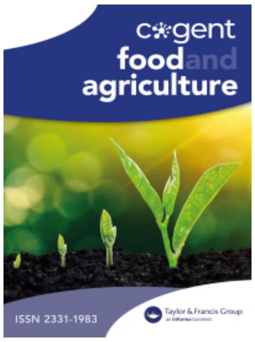

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Evaluation of potential industrial application of selected East African Highland cooking banana cultivars starches grown in Uganda

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ABSTRACT

The potential for industrial application of starches extracted from 11 East African Highland Cooking Banana (EAHCB) cultivars based on their structural, physicochemical, and functional profiles was assessed. Their starch granules were smooth with varying shapes and particle sizes across the cultivars. The starch content, homopolysaccharide content, mechanical properties and particle sizes of the native banana starches were generally higher than those of the standard starches. Their functional and pasting properties were lower than in the commercial food starch, laundry starch and pharmaceutical starches. Based on all the properties, PCA analysis revealed a wide variation between the native EAHCB starches and the standard food, laundry, and pharmaceutical starches on the market, pointing to the need for modification before industrial application. The results revealed that some EAHCB starches possess properties similar to commercial food, laundry, and pharmaceutical starches, indicating the potential for breeding EAHCB cultivars that produce starches suitable for industrial use, thereby reducing modification costs. We recommend further research into the genetic control of starch biosynthesis in specific EAHCB cultivars to facilitate the breeding of starches for industrial applications.

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Introduction

East African Highland Cooking Banana (EAHCB) is a subgroup of triploid (*Musa* AAA) cooking and beer bananas (ProMusa, 2020). This banana varieties provide food and income for over 30 million inhabitants of the African Great Lakes Region (FAOSTAT, 2022a; Vanlauwe et al., 2013). Uganda is among the world's leading producers and consumers of the EAHCB (De Steur et al., 2016; FAOSTAT, 2022b; Vazhacharickal et al., 2022), producing approximately four million tons of bananas on 807,000 ha. (Kikulwe & Asindu, 2020; Schnurr & Addison, 2017). The EAHCB is a primary source of nutrition and income. It holds significant promise not only for food security but also for its potential industrial applications for the east African sub region (Khakasa et al., 2024).

However, the challenge to production of this banana is postharvest loss (PHL). The banana production cycle in Uganda is characterized by episodes of surplus production, in which the risk of waste and losses are increased. During this period, many farmers fail to sell all their bananas, whereas others store their bananas for relatively longer periods, predisposing them to ripening (Kikulwe et al., 2018; Tinzaara et al., 2018). The reduction in postharvest losses is fundamental in sustainable global food systems. In Uganda, despite the interventions in place to minimize banana postharvest losses, PHL actually is still increasing, to date at 14.9–45% depending on the season and mode of value chain. This therefore, results in at least 1.1 billion tons per year of cooking banana lost. Minimization of losses could be attained through the adoption of modern equipment and technologies, which are still insufficient in developing countries (Kikulwe et al., 2018; Lee, 2023).

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The EAHCB cultivars are known for their high starch content (Khakasa et al., 2024). Therefore, beyond just their culinary use, the starch extracted from these bananas presents an untapped resource for various industrial sectors. Thus, creating more demand for banana starch through the diversification of its uses, especially as an industrial raw material, is a more feasible strategy to reduction of PHL.

Starch is a raw material widely used in the food, medical, and textile industries, and its application prospects continue to improve (He et al., 2023). The common commercial starches are obtained from cereals, such as corn, wheat, and various types of rice, and from tubers or roots, such as potatoes and cassava (or tapioca) (Reddy et al., 2015; Yazid et al., 2018). It is important to note that the source of starch plays a critical role in the starch properties owing to the ratio of amylose to amylopectin and the different structural properties of these macromolecules (Kaur et al., 2020; Molavi et al., 2015). Therefore, starches from different botanical sources have different properties and functionalities that are dependent on their different morphological and structural properties (Li et al., 2018) and their physical and chemical characteristics (Adewale et al., 2022; Jingyi et al., 2023; Zhang et al., 2017). Currently, there is a growing industrial demand for novel starches with different structural, physicochemical, and functional properties (Kushwaha et al., 2023), that are not met by traditional starches. Secondly, traditional starch sources are diminishing; hence, there is a need to explore new starch sources with improved functional properties (Bangar et al., 2022; Bello-Lara et al., 2014; Li et al., 2018).

Different industrial applications require specific starch properties (Adewale et al., 2022; Akeem Olayemi, 2020). For example, in textile applications, starch with enhanced hydrophobic properties, which improves fabric strength and printability, and good gelling properties to form films that enhance the gelling and sizing of fibers and with low viscosity and stability at low temperatures to improve fabric strength and printability (Compart et al., 2023) is preferred. For pharmaceutical applications, it should be non-toxic, pharmacologically inert, and have a relatively low amylose content (Builders & Arhewoh, 2016; Insan et al., 2022). Still in the same field of application, specifically for tableting pharmaceutical grade starch should have a smaller particle size to increase flowability, compressibility and compatibility (Šantl et al., 2012; Wang et al., 2014; Wünsch et al., 2021). Food-grade starch on the other hand, should have high solubility, swelling power, solubility, and water absorption capacity (Insan et al., 2022).

The properties of some varieties of banana starch have been evaluated in previous studies (Kaur et al., 2020). However, of the 79 EAHCB cultivars grown in Uganda (Karamura, 1999), only seven have been evaluated by Muranga (1998) and Ssonko and Muranga (2017). Owing to the increasing demand for starch as a raw material for industries (Kushwaha et al., 2023; Marta et al., 2019), we opted to analyze starches from more EAHCB to gauge their suitability for industrial applications. This study sought to evaluate the potential of starches derived from selected EAHCB cultivars grown in Uganda for industrial applications. It focused on analyzing their physical, chemical, and functional properties to determine their suitability for use in various industries. We provide banana starch cultivars that could guide the selection of starch with suitable properties for a particular industrial application and the selection of an appropriate modification method to obtain the required functional characteristics of starch for a specific end use. By understanding the unique attributes of these starches, this research aims to promote sustainable utilization of EAHCB bananas, contributing to both economic growth and environmental sustainability.

Methods and materials

Selection of EAHCB cultivars for study

The study was carried out on 11 clones of EAHCB commonly available in the PIBID field and on local farms that had not been analyzed in earlier studies. These were selected from the four cooking EAHCB clone sets as follows; Enzerabushera, Nyakinyika, Siira, Enjoogabakazi and Enzirabahima from Nfuuka clone set; Entaragaza and Kibuzi from Nakitembe clone set; Muzuba and Kisansa from Musakala clone set and Nakabululu and Butobe from the Nakabululu clone set.

Sampling procedure

For each clone, four plants were randomly selected and tagged at the beginning of anthesis. The selected banana plants were tagged in March 2021. The mature green banana fruits were harvested at green maturity in July 2021, after exactly 15 weeks from tagging date, the time reported by Kawongolo et al. (2016) in which EAHCB had the highest quantity of starch. For each clone, the harvested fruits were washed with clean water and packed in a well labelled black polythene bag to form a composite sample. The different composite samples were immediately transferred to the PIBID Starch laboratory for immediate starch extraction.

Starch extraction

Starch was extracted using the method described by Ssonko and Muranga (2017) with modifications. In brief for each cultivar, peeled banana fingers were sliced, placed in 0.045 M Sodium Hydroxide solution for 10 min, and blended into a slurry using a Waring 3 Speed blender (Model CB15P USA). Then, the slurry was diluted with distilled water and strained over 500 µm sieve and the filtrate was held at 4 °C for six hours. The starch filtrate was centrifuged at 5000 rpm for 15 min, and the supernatant was discarded while the starch was retained. The starches were then washed with distilled water three times, and for each wash, it was left to sit in water at 4 °C for 2 h and centrifuged at 5000 rpm for 15 min. Finally, the starches were dried in an oven (Haier, Electro-thermal thermostatic drying oven, UK HFS-160) at 40 °C for 24 h, after which it was milled and sieved through a 200 µm sieve. The dried starch of each clone was divided into three equal portions of 100 g each and then stored in air-tight and well labelled glass containers until further analysis. For comparison purposes, pure food grade starch, laundry starch, and pharmaceutical grade starch were obtained from LOBA CHEMIE PVT LTD and the pharmaceutical industry (Cipla Quality chemical Uganda Ltd).

Determination of total starch content of banana pulp

Total starch content was determined using the phenol-sulfuric acid method described by Albalasmeh et al. (2013) with modifications. Briefly, 0.1 g of the starch powder for each clone was transferred into a test tube, followed by 1 ml of 95% ethanol to remove the interfering sugars. The remaining starch was hydrolyzed with 5 ml of 10% sulfuric acid and placed in a water bath at 80 °C for 30 minutes in order to gelatinize the solution and then left for 10 min at room temperature to cool. Then 0.5 ml of this solution was transferred into a test tube, followed by 0.5 ml with 5% phenol with 1 ml of water and 1 ml of concentrated sulfuric acid, agitated to obtain a solution that was left to cool at room temperature for 10 min. The absorption of the solution was determined at 490 nm using a spectrophotometer (Agilent Technologies Cary 100 Series UV-Vis Spectrometer, USA).

Amylose content determination

The amylose content was determined using the iodo-colorimetric assay method of Sowbhagya and Bhattacharya (1971) as described by Afoakwa et al. Briefly, 1 ml of absolute ethanol (95%) was respectively added to 0.1 g of the extracted starch powders of the different cultivars in a 100 ml volumetric flask, followed by 10 ml of 1 N/M NaOH. The mixture was then incubated at room temperature overnight and made up to 100 ml by adding distilled water. To 2.5 ml of the extract in a 50 ml volumetric flask, 20 ml of distilled water and three drops of phenolphthalein (0.1 g in 80mls 95% ethanol and topped up with 100mls with DH_20) were added, followed by drops of 0.1 N/M HCl until the pink color just disappeared. One (1) ml of iodine reagent (1 g iodine crystals and 10 g potassium iodide in 500 ml) was added to a final volume of 50 ml. The absorbance was measured at 590 nm. The standard was prepared, and the absorbance was read at 590 nm. The amount of amylose was calculated using the following formula:

$$\text{Amylose \% on dry basis} = \frac{R}{A} \times \left(\frac{a(\text{mg})}{r(\text{mg})}\right) \times \left(\frac{1\text{ml}}{5\text{ml}}\right) \times 100$$

where R is the absorbance of the sample starch dispersion, A is the absorbance of standard amylose, and a is the amount of standard amylose weighed (mg); r = amount of starch sample weighed (mg).

Determination of amylopectin content

Amylopectin content was determined by subtracting the amylose content from the total starch content of each sample as was described and used by Afoakwa et al. (2013) and Souza et al. (2020). The amylopectin content was calculated by subtracting the amylose concentration from the total starch concentration. The average percentage of amylopectin was determined using the following equation, where total starch is considered 100%:

$$Amylopectin(\%) = 100 - Amylose\,content(\%)$$

Starch solubility determination

The total solubility of starch samples at room temperature was determined using the method described by Ariwaodo et al. (2017). In this method, 1 g of the sample was weighed in a centrifuge tube containing 10 mL of distilled water. The mixture was stirred, allowed to stand for 1h, and then centrifuged at 4,000 rpm for 15 min using a benchtop centrifuge (Eppendorf, Centrifuge 5810 R Hamburg, Germany). The supernatant was evaporated in previously clean, weighed moisture can at 90 °C for 24 h. Solubility was measured as the increase in weight of the can over the weight of the sample and was expressed as a percentage.

$$Solubility\,(\%) = \frac{Ws}{Sample\ weight\,(dry\ basis)} \times 100$$

Swelling power determination

These values were determined as described by Ssonko and Muranga (2017). Starch suspensions (1% w/w) were prepared and heated to 40, 50, 60, 70, 80, and 90 °C for 30 min with 5 min intermittent shaking. The final slurry was then centrifuged for 15 min at 3,000g using a benchtop centrifuge (Eppendorf, Centrifuge 5810 R Hamburg, Germany). The supernatant was then decanted off, and its volume was determined. The sediment was dried in an oven for 2 h at 110 °C, and the swelling power was then determined from difference.

Mechanical strength determination

This was done using a standard method as was used by Gujral et al. (2013). Briefly, starch solution (3%) was cooked in a boiling water bath for 3 min and gel formed was filled into 35-mm-diameter polypropylene tubes, and the tubes kept for 24 h at room temperature. The gel hardness test was carried out on a texture analyzer (TAplus Lloyd instruments, Ametek; Ssussex England). A rectangular probe (HDP/PFS) was used in texture profile analysis (TPA), and the distance calibration was 25 mm. Compression was selected as the test mode. The pre-test speed of 3 mm/s, test speed of 1 mm/s, and post-test speed of 1.00 mm/s. The compression strain was 75% and the triggering force was 5.0 g.

Starch granule shape and particle size determination

The starch granule morphology was obtained using a scanning electron microscope (Zeiss Sigma 300 FE-SEM) Carl Zeiss model. The starch samples were mounted on the specimen stub and sputter-coated with Cr. Finally, the coated samples were analyzed using scanning Electron Microscope (SEM) operated at 10.0KV. The particle size was determined using the J imaging software embedded in the SEM.

X-ray diffraction

X-ray diffraction was used to determine the crystallinity of the isolated starch where 500 mg of each sample starch powder were analyzed employing BRUKER AXS diffractometer, D8 Advance (Germany) fitted with Cu-Kα radiation (λKα1 = 1.5406 Å) from 2θ = 0.5° to 130°, with increment Δ2ϑ: (0.034°), voltage of 40 kV, current of 40 mA, power of 1.6 kW and counting time of 0.5 s/step. The generated data were analyzed using OriginPro Version 8.5, and the resultant peak 2θ values were compared with those of commercial starches for pharmaceutical, laundry, and food (potato) starch applications.

The crystalline and amorphous areas were calculated according to Liu et al. (2020) and Lopez-Rubio et al. (2008). The crystallinity was calculated as follows:

$$Rc = \left(\frac{Ac}{Ac + Aa}\right) \times 100$$

where: R_c is Degree of crystallinity, A_c is the total area under three crystalline peaks, and A_a is the total amorphous area of the diffractogram.

Determination of gelatinization pasting properties

The gelatinization and pasting properties of green banana starch were measured using a Rapid Visco Analyzer (RVA; PerkinElmer, Perten instrument RVA4500, USA) following the method described by Ariwaodo et al. (2017) and Kong et al. (2016). The starch was dispersed in distilled water, quantitatively mixed, and then transferred into a canister of the RVA according to the manufacturer's recommendations. Briefly, the starch (3.5 g, 14% moisture basis) was mixed with 25.2 g distilled water in an RVA sample canister. A programmed heating and cooling cycle was used which the samples were held at 50 °C for 1 min, heated to 95 °C for 3.5 min, held at 95 °C for 3 min, cooled back to 50 °C for 4.5 min and held at 50 °C for 2 min. The peak viscosity (PV), hot paste viscosity (holding; HPV), cool paste viscosity (CPV, Final viscosity), and pasting temperature (PT) were measured. Viscosities were presented in Rapid Visco Units (RVU).

Quality assurance

For each of the above procedures and tests on starch, each test was carried out in triplicate, and a control sample (blank) was run on each test to measure absorbance. For the blanks, 0.1 mL of water (in place of starch) was used, all the reagents were added in the same volumes as the starch, and their absorbance was recorded at 490 nm in measurements for starch and amylose content. Distilled water was used in the preparation of the reagents and solutions of the samples.

Statistical analysis

Data were analyzed using the Stata statistical package version STATAv15 (StataCorp., 2017). Before any statistical analysis, data distribution were checked for normality and homogeneity of variances using the Shapiro-Wilk test and Levene's test, respectively. In the case of deviations from normality or homoscedasticity, the statistical assumptions of the analysis were fulfilled using log transformation. Variability in means among the clones was analyzed using analysis of variance (ANOVA) followed by a post-hock test (Bonferroni test) with means considered to be significantly different at $p < 0.05$.

Results

Starch content of the selected EAHCB cultivars

The percentage composition of the total starch on dry basis (DB) ranged from 90.2 to 97.7% purity with Entaragaza showing the highest percentage followed by Kibuzi, Muzuba and Kisansa cultivars while Enzirabahima showed the least percentage with 90.22% starch (Table 1). Generally, the cultivars had an average of 94.1% total starch, indicating that the banana cultivars studied were rich in starch. The starch content of the standards was 95.09, 90.49 and 95.34% for the standard starches, laundry food, and pharmaceutical starches, respectively.

Amylose and amylose: Amylopectin ratio

The starch extracted from the 11 samples contained amylose, which differed significantly between the cultivars (Bonferroni test, $p < 0.05$) (Table 1). Nakabululu and Butobe, both of which belong to the Nakabululu cloneset, had the highest amylose contents 16.5 and 15.7%, respectively, and hence the corresponding amylose amylopectin ratios. This means that the amylopectin content of these two starches is lower that of those with lower amylose, Kisansa and Muzuba of the Musakala cloneset had the lowest amylose content and Kibuzi of Nakitembe clone set (13.65, 13.75 and 12.44% respectively). However, their low amylose content, by subtraction, resulted in the highest amylopectin content. The standards had high amylose contents, which were comparable to those of the Nakabululu cloneset cultivars.

The highest and lowest amylose: amylopectin ratios were found in the Nakabululu and Kibuzi cultivars (0.198 ± 0.001 and 0.143 ± 0.001, respectively) (Table 1). Generally, the standard starches in this study were found to have significantly higher amylose content and corresponding amylose: amylopectin ratios (Bonferroni test, $p < 0.05$) than for all 11 cultivars in this study. The amylose: amylopectin ratios were 0.194 ± 0.003, 0.187 ± 0.000, and

Table 1. Mean (($\bar{x} \pm SEM$, $n = 3$) starch content, amylose, amylose/amylopectin ratio and starch gel mechanical strength.

		Percentage content mean ± *SEM*			
Clone set	Cultivar	Starch	Amylose	Amy/Amyl	Mechancal strength
Musakala	Kisansa	94.80 ± 0.100^{a}	13.64 ± 0.057^{a}	0.16 ± 0.001^{a}	3.30 ± 0.007^{i}
	Muzuba	96.89 ± 0.037^{b}	13.75 ± 0.036^{b}	0.16 ± 0.001^{a}	3.36 ± 0.052^{i}
Nakabululu	Nakabululu	94.82 ± 0.086^{c}	16.501 ± 0.058^{c}	0.19 ± 0.001^{b}	2.37 ± 0.005^{f}
	Butobe	96.21 ± 0.015^{d}	15.7 ± 0.058^{d}	0.19 ± 0.001^{b}	3.14 ± 0.095^{h}
Nakitembe	Kibuzi	97.11 ± 0.006^{e}	12.44 ± 0.042^{e}	0.14 ± 0.001^{c}	2.36 ± 0.101^{f}
	Entaragaza	97.72 ± 0.015^{f}	15.24 ± 0.030^{f}	0.18 ± 0.001^{d}	2.01 ± 0.300^{d}
Nfuuka	Nakinyika	91.32 ± 0.050^{g}	14.30 ± 0.000^{g}	0.17 ± 0.000^{e}	1.42 ± 0.009^{c}
	Siira	92.91 ± 0.030^{h}	14.45 ± 0.029^{h}	0.17 ± 0.000^{e}	3.79 ± 0.083^{j}
	Enjogabakazi	91.68 ± 0.00^{i}	14.43 ± 0.033^{i}	0.17 ± 0.000^{e}	5.38 ± 0.122^{k}
	Enzirabahima	90.22 ± 0.056^{j}	14.26 ± 0.032^{j}	0.17 ± 0.001^{e}	2.24 ± 0.057^{ef}
	Enzerabushera	91.40 ± 0.026^{k}	14.27 ± 0.081^{j}	0.17 ± 0.001^{e}	2.74 ± 0.019^{g}
Standards	Laundry starch (LaSt)	95.09 ± 0.046^{l}	16.18 ± 0.118^{k}	0.19 ± 0.003^{b}	2.08 ± 0.025^{de}
	Food starch (Potato) (FdSt)	90.49 ± 0.020^{m}	15.71 ± 0.032^{l}	0.19 ± 0.000^{b}	1.26 ± 0.479^{a}
	Pharmaceutical starch (PhSt)	95.34 ± 0.019^{n}	15.52 ± 0.023^{m}	0.18 ± 0.000^{d}	0.67 ± 0.009^{b}

Means with different letters in the same column are significantly different ($p < 0.05$) (Bonferroni test).

0.184 ± 0.000 for standard laundry starch (LaSt), standard food starch (FdSt) and standard pharmaceutical starch (PhSt). However, the Nakaululu and Butobe cultivars had amylose: amylopectin ratios that were not significantly different from those of laundry and food starch, respectively.

Mechanical strength

The mechanical strength of the starch gels significantly varied among the cultivars (Oneway ANOVA, $F = 1417$, $p < 0.001$), ranging from 1.42 N to 5.38 N (Figure 1). With the exceptional case of Enzirabahima, Entaragaza and Nakinyika, all the EAHCB cultivars studied had starches with mechanical strength that was significantly higher than that of all the standard starches (Bonferroni test, $p < 0.05$). Enjogabakazi exhibited the highest mechanical strength (5.38 N), followed by Siira (3.79 N). The lowest mechanical strength was recorded in the starch of the Nakinyika cultivar (1.42 N), which was close to but significantly higher than that of the food starch (FdSt) and much higher than that of pharmaceutical starches (PhSt) (Bonferroni test, $p < 0.05$), but significantly lower than that of the laundry starch (Bonferroni test, $p < 0.05$).

Solubility and swelling power

The solubility and swelling power of the 11 starch samples increased with increasing temperature, showing their maximums at 90 °C (Figures 2 and 3). The study also revealed a slow and gradual increase from 40 °C to 70 °C but then from 70 °C to 9 °C the increase in solubility and swelling power were drastic. The only exception to this was the solubilities and swelling powers of the *Musakala* cloneset, in which both *Kisansa* and *Mujuba* cultivars showed slow solubility until 80 °C then it increased suddenly to its maximum at 90 °C. The percentage solubilities and swelling powers of the individual cultivars at 90 °C differed significantly (Bonferroni test, $p < 0.05$) among some cultivars. Compared to the standard starches, the solubilities and swelling powers of the EAHCB starches in this study were significantly lower. The standards were approximately 1.5 times higher than those of the EAHCB starches.

Pasting properties

The pasting properties of the starch are listed in Table 2. The pasting properties varied significantly ($p < 0.05$) with the pasting temperature of the banana starches ranging from 73.9 ± 0.7 °C to 75.8 ± 0.4 °C, *Enzirabahima* having the lowest while *Enjogabakazi* displayed the highest. The values for all the cultivar starches varied significantly (Bonferroni test, $p < 0.05$) from those of the standard starches (FdSt, LaSt, and PhSt). The peak viscosities (PV) varied from 414.2 ± 1.8 RVU to 843.3 ± 4.1 RVUs, while the trough viscosities had a range from 287.5 ± 4.2 to 541.4 ± 3.5 RVUs. The highest Peak viscosity was presented by *Siira* while the lowest was *Enzirabusera*. Values such as pasting temperatures were significantly lower than those of the standard starches (Bonferroni test, $p < 0.05$). Moreover, this trend was the same for the setback, breakdown, and final viscosities. The study also revealed that the trough, breakdown, and final viscosities differed significantly among the cultivar starches and were generally significantly lower than those of standard starches. The only exception was observed in the breakdown viscosity of standard food starch (FdSt), which showed the lowest breakdown viscosity (101.7 RVU) among all starches in this study. We noted here that the final viscosities of the EAHCB cultivar starches were lower than the peak

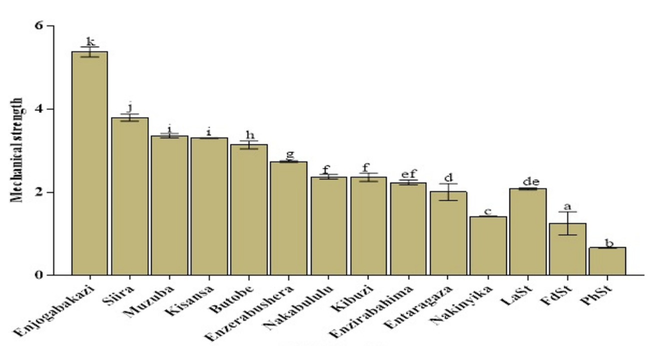

Figure 1. Mean mechanical strength ($\bar{x}$±*SEM*, $n = 3$) of starch gels for each cultivar and standard starches. LaSt; Laundry starch, FdSt; Food starch and PhSt; Pharmaceutical starch. Means for the bars with different letters of the alphabet are significantly different (Bonferroni test, $p < 0.05$).

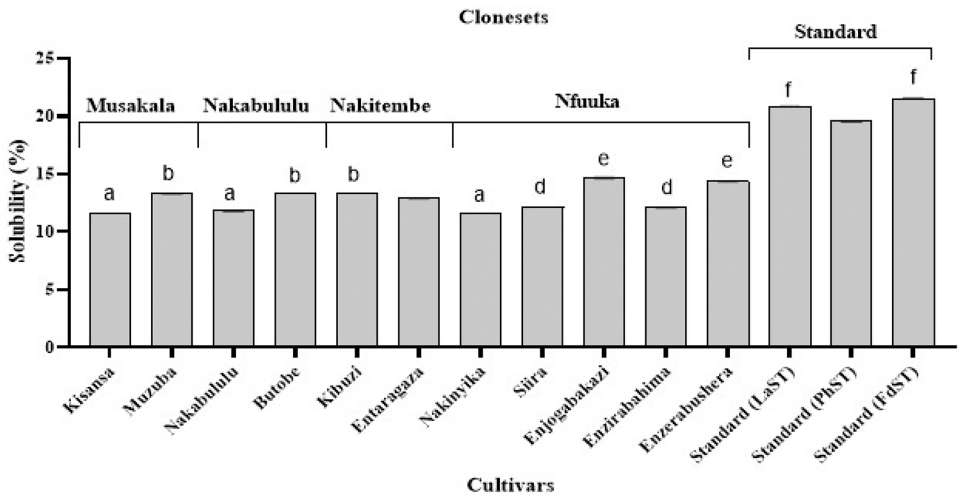

Figure 2. Starch Solubility variations for 1% db (w/w) starch dispersions of the eleven EAHCB cultivars at 90 °C. Values for each bar with same superscripts are not significantly different (Bonferroni test $p < 0.05$).

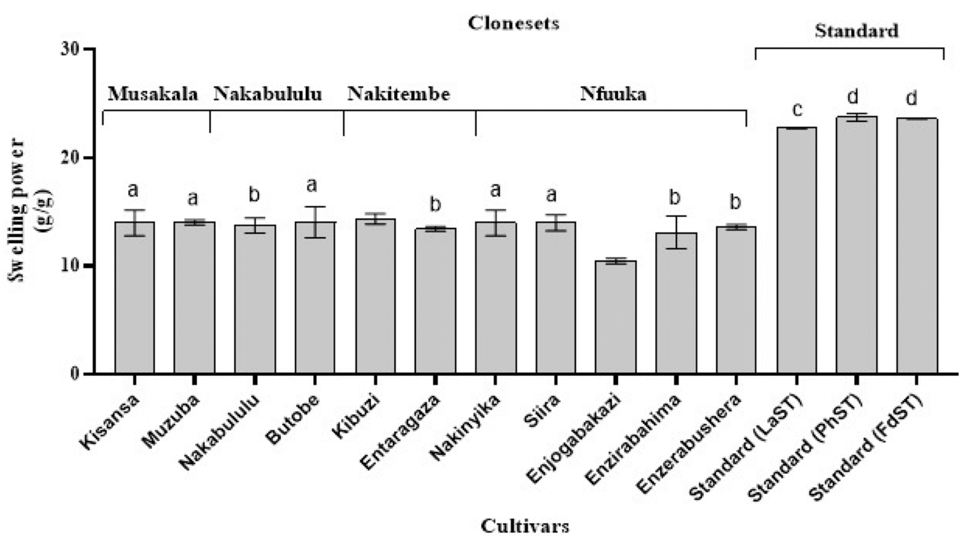

Figure 3. Swelling power variations of starch from eleven EAHCB cultivars of the eleven EAHCB cultivars and clones at 90 °C. Values at each bar with same superscripts are not significantly different (Bonferroni test $p < 0.05$).

Table 2. Mean (($\overline{x}$±*SEM*, $n = 3$) pasting properties for the eleven EAHCB cultivars.

	Pasting properties					
Cultivar	Peak	Trough	Break down	Final viscosity	Set back	Pasting Temp (°C)
Butobe	532.1 ± 8.5^{a}	402.9 ± 7.6^{a}	109.6 ± 1.7a	441.2 ± 7.4^{a}	61.2 ± 3.9^{a}	75.3 ± 1.9^{a}
Enjogabakazi	513.4 ± 0.7^{b}	335.6 ± 3.9^{b}	191.4 ± 2.7^{b}	354.5 ± 2.1^{b}	18.8 ± 1.9^{b}	75.8 ± 0.4^{b}
Entaragaza	638.4 ± 1.3^{c}	421.2 ± 2.4^{c}	213.9 ± 9.8^{c}	451.5 ± 3.6^{c}	35.0 ± 5.1^{c}	74.8 ± 0.2^{b}
Enzerabushera	414.2 ± 1.8^{d}	287.5 ± 4.2^{d}	123.3 ± 8.3^{d}	321.9 ± 5.7^{d}	36.0 ± 1.7^{c}	74.6 ± 0.0^{b}
Enzirabahima	568.7 ± 4.6^{e}	437.4 ± 9.5^{e}	154.5 ± 2.1^{f}	473.6 ± 1.7^{e}	78.2 ± 0.1^{d}	73.9 ± 0.7^{c}
Kibuzi	733.0 ± 1.2^{f}	341.5 ± 3.2^{f}	396.6 ± 3.7^{g}	366.8 ± 1.2^{b}	20.0 ± 1.8^{e}	74.4 ± 0.1^{c}
Kisansa	626.1 ± 7.6^{c}	355.3 ± 0.1^{g}	251.8 ± 2.8^{h}	392.6 ± 1.2^{e}	34.8 ± 8.4^{c}	75.3 ± 0.3^{a}
Muzuba	617.5 ± 1.5^{g}	441.9 ± 1.3^{e}	182.0 ± 6.7^{b}	460.4 ± 0.4^{c}	47.3 ± 5.8^{f}	75.0 ± 0.0^{d}
Nakabululu	725.1 ± 1.4^{h}	464.8 ± 0.3^{h}	260.3 ± 1.2^{h}	523.5 ± 2.3^{f}	58.7 ± 0.1^{g}	75.1 ± 0.0^{d}
Nakinyika	661.7 ± 8.5^{i}	541.4 ± 3.5^{i}	113.5 ± 1.4i	562.3 ± 2.5^{g}	24.9 ± 1.0^{h}	74.9 ± 0.3^{d}
Siira	843.25 ± 4.1^{j}	422.92 ± 0.9^{e}	420.34 ± 9.7^{j}	436.17 ± 25.9^{h}	20.5 ± 0.5^{e}	74.1 ± 0.2^{c}
FdST (potato)	848.0 ± 2.9^{j}	746.3 ± 3.2^{j}	101.7 ± 0.3^{k}	847.7 ± 9.1^{i}	99.3 ± 5.5^{i}	90.9 ± 0.6^{e}
LaSt	2782.3 ± 33.0^{i}	1205.3 ± 5.4^{l}	1556.3 ± 39.2^{k}	3397.0 ± 50.1^{k}	2153.0 ± 41.4^{k}	78.3 ± 0.0^{g}
PhSt	2510.7 ± 10.5^{h}	1177.3 ± 34.7^{k}	1392.7 ± 20.0^{l}	2747.7 ± 9.6^{j}	1563.3 ± 40.3^{j}	80.0 ± 0.0^{f}

Values in the same column with different superscripts are significantly different (Bonferroni test, $p < 0.05$).

viscosities, while the final viscosities of all the standard starches were higher than the peak viscosities.

Starch granule shape and particle size

The morphological features of the EAHCB starch granules captured by scanning electron microscopy (SEM) are shown in Figure 4. The particles have different sizes and shapes, with a mix of round, oval, ellipsoid, and elongated shapes. Standard starches had significantly smaller particles and similar shapes. The particle sizes are presented in Table 3. It ranged from 14.181 ± 0.01 µm to 21.163 ± 0.24 µm. Siira and Kibuzi had the smallest and largest particle sizes, respectively. These granules were significantly larger than those of the standard starches (Bonferroni test, $p < 0.05$).

Crystalline structure

The banana starch XRD curves for EAHCB in this study showed three strong peaks around 15, 17 and 23 2θ (Figure 5). The study revealed variation in the percentage crystallinities of the banana starches,

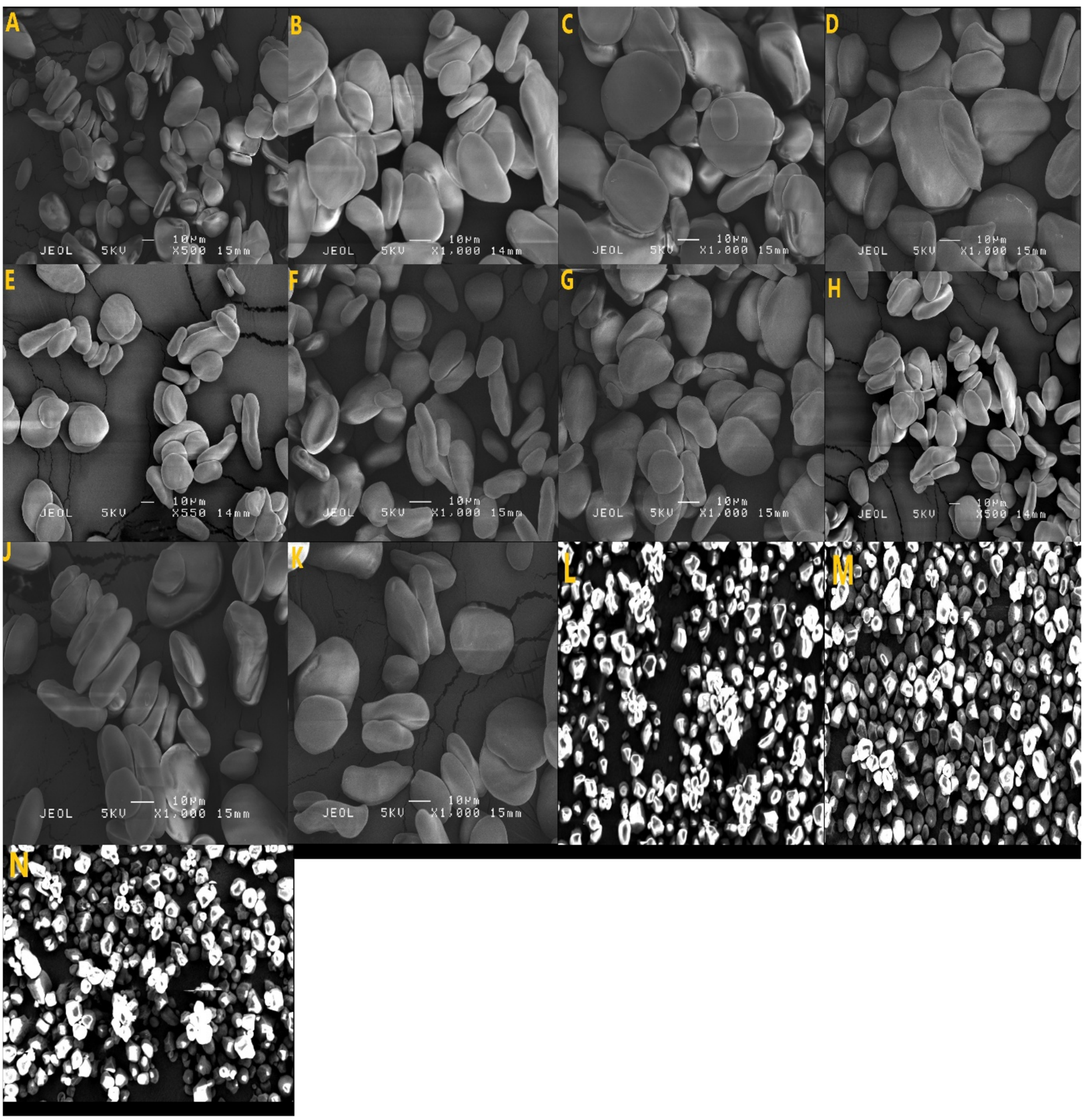

Figure 4. SEM micrographs showing Morphology of starch granules of: A-Kisanasa, B-Muzuba, C-Nakabululu, D-Butobe, E-Kibuzi, F-Entaragaza, G-Nakinyika, H-Siira, I-Enjogabakazi, J-Enzirabahima, K-Enziraushera, L-LaSt, M-FdSt, N-PhSt.

with the highest peak values recorded for *Enjogabakazi* at 31.08° and the lowest for *Kisansa* at 30.39° (Table 3). These values were higher than the crystallinity values of standard food starch (FdSt) and standard laundry starch (LaSt) (19.22 and 24.7%, respectively). However, they were close to that of standard pharmaceutical starch (PhSt) (32.8%), which was the highest in this study. Standard food starch, Standard Laundry starch, and standard pharmaceutical starch XRD curves all showed three strong peaks around 15, 20, and 23 2θ and an unresolved doublet at 17 and 18 2θ (Figure 6).

Principle component analysis

The starches adopted for the study were widely separated on the PC1 axis, with all the EAHCB starches distributed to the negative terminal of the axis with FdSt (Figure 7). Laundry and pharmaceutical standard starches were distributed to the positive terminal. Along the PC2 Siira, Kibuzi, Kisansa Enjogabakazi and Entaragaza were distributed along the positive terminal while Enzirabushera, Muzuba, Enzirabaima, Butobe, Nakinyika and Nakabululu were distributed along the negative terminal with the FdSt. The study revealed a dissimilarity between standard starches and EAHCB starches.

Table 3. Mean (($\bar{x}$±*SEM*, $n=3$) particle sizes for the eleven EAHCB cultivars starch granules and their corresponding crystallinity percentages.

Cloneset	Cultivar	Particle size (μm)	Percentage crystallinity
Musakala	Kisansa	19.41 ± 0.01^{a}	30.39.93
	Muzuba	20.6388 ± 0.01^{b}	31.03
Nakitembe	Kibuzi	21.163 ± 0.24^{b}	30.92
	Entaragaza	16.08 ± 0.01^{c}	30.83
Nakabululu	Nakabululu	15.84 ± 0.04^{c}	31.06
	Butobe	17.2944 ± 0.01^{d}	30.86
Nfuuka	Nakinyika	18.491 ± 0.01^{e}	30.89
	Siira	14.181 ± 0.01^{f}	30.85
	Enjogabakazi	14.93 ± 0.02^{g}	31.08
	Enzirabahima	17.7833 ± 0.01^{h}	30.90
	Enzerabushera	15.334 ± 0.03^{i}	31.06
Standard starches	Standard (FdSt)	$8.92 \pm 0.01 \pm 0.02^{j}$	24.70
	Standard (PhSt)	$9.13 \pm 0.02 \pm 0.01^{k}$	32.80
	Standard (LaSt)	$9.86 \pm 04 \pm 0.04^{i}$	19.22

Values in the column for particle size with different superscripts are significantly different (Bonferroni test, $p < 0.05$). FdSt, standard food starch; PhSt; Standard pharmaceutical starch; LaSt; Standard Laundry starch.

Discussion

Starch content

The study revealed that the EAHCB cultivars under study had an average of 94.1% total starch on dry basis. This is very close to the content of 81–90%, that was reported by Marta et al. (2019), and 81.71–91.69% reported by Yang et al. (2022) for 5 EAHCB clones in Tanzania, and 99.4–99.6% reported by Ssonko and Muranga (2017) for another 5 EAHCB clones in in Uganda. The starch content was relatively higher than 73.9 and 76.4% reported by Soares et al. (2011) for two cooking banana varieties from South America. The values in this study were higher than those reported by Yang et al. (2022) probably due to differences in geographical location, altitude, and other factors associated with plant growth.

Evidence from this study showed that the starch content on dry basis of EAHCB was higher than that of other crops commonly used as sources of industrial starch. The starch content range of the cultivars studied (90 to 97%) was higher than that of 72 to 73% for maize (Zhang et al., 2021), 20 to 32% for

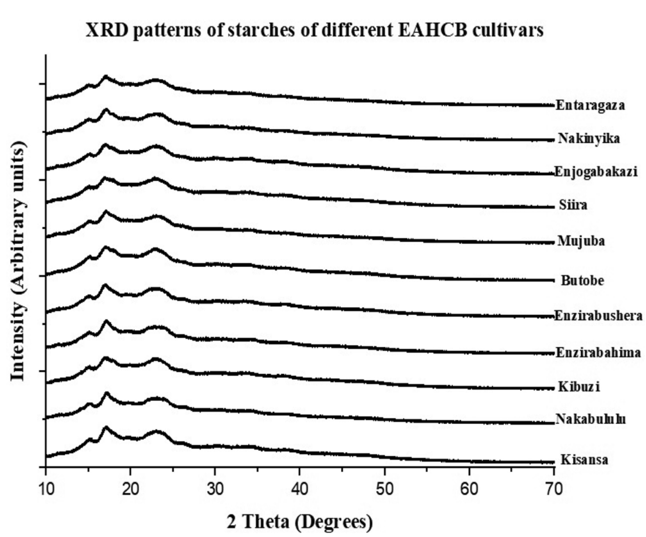

Figure 5. X-ray diffraction patterns of the different starches from the 11 cultivars.

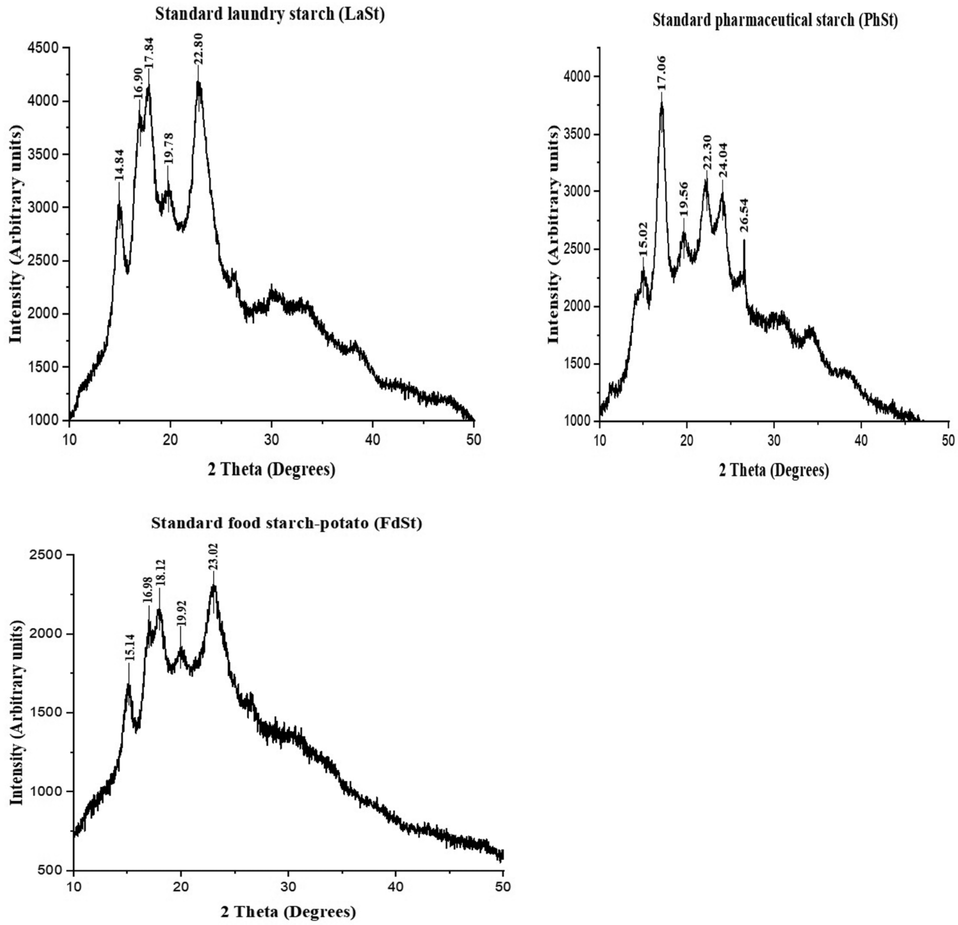

Figure 6. X-ray diffraction patterns of the Standard starches.

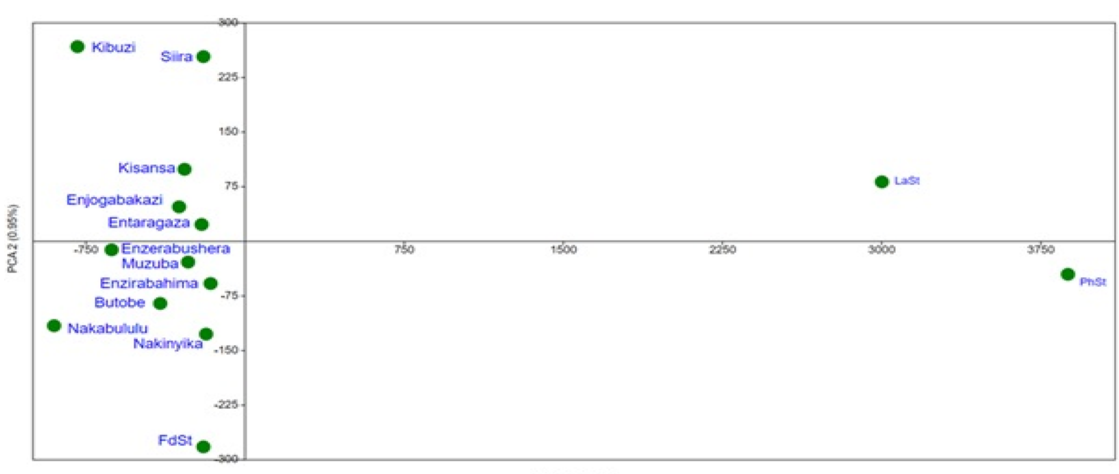

Figure 7. Biplot of the principal component analysis PC1 Vs PC2 describing the scores and variation in the starch homopolysaccaride content, functional, physical chemical properties and amorphous and crystalline structural properties of the EAHCB cultivar and starch standards. FdSt = Food standard starch, LaSt = Laundry standard starch and PhSt = Phamaceutical standard starch.

cassava (Surtono et al., 2019) and 43.5% for potato (Takamine et al., 2019) and 80 to 90% for rice (Alhambra et al., 2019; Romano et al., 2016). This suggests the suitability of EAHCB for sourcing starch for industrial applications as a result of this comparison to common industrial botanical sources.

Amylose and amylose: Amylopectin ratio

The starches of EAHCB were characterized by low amylose content as compared to the contents reported in other studies by de Barros Mesquita et al. (2016), Khawas and Deka (2017) and Syukriani et al. (2021) where the amylose contents were high, averaging at 20% and above. However, the amylose content of these EAHCB cultivars under study was relatively higher than that of EAHCB starches from the same region that were studied by Ssonko and Muranga (2017) but much lower than starches extracted from EAHCB varieties from Tanzania that were studied by Yang et al. (2022). Most of our values are in the range of 11–13% that were reported (Nowankunda, 2018) hence low amylose starches. Another study by Kajubi et al. (2024) who studied some native EAHCB varieties showed similar amylose content for example Nfuuka (14%), Nakitembe (13.9%) and Kibuzi (10%) The difference between the amylose content in this study and the other EAHCB cultivars studied previously may be due to variations in growth conditions and state of maturity at harvest (Li et al., 2022; Thanyapanich et al., 2021). We attribute the differences in the amylose and amylopectin content between cultivars in this study and those from other continents to differences in geographical location, altitude, soil conditions, and other factors associated with growth conditions as reported by Marta et al. (2022) which influence the homopolymers' content in banana fruits. With the exception of Nakabululu, all the standard starches had a higher amylopectin content than EAHCB. This can be partly explained by the fact that standard starches have different botanical origins (Haq et al., 2020; LeCorre et al., 2011).

We observed amylose contents and amylose:amylopectin ratios for Nakabululu, Butobe (Nakabululu clone set), and Entaragaza (Nakitembe Cloneset) comparable to those of the standard starches. This could suggest that their applications may be similar to or comparable to those of the standard starches. Because amylose has a high ability to form a gel during cooking, EAHCB, like other common starches, can be used as a source of a gelling agent and stabilizing agent in baby foods and cosmetic products and stabilizing emulsions to avoid phase separation (Thanyapanich et al., 2021) because of its thickening property. However, varieties whose amylose content is lower than that of the standards could perform the same applications after modifications that increase their amylose content.

Amylopectin content was higher than the amylose content in all 11 varieties (clones), which is in agreement with other studies (de Barros Mesquita et al., 2016; Ssonko & Muranga, 2017; Yang et al., 2022). The high amylopectin content of the starches in this study explains the observation that while this banana starch has a low amylose content, it possibility to form a high content of type II resistant starch. This is because of the formation of shorter amylopectin chains on cooking, resulting in apparent amylose. This apparent amylose contributes to the formation of resistant starch content, which is higher than that in other higher amylose-containing plants, such as wheat and corn (Chung et al., 2011; Jiang et al., 2015). The resistant starch of EAHCB has the potential to be used as an additive in foods as a probiotic to improve gut microbial flora, which improves digestion through production of short chain fatty acids (SCFA) and thereby managing blood cholesterol and glycemic index (GI) levels. This starch thus, has the potential to be used primarily in the production of foods, resulting in the natural control of conditions such as diabetes and obesity, and provides protection from conditions such as colon cancer, diverticulitis, and hemorrhoids (Raigond et al., 2018; Yang et al., 2017).

Granular shape and particle size

The granular structure of the starch particles revealed differences in size and shape, with irregular diameters dominated by elongated (rod) granules. All particles, regardless of cultivar type, were flat. This is in agreement with the earlier findings of de Barros Mesquita et al. (2016) who worked on banana varieties from Brazil. The observed differences in the particle shapes of the starches from different banana cultivars and standard starches could be due to differences in genetics and growing conditions (Yang et al., 2022). The particle sizes ranged from 14.181 ± 0.01 µm the smallest to 21.16 ± 0.24 µm. Other studies on EAHCB had average granule sizes ranging from 19.67 to 30.66 µm (Muranga, 1998), 16.31 to 21.98 µm (Ssonko & Muranga, 2017) and 21.73 to 24.67 µm (Yang et al., 2022) all from East Africa. Varieties from the Ivory Coast have an average granule size range of 3.33 to 56.66 µm (Coulibaly et al., 2006). Studies of varieties from Asia have ranged from 18 to 59 µm (Hung et al., 2013; Marta et al., 2019) whereas a study of the variety from South America had a granular size range of 30 to 50 µm (Utrilla-Coello et al., 2014). Studies have shown that physical and environmental factors, such as tissue maturity, growth temperature, and nutrient availability, affect the number and size of granules

(Kim & Kim, 2021). This may explain the observed differences between the granules and sizes of the starches in this study and those from other studies.

The variation in the size of granules may be of industrial significance by providing an opportunity for EAHCB starches for wider application in its processing, as well as modification to achieve desired functional properties or attributes in the food or non-food industries. For example, in the food industry, one study showed that starch noodles made from small-sized granule fractions were better than those made from unfractionated starches, and were much better than those made from large granule fractions (Li et al., 2021). This starch could also function as a good fat substitute, which can significantly improve functional properties, such as freeze-thaw, heat, acid, and shear stability (Park et al., 2020). Another study indicated that these variations in particle size could be important in stabilizing emulsions (Pickering emulsions) (de Carvalho-Guimarães et al., 2022). In other non-food applications, such as in the plastic industry, the size of starch granules can affect the properties of biodegradable starch-derived plastics. Starch is also used as a biodegradable filler (Li et al., 2021) which applications this starch could be exploited.

Crystallinity

All the EAHCB banana starches showed a B-type crystalline structure characterized by the presence of three strong peaks at 15° and 17° and a broad peak at about 23° 2θ. However, there were no peaks detected at 5.58° and 26.35°. These peaks were similar to the peaks reported for banana starch by Sharma et al. (2023), Waliszewski et al. (2003) and Marta et al. (2019). The percentage crystallinity of the EAHCB starches in this study was within the range of 14–45% reported by Dome et al. (2020) which is characteristic of native starches. Starch crystallinity is due to parallel packing of amylopectin double helices in a unit cell. Both amylose and amylopectin content and the variation between these diverse kinds of starch granules in the banana starches in this study are important factors that affect the degree of starch crystallinity (Cornejo-Ramírez et al., 2018; Zhang & Hamaker, 2012). Amylopectin molecules with longer chains, high molecular weight, and a lower degree of branching form a more stable crystalline structure. Previous studies have shown that banana starches contain a high proportion of long-chain amylopectin (Zhang & Hamaker, 2012). Thus, the observed higher crystallinities of EAHCB starches compared to those of standard starches suggest that they have a long-chain amylopectin composition. Zhang and Hamaker (2012) further observed that a higher proportion of long chains of banana amylopectin allows for greater retrogradation upon cooling after cooking, which renders them less susceptible to enzymatic degradation and, hence, resistant banana starch. EAHCB is therefore a good source for high-value starch, which is a combination of slowly digestible starch (SDS) and resistant starch (RS), compared with potato or corn starch for the food industry. These starches can also be used to increase the biodegradability of the commodity plastic polymer polystyrene, which has a low biodegradation rate. By adding starch, the polymer blend will have increased biodegradation rates (Muralisrinivasan, 2014). When compared to the XRD patterns of the standard starches, the standard starches showed sharp peaks at about 15°, 18° and 23° 2θ and additional smaller peaks at 17 and 19°2θ. Similar peaks were revealed in a study by Taguchi et al. (2023) on modified rice starch of type A crystallinity. This indirectly gives insight into these standard starches, as being modified.

While this study revealed that starches from all these cooking banana cultivars were of crystallinity type B, some previous studies have reported that native banana starch exhibited different types of crystalline structures like A-type and C-type (Marta et al., 2019; Pelissari et al., 2012),. Also, the crystallinity values of the starches in this study were much lower than those in other EAHCB cultivars in other studies (Muranga, 1998; Yang et al., 2022) but were generally found to be much higher than those in banana starches from other regions (Dome et al., 2020). This could be attributed to the differences in geographical location, altitude, and other factors associated with growth conditions (Marta et al., 2022; de Barros Mesquita et al., 2016).

Mechanical strength

The mechanical strength, measured as gel hardness, varied significantly between the cultivars. The Enjogaakazi cultivar showed the highest mechanical strength (5.33 N), whereas Nakinyika was the weakest (1.42 N). For all cultivars, mechanical strength is generally higher than the mechanical hardness of potato starch, but lower than that of corn starch (Fonseca-Florido et al., 2017). The variation in the mechanical strength can be explained in terms of the gelatinization and retrogradation of starch. Banana starch is composed of porous and semi crystalline granules packed with amylose and amylopectin. During gelatinization, water first enters the amorphous area and then diffuses into the crystalline regions, irreversibly disrupting the crystalline structure. Owing to particle swelling, amylose molecules leach out of the granules, thereby increasing the viscosity of the continuous phase of the starch suspension. After gelatinization, starch molecules rearrange, forming a rigid and stiff gel (Alvarez et al., 2015; Ji et al., 2022; Matignon & Tecante, 2017).

According to Domene-López et al. (2019), amylose content affects the mechanical behavior of starch, with higher amylose values correlated with greater gel hardness. The findings of the current study are not in agreement with later observations. For example, the Njogabakazi cultivar, which had the highest mechanical strength (5.38 N) had a lower amylose content than Nakabululu (2.37 N), which on the other hand had the highest amylose content. This contradiction in the mechanical properties of the starches may be due to the difference in the rheological properties of amylose matrix interactions between the dispersed and continuous phases of the gel, structure of amylopectin, and variations in the cultivars (Castanha et al., 2021). Generally, the weak texture exhibited by these starches could be due to the low amylose content (Biduski et al., 2018) in the banana starches in this study.

However, these starches have higher mechanical strength than standard starches. This could be due to the crystalline domains of the amylose in these starch molecules being embedded in the amorphous matrix compared to other starches. These domains can act as reinforcements to improve the mechanical properties of the film. Additionally, the molecular weight of starch has been reported to influence the mechanical strength, but this has not yet been investigated for banana starch (Domene-López et al., 2019). The higher mechanical strength of the EAHCB cultivars studied as compared to the standard starches suggests the potential for application in packaging and natural plastic industries as thermoplastic starch. This is a promising alternative to synthetic polymers in the packaging field because of their biodegradability, low cost, and abundant availability (Agarwal et al., 2023; Domene-López et al., 2019; Ogunsona et al., 2018).

Starch solubility and swelling power

The solubility of EAHCB starch solubility at 90 °C varied significantly from that of the standard starches and across the cultivars, although they did not differ much quantitatively. In general, starch granules are insoluble in water. They can only be hydrated at high temperatures in excess water, during which the hydrogen bonds holding the starch molecules are broken, which disrupts the crystalline structure of starch. The starch molecules then bind with water molecules through hydroxyl groups, resulting in swelling and dissolution of the starch granules and dissolving (Cornejo-Ramírez et al., 2018). The solubility indices of the EAHCB starches were comparable to those reported by Ssonko and Muranga (2017) but were much higher than those reported by Yang et al. (2022). The relatively high solubility and indeed also high swelling power of banana starches may be due to the lower amylose content, because amylose plays an important role in limiting the water absorption and expansion of starch (Khoozani et al., 2019). Additionally, banana starch granules with smooth and dense surfaces are a limiting factor for water infiltration into granules for starch hydration and leaching (Du et al., 2020; Yang et al., 2022). The ability of starch to dissolve is crucial for its applications (Compart et al., 2023). The solubility indices and swelling powers of the EAHCB starches in this study were significantly lower than those of the standard starches. This could limit their applications and thus calls for modification before industrial application.

The swelling powers of the starches in this study followed the same trend as solubility. It varied among the cultivars and was much lower than that of the standard starches. The capacity of starch granules to hydrate and swell depends on the capacity of starch molecules to hold water via hydrogen bonding, which is influenced by the amylose content, lateral chains of amylopectin, and the size of the starch granules among others (Cornejo-Ramírez et al., 2018). Generally, we observed that the higher the relative solubility and swelling power (Figures 2 and 3), the smaller was the particle size (Table 3). This is in agreement with the findings of Cornejo-Ramírez et al. (2018) who reported that small granules have a high capacity to hydrate and swell because the amylose content in small granules is low and their small size allows them to pack closely with more starch granules in the same unit weight than the larger ones (Cornejo-Ramírez et al., 2018). Between the cultivars, the difference in swelling power could be due to the change in strength of the bonding forces within the starch granules (Kumar & Khatkar, 2017) which could be attributed to differences in genetic factors. However, the low swelling powers of these starches compared to the standards are another limiting factor to their applicability (Compart et al., 2023) hence, there is a need for modification.

Pasting properties

The pasting properties of EAHCB starch differed significantly among the cultivars' and standard starches. These properties in the EAHCB starches are generally lower than those of standard starches and starches of bananas from other African regions (Nwakego et al., 2022; Yang et al., 2022) and Asia (Marta et al., 2019). The pasting parameter variations are completely dependent on amylose content, leaching of amylose molecules, and swelling of granules (Reddy et al., 2015; Yadav et al., 2016; Yang et al., 2022). The study revealed that the final viscosities of the EAHCB cultivar starches were lower than the peak viscosities, while for all the standard starches; their final viscosities were higher than the peak viscosities. These findings are similar to those of native maize and potato starches (Heo et al., 2017; Marta et al., 2022). The pasting temperature showed less significant differences between cultivars. This is in agreement with the results of previous studies (Ssonko & Muranga, 2017; Yang et al., 2022). At pasting temperatures, viscosity begins to increase during the heating process. A high pasting temperature of starch indicates a higher resistance to swelling and rupture (Kumar & Khatkar, 2017; Reddy et al., 2015). The observed differences in starch setback viscosities may be attributed to the differences in amylose content of the different EAHCB varieties. Their generally low setback indicates low gel strength, which could be due to short amylose chain length as a result of amylolysis, which limits hydrogen bonding, leading to the formation of weak gels (Alqah et al., 2020).

All cultivars in this study showed low breakdown viscosity values, which suggested that they possessed strong resistance to shear force and heat. Likewise, the setback values of all cultivars were low and significantly lower than those of the standard starches, indicating their favorable cold paste stability and low tendency of retrogradation. Therefore, these starches can be used in their native form in industrial applications that require harsh processing conditions, such as in the food industry (Heo et al., 2017). Thus, they are suitable for making elastic foods. In addition, these starches showed better properties that are comparable to those of slightly cross-linked starch, such as low pasting temperature and low breakdown viscosities, and hence higher thermal stability (Marta et al., 2022). Thus, they have the potential to be used in various applications that require stable viscosity to reduce and replace the use of chemically cross-linked starches (Kaur et al., 2020; Yang et al., 2022). With its high viscosity at 95^{0}C, that the banana starch paste could be used as a potential functional thickener in the food and paint industries.

Principle component analysis

PCA analysis based on the starch properties under study revealed a wider separation from the standard starches, especially LaSt and PhSt. This wide separation could be attributed to modifications of standard industrial starches, which affects their initial native properties.

Therefore, this study revealed that while EAHCB starches have great potential for industrial applications in their native form, their industrial applications are limited. Thus, for full industrial potential, a degree of modification is required. We recognized EAHCB starches with specific properties in the ranges of standard starches, such as the amylose content of Nakabululu, Butobe, and Entaragaza cultivars. Therefore, such cultivars could be exploited for breeding EAHCB cultivars that can produce starches for industrial applications to minimize the cost of modifications. Unraveling the genetic control of starch biosynthesis in EAHCB of specific cultivars could pave the way for the genetic breeding of cultivars that yield starches that can be utilized in their native form in industrial applications, thus eliminating the cost of modification.

Conclusion

Starches from EAHCB cultivars show unique properties like high starch content, B-type crystallinity, favorable pasting behavior, and strong mechanical strength therefore offering a great industrial potential. However, low solubility, swelling power, and amylose content limit their direct use, indicating the need for modification before specific applications. Some cultivars however, such as Nakabululu, Butobe, and Entaragaza, displayed properties similar to standard commercial starches, making them ideal for breeding and targeted industrial use. Fully utilizing EAHCB starch potential requires both selective breeding and modification, with genetic improvement being a promising approach to reduce processing costs and broaden application in food, packaging, and bio-based industries. Understanding the genetic control of starch biosynthesis in these cultivars will support the development of varieties capable of producing starch suitable for industrial use in its native form, eliminating the need for extensive modification.

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P. A. and F.I.M. conceived the research idea, participated in designing the study, searching and reviewing the research articles, carrying out all the experiments, data analysis. J.E.S., A.N.M., and C.N. participated in searching and reviewing the appropriate research articles, designing the study, data analysis, and drafting of the manuscript. J.B.K. approved access to use of the SEM facilities in MAPRONANO ACE and interpreted SEM micrographs and X-ray crystallinity data. All authors read and approved the final manuscript.

Ethical statement

This study was based on plants samples (The cooking banana) which commonly is cultivated for food locally, The study did not require any ethical approvals and clearance since there were no interviews of local farmers involved or use of banana material from local farms and therefore no breach of ethical guidelines. Access and use of the banana germplasm was granted by the Banana Industrial Research and Development Center (BIRDC/PIBID) who own the germplasm and own this work.

Author contributions

CRediT: **Paul Akuyenze**: Formal analysis, Investigation, Methodology, Software, Writing – original draft; **Florence I. Muranga**: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision; **Jamilu E. Ssenku**: Data curation, Formal analysis, Resources, Supervision, Writing – original draft, Writing – review & editing; **Agnes Nandutu Masawi**: Resources, Supervision, Writing – review & editing; **Clement Nyakoojo**: Resources, Supervision, Writing – review & editing; **John Baptist Kirabira**: Formal analysis, Investigation, Supervision, Visualization, Writing – review & editing.

Disclosure Statement

The authors hereby declare that all authors of this manuscript have no conflicts of interest pertaining to this study.

Data availability

Datasets generated and analyzed during this study are available from the corresponding author on request.

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