

Journal of Food Innovation, Nutrition, and Environmental Sciences
November, 2026, Volume 3; Issue 4: 277–288
ISSN No: 3078-5537

ORIGINAL RESEARCH ARTICLE

Comparative Evaluation of Physicochemical and Bioactive Properties of *Adansonia digitata* Seed Roasted Brew from Selected Zimbabwean Locations and Roasting Conditions.

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DOI: https://doi.org/10.70851/jfines.2026.3(4).277.288

ABSTRACT

The increasing demand for functional foods has stimulated interest in underutilized indigenous resources with potential nutritional and health benefits. This study comparatively evaluated the physicochemical and bioactive properties of *A. digitata* seed roasted brew prepared from selected Zimbabwean locations under different roasting conditions. Baobab seeds collected from three ecologically distinct regions of Zimbabwe, Manicaland, Masvingo and Mashonaland East were roasted at 150 °C, 175 °C and 200 °C, representing light, medium and dark roasts, respectively. Brewed samples were evaluated for physicochemical attributes (pH, titratable acidity, moisture content, total soluble compounds, viscosity, crude fibre, and sugar concentration) and bioactive properties (total phenolics, flavonoids, antioxidant activity and caffeine content). Variation in the measured parameters was observed across the roasting temperatures and selected locations investigated. The 175 °C roasting condition produced comparatively favourable values for several measured physicochemical and bioactive characteristics. Masvingo samples exhibited the highest total phenolic content (4.39 ± 0.12 mg GAE/g), total flavonoid content (9.39 ± 0.26 mg RE/g), and DPPH radical scavenging activity (77.69 ± 3.60%), indicating potential for functional beverage production. In contrast, Manicaland samples showed higher moisture content and comparatively lower antioxidant constituents, while Mashonaland East samples retained higher crude fibre levels. Caffeine was not detected in the analysed samples under the analytical conditions employed. Overall, the findings demonstrate variation in the physicochemical and bioactive characteristics of *A. digitata* seed roasted brew across the selected locations and roasting conditions, while sensory responses varied across the geographical samples evaluated at 175 °C. The results provide preliminary evidence supporting further investigation of baobab seed as a potential raw material for development of alternative roasted beverages. Further studies using multiple independent biological lots from each location are recommended to establish the reproducibility and broader applicability of these observations.

Article history

Received:
01 July 2026

Revised:
16 September 2026

Accepted:
30 September 2026

Keywords

Adansonia digitata, bioactive compounds, Functional beverage, Geographical origin, Physicochemical properties.

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Peer review under responsibility of Journal of Food Innovation, Nutrition, and Environmental Sciences.

A Publication of EcoScribe Publishers company Limited, Uganda. www.ecoscribepublishers.com

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1 Introduction

Global consumption of food products for the sake of their health benefits and physiological functions has steadily increased over the past few decades. In an era of rising health consciousness and a global shift towards plant based nutrition, the development of functional beverages has become a pivotal pillar to fill in the gap of modern dietary and wellness demands (Gupta et al., 2023; Patra et al., 2023). A functional beverage can be defined as "any non-alcoholic drink or brew that provides additional health benefits due to the inclusion of any bioactive component from a plant, animal, marine or microorganism source" (Gayathry & John, 2021). Currently there is a surge of consumers seeking natural, caffeine free alternatives that are not only limited to refreshment and flavor but also deliver physiological benefits such as enhanced immunity, antioxidant protection, and optimal gastrointestinal metabolic regulation (Yan et al., 2023; Gebre et al., 2024; Sharma & Orsat, 2024).

Amid this functional food revolution, *Adansonia digitata* (Baobab) a multipurpose tree which is native to the Sub Saharan Africa, remains one of the most underexploited botanical treasures (Fischer et al., 2020; Musyoki, 2022; Magava et al., 2026). The pulp of *A. digitata* has been recognized due to its high vitamin C content, prebiotic properties, however, the nutrient dense seeds which comprise 43–60% of the total fruit mass, are often discarded or underutilized despite them being reservoirs of bioactive compounds, amino acids, reducing sugars and healthy lipids (Oyesiji, 2020; Foltz et al., 2021; Ismail et al., 2022; Nyoni et al., 2024, Vinha et al., 2024).

Thermal processing is essential to fully exploit the potential of these seeds, given that their macronutrient, micronutrient, and bioactive compound composition is particularly suited to supporting consumer health (Asogwa et al., 2021; Silva et al., 2023; Yakubu, 2024). The integration of these seeds into food systems will come up with a number of benefits such as nutritional diversification, rural livelihood transformation, sustainability and contribution towards the sustainable development goal number 2 of zero hunger (Meinhold & Darr, 2022; Chen et al., 2023; Offiah, & Falade, 2024). Despite the daily increasing interest in functional beverages and *A. digitata's* nutritional value, there is limited research on the dual impact of how roasting temperature and geographical origin affect the bioactive composition and physicochemical parameters of *A. digitata* seed beverages.

Roasting is an essential food processing method as it improves flavor and shelf stability (Farah, 2019; Das et al., 2023; Mohammadi-Moghaddam et al., 2024). This technique is well dependent on the Maillard reaction, which is a thermal based chemical reaction where seed resident amino acids interact with reducing sugars (Murata, 2021; Sun et al., 2022; Chen et al., 2023). Geographical variability, including climatic, edaphic, and genetic factors, can also significantly influence seed phytochemical composition (Iannucci, 2021; Lima et al., 2021; Yan et al., 2023). Therefore, a standardized roasting protocol or product formulation cannot be universally applied without an analysis of these interactions, roasting temperature and geographical origin of seeds.

Geographical origin has been widely shown to directly influence the content of secondary metabolites in seed due to variations in climatic conditions, altitude, soil nutrients, and ecological stressors (Petisca et al., 2013; Przybylska-Balcerek, 2020; Lopes et al., 2021). Roasting temperature also has been shown to directly impact Maillard reactions, thereby affecting caramelization, degradation of thermolabile compounds such as phenolics, henceforth altering the final product's health promoting properties of roasted products (Taş & Gökmen, 2017; Ghafoor et al., 2020; Mohamed Ahmed et al., 2023). Roasting has a direct impact on the food quality as it alters the physical (e.g., color, pH, solubility), chemical (eg., total phenolic content, antioxidant activity) and nutritional (eg., protein digestibility, fat digestibility) parameters (Benmeziane-Derradji et al., 2020; Das et al., 2023; Lu & Chen, 2023). Complex chemical interactions of heat induced degradation, polymerization, and volatile formation, which may enhance or diminish bioactive potential are all dependent on roasting (Mahmud et al., 2020; Grzelczyk et al., 2022; Shakoor et al., 2022; Gao et al., 2025).

This study aimed to comparatively evaluate the effects of roasting temperature on the physicochemical and bioactive characteristics of *Adansonia digitata* seed brews prepared from samples obtained from selected Zimbabwean locations. Given that *A. digitata* grows in ecologically diverse zones across Zimbabwe, including semiarid lowveld regions like Chiredzi, humid highlands like Manicaland and moderately dry zones like Mashonaland East, it is critical to assess how these environments influence the bioactive and physicochemical parameters of the roasted beverage. Evaluation of different roasting temperatures is of importance as it allows for the identification of optimal heat conditions that retain or enhance the beneficial bioactive compounds while improving the organoleptic profile as well.

Assessment of the physicochemical parameters such as pH, total soluble solids (TSS), and titratable acidity, alongside bioactive compounds such as total phenolic content (TPC), flavonoids, and DPPH based antioxidant activity is key in ensuring provision of a holistic view of beverage quality and potential health functionality (Donno & Turrini, 2020; Staroszczyk & Sikorski, 2023). These parameters are crucial in determining the shelf life, organoleptic acceptability and nutraceutical efficacy (Matveeva & Khasanov, 2016; Idris Ali et al., 2023; Nicolescu et al., 2023). In conclusion, the conception "Let food be thy medicine and medicine be thy food" introduced by the father of medicine "Hippocrates" highlights the significance of *A. digitata* seed bioactive substances in contributing towards optimal human health (Abbasi et al., 2024).

2 Materials and methods

2.1 Sample Collection and Sampling Design

Mature, unblemished fruits of *A. digitata* were collected from three geographical regions of Zimbabwe, namely Manicaland, Masvingo and Mashonaland East, during the optimum July harvesting season. Three independent collection sites were selected within each geographical region, and five mature trees were sampled at each site, resulting in 15 sampled trees per region and 45 trees across the three geographical regions. The collection sites were selected to capture spatial variation within each geographical origin while maintaining the geographical identity of the samples.

Fruits collected from the selected trees were assigned individual collection identifiers and maintained as separate lots during initial sample handling to facilitate traceability of the biological material. Collection location and date were recorded for each sample lot. Following collection, the fruits were transported to the laboratory in clean, labeled containers. The fruits were manually opened and the seeds separated from the surrounding fruit material. The seeds were cleaned to remove adhering pulp and other extraneous materials. The cleaned seeds were stored in labeled airtight containers until roasting and subsequent laboratory analyses. Samples from the different geographical origins were maintained separately throughout sample preparation.

2.2 Roasting of *A. digitata* seeds

The prepared *A. digitata* seeds from all the three (3) regions were roasted in a Hisense airfry oven model H32AOSL1S5 for 30 minutes at different roasting temperatures. Light roast 150 °C, medium roast 175 °C and dark roast 200 °C. For each geographical-origin × roasting-temperature combination, three independent roasting batches were prepared, resulting in 27 independent roasting batches across the three geographical origins and three roasting temperatures. Each roasting batch was prepared from an independently identified seed lot and treated as an independent experimental unit.

For each roasting batch, seeds were loaded into the roasting chamber as a single, evenly distributed layer to ensure uniform exposure to heat. The roasting equipment, batch mass, roasting duration and temperature were maintained consistently across all treatments. Immediately after roasting, the seeds were removed from the oven and allowed to cool to room temperature before grinding. The cooled seeds were ground and passed through a Kingtest laboratory test sieve to obtain a uniform particle size. The resulting roasted seed powders were stored in labeled airtight containers until preparation of the brew samples and subsequent physicochemical and bioactive analyses.

Three independent roasting batches were therefore obtained for each geographical-origin × roasting-temperature combination. Each independent roasted batch was subsequently analyzed in triplicate for the respective physicochemical and bioactive parameters. The analytical triplicates were treated as technical replicates of the corresponding independent roasting batch and were not considered independent experimental treatments.

2.3 Beverage Preparation

The roasted *A. digitata* seed samples were ground and sieved prior to preparation of the roasted seed brew. For each sample, 10 g of the roasted seed powder was mixed with 100 mL of distilled water, corresponding to a 1:10 (w/v) preparation ratio and the mixture was continuously stirred with a glass rod for 30 minutes to facilitate extraction of soluble components from the roasted seed powder. The resulting brew was then filtered through filter paper to remove residual particulate material and obtain a clear filtrate. The prepared filtrates were subsequently used for the physicochemical and bioactive analyses. The same 1:10 (w/v) preparation ratio, extraction time and filtration procedure were applied consistently to the samples from all three selected locations and the three roasting temperatures.

2.4 Physicochemical tests

Determination of the physicochemical parameters of the *A. digitata* roasted seed brews were done in accordance with a protocol by Ismail et al (2022). To test for pH an AD12OO pH/mV/SE meter was used. Prior to measurement, the pH meter was calibrated using standard buffer pH 4.00 and 7.00 at the measurement temperature. Each regional brew sample roasted at 150 °C, 175 °C and 200 °C were tested by placing the pH and temperature rods in the beakers with the baobab seed extracts.

2.5 Titratable acid (TA) analysis

To test for TA, the titration technique was used using 0.1M sodium hydroxide (NaOH). 4 g of NaOH pellets were measured on an analytical balance and placed in a 1000 mL volumetric flask. Distilled water was added into the flask up to the mark. To prepare the *A. digitata* powder brew 10 g of each sample was measured and 100 mL of distilled water was added and stirred (Samsonowicz et al., 2019). The residue was filtered using a filter paper. 10 mL of the extract from each sample was placed into a conical flask. 3 drops of phenolphthalein indicator were added to the extract. A 50 mL burette was filled with NaOH. The roasted seed powder extract was titrated until the end point. The tests were done in triplicates for each sample. The initial and final volumes were recorded on a table.

2.6 Total soluble solids (TSS) analysis

Total soluble solids (TSS) were measured using a digital refractometer (Brix/RI-Check, model 13 940 000, Reichert Inc., Japan). The roasted *A. digitata* seed powder extract was used to test for TSS. The refractometer was calibrated using distilled water. Drops of each sample were placed on the well and the Brix reading was measured. Each sample was measured in triplicates and recorded.

2.7 Moisture content (MC) analysis

Moisture was calculated and determined as described by Lamidi et al. (2023). The oven drying method was used to determine moisture content of the baobab seed powder. The constant- temperature Drying Oven, model BOV-T30C, Biobase, China) was used to determine the MC. 27 crucibles were washed and placed in the oven at 105 °Cfor 1 hour. Tongs were used to place crucibles in a desiccator to cool. After cooling the empty crucibles were weighed on an analytical balance. The balance was tared and 5 g of each powdered baobab seed were weighed in the crucibles. The samples were placed in an oven for 3 hours. After 3 hours samples were removed and placed in a desiccator to cool and the weight of the sample plus crucible was recorded. The tests were repeated for 30 minutes until the samples reached a constant weight. Moisture was calculated and determined as described by Lamidi et al. (2023).

2.8 Crude fiber Analysis

To determine crude fiber the Weende method was used. 0.128M of sulphuric acid (H_2SO_4) was prepared by measuring 14 mL of H_2SO_4 (98%) using a measuring cylinder. 1.6 liters of distilled water was added into a 2000 mL volumetric flask. 14 mL of the acid was added to the water in the volumetric

flask. The flask was filled up to the mark with distilled water. 0.313M of NaOH was prepared by measuring 1.6liters of distilled water into a 2000 mL volumetric flask. 25 g of NaOH measured on an analytical balance was placed in the volumetric flask, the flask was filled up to the mark with distilled water. From each sample 2 g of each roasted seed powder was measured using an analytical balance and placed in a conical flask. 100 mL of H_2SO_4 was added to the conical flask, the mixture was heated in a boiling water bath (Julaba SW22) for 30 minutes. The samples were filtered using a cotton cloth and the residue was washed using hot water to remove the acid. NaOH was added to the filtered residue in a conical flask. The mixture was heated in a water bath for 30 minutes. The mixture was filtered and the residue was washed with hot water to remove any remaining alkali. The residue samples were placed in crucibles and were dried in a drying oven at 105 °Cfor 2 hours. The dried residue was measured and washed in a muffle furnace at 550 °Cfor 2 hours. The ash was measured. Crude fiber was calculated using the following formula;

Crude Fiber (%) = ((W2−W3)/W1) ×100

W1= Weight of the sample (g)

W2= Weight of crucible and dried residue after digestion (g)

W3 = Weight of crucible and ash after incineration (g)

2.9 DPPH free radical scavenging assay

A DPPH solution (0.2 mM) was prepared (0.0078864 g of DPPH in 100 mL methanol). In a microtiter plate, 150 µl of 0.2 mM DPPH was added and followed by a 50 µl of standard (ascorbic acid; ranging 40 µg/mL to 200µg/mL) or extract (BO/DBEE/BFWE; ranging 200µg/mL to 1000 µg/mL). The mixture was left to stand in the dark at 27 °C for 30 min. From the resulting solution absorbances were taken against a blank at 517 nm with a spectrophotometer ((SHIMADU CORP., model 01051). The scavenging activity of the brews against the DPPH radical was calculated using the following equation: DPPH scavenging activity (%) = [(Acontrol − Asample)/Acontrol] × 100, as described by Gulcin and Alwasel (2023). Where Acontrol represents the absorbance of the DPPH solution without the sample extract, and Asample represents the absorbance of the DPPH solution containing the sample extract.

2.10 Determination of total Phenolic

The Folin-Ciocalteu method was used to quantify the phenolic content of the prepared brews as described by Thompson et al., (2024). One milliliter of the test solution, (gallic acid; 100 µg/mL, 50 µg/mL, 25 µg/mL, 12.5 µg/mL, 6.25 µg/mL, 3.125 µg/mL) and (extracts; 1000 µg/mL, 500 µg/mL, 250 µg/mL, 125 µg/mL, 62.5 µg/mL, 31.25 µg/mL) were transferred separately into capped test tubes. To each tube Folin-Ciocalteu reagent (1 mL) was added and allowed to incubate at 27 °C for 6 min. Two milliliters of 7.5 % sodium carbonate (*m/v*) were added to the solutions and further incubated at 50 °C for 10 min. The absorbance of all prepared solutions was taken at 765 nm against a blank by a spectrophotometer (SHIMADU CORP., model 01051). A standard calibration curve of gallic acid was plotted (y = 0.0159x – 0.0407; R2 = 0.9964). The total phenolic content was expressed in mg equivalent of gallic acid per 100 g of the raw extract (mg GAE/g).

2.11 Determination of total flavonoid content

The TFC was determined according to Ismail et al. (2019). “Briefly, an aliquot (5.0 mL) of the sample was mixed with 0.5 mL sodium nitrite (0.725 mol L-1), and the solution was allowed to stand for 6 min at ambient temperature. After which, 0.5 mL aluminium nitrate (0.469 mol L-1) was added, and the solution was kept for another 6 min at ambient temperature. Finally, 4 mL sodium hydroxide (1 mol L-1) was added, and the solution was kept for 20 min at ambient temperature. Absorbance was measured with a UV–visible spectrophotometer (UV-Vis spectrometer (SHIMADU CORP., model 01051) at 502 nm. A calibration curve was prepared using a standard solution of rutin (0.1–1.0 mg mL−1).

2.12 Determination of Viscosity

The apparent viscosity of the *A. digitata* seed brews was determined using a calibrated rotational viscometer (Brookfield-type). A certified viscosity reference standard was used for the expected viscosity range prior to sample analysis. The brew samples were gently homogenized and allowed to equilibrate to 25 ± 1 °C before measurement. Approximately 100 mL of sample was transferred into a clean viscometer beaker, ensuring that sufficient sample depth was available to completely immerse the spindle to the manufacturer's specified immersion mark.

A suitable spindle was selected according to the expected viscosity of the samples, and the rotational speed was maintained at 60 rpm. The spindle was immersed centrally in the sample without introducing air bubbles and allowed to equilibrate for approximately 60 seconds before the viscosity reading was recorded. The viscometer was checked for zero reading before measurements and was verified with the reference standard at the beginning of each analytical session.

2.13 Determination of Total Sugar Content

Total soluble carbohydrate content of the *A. digitata* seed brews was determined using the phenol–sulfuric acid colorimetric method, with glucose as the calibration standard. Samples were clarified by centrifugation or filtration, appropriately diluted, and 1.0 mL of each sample or glucose standard was mixed with 1.0 mL of 5% phenol solution and 5.0 mL of concentrated sulfuric acid. The mixtures were thoroughly mixed and allowed to develop colour at room temperature for approximately 30 min. Absorbance was measured at 490 nm using a UV–visible spectrophotometer against a reagent blank. Carbohydrate concentration was calculated from the glucose calibration curve, corrected for dilution, and expressed as mg glucose equivalents per gram of sample (mg GE/g). Each sample was analysed in triplicate, and results were reported as mean ± standard deviation.

2.14 Determination of caffeine content

The quantitative determination of caffeine content was performed using the methodology by Wondimkun et al. (2016). Absorbance was measured with a UV–visible spectrophotometer (UV-Vis spectrometer (SHIMADU CORP., model 01051) at 275 nm. Standard linear calibration curve

was run to obtain the linear range of sample analysis. The quantitative amount of caffeine in samples (ppm) was then determined using the standard curve on the basis of the sample extracts relative to the caffeine standard (Dado, 2020).

2.15 Sensory Evaluation

Sensory evaluation was conducted using 30 panelists from the Department of Food Science and Technology at Chinhoyi University of Technology. The panelists were adults aged 18–45 years and had received prior orientation to the sensory evaluation procedure and the attributes to be assessed. A 9-point hedonic scale was used to evaluate appearance, texture, taste, aroma, flavour, mouthfeel and overall acceptability, where 1 represented "dislike extremely" and 9 represented "like extremely" according to a protocol by Wangiyana et al., (2024). The scale is presented in **Table 1**.

The medium-roasted samples (175 °C) were evaluated using 50 mL portions served at approximately 45 °C. Samples were assigned random three-digit codes and presented in a randomized order to minimize order and identification bias. Panelists were provided with distilled water for palate cleansing and were allowed approximately 3 min between samples. The sensory evaluation was conducted in a quiet laboratory environment under natural lighting. Panelists were instructed to evaluate each coded sample independently and to record their responses using the provided hedonic scale.

Table 1. Nine-point hedonic scale used for sensory evaluation of *A. digitata* roasted seed brew.

Scale Point	Description
1	Dislike extremely
2	Dislike very much
3	Dislike moderately
4	Dislike slightly
5	Neither like nor dislike
6	Like slightly
7	Like moderately
8	Like very much
9	Like extremely

[a]Scale adapted and standardized sensory evaluation practices as outlined by Wangiyana et al., (2024).

2.16 Statistical analysis

The experiment was conducted using a 3 × 3 factorial arrangement in a completely randomized design (CRD), comprising three geographical origins of *Adansonia digitata* seeds (Manicaland, Masvingo, and Mashonaland East) and three roasting temperatures (150 °C, 175 °C, and 200 °C). All physicochemical, bioactive, and sensory analyses were performed in triplicate, and results were expressed as mean ± standard deviation (SD).

Data were subjected to two-way analysis of variance (Two-Way ANOVA) to determine the main effects of geographical origin, roasting temperature, and their interaction on the measured parameters. The statistical model used was:

$$Yijk = \mu + Gi + Tj + (GT)ij + \varepsilon ijk$$

Where: Yijk = observed response variable

μ = overall mean

Gi = effect of the ith geographical origin

Tj = effect of the jth roasting temperature

(GT)ij = interaction effect between geographical origin and roasting temperature

εijk = random experimental error

Where significant differences were detected, means were separated using Tukey's Honest Significant Difference (HSD) post hoc test. Statistical significance was accepted at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics Version 29.0 (IBM Corp., Armonk, NY, USA).

3 Results

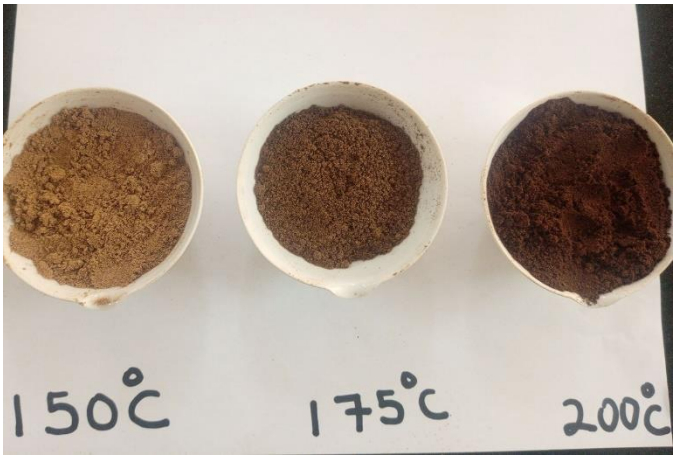


Fig 1. The resultant milled powder post roasting of the *A. digitata* seeds at different temperatures.

Figure 1 shows the visual appearance of milled *A. digitata* seed powder following roasting at 150 °C, 175 °C, and 200 °C. As roasting temperature increased, the powder exhibited a progressively darker coloration ranging from light brown at 150 °C, medium brown at 175 °C, to dark brown at 200 °C indicating Maillard reactions and caramelization. The texture also appeared finer and less clumpy at higher temperatures, suggesting improved brittleness and ease of grinding at advanced roast levels.

The results shown in **Table 2** presents the mean physicochemical and bioactive compound profiles of *A. digitata roasted seed brews* subjected to three roasting temperatures (150 °C, 175 °C, and 200 °C) light, medium and dark roast from across three geographical locations Manicaland, Masvingo, and Mashonaland East. Parameters include pH, titratable acidity, moisture content, total soluble solids, crude fibre, viscosity, sugar concentration, total phenolics, flavonoids, and antioxidant activity (DPPH % inhibition).

Table 2. Physicochemical and bioactive characteristics of *A. digitata* roasted seed powder and prepared roasted seed brews from selected Zimbabwean locations at different roasting temperatures.

Parameter	Manicaland 150 °C	Manicaland 175 °C	Manicaland 200 °C	Masvingo 150 °C	Masvingo 175 °C	Masvingo 200 °C	Mashonaland East 150 °C	Mashonaland East 175 °C	Mashonaland East 200 °C
pH	5.9 ± 0.3^{ab}	5.8 ± 0.1^{b}	5.2 ± 0.2^{d}	6.3 ± 0.1^{a}	5.9 ± 0.3^{ab}	5.5 ± 0.3^{c}	6.3 ± 0.3^{a}	5.7 ± 0.2^{bc}	5.5 ± 0.1^{c}
Titratable Acids (%)	0.19 ± 0.01^{cd}	0.24 ± 0.01^{a}	0.22 ± 0.01^{ab}	0.18 ± 0.02^{d}	0.22 ± 0.01^{ab}	0.20 ± 0.01^{bc}	0.16 ± 0.01^{c}	0.21 ± 0.01^{b}	0.21 ± 0.01^{b}
Moisture Content (%)	6.22 ± 0.25^{a}	4.81 ± 0.07^{c}	3.20 ± 0.16^{f}	5.52 ± 0.43^{b}	4.00 ± 0.16^{e}	2.73 ± 0.09^{g}	5.63 ± 0.34^{b}	4.48 ± 0.31^{d}	3.00 ± 0.04^{fg}
Total Soluble Solids (ºBrix)	33.52 ± 2.99^{c}	41.77 ± 0.58^{a}	38.18 ± 1.11^{b}	31.72 ± 0.8^{c}	31.30 ± 2.60^{c}	37.08 ± 2.16^{b}	30.87 ± 1.89^{c}	40.35 ± 2.37^{a}	37.85 ± 3.33^{b}
Crude Fibre (%)	10.82 ± 0.15^{b}	10.09 ± 1.05^{c}	8.50 ± 0.50^{e}	11.19 ± 0.66^{b}	10.59 ± 0.16^{bc}	8.91 ± 0.34^{de}	12.00 ± 0.34^{a}	10.54 ± 0.45^{bc}	9.36 ± 0.41^{d}
Viscosity (mPa•s)	1.30 ± 0.07^{d}	1.58 ± 0.06^{b}	1.49 ± 0.04^{c}	1.40 ± 0.06^{cd}	1.67 ± 0.10^{a}	1.59 ± 0.05^{b}	1.51 ± 0.09^{bc}	1.60 ± 0.09^{b}	1.50 ± 0.11^{c}
Total soluble carbohydrate (mg GE/g)	16.40 ± 1.71^{c}	12.88 ± 0.49^{d}	9.14 ± 0.30^{f}	18.84 ± 0.97^{a}	14.44 ± 0.46^{cd}	9.51 ± 0.23^{ef}	17.04 ± 0.90^{b}	12.99 ± 0.65^{d}	8.69 ± 0.25^{f}
Total Phenolic Compounds (mg GAE/g)	2.87 ± 0.15^{d}	3.44 ± 0.23^{c}	2.80 ± 0.16^{d}	3.86 ± 0.26^{b}	4.39 ± 0.12^{a}	3.98 ± 0.22^{b}	2.79 ± 0.08^{d}	3.36 ± 0.26^{c}	2.92 ± 0.14^{d}
Total Flavonoids (mg RE/g)	3.59 ± 0.33^{f}	4.61 ± 0.25^{e}	3.82 ± 0.17^{f}	8.05 ± 0.86^{b}	9.39 ± 0.26^{a}	7.52 ± 0.44^{b}	5.31 ± 0.28^{d}	6.10 ± 0.22^{c}	4.75 ± 0.08^{e}
DPPH (% inhibition)	43.98 ± 3.87^{f}	53.82 ± 3.93^{e}	41.75 ± 1.69^{f}	70.51 ± 3.45^{b}	77.69 ± 3.60^{a}	66.04 ± 1.83^{c}	59.94 ± 1.77^{d}	69.26 ± 1.41^{b}	59.86 ± 4.21^{d}
Caffeine	ND	ND	ND	ND	ND	ND	ND	ND	ND

Different superscript letters within the same row indicate statistically significant differences between treatment means ($p < 0.05$), whereas means sharing at least one superscript letter are not significantly different.

***ND** = not detected under the analytical conditions employed; values represent mean ± SD. ***Matrix description:** Moisture content and crude fibre were determined using the roasted seed powder, while pH, titratable acidity, total soluble solids and viscosity were determined using the prepared roasted seed brew. Total soluble carbohydrate, total phenolic content, total flavonoid content and DPPH antioxidant activity were determined from the prepared extract and caffeine was assessed in the corresponding brew extract. Values are reported using the units specified for each parameter.

Table 2 shows that the measured physicochemical and bioactive characteristics varied across the investigated locations and roasting temperatures. Moderate roasting at 175 °C consistently enhanced antioxidant parameters, with Masvingo 175 °C samples recording the highest total phenolics (4.39 ± 0.12 mg GAE/g), flavonoids (9.39 ± 0.26 mg RE/g), and DPPH inhibition (77.69 ± 3.60%). Manicaland brews exhibited higher moisture content but lower bioactive levels, while Mashonaland East samples retained more fibre. Across all treatments, no caffeine was detected under the analytical conditions employed.

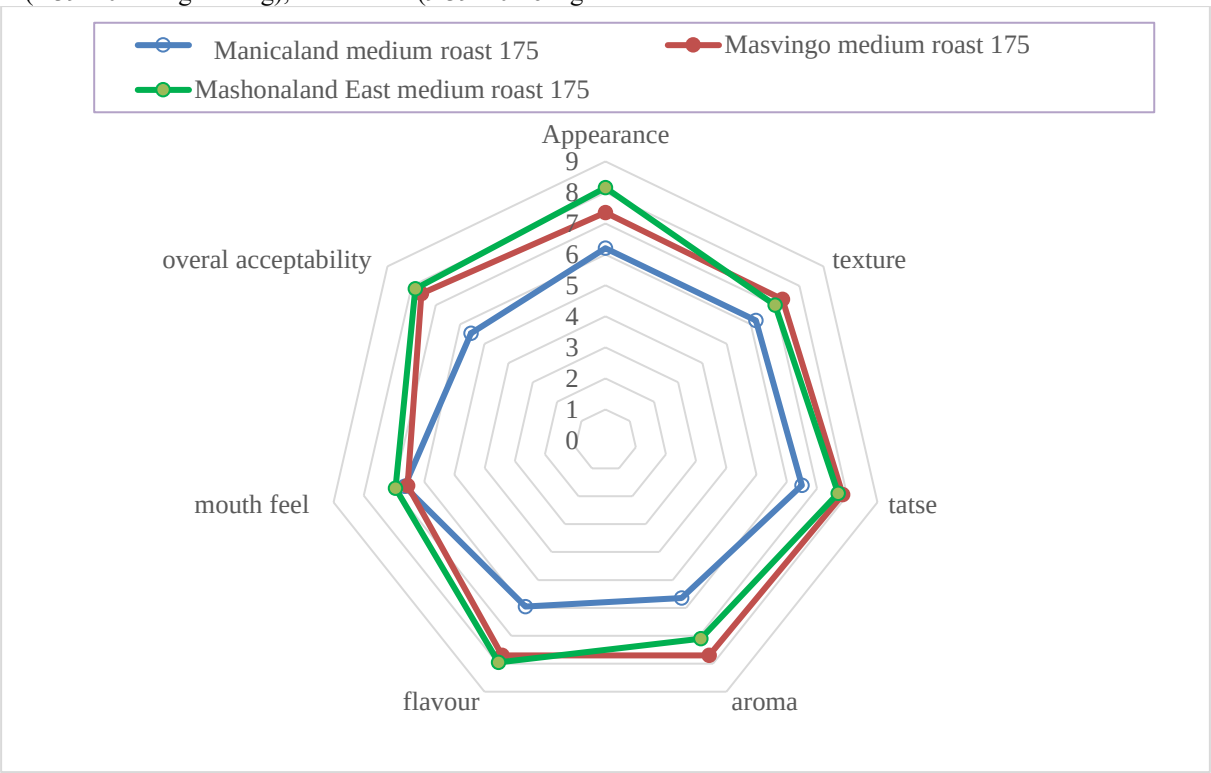


Fig 2. Radar chart showing sensory evaluation scores of *A. digitata* seed roasted brews from selected locations at 175 °C.

The radar chart in **Figure 2** visually compares the medium (175 °C) roast baobab seed brew from the 3 regions based on their sensory attributes. For instance, it can be observed that Masvingo consistently scores higher in aroma, taste and texture. In contrast Mashonaland East, shows a stronger profile in flavour, mouthfeel, appearance and overall acceptability. Manicaland had the least scores in all sensory attributes. The corresponding scores are presented in **Table 3**.

Table 3. Sensory evaluation scores of *A. digitata* roasted seed brews prepared at 175 °C and evaluated using a 9-point hedonic scale.

Attribute	Manicaland	Masvingo	Mashonaland East
Appearance	6.4±1.2a	7.5±1.0b	8.1±0.8b
Texture	5.9±1.4a	6.8±1.1b	6.5±1.0b
Taste	6.1±1.5a	7.2±0.9b	7.1±0.8b
Aroma	5.5±1.3a	7.0±1.0b	6.4±1.2b
Flavour	6.0±1.1a	8.0±0.7b	8.2±0.6b
Mouthfeel	6.2±1.0a	6.8±0.8ab	7.0±0.9b
Overall Acceptability	5.7±1.4a	7.3±0.9b	7.5±0.8b

Note: Values are expressed as mean ± standard deviation (SD). Mean values within the same row bearing different superscript letters (a, b) are significantly different at $p < 0.05$ according to Tukey's Honest Significant Difference (HSD) post hoc test following one-way ANOVA. Means sharing at least one common superscript letter are not significantly different. Sensory attributes were evaluated using a 9-point hedonic scale, where 1 = dislike extremely and 9 = like extremely.

4 Discussion

4.1 pH and Titratable Acidity (TA)

In **Table 2**, the pH of *A. digitata* seed beverages showed a consistent decline with increased roasting temperature across all regions, dropping from 6.3 ± 0.27 (Mashonaland East 150 °C) to 5.2 ± 0.17 (Manicaland 200 °C). This decrease reflects enhanced Maillard reaction activity at higher temperatures, leading to the formation of acidic compounds (Ghafoor et al., 2020; Das et al., 2023). Geographically, higher pH values were observed in the Mashonaland East and Masvingo 150 °C samples, potentially due to lower initial acidity of seeds grown in drier zones with neutral to slightly alkaline soil pH (Przybylska-Balcerek, 2020). In contrast, Manicaland, a high rainfall and high-humidity region, showed lower pH and higher titratable acidity at 175 °C (0.24 ± 0.01%). This reflects higher organic acid content in seeds from wet regions, as observed by Yadav et al. (2021), where prolonged precipitation enhances acid biosynthesis and metabolic flux. Therefore, regional climatic factors, in tandem with thermal

exposure, influence final beverage acidity, which in turn affects taste and shelf stability (Lu & Chen, 2023).

4.2 Moisture Content and Total Soluble Solids (TSS)

A clear temperature-driven reduction in moisture content was recorded, consistent with thermal dehydration. Moisture declined from 6.22 ± 0.25% (Manicaland 150 °C) to 2.73 ± 0.09% (Masvingo 200 °C), in line with roasting-induced water loss (Lamidi et al., 2023). Among geographical regions, Manicaland consistently exhibited the highest moisture content at all roasting levels (See **Table 2**). This can be attributed to its high annual rainfall (>1000 mm), cool climate, and elevated humidity, which promotes water retention in seed tissues (Souza et al., 2019). Masvingo and Mashonaland East, with lower rainfall (approx. 585 mm and 721 mm annually respectively), recorded significantly lower moisture contents. This reinforces the idea that seeds from drier regions are naturally more dehydrated, an attribute favorable for long shelf-life and processing efficiency (Benmeziane-Derradji et al., 2020). The response of total soluble solids (TSS) to roasting temperature varied across the geographical locations. TSS peaked at 175 °C in Manicaland (41.77 ± 0.58 °Brix) and Mashonaland East (40.35 ± 2.37 °Brix), before declining at 200 °C. In contrast, Masvingo samples showed a slight decrease from 31.72 ± 0.80 °Brix at 150 °C to 31.30 ± 2.60 °Brix at 175 °C, followed by an increase to 37.08 ± 2.16 °Brix at 200 °C. Moderate roasting appears to optimize matrix disintegration and release of sugars and polyphenolics, a phenomenon described by Farah (2019). The differences observed among locations may reflect variation in the initial composition of the seeds; however, the present study does not permit specific environmental or genetic factors to be attributed to these differences.

4.3 Crude Fibre and Viscosity

Crude fibre content decreased with roasting, ranging from 12.00 ± 0.34% (Mashonaland East 150 °C) to 8.50 ± 0.50% (Manicaland 200 °C) as indicated in **Table 2**. Roasting likely degraded cellulose and hemicellulose, corroborating Silva et al. (2023), who described thermal weakening of insoluble dietary fibre. Notably, Mashonaland East samples retained the highest fibre content, likely due to lower rainfall and arid soil conditions which promote lignification in plant tissues (Petisca et al., 2013). Manicaland's lower fibre content, especially at higher temperatures, supports the idea that seeds from wetter climates are less structurally fibrous, and therefore more prone to thermal degradation. Viscosity showed mild fluctuations, highest at 175 °C, likely due to partial solubilization of fibres and proteins (Grzelczyk et al., 2022). Masvingo samples, despite lower fibre content, displayed relatively higher viscosity (1.67 ± 0.10 mPa·s at 175 °C), possibly due to the presence of mucilaginous polysaccharides or soluble fibres retained during moderate heating. However, further compositional analysis would be required to identify the compounds responsible for the observed differences.

4.4 Sugar Quantity

Results in **Table 2** indicated that the sugar content declined progressively with temperature, with the highest recorded at 150 °C (Masvingo: 18.84 ± 0.97 mg/g; Mashonaland East: 17.04 ± 0.90 mg/g) and the lowest at 200 °C (Mashonaland East: 8.69 ± 0.25 mg/g). This decline is attributed to caramelization and Maillard degradation (Sun et al., 2022). The higher sugar content in Masvingo and Mashonaland East may reflect climatic stress adaptations, where plants accumulate soluble sugars for osmotic regulation under drought conditions (Lima et al., 2021). Manicaland's lower sugar levels align with its humid, less stressful environment, which reduces sugar accumulation. The observed temperature-dependent changes indicate that roasting conditions can alter the soluble carbohydrate characteristics of the resulting brew.

4.5 Total Phenolic Compounds (TPC) and Total Flavonoids (TFC)

Both TPC and TFC peaked at 175 °C for Masvingo (4.39 ± 0.12 mg GAE/g and 9.39 ± 0.26 mg RE/g, respectively) as shown in **Table 2**, validating that moderate roasting enhances phenolic release without degradation. Beyond 175 °C, the levels declined due to thermal decomposition (Mohamed Ahmed et al., 2023). Importantly, Masvingo consistently recorded the highest bioactive content across all roast levels, pointing to a strong geographical influence likely driven by soil mineral composition, UV radiation exposure, and mild drought stress, all of which are known to enhance secondary metabolite synthesis (Yan et al., 2023; Lopes et al., 2021). This consistent elevation in TPC and TFC from Masvingo strongly supports the designation of Masvingo as a potential geographical indicator for *A. digitata*seed beverages due to its superior biofunctional profile. These observations also align with previous studies emphasizing the role of edaphoclimatic stress in promoting antioxidant potential in plant materials (Staroszczyk & Sikorski, 2023).

4.6 Antioxidant Activity (DPPH Assay)

DPPH inhibition mirrored the TPC and TFC patterns, peaking at 77.69 ± 3.60% (Masvingo 175 °C), confirming the direct contribution of polyphenols and flavonoids to antioxidant activity (Donno & Turrini, 2020). In contrast, Manicaland samples showed the lowest antioxidant capacity, especially at 200 °C (41.75 ± 1.69%) (see **Table 2**), likely due to both phenolic degradation and lower initial bioactive content highlighting the climatic limitation for bioactive yield in humid ecologies (Mahmud et al., 2020). Thus, the observed antioxidant activity varied across roasting temperatures and selected locations, with Masvingo samples showing comparatively higher DPPH radical-scavenging activity in the present dataset. These findings warrant further investigation of samples from this location under controlled and independently replicated conditions.

4.7 Caffeine Content

The absence of detectable caffeine in the analyzed samples suggests that caffeine was not measurable under the analytical conditions employed. However, recovery, limit of detection (LOD) and limit of quantification (LOQ) were not established as part of the present analytical validation. Therefore, the finding should be interpreted as non-detection rather than confirmation of complete caffeine absence. Further analysis using a validated quantitative method would be required to establish the actual caffeine concentration and confirm caffeine-free status.

4.8 Sensory Evaluation

The sensory evaluation using a 9-point hedonic scale provided an assessment of the panel responses to the medium-roasted (175 °C) *A. digitata* seed brews from Manicaland, Masvingo and Mashonaland East. Differences in sensory scores were observed among the three samples. These results indicate variation in the sensory responses of the panel to the investigated brews; however, the 30-member departmental panel should not be considered representative of the broader consumer population. Masvingo's 175 °C roasted brew received the highest ratings in aroma, taste, and texture, correlating well with its objectively superior bioactive profile highest total phenolic (4.39 ± 0.12 mg GAE/g) and flavonoid content (9.39 ± 0.26 mg RE/g) and highest antioxidant capacity (77.69 ± 3.60%).

This reinforces findings by Donno and Turrini (2020) and Sharma & Orsat (2024) who stated that bioactive-rich matrices often deliver enhanced taste and aroma due to polyphenol-induced flavor notes and antioxidant-stabilized volatiles. Furthermore, medium roasting has been widely reported to optimize aroma and flavor compounds by balancing Maillard reaction products and retaining natural seed volatiles (Farah, 2019; Mohamed Ahmed et al., 2023). Further chemical and sensory studies would be required to establish relationships between specific compounds and sensory attributes.

In contrast, Mashonaland East's 175 °C brew excelled in mouthfeel, flavour intensity, appearance, and overall acceptability, indicating a strong consumer response to its visual and textural characteristics. This can be explained by the higher crude fibre retention (10.54 ± 0.45%) in Mashonaland East samples (**Table 2**), which may enhance the body and viscosity of the brew, resulting in a smoother mouthfeel (Benmeziane-Derradji et al., 2020). The increased viscosity (1.60 ± 0.09 mPa•s at 175 °C) likely contributed to the brew's perceived thickness and richness, a desirable trait in herbal brews and decaffeinated beverages. Additionally, the darker color developed during roasting in semi-arid Mashonaland East may have positively influenced the visual appeal, as color has been shown to impact perceived quality and flavor intensity (Lu & Chen, 2023).

Conversely, the Manicaland medium-roasted brew scored the lowest across all sensory attributes. This lower acceptability can be directly linked to its comparatively higher moisture content (4.81 ± 0.07%), lower TPC (3.44 ± 0.23 mg GAE/g), and reduced flavonoids (4.61 ± 0.25 mg RE/g), which together result in a flatter flavor profile, diminished aroma, and a less vibrant appearance. Additionally, the higher relative acidity (TA 0.24 ± 0.01%) in Manicaland samples may have contributed to unfavorable taste notes, such as sourness or astringency, potentially reducing consumer appeal. This is consistent with findings by Idris Ali et al. (2023) who noted that excess acidity and moisture negatively affect brew stability and flavor complexity.

Sensory evaluation at 175 °C revealed differences among samples from the three locations. However, since only this temperature was tested, further evaluation across all roasting temperatures is needed to establish the optimum temperature for sensory quality. These results also align with prior findings by Gayathry & John (2021) and Omotayo & Aremu (2020) who emphasized the need for functional foods to meet both health and sensory satisfaction criteria for successful market adoption.

4.9 Study limitations

A limitation of the present study is that the environmental and biological factors associated with sample provenance were not independently characterised. Regional climate, soil properties, genotype or landrace, tree-to-tree variation, harvest history and other pre-harvest conditions may contribute to differences in the physicochemical and bioactive characteristics of *A. digitata* seeds. However, these factors were not measured or experimentally separated in the present study and are therefore confounded with the sampled location and lot history. Future studies incorporating multiple independent lots and trees within each location, together with characterisation of soil and climatic conditions and genetic or genotype information, would allow the relative contributions of provenance, environment and genotype to be evaluated more rigorously.

5 Conclusion and Recommendations

The research comparatively assessed the physicochemical and bioactive properties of *A. digitata* seed roasted brews from selected Zimbabwean locations and roasting conditions. The results provide comparative information on variation in the measured characteristics across the investigated roasting conditions and selected locations. The measured parameters varied across the roasting temperatures investigated. The 175 °C roasting condition produced comparatively favourable values for several measured characteristics, further enhancing the release of bioactive compounds total phenolics (4.39 ± 0.12 mg GAE/g), total flavonoids (9.39 ± 0.26 mg RE/g), and antioxidant activity (77.69 ± 3.60 % inhibition) while also achieving desirable physicochemical properties like viscosity (1.67 ± 0.10 mPa·s) and total soluble solids (41.77 ± 0.58 ^{o}Brix). Extreme roasting at 200 °C was associated with reduced phenolic, flavonoid and antioxidant levels, reducing phenolics to as low as 2.92 ± 0.14 mg GAE/g and flavonoids to 3.82 ± 0.17 mg RE/g.

Variation was also observed among samples obtained from the selected locations. Samples from Masvingo showed comparatively higher measured total phenolics (up to 4.39 ± 0.12 mg GAE/g), flavonoids (up to 9.39 ± 0.26 mg RE/g), and antioxidant activity (77.69 ± 3.60 % inhibition) in the present dataset. Conversely, Manicaland seeds from high-rainfall, humid environments had higher moisture content (up to 6.22 ± 0.25 % at 150 °C roast) but lower phenolic (as low as 2.80 ± 0.16 mg GAE/g) and sugar levels (9.14 ± 0.30 mg/g), possibly due to reduced environmental stress and compound dilution.

Physicochemical parameters like pH, titratable acidity, and moisture also varied with both roasting and location. Mashonaland East seeds had the highest crude fibre (12.00 ± 0.34 % at 150 °C roast), reflecting adaptation to semi-arid growth conditions, while pH values ranged from 6.3 ± 0.3 (light roast) to 5.2 ± 0.2 (dark roast), showing slight acidification with heat treatment. Caffeine was not detected in the analysed samples under the analytical conditions employed.

In conclusion, this research provides scientific validation for the valorization of *A. digitata* seeds into functional beverages. The findings support further investigation of moderate roasting (175 °C), particularly for its favourable physicochemical and bioactive characteristics. Masvingo samples also warrant further investigation due to their comparatively higher measured bioactive values. However, since sensory evaluation was conducted only at 175 °C, further studies should assess samples across all roasting temperatures to establish the optimum roasting condition for sensory quality. Future studies should also employ independent experimental replication for validation of the findings. This research provides comparative evidence supporting further investigation into the potential valorisation of *A. digitata* seeds.

Author Contributions

Kelvin Magava and Tanaka Masaiti contributed to the conceptualization of the study, experimental design, data collection, laboratory analyses, interpretation of results, data analysis, statistical evaluation, interpretation of analytical results and drafting of the manuscript. Dr. Chigu and Dr. Chisango provided academic supervision, guided the study design and methodology, critically reviewed the manuscript, and offered intellectual input throughout the research process. All authors reviewed and approved the final version of the manuscript for publication.

Funding: This research received no external funding.

Data Availability Statement

The data generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgements

The authors would like to express their sincere gratitude to the Department of Biotechnology, School of Health Sciences, Chinhoyi University of Technology, for providing laboratory facilities and technical support throughout this study. Special thanks go to the Department of Food Science and Technology for assistance with sensory evaluation and data analysis. The authors also acknowledge the invaluable contributions of laboratory technologists and student assistants who participated in the roasting, brewing and analytical procedures.

Conflicts of Interest

The authors declare that there are no conflicts of interest in this work.

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