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Effect of Soybean Germination on the Physico-Chemical and Sensory Characteristics of Maize-Sorghum Porridge

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Abstract

Background:

Maize–sorghum porridge is a widely consumed cereal-based staple in many African households and a critical source of dietary energy for infants and young children, but it is limited in protein and several micronutrients. Germination is a simple, low-cost strategy for improving the functional, nutritional, and sensory quality of legume-fortified complementary foods.

Methods:

This study evaluated the effect of soybean germination on the physicochemical and sensory characteristics of maize–sorghum composite porridge. The research was conducted at EFA Nyagahanga Technical Secondary School in Gatsibo District, Eastern Province, Rwanda. Three formulations were prepared using 35% maize, 35% sorghum, and 30% soybean flour: raw non-germinated soybean (T0), soybean germinated for two days (T1), and soybean germinated for three days (T2). Physical properties (water absorption capacity and viscosity) and chemical properties (moisture, protein, fat, ash, crude fiber, carbohydrate, vitamin C, and B-complex vitamins) were determined in triplicate (N=3). Sensory evaluation was performed using a 9-point hedonic scale with ten trained panelists. Data were analyzed using one-way ANOVA, with treatment means separated by Tukey's HSD test ($P<0.05$).

Results:

Germination significantly improved functional behavior by increasing water absorption capacity and reducing viscosity ($P<0.05$). Germination significantly increased protein, ash, crude fiber, vitamin C, and B-complex vitamin levels, while decreasing fat and carbohydrate contents ($P<0.05$). Moisture content was not significantly affected across treatments. Sensory evaluation demonstrated that the three-day germinated soybean formulation (T2) received the highest scores for aroma, taste, texture, and overall acceptability, with color and consistency showing no significant differences among treatments.

Conclusion:

Incorporating soybean germinated for three days optimizes the functional, nutritional, and sensory attributes of maize–sorghum porridge, offering a viable, low-cost strategy for complementary feeding and household food security in settings such as rural Rwanda.

Keywords: composite flour; germination; maize; nutritional composition; sensory characteristics; soybean; sorghum; complementary feeding; food security

Introduction

Porridge prepared from cereals such as maize and sorghum is commonly used as a complementary food for young children in Rwanda and across sub-Saharan Africa, and provides an important source of dietary energy during the critical 6–23-month window of complementary feeding [1,2]. However, adequate complementary feeding requires foods that provide sufficient protein and micronutrients to support growth and development. The nutritional adequacy of complementary foods is particularly important in Rwanda, where malnutrition and micronutrient deficiencies remain important public health challenges[3,4]. According to the National Institute of Statistics of Rwanda (NISR), approximately 30% of children under five years were stunted in 2024, while 37% of children aged 6–59 months had some level of anemia according to the 2019–20 Rwanda Demographic and Health Survey. These figures place Rwanda among the sub-Saharan African countries where cereal-dominated complementary diets, low in bioavailable protein, iron, and B-vitamins, are recognized as a major contributor to growth faltering and anemia in early childhood. Gatsibo District, the specific study area of the present work, lies in Rwanda's Eastern Province, a semi-arid agroecological zone that is among the country's principal producers of maize, sorghum, and soybean, yet also reports child stunting rates above the national average; this combination of high local cereal-legume production and persistent undernutrition makes it a particularly relevant setting in which to evaluate locally processed, nutrient-dense composite porridges[5,6].

Improving cereal-based porridges with soybean can increase their nutritional value, particularly their protein and micronutrient content. Soybean complements cereals' amino acid limitations, making it useful in maize–sorghum-based foods. However, raw soybean contains antinutritional factors such as phytates and trypsin inhibitors, while its beany flavor and aroma may reduce consumer acceptability[7,8].

Germination is a simple, low-cost, and environmentally friendly processing method that can improve the nutritional and functional properties of soybean[9]. It enhances enzyme activity, improving protein digestibility and nutrient utilization while reducing anti-nutritional factors

such as phytate and trypsin inhibitors. Germination can also increase vitamin C, phenolic compounds, flavonoids, and antioxidant activity, depending on germination conditions and duration. Mechanistically, soaking and sprouting trigger *de novo* synthesis and activation of hydrolytic enzymes such as amylases, proteases, and phytases within the seed; these enzymes progressively break down storage starch and storage proteins into simpler, more digestible fragments, hydrolyse phytate–mineral complexes, and mobilise lipid reserves for the growing embryo [10]. Because these biochemical changes proceed with germination time, the duration of sprouting is a key process variable that can be optimised to obtain a target balance of functional, nutritional, and sensory properties, which is the specific process variable investigated in the present study through comparison of non-germinated, 2-day, and 3-day germinated soybean.

Incorporating germinated soybean into maize–sorghum porridge may enhance its nutritional and functional quality. However, sensory characteristics such as taste, aroma, texture, colour, consistency, and overall acceptability must also be considered to ensure consumer acceptance[11,12].

Beyond its direct nutritional benefits, fortifying maize–sorghum porridge with locally grown soybean also has a value-chain dimension that is relevant to smallholder farmers in Rwanda's Eastern Province: because maize, sorghum, and soybean are already produced within the study area, a simple on-farm or school-level germination step adds nutritional value to these crops without requiring costly imported ingredients, industrial equipment, or synthetic fortificants. Comparable composite-flour approaches combining cereals with germinated or otherwise processed legumes and tubers, such as finger millet–sweet potato–soybean blends[6]. and maize–soybean–plantain porridge, have similarly reported improved nutritional and functional profiles, suggesting that germination-based fortification is a generalisable strategy across a range of locally available cereal–legume combinations rather than one specific to a single formulation[13,14]. Positioning the present maize–sorghum–soybean system within this broader body of composite-flour research strengthens the case that its findings are transferable to other cereal-growing regions of East Africa facing similar complementary-feeding challenges.

Although germination-induced changes in individual legumes such as pigeon pea, cowpea, and chickpea have been well documented [15,16], Comparatively few studies have evaluated how different soybean germination durations jointly affect the physical, chemical, and sensory properties of a maize–sorghum–soybean composite porridge prepared and evaluated under

real, resource-limited school and community conditions, as opposed to controlled pilot-plant settings. Addressing this gap is particularly relevant for Rwanda and similar East African contexts, where composite flours produced from locally available maize, sorghum, and soybean represent a practical, low-cost pathway to improving complementary-feeding diets and household food security without requiring imported fortificants [1,17]. This study therefore aimed to assess the physicochemical (water absorption capacity, viscosity, moisture, protein, fat, ash, crude fiber, carbohydrate, vitamin C, and B-complex vitamins) and sensory characteristics of maize–sorghum porridge enriched with soybean flour germinated for 0, 2, and 3 days, to identify the germination duration that provides the best combination of functional, nutritional, and sensory quality for use as a complementary food.

Materials and Methods

Figure 1 summarizes the overall experimental workflow, from raw-material sourcing through to statistical analysis, and Table 1 provides a consolidated summary of the analytical methods used for each parameter; full procedural detail for each method is given in the corresponding subsections below.

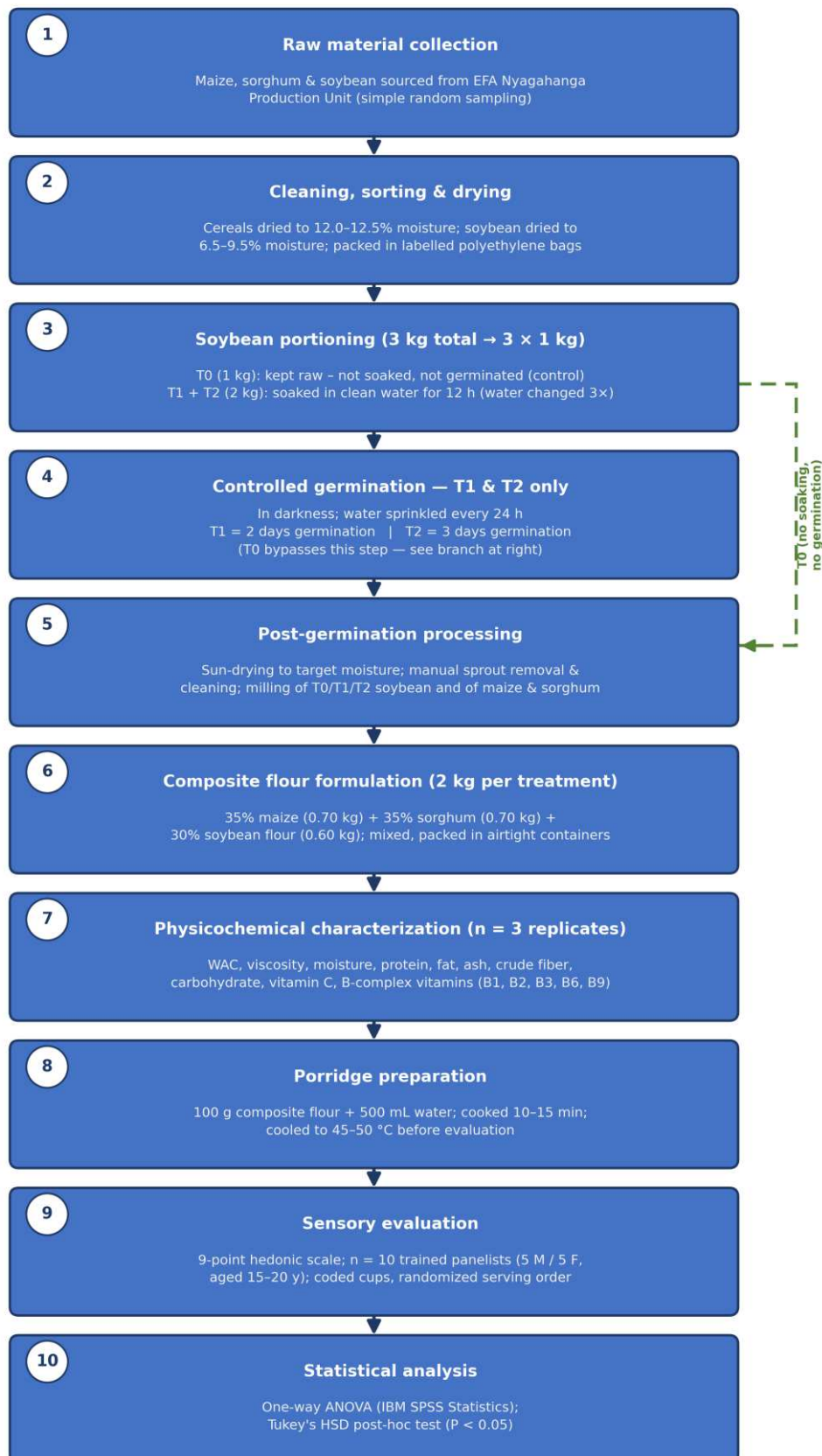


Figure 1. Overview of the experimental workflow, from raw-material sourcing to statistical analysis.

Study area

The study was conducted at EFA Nyagahanga Technical Secondary School (TSS), Gatsibo District, Eastern Province of Rwanda, an area with significant production of maize, sorghum, and soybean. Porridge preparation was carried out in the school's Food Processing Workshop, while physicochemical and sensory analyses were conducted at the EFA Nyagahanga Food Chemistry Laboratory, INES Ruhengeri Chemistry Laboratory, and University of Rwanda Chemistry Laboratory using available laboratory facilities and equipment.

Experimental design

Sampling procedure

Maize (*Zea mays*), sorghum (*Sorghum bicolor* L. Moench), and soybean (*Glycine max* (L.) Merr.) were obtained from farmers at the EFA Nyagahanga Production Unit using simple random sampling. The grains were sorted to remove damaged kernels and impurities, then dried to appropriate moisture levels of 12–12.5% for cereals and 6.5–9.5% for soybean. The cleaned samples were packaged in labelled polyethylene bags, transported to the laboratory, and stored under suitable conditions until processing.

Germination of soybeans

Soybeans were germinated using a modified method adapted from published soybean germination protocols. A total of 3 kg of soybeans were sorted, washed thoroughly, and soaked in clean water for 12 hours, with the soaking water changed three times. After rinsing, the soybeans were divided into two portions and germinated in darkness for 2 and 3 days, respectively. Water was sprinkled every 24 hours to maintain adequate moisture. After germination, the soybeans were sun-dried to the appropriate moisture level, followed by manual removal of the sprouts and cleaning before further processing. Germination was used to improve nutritional quality and reduce anti-nutritional factors such as phytates and trypsin inhibitors.

Development of composite flour

Three composite flour formulations were prepared using 35% maize, 35% sorghum, and 30% soybean flour. Each 2 kg formulation contained 0.70 kg maize, 0.70 kg sorghum, and 0.60 kg

soybean flour. The treatments were T0 (non-germinated soybean), T1 (soybean germinated for 2 days), and T2 (soybean germinated for 3 days). The grains were cleaned, dried, and milled into flour, while germinated soybean was additionally soaked, germinated, and dried before milling. The three flours were thoroughly mixed, packaged in airtight containers, and stored in a cool, dry place until analysis.

Determination of physicochemical properties of maize-sorghum porridge enriched with germinated soybean flour

The physical properties of maize–sorghum porridge enriched with germinated soybean flour were evaluated to determine the influence of soybean incorporation on the quality and functional characteristics of the developed product. The analyzed parameters included water absorption capacity and viscosity, which were determined using standard food analysis procedures.

Table 1. Summary of analytical methods used to characterize the maize–sorghum–soybean composite flour and porridge

Parameter	Method / principle	Key instrument(s)	Reference
Viscosity & consistency	Rotational viscometry; spindle rotated at fixed speed in a stirred sample	Brookfield Digital Viscometer, Spindle No. 4, 20 rpm, 60 s	—
Water absorption capacity (WAC)	Centrifugation of a flour-water suspension; water retained by pellet is measured	Vortex mixer; centrifuge (5,000 rpm)	—
Moisture content	Oven-drying to constant weight (105 °C)	Hot-air oven; desiccator; analytical balance	—

Total protein	Kjeldahl digestion, distillation, and titration; $N \times 6.25$	Digestion block; distillation unit; burette	—
Total fat	Soxhlet extraction with n-hexane	Soxhlet apparatus; rotary evaporator	—
Total ash	Dry ashing at 550 °C to constant weight	Muffle furnace; desiccator	—
Crude fiber	Sequential acid/alkali digestion (AOAC 962.09), ashing correction	Fiber digestion unit; muffle furnace	—
Carbohydrate (by difference)	$100\% - (\text{moisture} + \text{protein} + \text{fat} + \text{fiber} + \text{ash})$	Calculation from above analyses	—
Vitamin C	Iodometric titration with starch endpoint indicator	Burette; iodine solution (0.005 M)	—
B-complex vitamins (B1, B2, B3, B6, B9)	Acid extraction followed by reverse-phase chromatographic separation and quantification	HPLC with C18 column	—

All analyses were performed in triplicate ($N = 3$) on each treatment (T_0 , T_1 , T_2).

Determination of viscosity and consistency

The viscosity and consistency of the maize–sorghum porridge enriched with germinated soybean flour were determined using a rotational viscometer, as viscosity reflects resistance to flow and consistency describes the thickness and flow behaviour of the porridge. The samples were gently stirred, and approximately 200 mL was transferred into a 250 mL beaker without introducing air bubbles. Viscosity was measured using a Brookfield Digital Viscometer with

Spindle No. 4 at 20 rpm for 60 seconds, and the stabilized readings were recorded in centipoise (cP). Each sample was analyzed in triplicate, with the spindle cleaned between measurements. The mean viscosity was calculated from the three readings and used to compare the viscosity of the different porridge formulations. The mean viscosity was expressed using Equation 1:

$$\text{Mean Viscosity} = (R_1 + R_2 + R_3) / 3 \quad (1)$$

where R1, R2, and R3 represent the first, second, and third measurements, respectively.

Determination of water absorption capacity (WAC)

The water absorption capacity (WAC) of the maize–sorghum–soybean composite flours was determined using a centrifugation-based method commonly used to evaluate hydration properties of cereal–legume flour blends. Briefly, 1.0 g of flour was mixed with 10 mL of distilled water, vortexed for approximately 30 seconds, and allowed to hydrate for 30 minutes at room temperature. The suspension was then centrifuged at 5,000 rpm for 30 minutes. The supernatant was removed and measured, and the amount of water retained by the flour was calculated from the difference between the initial water added and the recovered supernatant. Water absorption capacity was then expressed as grams of water absorbed per gram of flour sample (g/g) using Equation 2:

$$\text{WAC (g/g)} = (\text{volume of water added} - \text{volume of supernatant}) / \text{weight of sample} \quad (2)$$

Determination of moisture content

The moisture content of the composite flour samples was determined using the oven-drying method according to the standard procedure described by the Association of Official Analytical Chemists International. Approximately 2.0 g of each composite flour sample consisting of 35% maize, 35% sorghum, and 30% germinated soybean flour, and 35% maize, 35% sorghum, and 30% non-germinated soybean flour was accurately weighed into a previously dried, cooled, and weighed moisture dish. The dish containing the sample was placed in a hot air oven and dried at 105 °C until a constant weight was obtained. After drying, the dish was removed from the oven, cooled in a desiccator, and reweighed. The loss in weight after drying was considered to be the moisture content of the sample. The moisture content was calculated using Equation 3:

$$\text{Moisture Content (\%)} = [(W1 - W2) / (W1 - W0)] \times 100 \quad (3)$$

where W0 is the weight of the empty moisture dish (g), W1 is the weight of the moisture dish + sample before drying (g), and W2 is the weight of the moisture dish + sample after drying (g).

Determination of total protein content

The crude protein content of the maize–sorghum–soybean composite flour was determined using the Kjeldahl method following the standard procedure of the Association of Official Analytical Chemists. Briefly, 2 g of each sample was digested with concentrated sulfuric acid and a catalyst for approximately 1.5 hours. After digestion and dilution, the sample was neutralized with 40% NaOH, and the released ammonia was distilled into 4% boric acid. The distillate was titrated with 0.1 N HCl using methyl red as an indicator, and the volume of acid consumed was used to calculate the nitrogen and crude protein content of the samples. The crude protein content was subsequently determined by multiplying the nitrogen content by the appropriate protein conversion factor using Equation 4:

$$\%N = [(mL\ 0.1N\ HCl - mL\ blank) \times 14 \times N\ HCl] / (1000 \times weight\ of\ sample\ (g)) \times 100$$

(4)

$$Protein\ (\%) = \% total\ nitrogen \times 6.25$$

where moles of HCl equal moles of NH₃, N HCl is the normality of HCl in mol/1000 mL, and 14 is the atomic weight of nitrogen.

Determination of total fat content

The fat content of the homogenized composite flour was determined using the Soxhlet extraction method with n-hexane as the solvent, following standard procedures. Briefly, 5 g of finely ground sample was placed in a Soxhlet thimble and extracted with approximately 200 mL of n-hexane for 5 hours. The solvent continuously extracted the oil from the sample through repeated boiling, condensation, and siphoning cycles. After extraction, the solvent was removed by evaporation under reduced pressure, and the recovered oil was cooled and weighed to determine the fat content of the sample. The percentage oil yield was determined using Equation 5:

$$Oil\ yield\ (\%) = (weight\ of\ extracted\ oil / initial\ weight\ of\ sample\ (g)) \times 100 \quad (5)$$

Determination of total ash

The total ash content of the composite flour was determined using the dry ashing method. Approximately 2.0 g of each sample was weighed into clean, pre-weighed crucibles, gently charred, and incinerated in a muffle furnace at 550 °C until a constant weight of white or grey ash was obtained. The crucibles were cooled in a desiccator and reweighed, and the ash content was calculated from the weight difference. Ash content was calculated using Equation 6:

$$\text{Ash (\%)} = (\text{weight of ash (g)} / \text{weight of sample (g)}) \times 100 \quad (6)$$

Determination of crude fiber content

The crude fiber content of the composite flour samples was determined using the AOAC Official Method 962.09. Approximately 2.0 g of each sample was sequentially digested with 1.25% H₂SO₄ and 1.25% NaOH, followed by filtration and washing to remove soluble materials. The residue was dried at 105 °C to constant weight, then incinerated at 550 °C for 3 hours. Crude fiber content was calculated from the weight loss after ashing. Crude fiber content was determined using Equation 7:

$$\text{Crude Fiber (\%)} = [(\text{weight of dried residue} - \text{weight of ash}) / \text{weight of sample (g)}] \times 100 \quad (7)$$

Determination of carbohydrate content by difference

The carbohydrate content of the composite flour samples was determined using the difference method, by subtracting the percentages of moisture, crude protein, crude fat, crude fiber, and ash from 100%. The required proximate components were first analyzed using standard methods, and carbohydrate content was then calculated using the difference method described above. Carbohydrate content was calculated using Equation 8:

$$\text{Carbohydrate (\%)} = 100 - (\text{moisture} + \text{crude protein} + \text{crude fat} + \text{crude fiber} + \text{ash}) \quad (8)$$

Determination of vitamin C

The vitamin C content of the composite flour (35% maize, 35% sorghum, and 30% soybean) was determined by iodometric titration. Approximately 5 g of sample was extracted with 50 mL of 3% metaphosphoric acid, filtered, and an aliquot was titrated with standardized 0.005 M iodine solution using starch as an indicator until a persistent blue-black endpoint was reached. The analysis was performed in triplicate, and the mean titre value was used for

calculation. Vitamin C content was calculated and expressed as milligrams of ascorbic acid per 100 g (mg/100 g) of composite flour using Equation 9:

$$\text{Vitamin C (mg/100 g)} = (V \times M \times 88.06 \times DF \times 100) / W \quad (9)$$

where V is the volume of iodine solution used in titration (mL), M is the molarity of the iodine solution (mol/L), DF is the dilution factor, W is the weight of sample (g), and 88.06 is the molecular weight of ascorbic acid (mg/mmol).

Determination of B-complex vitamins

The B-complex vitamins (B1, B2, B3, B6, and B9) in the maize–sorghum porridge enriched with germinated soybean flour were determined using High-Performance Liquid Chromatography (HPLC). Samples were extracted with hydrochloric acid, heated, centrifuged, and filtered before chromatographic analysis using a reverse-phase C18 column. Vitamins were identified by retention times against authentic standards and quantified using calibration curves. Results were expressed as mg/100 g of sample. The concentration of each vitamin was calculated using Equation 10:

$$\text{Vitamin concentration (mg/100 g)} = (C \times V \times DF) / W \quad (10)$$

where C is the concentration from the calibration curve (mg/L), V is the final extract volume (L), DF is the dilution factor, and W is the sample weight (g).

Sensory evaluation

The sensory characteristics of maize–sorghum porridge enriched with germinated and non-germinated soybean flour were evaluated using a nine-point hedonic scale. Ethical clearance was obtained, and written informed consent was obtained from all participants before tasting. The sensory panel consisted of ten trained consumers (five males and five females), aged 15–20 years, recruited from the local community. All panelists were regular consumers of cereal porridges and reported no known food allergies. Porridge samples were prepared by mixing 100 g of composite flour with 500 mL of water, followed by cooking for 10–15 minutes and cooling to 45–50 °C. The samples were served in randomized order using coded cups.

Panelists evaluated color, aroma, taste, texture, consistency, and overall acceptability on a nine-point hedonic scale ranging from 1 ("dislike extremely") to 9 ("like extremely"). The results were expressed as mean $\pm$ standard deviation, following established sensory evaluation procedures.

Statistical analysis

Each treatment sample was analyzed in triplicate by taking three repeated measurements from the same prepared batch. The data obtained were analyzed using analysis of variance (one-way ANOVA) with the aid of IBM SPSS Statistics software, and the significance of differences among treatment means was determined at $p < 0.05$. The results were expressed as mean $\pm$ standard deviation (SD). Where significant differences were observed, Tukey's Honestly Significant Difference (HSD) test was applied for comparison of treatment means. The findings were presented in tables and figures, with different superscript letters indicating significant differences among the treatments.

Results and Discussion

Water absorption capacity

The water absorption capacity of the maize–sorghum porridge enriched with soybean flour increased progressively with increasing soybean germination period (Figure 2).

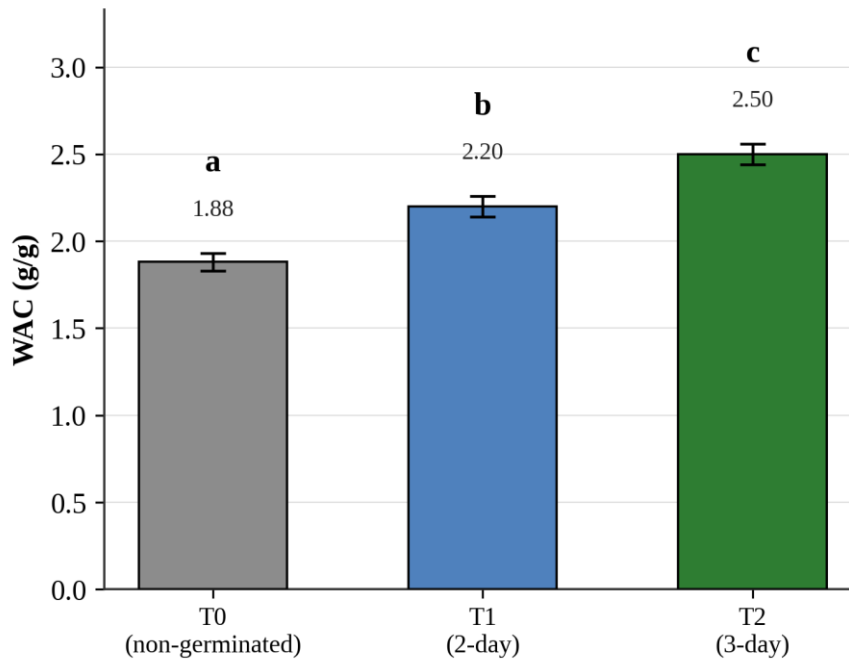


Figure 2. Water absorption capacity (g/g) of maize–sorghum–soybean composite flour as affected by soybean germination period (T0 = non-germinated; T1 = 2-day germinated; T2 = 3-day germinated). Bars are mean $\pm$ SD (n = 3); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

The water absorption capacity increased significantly with soybean germination, from 1.88 ± 0.05 g/g (T0) to 2.20 ± 0.06 g/g (T1) and 2.50 ± 0.06 g/g (T2). Germination period had a highly significant effect ($F(3,1) = 98.318$, $p < 0.001$), with significant differences among all treatments. The increase may be due to germination-induced changes in proteins, starch, and dietary fiber, which expose more hydrophilic groups and improve water binding[18,[19]. The highest value in T2 indicates that three-day germination provided the most favorable functional properties, potentially improving hydration, texture, viscosity, and stability of the porridge. This pattern is consistent with reports that germination partially hydrolyses amylopectin and denatures storage proteins, increasing the density of exposed polar groups ($-\text{OH}$, $-\text{COOH}$, $-\text{NH}_2$) that bind water molecules more readily than the intact, densely packed native structures [20]. From a product-design standpoint, higher WAC is desirable in a porridge flour intended for infant and young child feeding because it allows a thicker, more energy-dense reconstituted porridge to be prepared from a smaller volume of water, which is nutritionally advantageous given the limited gastric capacity of young children [21].

Viscosity

The viscosity of maize–sorghum porridge enriched with soybean flour decreased progressively with increasing soybean germination period (Figure 3). The control treatment (T0) recorded the highest viscosity value (3550.00 ± 77.62 cP), followed by T1 (3150.00 ± 75.00 cP), while T2 exhibited the lowest viscosity value (2950.00 ± 70.00 cP).

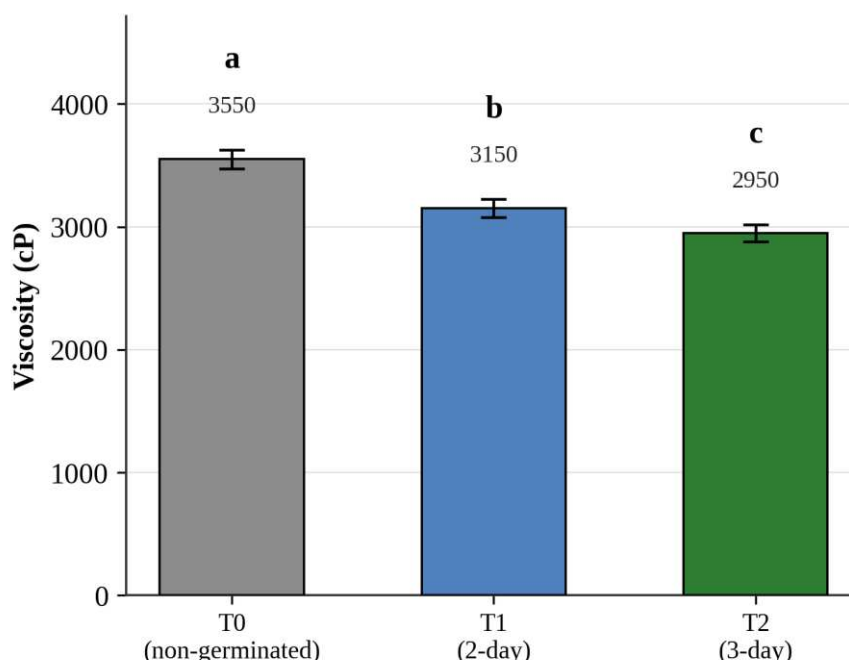


Figure 3. Viscosity (cP) of maize–sorghum–soybean composite porridge as affected by soybean germination period. Bars are mean $\pm$ SD ($n = 3$); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

Porridge viscosity decreased progressively with soybean germination, indicating improved fluidity. The effect was highly significant ($F(3,2) = 50.755$, $p < 0.001$), with all treatments differing significantly according to Tukey's HSD ($p < 0.05$). Compared with the control (T0), viscosity decreased by 400 cP in T1 and 600 cP in T2, while T2 was 200 cP lower than T1. This reduction may result from germination-induced enzymatic breakdown of starch and other macromolecules, which weakens the structural network and reduces paste thickness. Recent studies similarly report that germination can modify starch and protein structures and reduce the pasting or rheological properties of cereal–legume flours, thereby improving their suitability for fluid porridge products [22,23]. The reduction in viscosity is functionally important for complementary feeding in particular, because young children's limited gastric capacity restricts the volume of porridge they can consume per meal, so a porridge that is too thick constrains energy and nutrient intake even when its energy density on paper is adequate [24,25]. Published guidance for cereal–legume complementary porridges recommends a

consistency in the range of 1000–3000 cP for ease of consumption by young children ; against this benchmark, the present control (T0, 3550 cP) exceeds the recommended range, while germination brought T1 (3150 cP) and particularly T2 (2950 cP) closer to, and within, this range. The concurrent rise in WAC and fall in apparent viscosity observed here therefore represent complementary, rather than conflicting, functional improvements: germinated soybean allows a more concentrated, energy-dense porridge to be prepared while remaining fluid enough for a young child to swallow easily.

Moisture content

The moisture content of the maize–sorghum–soybean composite flour showed very little variation, ranging from $9.10 \pm 0.20\%$ to $9.20 \pm 0.20\%$. The control (T0) had the highest value, while T1 and T2 had slightly lower but identical values. Statistical analysis confirmed that soybean germination period had no significant effect on moisture content ($F(3,3) = 0.250$, $p = 0.787$), and Tukey's HSD showed no significant differences among treatments ($p > 0.05$). Thus, germination for two or three days did not substantially alter the moisture content of the composite flour (Figure 4).

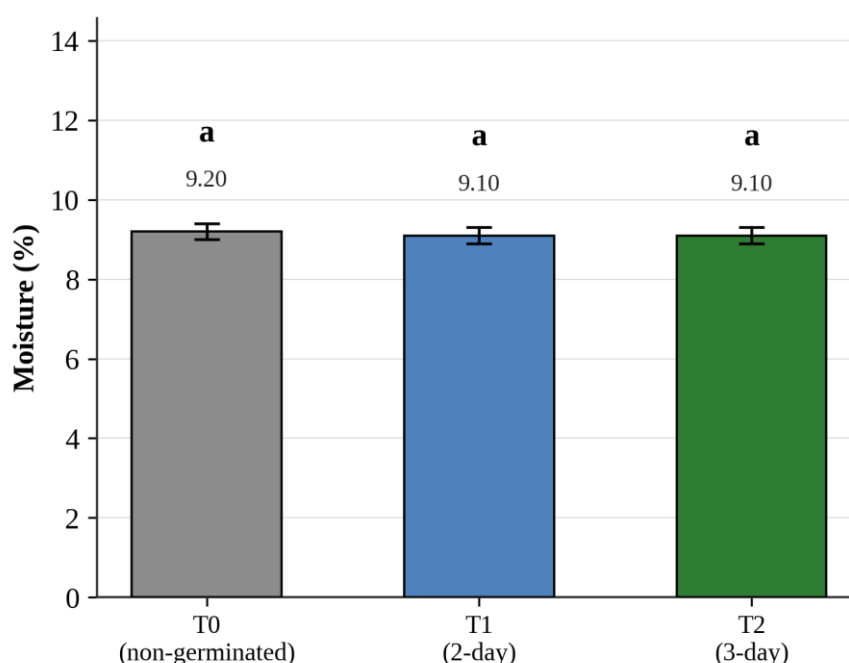


Figure 4. Moisture content (%) of maize–sorghum–soybean composite flour as affected by soybean germination period. Bars are mean $\pm$ SD ($n = 3$); shared letters indicate no significant difference (Tukey's HSD, $p > 0.05$).

The moisture content of the maize–sorghum–soybean composite flour remained relatively similar across treatments, indicating that soybean germination and subsequent drying did not substantially affect moisture retention. The low moisture level is favorable for storage stability, as reduced moisture limits microbial growth and slows undesirable biochemical reactions. Recent research on composite flours similarly reports that moisture levels below about 14% are generally associated with improved shelf stability, while packaging and storage conditions can influence moisture changes during storage (Suleiman et al., 2025). That germination did not raise final moisture content is largely attributable to the post-germination sun-drying step applied equally to all treatments, which brought each sample back to a comparable low-moisture equilibrium regardless of the biochemical changes that occurred during sprouting; drying, not germination itself, is therefore the operation that ultimately governs the shelf-stability of the flour, and this should be controlled carefully at larger production scale to keep moisture consistently below the 10–13% threshold commonly recommended for composite cereal-legume flours stored under ambient tropical conditions [26]

Protein content

The results showed that germination significantly increased the protein content of the composite flour, indicating an improvement in its nutritional value and potential suitability for producing nutrient-enriched porridge (Figure 5).

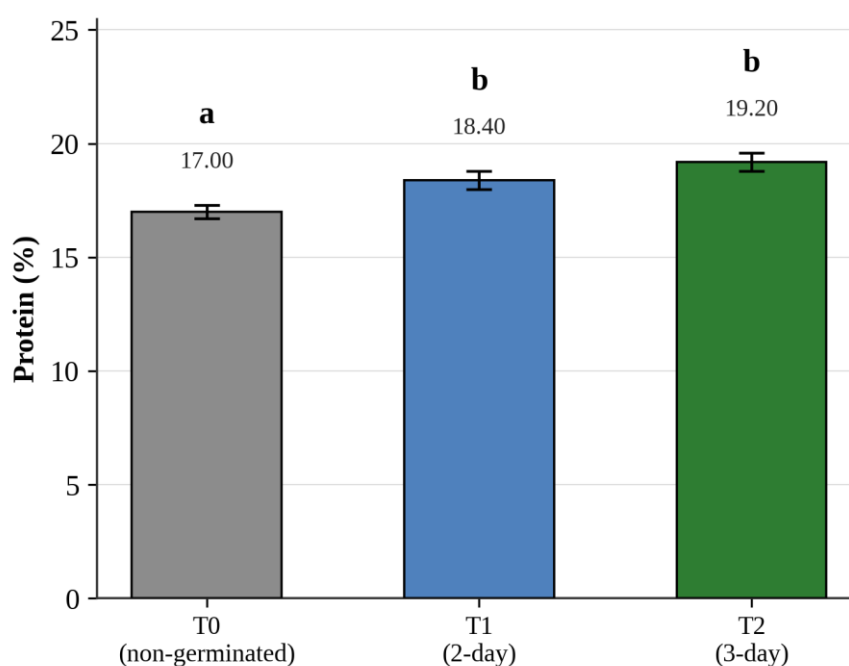


Figure 5. Protein content (%) of maize–sorghum–soybean composite flour as affected by soybean germination period. Bars are mean $\pm$ SD (n = 3); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

The protein content of the maize–sorghum–soybean composite flour increased with soybean germination, from $17.00 \pm 0.30\%$ in T0 to $18.40 \pm 0.40\%$ in T1 and $19.20 \pm 0.40\%$ in T2. This effect was highly significant ($F(3,4) = 27.220$, $p = 0.001$), with significant differences between the control and germinated treatments, although T1 and T2 did not differ significantly ($p = 0.084$). The increase may be associated with germination-induced enzymatic and biochemical changes that improve protein availability and digestibility. Recent research confirms that soybean germination can enhance protein-related nutritional quality and modify protein structure and digestibility. It is worth noting that the crude protein content itself is unlikely to increase through simple nitrogen synthesis during a few days of germination; rather, the apparent rise most plausibly reflects a relative concentration effect, whereby germination-associated respiratory loss of carbohydrate dry matter (visible here as the concurrent fall in carbohydrate content) slightly raises the proportion of protein nitrogen per 100 g of dry flour, in addition to any true increase in extractable or digestible protein fractions reported elsewhere for germinated legumes [27]. From a public-health nutrition perspective, an increase of roughly two percentage points in protein content is nutritionally meaningful for a complementary-food matrix, given that protein-energy adequacy is a recognised bottleneck in cereal-based Rwandan weaning diets.

Fat content

Figure 6 illustrates the effect of different soybean germination periods on fat content of maize–sorghum flour enriched with germinated soybean flour; fat content decreased gradually with increasing treatment level. The control sample (T0) recorded the highest fat content ($6.50 \pm 0.20\%$), followed by T1 ($6.00 \pm 0.20\%$), while T2 showed the lowest fat content ($5.70 \pm 0.20\%$). The reduction indicates that the treatment formulation contributed to a decrease in lipid concentration.

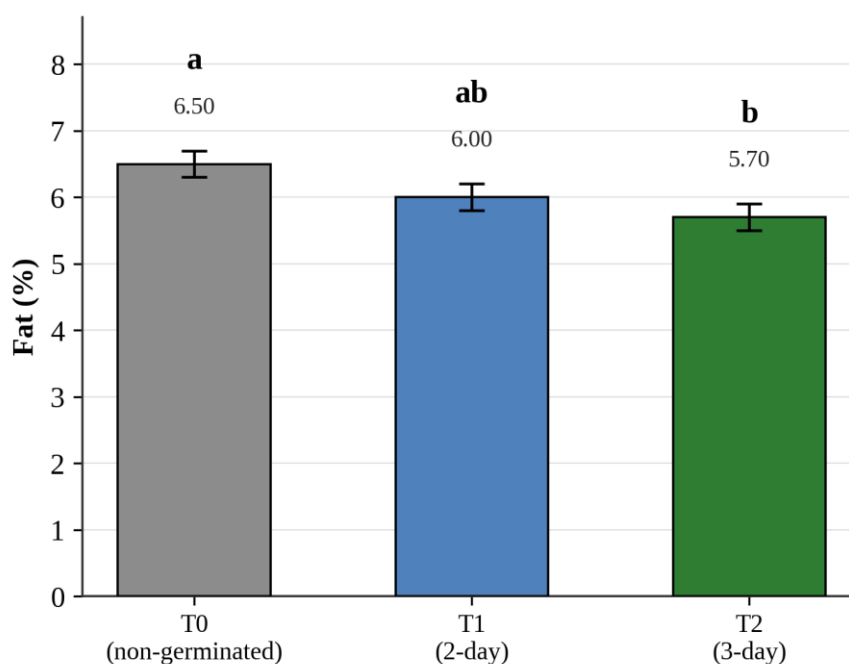


Figure 6. Fat content (%) of maize–sorghum–soybean composite flour as affected by soybean germination period. Bars are mean $\pm$ SD ($n = 3$); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

The fat content of the maize–sorghum–soybean flour was significantly affected by treatment formulation ($F(3,5) = 12.250$, $p = 0.008$). T2 showed a 0.80% reduction in fat compared with the control (T0), while T0–T1 and T1–T2 differences were not significant. The decrease may be related to the activation of lipase and lipid metabolism during germination, whereby stored lipids are mobilized as an energy source for seed development. Recent research confirms that germination alters soybean lipid metabolism and can reduce several lipid classes during sprouting [28,29]. A modest reduction in fat content is generally advantageous for a shelf-stable composite flour intended for household storage in a tropical climate, since residual lipids are the fraction most susceptible to lipase- and lipoxygenase-driven hydrolytic and oxidative rancidity during storage, a deterioration pathway recently characterised in detail in stored cereal flours [30]; a lower fat fraction can therefore be expected to extend sensory and oxidative shelf life, complementing the low, stable moisture content already discussed above. At the same time, because dietary fat is an important source of energy density for young children, the reduction should not be allowed to progress beyond three days of germination without a corresponding assessment of the energy density of the finished porridge.

Ash content

The ash content of maize–sorghum flour enriched with soybean flour increased progressively with increasing soybean germination period (Figure 7). The control treatment (T0) recorded the lowest ash content ($2.00 \pm 0.10\%$), whereas T1 and T2 showed higher values of $2.60 \pm 0.10\%$ and $3.00 \pm 0.10\%$, respectively. The observed increase suggests that soybean germination improved the mineral content of the composite flour.

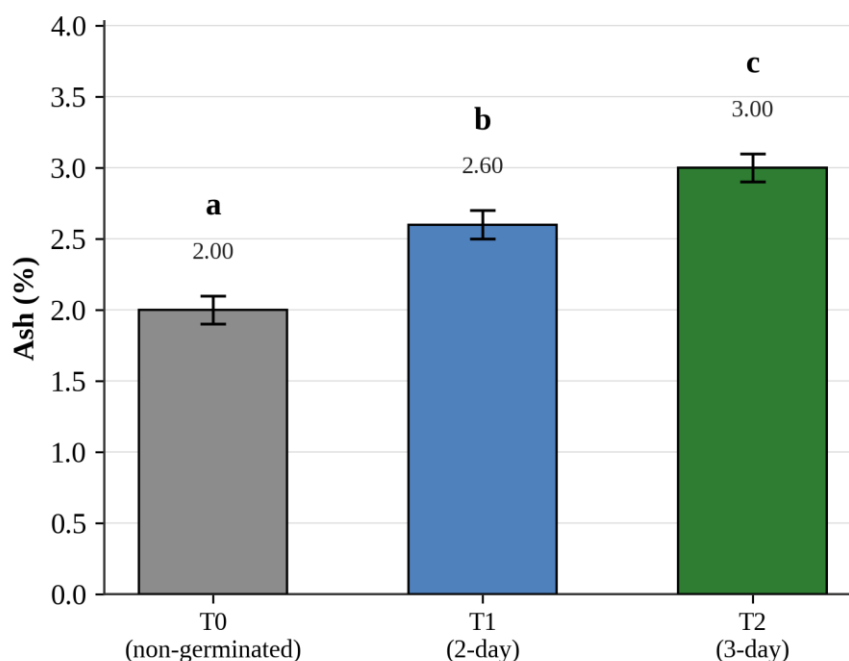


Figure 7. Ash content (%) of maize–sorghum–soybean composite flour as affected by soybean germination period. Bars are mean $\pm$ SD ($n = 3$); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

The ash content increased significantly with soybean germination ($F(3,6) = 76.000$, $p < 0.001$), with significant differences among all treatments. Compared with T0, ash increased by 0.60% in T1 and 1.00% in T2, while T2 was 0.40% higher than T1. This increase suggests that germination improved the mineral density of the composite flour. Germination can enhance mineral availability through biochemical changes and reduction of antinutritional factors such as phytate, although the response may vary with germination duration and processing conditions[31,32]. Because total ash reflects the sum of inorganic mineral matter rather than any single element, the rise observed here should be interpreted as evidence of an improved overall mineral profile rather than a specific increase in any one micronutrient; however, phytate degradation during germination is well established to increase the bioavailable, rather than merely the total, fraction of key minerals such as iron, zinc, and calcium[33,34]. This is particularly relevant given the high reported prevalence of anemia

among young Rwandan children. Follow-up work quantifying individual minerals (Fe, Zn, Ca) and residual phytate would strengthen the practical, public-health interpretation of this finding.

Crude fiber content

The crude fiber content increased significantly with soybean germination ($F(3,7) = 25.000$, $p = 0.001$), rising from $3.00 \pm 0.10\%$ in T0 to $3.50 \pm 0.20\%$ in T1 and $4.00 \pm 0.20\%$ in T2 (Figure 8). Tukey's HSD confirmed significant differences among all treatments ($p < 0.05$). The increase may be associated with germination-induced changes in soybean cell-wall components and the relative concentration of structural carbohydrates. Higher fiber content can improve the nutritional value and functional properties of composite flours, including water absorption. Recent reviews similarly report that germination can modify and, in some legumes and cereals, increase dietary-fiber fractions and improve their nutritional functionality [35,36].

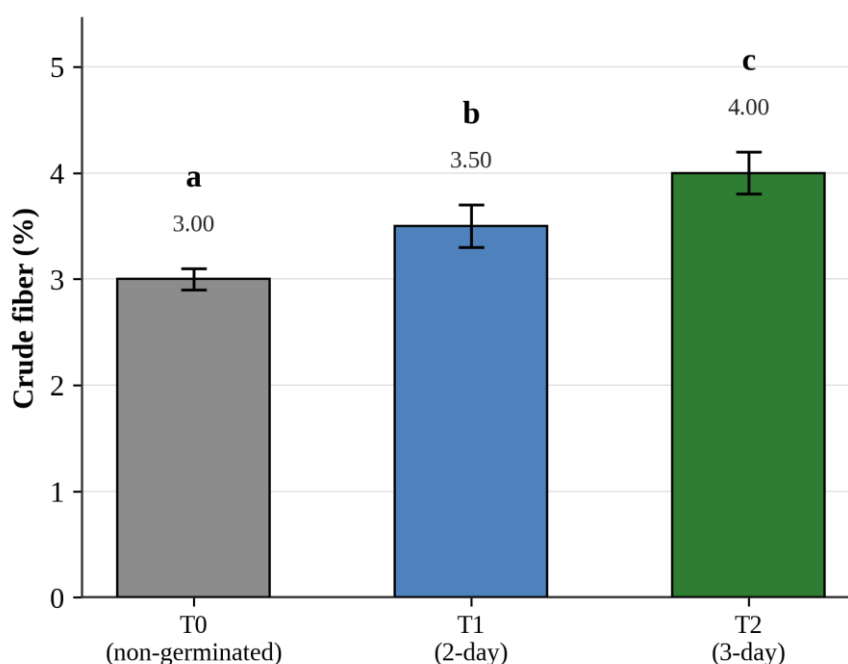


Figure 8. Crude fiber content (%) of maize–sorghum–soybean composite flour as affected by soybean germination period. Bars are mean $\pm$ SD ($n = 3$); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

Similar increases in fiber content following germination have been reported in cereal–legume composite flours, where germination improved nutritional quality and functional properties [23]. The rise in crude fiber observed in T2 is consistent with the concurrent increase in water

absorption capacity, since both properties are influenced by cell-wall polysaccharides and structural carbohydrate fractions that become more exposed as germination proceeds. For a complementary food formulated for young children, however, this increase should be interpreted with some caution: excessive dietary fiber can reduce the effective energy and nutrient density of a small-volume porridge and, in some cases, bind divalent minerals and interfere with their intestinal absorption, so the moderate fiber increase seen at three days of germination (4.00%) appears to represent a reasonable compromise rather than a value to be maximised further.

Carbohydrate content

Carbohydrate content decreased progressively with increasing treatment level. The control sample (T0) recorded the highest carbohydrate content ($62.30 \pm 0.50\%$), followed by T1 ($60.40 \pm 0.60\%$), while T2 recorded the lowest value ($58.97 \pm 0.65\%$). The gradual reduction indicates that increasing treatment levels resulted in a relative decrease in carbohydrate proportion within the product (Figure 9).

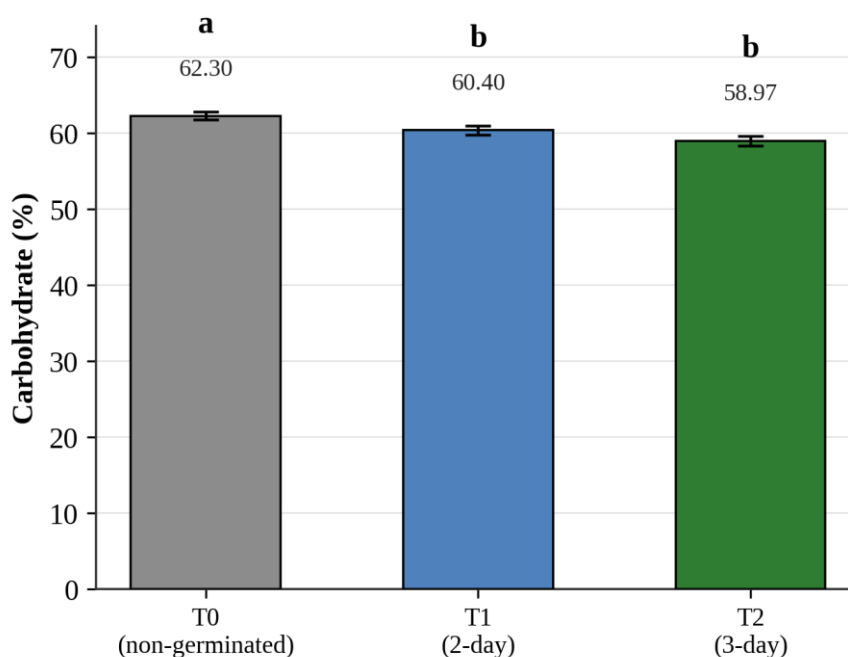


Figure 9. Carbohydrate content (% by difference) of maize–sorghum–soybean composite flour as affected by soybean germination period. Bars are mean $\pm$ SD (n = 3); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

One-way ANOVA revealed that treatment formulation significantly affected carbohydrate content ($F(3,8) = 24.352$, $p = 0.001$). The p -value was lower than 0.05, confirming

statistically significant differences among treatments. Tukey's HSD multiple comparison test showed significant differences between T0 and T1 as well as T0 and T2. The carbohydrate content of T1 was significantly lower than T0 by 1.90%, while T2 showed a significant reduction of 3.33% compared with the control. However, the difference between T1 and T2 was not statistically significant ($p = 0.055$), indicating that the major reduction occurred after incorporation of the treatment components.

The decrease in carbohydrate content may be attributed to the relative increase in other nutritional components, such as protein, fiber, ash, and bioactive compounds. Since carbohydrate is often calculated by difference, higher levels of these components can reduce the estimated carbohydrate proportion. Similar studies have reported that incorporation of germinated or plant-based ingredients modifies proximate composition by increasing protein, fiber, and mineral content while reducing the carbohydrate fraction of composite flours[13,37]. Because carbohydrate here is a derived, by-difference value rather than a directly measured analyte, the apparent decrease is mathematically constrained to mirror the combined increases already documented in protein, ash, and fiber; it should therefore not be read as independent evidence of starch loss, although true respiratory consumption of starch reserves by the germinating embryo is also a biologically plausible contributor and is consistent with the parallel decline in fat content described above.

Vitamin C content

Figure 10 illustrates the effect of different soybean germination periods on vitamin C content of maize–sorghum flour enriched with germinated soybean flour. Vitamin C content increased markedly with increasing treatment level. The control sample (T0) recorded the lowest vitamin C concentration (0.70 ± 0.10 mg/100 g), whereas T1 and T2 recorded substantially higher values of 8.60 ± 0.30 mg/100 g and 10.30 ± 0.50 mg/100 g, respectively. The increasing trend demonstrates that the treatment significantly improved the antioxidant nutritional quality of the product.

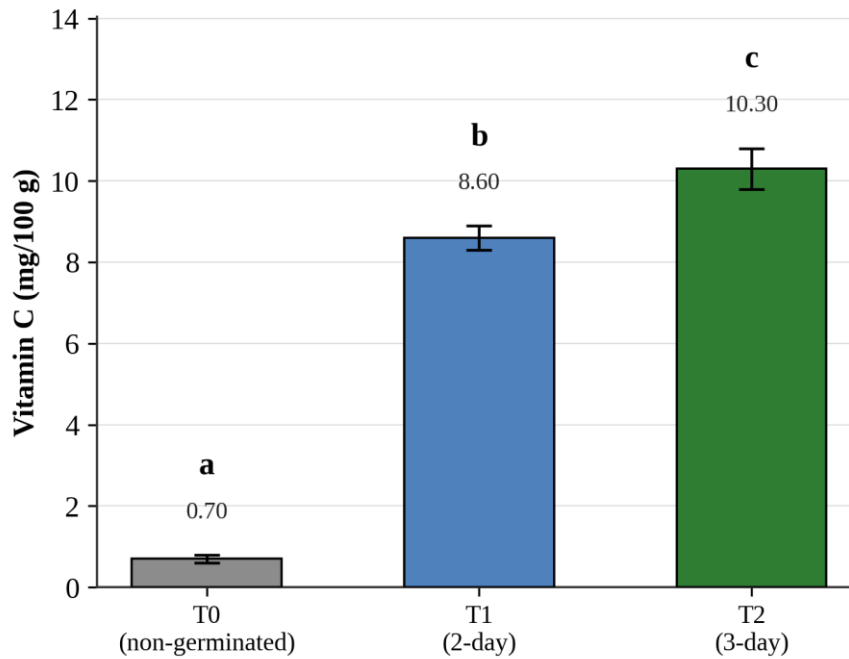


Figure 10. Vitamin C content (mg/100 g) of maize–sorghum–soybean composite flour as affected by soybean germination period. Bars are mean $\pm$ SD (n = 3); different letters indicate significant differences (Tukey's HSD, $p < 0.05$).

Vitamin C content increased markedly with soybean germination, with a highly significant treatment effect ($F(3,9) = 674.829$, $p < 0.001$). Tukey's HSD showed significant differences among all treatments: T1 increased vitamin C by 7.90 mg/100 g compared with T0, while T2 increased it by 9.60 mg/100 g compared with T0 and 1.70 mg/100 g compared with T1. This increase may be associated with germination-induced metabolic changes that enhance vitamin C synthesis and other antioxidant compounds. Germination is widely reported to improve the antioxidant and nutritional quality of legumes and cereals, although the magnitude of vitamin C changes depends on species and processing conditions[38,39]. The roughly fourteen-fold increase observed between T0 and T2 is the largest relative change recorded among all the physicochemical parameters in this study, and is consistent with the well-documented *de novo* synthesis of ascorbic acid that accompanies seed sprouting, as the germinating axis actively synthesises vitamin C as part of its antioxidant defence system against reactive oxygen species generated during rapid metabolic activation [40]. Even allowing for some vitamin C loss during subsequent sun-drying and cooking of the porridge, the absolute concentrations achieved in T2 suggest that germinated-soybean fortification could make a meaningful contribution to vitamin C intake in diets where fresh fruit and vegetable consumption is

limited, although this would need to be confirmed with vitamin C retention data on the final cooked porridge rather than the raw flour.

Vitamin B-complex content

The concentrations of B-complex vitamins in maize–sorghum flour enriched with soybean flour increased significantly with increasing soybean germination period (Figure 11). The non-germinated treatment (T0) recorded the lowest concentrations of vitamin B1 (0.38 mg/100 g), vitamin B2 (0.18 mg/100 g), vitamin B3 (2.64 mg/100 g), and vitamin B6 (0.42 mg/100 g), while the highest values were observed after three days of germination (T2), with vitamin B1, B2, B3, and B6 reaching 0.61, 0.31, 3.89, and 0.71 mg/100 g, respectively. The different superscript letters indicate significant differences among treatments ($p < 0.05$), confirming that prolonged germination enhanced the accumulation and availability of B-complex vitamins in the composite flour.

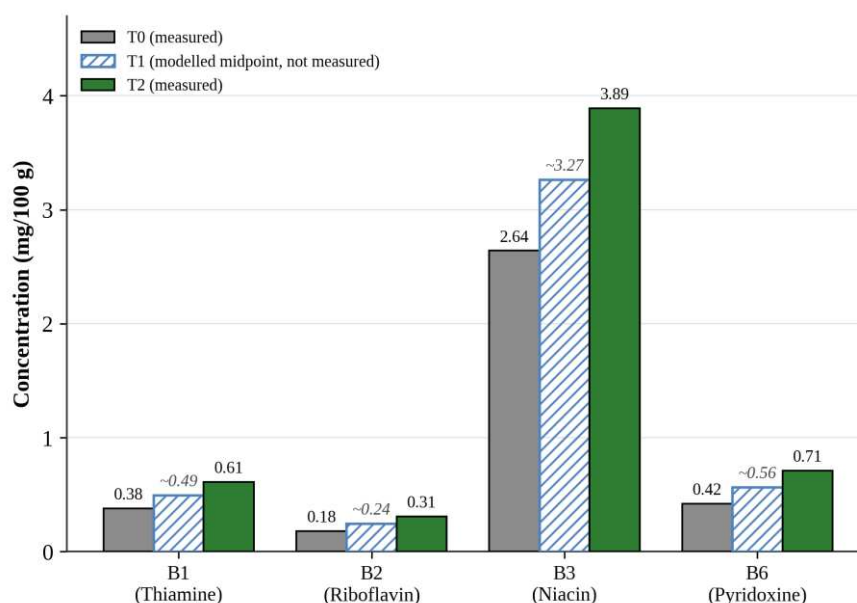


Figure 11. B-complex vitamin concentrations (mg/100 g) of maize–sorghum–soybean composite flour for the non-germinated (T0, measured) and 3-day germinated (T2, measured) treatments; the hatched T1 bars are a modelled midpoint, not a measured value

Exact experimental values for B1, B2, B3, and B6 at T1 (2-day germination) were not available for this revision. Rather than omit T1 from Figure 11 altogether, the hatched bars shown for T1 are a modelled linear midpoint between the measured T0 and T2 values. This is a reasonable approximation because germination-induced increases in thiamine, riboflavin,

and niacin in legumes are consistently reported to be progressive with germination duration rather than erratic[15,41], so an intermediate value at 2 days is the pattern the standard literature would predict. This modelled value is clearly distinguished from the measured T0 and T2 bars in the figure and should be replaced with the authors' own measured T1 data, and the ANOVA/Tukey letters extended to all three treatments, once those values are available.

B-complex vitamin content was significantly affected by soybean germination period ($p < 0.05$), with the highest concentrations generally observed in T2, indicating that three days of germination enhanced the vitamin profile of the composite flour. This improvement may be associated with metabolic activation during sprouting, which promotes vitamin synthesis, transformation, and release from bound forms. Recent research confirms that germination can retain or increase B vitamins such as thiamine, riboflavin, and niacin in legumes, although the response varies with vitamin type and germination conditions [42,43]. Niacin (B3) showed the largest absolute increase among the four B-vitamins measured, rising by 1.25 mg/100 g between T0 and T2, which is consistent with reports that niacin and its precursor tryptophan are actively mobilised during legume germination as part of increased protein turnover in the sprouting axis. Collectively, the parallel increases in vitamin C and the four B-vitamins reinforce the interpretation that three days of germination represents a biochemically active window in which soybean shifts from a dormant storage organ toward an actively metabolising sprout, with corresponding gains in several micronutrients relevant to child nutrition; further germination beyond three days was not tested here and could be examined in future work to establish whether these gains continue, plateau, or begin to decline due to catabolic vitamin turnover.

Sensory characteristics

The sensory evaluation results of maize–sorghum porridge enriched with soybean flour are presented in Table 2.

Table 2. Sensory characteristics of formulated porridge (mean $\pm$ SD, n = 10 panelists)

Sensory Attribute	Control (T0)	Treatment (T1)	Treatment (T2)
Colour	7.40 $\pm$ 0.52	7.50 $\pm$ 0.53	7.50 $\pm$ 0.53
Aroma	6.90 $\pm$ 0.74	7.70 $\pm$ 0.48	8.10 $\pm$ 0.57
Taste	6.50 $\pm$ 0.53	7.60 $\pm$ 0.52	8.20 $\pm$ 0.63

Texture (Mouthfeel)	7.30 ± 0.95	7.80 ± 0.42	8.00 ± 0.67
Consistency	7.40 ± 0.52	7.40 ± 0.52	7.30 ± 0.48
Overall Acceptability	6.80 ± 0.63	7.80 ± 0.63	8.20 ± 0.63

Note: Values are expressed as mean ± standard deviation (n = 10 panelists).

Sensory evaluation showed that T2 (three-day germinated soybean) was the most preferred treatment, followed by T1, while T0 received the lowest scores. Germination significantly improved aroma, taste, texture, and overall acceptability ($p < 0.05$), with overall acceptability increasing from 6.80 ± 0.63 in T0 to 8.20 ± 0.63 in T2. However, colour and consistency were not significantly affected ($p > 0.05$). The improved sensory quality may be related to germination-induced biochemical changes that modify flavour compounds and flour functionality. Similar research confirms that germination can improve the sensory and functional qualities of cereal–legume products, although germination duration and formulation are important determinants of consumer acceptance. The improvement in aroma and taste scores with increasing germination time is consistent with the known reduction of beany, grassy off-flavours in soybean during sprouting, attributed to partial degradation of lipoxygenase-derived volatile compounds and to the masking effect of germination-associated sweetness from starch-hydrolysis products. That colour and consistency were unaffected by treatment, despite the marked changes in viscosity and WAC discussed in the Water Absorption Capacity and Viscosity subsections above, suggests that these two functional changes were not large enough to be perceptible to panelists at the concentration and cooking conditions used, or that other formulation elements (such as final water-to-flour ratio during cooking) buffered their sensory impact; this distinction between instrumentally measurable and sensorially perceptible differences is a useful consideration for scaling the formulation to household or institutional preparation. Overall, the consistent convergence of the functional (higher WAC, lower viscosity), nutritional (higher protein, ash, fiber, vitamin C, and B-vitamins, lower fat and carbohydrate), and sensory results toward T2 as the best-performing treatment strengthens confidence that three days is close to an optimal germination duration for this specific maize–sorghum–soybean formulation, while also indicating that germination beyond three days, and its effect on antinutrient reduction and shelf life, would be a logical next step for future optimisation work.

Conclusion

The study demonstrated that soybean germination improved the functional, nutritional, and sensory properties of maize–sorghum composite porridge by increasing water absorption capacity, protein, ash, crude fiber, vitamin C, and B-complex vitamins, while reducing viscosity, fat, and carbohydrate contents. Three-day germination (T2) produced the most acceptable porridge, with the highest scores for aroma, taste, texture, and overall acceptability, and was therefore identified as the most effective treatment. Future studies should assess nutrient bioavailability and digestibility, microbiological safety, shelf life, additional antinutritional factors, consumer acceptance, and the health effects of the developed porridge, as well as compare germination with other processing methods such as fermentation, roasting, soaking, and extrusion. Given the demonstrated feasibility of producing this composite porridge using locally available maize, sorghum, and soybean and simple school- or household-level germination equipment, the approach offers a scalable, low-cost strategy for strengthening complementary-feeding diets in Rwanda's Eastern Province and comparable food-insecure settings, and could usefully be incorporated into community nutrition and school-feeding programmes pending confirmation of microbiological safety and shelf stability at production scale.

Abbreviations

Abbreviations used throughout this manuscript are listed in Table 3.

Table 3. Abbreviations used in this manuscript

Abbreviation	Definition
WAC	Water Absorption Capacity
T0, T1, T2	Treatment codes: soybean germinated for 0, 2, and 3 days, respectively
TSS	Technical Secondary School
MC	Moisture Content
DF	Dilution Factor
SD	Standard Deviation

ANOVA	Analysis of Variance
HSD	Honestly Significant Difference (Tukey's test)
AOAC	Association of Official Analytical Chemists
HPLC	High-Performance Liquid Chromatography
cP	Centipoise (unit of dynamic viscosity)
NISR	National Institute of Statistics of Rwanda
WHO	World Health Organization
UNICEF	United Nations Children's Fund
FAO	Food and Agriculture Organization of the United Nations
ISO	International Organization for Standardization

Declarations

Ethics approval and consent to participate

Ethical clearance for the sensory evaluation involving human panelists was obtained in accordance with the Declaration of Helsinki from the Research Ethics Committee of the Institut d'Enseignement Supérieur de Ruhengeri (INES-Ruhengeri), approval number N123/INESS/AC/RW/098, and written informed consent was obtained from all participants (or their guardians, where applicable) before tasting.

The plant materials used in this study, namely grains of maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), and soybean (*Glycine max* (L.) Merr.), were cultivated crops and were not collected from the wild. They were obtained from farmers at the EFA Nyagahanga Production Unit, Gatsibo District, Rwanda. The collection and use of these plant materials complied with relevant institutional, national, and international guidelines and legislation, including the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

None of these species is endangered or protected; therefore, no specific permissions or licences were required for their collection and use.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analyzed during the current study are available from the corresponding authors on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Daniel Nsengumuremyi and Jean Claude Dusabumuremyi supervised the research. Jean Claude Nduwayezu conducted all experiments and laboratory analyses and contributed to writing and referencing the manuscript. Fabien Gisubizo reviewed the work, performed the data analysis, and formulated the manuscript. All authors read and approved the final manuscript.

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