditions. Agricultural soil (classified as clay loam per USDA standards) was sieved through a 2 mm mesh and placed in perforated containers. Three replicates of 10.00 g of hydrogel were placed in nylon mesh bags and buried at a depth of 10 cm. Soil moisture was maintained at 30% field capacity. At 5-day intervals (up to 30 days), samples were recovered, cleaned, oven-dried at 50°C to a constant weight, and weighed. Weight loss was calculated as:

$$Weight\ Loss (\%) = \frac{W_i - W_t}{W_i} \times 100 \dots\dots\dots(3)$$

Where W_t is the weight of residual dry weight at time t and W_i is the initial dry weight of hydrogel (10.00 g)

2.3.6 Nutrient Content (N, P, K)

- Macronutrient concentrations were determined to assess the hydrogel's potential as a

slow-release fertilizer. Nitrogen (N): Total N was determined using the Kjeldahl method, involving digestion with concentrated H₂SO₄, distillation, and titration.

- Phosphorus (P): Total P was measured using the vanadomolybdophosphoric acid colorimetric method via UV-Visible Spectrophotometry at 430 nm.
- Potassium (K): Total K was determined by flame photometry at 766 nm.

2.3.7 Organic Matter Content

Organic matter was determined via the loss on Ignition (LOI) method. Samples were dried, weighed (W_1), and ignited in a muffle furnace at 550°C for 4 hours. After cooling in a desiccator, the residual inorganic ash weight (W_2) was measured. Organic matter (%) was calculated as :

$$\text{Organic Matter (\%)} = \frac{W_1 - W_2}{W_1 - W_c} \times 100 \dots\dots\dots(4)$$

Where W_c is the weight of the empty crucible

2.4 Statistical Analysis

Data were analyzed using IBM SPSS Statistics (Version 26.0). A one-way Analysis of Variance (ANOVA) was performed to determine significant differences among treatments. Where results were significant ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) test was used for mean separation.

3. Results

The synthesized cassava peel-based hydrogel was systematically characterized in triplicate. The empirical baseline values, including mean, standard deviation (SD), are presented in Table 3.1. Statistical validation confirmed no significant differences between experimental replicates ($p > 0.05$), indicating high formulation homogeneity and reproducibility.

Table3.1: 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

3.1 Starch and Organic Matter Content

The synthesis process yielded a hydrogel with a mean starch content of $19.21 \pm 0.03\%$ and an organic matter content of $18.01 \pm 0.39\%$. These values confirm the retention of the structural biopolymer matrix after thermal processing.

3.2 Swelling Capacity

The hydrogel exhibited a mean equilibrium swelling capacity of 0.1375 g/g. This capacity represents the maximum theoretical water absorption of the cross-linked macromolecular matrix in distilled water at 25°C.

3.3 Water Retention and Release Kinetics

The hydrogel showed a time-dependent decrease in water retention over 168 hours (Table 3.2). The water release was modeled linearly ($y = -0.0083x + 1.341$), showing a strong negative correlation ($R = -0.994$) and a high coefficient of determination ($R^2 = 98.8\%$).

Table 3.2: Water retention capacity over 168 hours

Time (hrs)	Total Weight (g)	Water Weight (g)	Retention (%)
0 (Sat.)	11.375	1.375	100.0
24	11.116	1.116	81.2

48	10.941	0.941	68.4
72	10.720	0.720	52.4
120	10.400	0.400	29.1
144	10.170	0.170	12.4
168	10.000	0.000	0.0

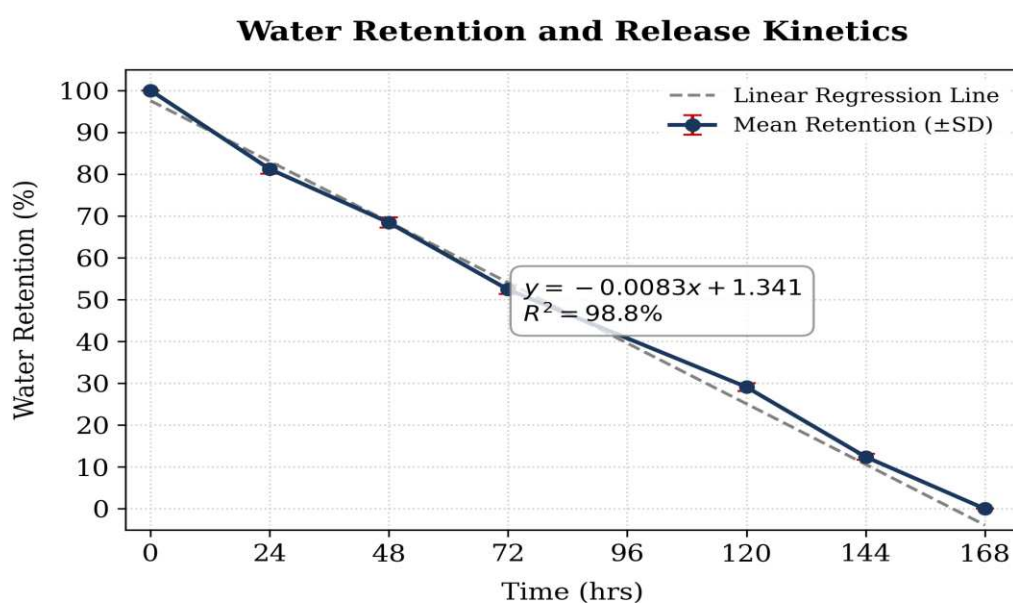


Figure 3.1: Water retention and release curve of hydrogel

3.4 pH and Nutrient Composition

The hydrogel maintained a uniform near-neutral pH of 6.7, ensuring compatibility for soil application. Nutrient analysis revealed the hydrogel acts as a reservoir for essential macronutrients, with potassium being the most abundant (10.647 mg/g), followed by nitrogen (7.37 mg/g) and phosphorus (0.933 mg/g).

3.5 Biodegradability

The soil burial test demonstrated high environmental degradability. The hydrogel experienced a cumulative weight loss of 82.5% over 30 days, with the degradation rate following a linear trend ($y = -0.297x + 9.77$, $R^2 = 98.2\%$).

Table 3.3: Hydrogel weight loss over 30 days

Day	Mean Residual Weight (g)	Cumulative Weight Loss (%)
0	10.00	0.0%
5	8.77	12.3%
10	7.12	28.8%
15	4.95	50.5%
20	3.14	68.6%
25	2.16	78.4%
30	1.75	82.5%

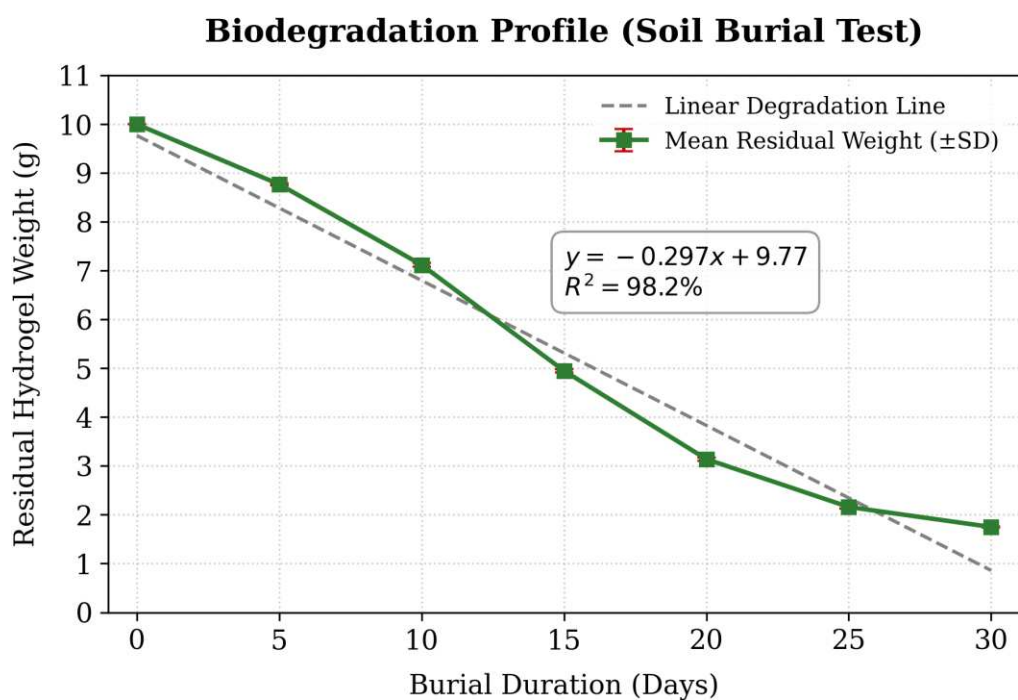


Figure 3.2: Gravimetric Degradation Curve

4. Discussion

4.1 Physicochemical Composition and Functional Implications

The starch content of 19.21% confirms that cassava peels remain a viable source of biopolymer even after processing. This starch provides the primary hydrophilic backbone necessary for water interaction within the matrix. The organic matter content (18.01%) indicates that a substantial proportion of the hydrogel consists of biodegradable biomass, which is expected to contribute to long-term soil organic carbon enrichment upon .The near-neutral pH (6.7) is highly favorable for agricultural use, as it falls within the optimal range (6.0–7.5) for nutrient availability and beneficial microbial activity in rice soils.

4.2 Nutrient Dynamics and Slow-Release Potential

The inherent macronutrient concentrations-nitrogen (7.37 mg/g), phosphorus (0.933 mg/g), and potassium (10.647 mg/g)-demonstrate the hydrogel's dual functionality as both a moisture retainer and a nutrient reservoir. Potassium dominance is particularly beneficial for rice, as it supports essential physiological processes, including osmotic regulation, stomatal control, and disease resistance. Because these nutrients are physically embedded within the polymeric matrix, the material exhibits strong potential as a slow-release fertilizer carrier, which may significantly reduce nutrient leaching-a major challenge in flooded rice systems.

4.3 Water Absorption, Retention, and Matrix Integrity

The equilibrium swelling capacity of 0.1375 g/g is lower than that of conventional synthetic superabsorbent hydrogels, which often exceed 100-500 g/g. However, this moderate swelling is advantageous in flooded rice paddies; excessive expansion in such environments could lead to a loss of structural integrity and matrix dissolution. The controlled, linear water release observed over 168 hours suggests that the hydrogel can effectively bridge moisture availability gaps during short-term dry spells, potentially optimizing irrigation frequency.

4.4 Biodegradability and Environmental Impact

The observed 82.5% weight loss within 30 days confirms the material's excellent environmental degradability. This rapid decomposition ensures that the hydrogel does not persist as a non-degradable pollutant, contrasting sharply with the environmental accumulation risks associated with synthetic, polyacrylamide-based hydrogels. Such behavior directly supports circular bio

economy principles by efficiently returning organic matter and recycled nutrients to the soil profile.

5. Conclusion

This study provides a definitive empirical baseline for the utilization of indigenous Mkombozi cassava peel waste as a sustainable soil amendment. The key findings are as follows:

- **Synthesis Efficiency:** Unrefined cassava peel waste possesses a sufficient starch fraction for thermal gelatinization, enabling the formulation of a robust bio-composite matrix without the need for expensive, commercial-grade biopolymer isolation.
- **Structural Characteristics:** The synthesized material functions as a dense, physically cross-linked thermoplastic starch-cellulose bio-composite network. The low equilibrium swelling capacity observed is the result of high-density intra-and intermolecular hydrogen bonding between the gelatinized starch paste and the native crystalline cellulose microfibrils.
- **Functional Suitability:** Despite its lower swelling capacity compared to synthetic alternatives, the hydrogel's structural stability, near-neutral pH, and inherent macronutrient content render it uniquely suited for the high-moisture conditions of paddy rice cultivation.
- **Sustainability:** The high rate of biodegradability (82.5% in 30 days) confirms the hydrogel as an environmentally benign alternative that mitigates the long-term ecological risks associated with petroleum-based superabsorbent.

6. Recommendation

- **Optimization:** While the current formulation is stable, future research should explore the modification of processing conditions or the inclusion of eco-friendly additives to moderately enhance the swelling capacity without compromising structural integrity.
- **Field Validation:** The laboratory-scale results establish a solid foundation for scaling up. It is strongly recommended that field trials be conducted at the Ruwhiti Irrigation Scheme to evaluate the hydrogel's real-world impact on rice grain yield, water use efficiency (WUE), and nutrient uptake in local soil conditions.
- **Integrated Management:** Future studies should investigate the synergetic effects of combining this hydrogel with varying irrigation schedules (Alternate Wetting and Drying-AWD) to maximize water productivity in rice production systems.

7. Declarations

7.1 Clinical Trial Registration

This study is not a clinical trial; therefore, clinical trial registration is not applicable.

7.2 Ethics, Consent to Participate, and Consent to Publish

This research involved experimental agricultural fieldwork and did not involve human or animal subjects. The plant material used in this study consisted of peels from cultivated cassava (*Manihot esculanta* Crantz, Mkombozi variety). The plant material originated from cultivated farms. Collection and use of plant material complied with the applicable institutional and national guidelines of Tanzania. No endangered or protected plant species were involved, therefore no collection permit or ethical approval was required.

Cassava peels were obtained as agricultural waste material, no plant specimens were collected from natural habitats, no specific permits or licenses were required for the collection of plant material.

7.3 Author Contributions

Jenard Mathayo Mlengera (Corresponding author): Conceptualization, methodology, formal analysis, investigation, writing – original draft.

Dr. Stanslaus Terengia Materu: Supervision, validation, writing – review and editing.

Dr. Yusto Mugisha Yustas: Supervision, methodology review, writing – review and editing.

7.4 Conflict of Interest

The authors declare no conflict of interest.

7.5 Funding Source

This research received no external funding.

7.6 Data Availability

The data used in this study are available from the corresponding author upon reasonable request.

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