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Bioactive compounds and antioxidant activities in peeled and unpeeled sweetpotato roots of different varieties and clones in Uganda

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ABSTRACT

Rising incidences of non-communicable diseases (NCDs) in Sub-Saharan Africa (SSA) necessitates research into local functional foods, crucial in managing these conditions. This study aimed to investigate compositional changes in the bioactive compounds and antioxidant activities of peeled and unpeeled roots of Ugandan sweetpotato varieties with different flesh colours using spectrophotometric methods. Bioactive compounds and antioxidant activities, on dry weight basis were significantly higher ($P<0.05$) in unpeeled than peeled roots. Phenolic compounds were significantly higher ($P = 0.001$) in white, cream, and purple-fleshed roots (59.67–121.04 mg GAE/g) than in yellow and orange-fleshed roots (0.89–10.89 mg GAE/g). The deep orange-fleshed had the highest total carotenoids (averagely 269.82 μg/g) and the white the lowest (averagely 8.36 μg/g). Total alkaloids in the sweetpotato roots ranged between 24.05 and 233.70 μg CE/g, below the potential toxicity range of 3–10 mg/g. The anthocyanin content of purple-fleshed roots was significantly higher (15.29 mg/g; $P<0.001$) than the other varieties, which ranged between 0.86 and 2.44 mg/g. Principal component analysis showed a stronger relationship between phenolics, anthocyanins, tannins, and ABTS radical scavenging antioxidant activity. Vitamin C and total carotenoids were more correlated with FRAP antioxidant activity. Consumption of different sweetpotato varieties with the peels could aid in managing NCDs in SSA.

1. Introduction

Functional foods have gained attention recently as sustainable food-based approaches for alleviating the global incidences of non-communicable diseases (NCDs). Urbanisation in the developing world has contributed to increased risks of NCDs such as metabolic syndrome and Type 2 diabetes mellitus (T2DM), cardiovascular diseases and stroke, and cancers due to poor dietary habits and sedentary lifestyles (Islam et al., 2014). A recent report from the World Health Organisation (WHO) indicated that NCDs were disproportionately higher in low- and middle-income countries, where over 85% of global premature deaths due to NCDs occurred (WHO, 2021). Further, it has been projected that by the year 2030, NCDs will overtake communicable diseases, maternal and neonatal illnesses, and malnutrition, put together as the leading cause of mortality in Sub-Saharan Africa (SSA) (Bigna and Noubiap, 2019). Since unhealthy diets are one of the modifiable risk factors contributing to NCDs (Galanakis, 2017), dietary changes such as regular consumption of diverse functional foods could contribute to the gradual decline of these statistics. In Uganda for example, the adult population (20–79 yr) with T2DM was projected to rise by as much as 166.9% within the period 2013 to 2035, with a mean annual increment of 47,000 cases (Guariguata et al., 2014). This situation is a public health concern and deserves attention.

Sweetpotato (*Ipomoea batatas* (L.) Lam, Convolvulaceae) is one of the cheap, desirable, readily available, and easy to cultivate crops that could serve as a functional food in SSA (Amagloh et al., 2021). In developing countries, sweetpotato is the fifth most popular staple after rice, wheat, maize, and cassava (Mohanraj, 2018). In Uganda, sweetpotato is the fourth most widely-consumed staple, cultivated by about 44% of farmers, with an annual production of 1.5 million metric tonnes as of 2018 (UBOS, 2020). Sweetpotato is a climate-smart crop as it is widely adapted to most ecologies, is drought-tolerant once established, and has a short maturity period of three to five months (Motsa et al., 2015). In addition, its production could be staggered, thus, ensuring availability

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all year round (Motsa et al., 2015). Therefore, sweetpotato can improve food and nutrition security, especially in the developing world where droughts could affect other staple foods such as cereals and long duration root crops like cassava and yam (Hotz et al., 2012).

In addition to sweetpotato serving as a source of macronutrients (starch, dietary fibre, and protein) and micronutrients (manganese, copper, potassium, iron, vitamin B complex, vitamin C, vitamin E, and provitamin A), it can also be regarded as a functional food because it provides other physiological benefits (Mohanraj and Sivasankar, 2014). The roots have substantial bioactive compounds, primarily phytochemicals, including phenolic compounds, flavonoids, carotenoids, anthocyanins, saponins, tannins, alkaloids, terpenoids, and tocopherols (de Albuquerque et al., 2019; Mohanraj, 2018). These bioactive phytochemicals potentially act as antioxidants to mitigate the effects of reactive oxygen species, hence inhibiting cellular damage and ultimately reducing metabolic oxidative stress (Mohanraj, 2018). This action imparts potential anti-inflammatory, antidiabetic, cardioprotective, neuroprotective, and bowel regulation properties to sweetpotato consumers (Panda and Sonkamble, 2012).

Sweetpotato research in SSA has drawn attention to its importance as a food security crop for improving nutrition in low-income groups. Biofortified varieties such as the orange-fleshed sweetpotato (OFSP) have been endorsed to reduce vitamin A deficiency, hence the focus of breeding programmes in SSA countries like Uganda, Kenya, Malawi, Mozambique, Ethiopia, Ghana, and Nigeria (Low et al., 2017). However, due to the appreciable amounts of bioactive compounds in sweetpotato, it is necessary for more investigations to be conducted in this regard and thus make recommendations regarding the varieties grown in SSA and their potential uses as a functional food. This could be of particular interest to urban dwellers, who are mainly at risk of NCDs such as T2DM due to their unhealthy diets and largely sedentary lifestyles (Alkhatib et al., 2017).

Both local and improved sweetpotato varieties cultivated in Uganda have distinctive agronomic traits such as leaf and stem morphology and storage root peel and flesh colours (Mwanga et al., 2016, 2011, 2009; Yada et al., 2010). The genetic and environmental factors responsible for expressing these varying traits have also been reported to influence the types and amounts of bioactive compounds present in sweetpotato (Kourouma et al., 2019). Furthermore, different concentrations of phytochemicals are present in the flesh versus the peel of sweetpotato roots (Ooi et al., 2021).

Research on the functional potential of sweetpotato varieties, especially in SSA are scanty and two previous studies that have been considered are not without limitations. Research involving Kenyan sweetpotato varieties used orange-fleshed, yellow-fleshed and white-fleshed roots and considered only peeled roots (Abong' et al., 2020). Another study using Nigerian sweetpotato varieties compared root flesh and peels of two varieties (white-skinned and purple-skinned; no mention was made of flesh colour) (Salawu et al., 2015). For the functional potential of sweetpotato in SSA to be well understood and appreciated, there is the need for studies to be conducted, expounding all the different aspects. Against this backdrop, this study aimed to profile the inherent phytochemicals and antioxidant activities of storage roots of different sweetpotato varieties grown in Uganda and the effect of peeling on these parameters.

2. Materials and methods

2.1. Sweetpotato sampling and experimental design

The six (6) varieties of sweetpotato used for the study were: a local farmer variety, 'Ssetyabule' (white-fleshed), and five (5) other improved varieties from the National Crops Resources Research Institute (NaCRRI), Namulonge, Uganda. These were NASPOT 11 (cream-fleshed), NAROSPOT 1 (pale yellow-fleshed), NASPOT 8 (pale orange-fleshed), NASPOT 13 O (deep orange-fleshed) (Mwanga et al., 2016, 2011, 2009), and PF-167 (deep purple-fleshed advanced yield trial clone). All varieties were planted in an experimental field in NaCRRI and harvested 4–5 months after planting. Each variety was harvested separately on three occasions to generate three independent samples (biological replications) for all analytical procedures.

Table 1
Experimental design used for this study.

Independent variables		Dependent variables
Factors	Levels	
Peel condition	With peel Without peel	total phenolic compounds, total flavonoids content, total carotenoids content, vitamin C content, total alkaloids content, total saponins content, total tannins content, total anthocyanins content, antioxidant activity.
Sweetpotato variety	'Ssetyabule' NASPOT 11 NAROSPOT 1 NASPOT 8 NASPOT 13 O PF-167	

At least, 20 damage-free roots of different sizes were randomly selected for analytical sample preparation from each variety. Roots were washed under running tap water to remove soil and other extraneous material, air-dried and stored at room temperature in a well-ventilated room for three (3) days before processing. The experimental design used for this study was a 2 × 6 factorial design as presented in Table 1.

2.2. Sample preparation

Before processing, sweetpotato roots were again washed under running water, while being brushed with a soft-bristled brush to remove any remaining soil. Roots were then cut off at both ends, about 1 cm each. Each root was cut into two longitudinal halves, one half used for the peeled treatment and the other for the unpeeled treatment. One part of the halved root was peeled with a kitchen knife to remove the peel entirely for peeled treatment. The cut roots were then sliced, 1.5 mm thick, with a mechanical slicer and immediately frozen at −18 to −20 °C for at least a week. Frozen samples were lyophilised for 72 h at −35 to −40 °C; afterwards, the dried roots were finely ground with an electric mill (Model No. 6XH63BA, Dayton Electric Mfg. Co., USA) to pass a 420 μm aperture sieve, packaged in polyethene bags, and stored at −18 to −20 °C until required for laboratory analysis.

2.3. Sample extraction

To 5 g of sweetpotato root flour was added 20 ml of 80% freshly prepared acetone. The suspension was homogenised for 1 min with a vortex mixer (Labnet International Inc., USA) and then for 1 h on an orbital shaker (Heidolph UNIMAX 1010 DT, Germany). Samples were centrifuged (HERMLE Benchmark Centrifuge, Z 326 K, Germany) at 4400 x g at 4 °C for 10 min. The clear supernatant was used as an extract to analyse total phenolic compounds, total flavonoids content, total tannins content, total alkaloids content, and antioxidant activity.

2.4. Analysis of bioactive compounds and antioxidant activities

The total phenolic compounds content was determined by the Folin-Ciocalteu colourimetric assay, as described by Singleton et al. (1999). This was modified slightly by incubating the reaction mixture at 40 °C for 30 min instead of allowing it to stand at room temperature for 2 h. The total phenolic compounds content was expressed with reference to a gallic acid standard calibration curve (10–100 μg/ml) as mg of gallic acid equivalent (GAE)/g.

The total flavonoids content was measured by the aluminium chloride colourimetric assay (Bouayed et al., 2011) and expressed with reference to a quercetin standard calibration curve (5–200 μg/ml) as mg of quercetin equivalent (QE)/g.

For total tannins content, the Harborne (1998) method was used and the total tannins content was expressed with reference to a tannic acid standard calibration curve (10–100 μg/ml) as mg of tannic acid equivalent (TA)/g.

The total alkaloids content was determined by the method of Fazel et al. (2010) with slight modification. The extraction was with acetone rather than methanol, and expressed with reference to a catechin standard calibration curve (10–100 μg/ml) as μg of catechin equivalent (CE)/g.

The antioxidant activity was determined by two methods: the reducing antioxidant capacity that was assessed by the Ferricyanide Reducing Antioxidant Potential (FRAP) (Oualcadi et al., 2020), and the free radical scavenging activity that was assessed by the 2,2′-azino-bis (3-ethylbenzthiazoline-6-sulphonic acid) (ABTS) assay (Teow et al., 2007). Both FRAP and ABTS were expressed with reference to an ascorbic acid standard calibration curve (5–50 μg/ml) as μg ascorbic acid equivalent (AAE)/g.

For total carotenoids content, the extraction was done by adding 15 ml of 80% acetone to 1 g of sweetpotato flour and homogenised for 3 h on an orbital shaker. The Ooi et al. (2021) method was then followed, the total carotenoids was calculated and expressed in $\mu g/g$.

The total monomeric anthocyanin content was determined using the pH-differential method (Giusti and Wrolstad, 2001), calculated based on cyanidin-3-glucoside equivalents and concentrations expressed in mg/g.

Vitamin C content was evaluated by the method of Khan et al. (2006) and content was expressed with reference to an ascorbic acid standard calibration curve (5–50 μg/ml) as μg AAE/g.

The vanillin-sulphuric acid method (Le et al., 2018) was used to measure total saponins content by extracting 1 g sweetpotato flour with 4 ml 80% ethanol. This was expressed with reference to an aescin standard calibration curve (0.95–15 mg/ml) as mg of aescin equivalent (AE)/g

2.5. Colour measurement

The colour of the sweetpotato root flour was measured with a Minolta CR-400 Chroma meter (Konica Minolta Inc., Japan) using the CIE L*a*b* system of colour measurement. The L* coordinate estimates the relative degree of luminosity, where 0 is black and 100 is white; a* takes positive values for reddish colours and negative values for greenish colours; and b* takes positive values for yellowish colours and negative values for bluish colours. The results presented for each sample were computed from the average of nine (9) measurements.

2.6. Statistical analysis

A two-factor analysis of variance (ANOVA) was carried out using Agricolae Package in R Statistical Programme (version 4.1.0) to compare the individual effects of sweetpotato variety and peel condition, and the interaction effects on the individual bioactive compounds and antioxidant activities. The Fisher's LSD was carried out to compare differences between means when the ANOVA result was significant at $P<0.05$. In cases where the interaction effects were significant, those results have been presented instead of the main effects of variety and/or peel condition. All values were expressed as the means ± standard deviations (SD) of triplicate replications and reported on a dry weight basis. The correlation matrix was determined using Pearson's correlation coefficients (r) between each pair of variables. Principal component analysis (PCA) was carried out to determine the contribution of the individual response variables to the variation of the dataset and also to identify the interrelationships amongst the individual bioactive compounds and antioxidant activities.

3. Results and discussion

3.1. Bioactive compounds content

The total phenolics, flavonoids, carotenoids, vitamin C, alkaloids, saponins, and tannin contents of all the sweetpotato varieties in both peeled and unpeeled forms are presented in Table 2. Generally, all bioactive compounds were higher in unpeeled than peeled sweetpotato roots. Plants synthesise various secondary metabolites as a response to biotic and abiotic conditions such as pathogenic attacks and harmful UV rays (Crozier et al., 2006). This could account for the higher values of bioactive compounds in samples with peel. This observation ties with findings from other research that compared peels and flesh of sweetpotato roots (Ooi et al., 2021; Salawu et al., 2015).

Sweetpotato is generally peeled before cooking, or if cooked with the peel, it is usually discarded before consumption. However, these results highlight the benefits of maintaining the peel for consumption due to a higher bioactive compounds content. Further, instead of wasting sweetpotato peels by discarding them, valorisation options could be explored to enhance their value addition, such as food fortification, nutraceutical preparations, and improving the nutrition of animal feeds.

3.1.1. Total phenolic compounds and total flavonoids content

Phenolic acids, polyphenols and flavonoids are the major phenolic compounds found in sweetpotato (Meng et al., 2019). These compounds have been found to exert several physiological benefits when consumed, such as antioxidant, antimicrobial, and hypoglycaemic activities, thereby reducing the incidences of some chronic diseases (Hogervorst Cvejić et al., 2017). Sweetpotato roots differed significantly by variety and peel condition for phenolics ($P = 0.001$), and flavonoids ($P = 0.034$). Irrespective of the peel condition, phenolics in NAROSPOT

Table 2
Bioactive compounds content of sweetpotato storage roots as influenced by variety and peel condition.

Variety	Peel	TPC(mg GAE/g)	TFC(mg QE/g)	TCC(μg/g)	VC(μg AAE/g)	TAL(μg CE/g)	TSC(mg AE/g)	TTC(mg TA/g)
'Ssetyabule'	WP	121.04 ± 17.74^{a}	1.50 ± 0.03^{a}	9.42 ± 1.77^{f}	40.91 ± 10.98^{e}	233.7 ± 38.88^{a}	441.07 ± 88.46^{a}	4.06 ± 1.03^{a}
	WTP	59.67 ± 6.98^{c}	0.87 ± 0.06^{ef}	7.29 ± 0.55^{f}	30.40 ± 6.47^{e}	24.05 ± 2.42^{g}	200.96 ± 21.53^{bcd}	1.29 ± 0.23^{def}
NASPOT 11	WP	108.89 ± 19.56^{ab}	1.39 ± 0.37^{ab}	11.70 ± 1.47^{f}	166.98 ± 22.68^{a}	73.14 ± 11.27^{de}	116.29 ± 43.78^{de}	2.35 ± 0.82^{bc}
	WTP	73.31 ± 6.25^{c}	0.75 ± 0.09^{fg}	11.43 ± 2.38^{f}	113.13 ± 15.00^{bc}	36.65 ± 8.86^{efg}	77.07 ± 18.47^{e}	1.36 ± 1.08^{def}
NAROSPOT 1	WP	10.89 ± 0.86^{d}	1.13 ± 0.13^{cd}	91.65 ± 3.58^{e}	124.13 ± 13.62^{b}	40.16 ± 4.39^{efg}	156.96 ± 13.35^{bcde}	2.77 ± 0.42^{b}
	WTP	1.48 ± 0.46^{d}	0.81 ± 0.03^{efg}	87.48 ± 6.44^{e}	87.26 ± 11.23^{d}	29.97 ± 2.66^{fg}	146.4 ± 24.83^{cde}	0.97 ± 0.15^{def}
NASPOT 8	WP	9.02 ± 1.06^{d}	1.02 ± 0.12^{de}	190.13 ± 24.79^{c}	165.52 ± 13.21^{a}	99.16 ± 13.59^{cd}	218.29 ± 56.82^{bcd}	1.27 ± 0.28^{def}
	WTP	0.89 ± 0.15^{d}	0.58 ± 0.05^{g}	155.38 ± 10.58^{d}	101.96 ± 2.96^{bcd}	67.77 ± 9.69^{def}	179.07 ± 18.19^{bcde}	0.52 ± 0.16^{f}
NASPOT 13 O	WP	10.00 ± 1.44^{d}	1.37 ± 0.15^{ab}	285.28 ± 11.68^{a}	153.96 ± 5.16^{a}	129.45 ± 22.96^{c}	253.4 ± 17.63^{b}	1.36 ± 0.27^{def}
	WTP	1.37 ± 0.18^{d}	0.80 ± 0.14^{efg}	254.35 ± 0.86^{b}	95.56 ± 4.16^{cd}	32.27 ± 4.76^{efg}	211.18 ± 10.55^{bcd}	0.61 ± 0.16^{ef}
PF-167	WP	121.02 ± 6.45^{a}	1.27 ± 0.02^{bc}	15.66 ± 1.17^{f}	94.36 ± 9.80^{cd}	188.5 ± 16.59^{b}	251.73 ± 51.52^{bc}	1.8 ± 0.48^{bcd}
	WTP	100.80 ± 18.61^{b}	1.11 ± 0.09^{cd}	13.72 ± 1.98^{f}	84.33 ± 12.42^{d}	38.79 ± 3.77^{efg}	178.51 ± 24.79^{bcde}	1.55 ± 0.70^{cde}
P-value		0.001	0.034	0.003	0.011	<0.001	0.049	0.013

All values are on dry weight basis. Values are means ± SD of three independent biological replicates ($n = 3$). Means in the same column with different superscripts are significantly different ($P < 0.05$). WP=with peel; WTP=without peel; TPC=total phenolic compounds; GAE=gallic acid equivalent; TFC=total flavonoids content; QE=quercetin equivalent; TCC=total carotenoids content; VC=vitamin C; AAE=ascorbic acid equivalent; TAL=total alkaloids content; CE=catechin equivalent; TSC=total saponins content; AE=aescin equivalent; TTC=total tannins content; TA=tannic acid.

1, NASPOT 8 and NASPOT 13 O (the yellow and orange varieties) were significantly lower (0.89–10.89 mg GAE/g; $P = 0.001$) than in 'Ssetyabule', NASPOT 11 and PF-167 (59.67–121.04 mg GAE/g; $P = 0.001$). Previous research comparing phenolics content of white, orange and purple sweetpotato roots, reported the highest level of phenolics in purple, followed by orange and lastly, white-fleshed sweetpotato (WFSP) (Teow et al., 2007). This contrast with the current study could be explained by the fact that genetic and environmental conditions such as climate could influence the varied accumulation of different phytochemicals in sweetpotato (Othman et al., 2017).

Comparing total phenolic compounds content in unpeeled with peeled roots for all the sweetpotato varieties, NASPOT 8 had the greatest difference, with as much as 10-folds higher in unpeeled samples. The results from the current study agree with the observation that sweetpotato peels contain more phenolic compounds than flesh tissues (Truong et al., 2007). Furthermore, the polyphenol oxidase enzyme is activated during mechanical processes like peeling, slicing, and chopping that may degrade phenolic compounds in fresh sweetpotato roots (Ruiz-Rodriguez et al., 2008), hence may explain the loss of total phenolics in the peeled samples.

3.1.2. Total carotenoids content

The total carotenoids content reflected the intensity of the orange colour as NASPOT 13 O had the highest level and 'Ssetyabule' the lowest. On average, NASPOT 13 O had about 32 times the total carotenoids in 'Ssetyabule'. Carotenoids content in NASPOT 13 O is comparable to values observed in OFSP varieties in South Africa (143–278 μg/g) (Rautenbach et al., 2010), but higher than those reported in Burkina Faso (132–180 μg/g) (Koala et al., 2013). Apart from environmental and genetic factors influencing carotenoids content in sweetpotato, cultural management practices such as fertilisation and maturity levels at harvest have been reported to be of significance (Rautenbach et al., 2010). Since agronomic practices vary per geographical location, this could account for the observed differences in total carotenoids content.

Although PF-167 had more total carotenoids than 'Ssetyabule' and NASPOT 11, pigments such as anthocyanins and chlorophyll can mask carotenoids, hence plant foods with these pigments may not show a yellowish or orange colour (Ruiz-Rodriguez et al., 2008). Furthermore, carotenoids, especially β-carotene, have provitamin A activity and OFSP is considered one of the best sources of β-carotene that can increase serum vitamin A levels (Low et al., 2017). With this background, the consumption of NASPOT 13 O in Uganda could be promoted to address vitamin A deficiency, particularly amongst children.

3.1.3. Vitamin C content

Vitamin C in sweetpotato roots varied significantly ($P = 0.011$) with variety and peel condition, being highest in unpeeled NASPOT 11 (166.98 μg AAE/g) and lowest in peeled 'Ssetyabule' (30.40 μg AAE/g). Vitamin C levels in sweetpotato roots in this study were comparable to those reported in Kenyan OFSP roots, having about 45.3–190.5 μg/g (Abong' et al., 2020). The synthesis and accumulation of vitamin C within the same species may vary between different cultivars, developmental stages, and tissue types (Mellidou and Kanellis, 2017). This could account for the differences observed amongst the six (6) varieties of sweetpotato in this study.

Vitamin C is an essential micronutrient in humans required to synthesise neurotransmitters, for protein metabolism, as a cofactor of many enzymes in the body, as an antioxidant and as a regulator of immune function (Li and Schellhorn, 2007). Vitamin C also plays a role in plants by enhancing stress tolerance (Fenech et al., 2019). Although the primary sources of vitamin C in the diet may be fruits and vegetables, increasing the vitamin C content in sweetpotato during breeding activities may serve a dual role for human nutrition and produce crops with high stress tolerance.

3.1.4. Total alkaloids content

Total alkaloids in the evaluated sweetpotato samples ranged from 24.05 to 233.70 μg CE/g. It is noteworthy that plants produce alkaloids as a defence mechanism for protection against invading microorganisms, and subsequent infection (Crozier et al., 2006). Alkaloids have been documented as potentially toxic to humans when consumed in large quantities of greater than 3–10 mg/g (Furrer et al., 2018). Some of the effects include neurotoxicity and inflammation of the gut. However, alkaloids have been shown to have anti-inflammatory, antidiabetic, and anticancer properties at lower concentrations (Adhikari, 2021; Furrer et al., 2018). We observed that the total alkaloid levels in the varieties are far below the potential toxicity range and would therefore be beneficial for managing NCDs in Uganda.

3.1.5. Total saponins content

Apart from unpeeled 'Ssetyabule' having a significantly higher ($P = 0.049$) total saponins content than the peeled form, the saponins content in the other varieties did not differ considerably between unpeeled and their respective peeled states. Total saponins in the studied sweetpotato varieties ranged from 77.07 to 441.07 mg/g, and this is comparable to the average amount of 200 mg/g reported in soybeans, a saponin-rich food (Isanga and Zhang, 2008). Saponins are a broad group of compounds, and in the past were recognised as antinutrients because they seemed extremely toxic to fish and some ruminants (Shi et al., 2004). However, more recent research has suggested that saponin toxicity in humans is unlikely, unless consumed in large doses or administered intravenously, in which case it could cause haemolysis of red blood cells (Marrelli et al., 2016). The therapeutic benefits of many medicinal plants have been associated with their saponin content and some human nutrition studies have documented saponins as antidiabetic, anticancer and cholesterol-lowering agents (Calderón Guzmán et al., 2020; Isanga and Zhang, 2008). More research into sweetpotato as a dietary source of beneficial saponins is therefore warranted.

3.1.6. Total tannins content

The total tannins content in all sweetpotato roots varied significantly ($P = 0.013$) with variety and peel condition, with unpeeled 'Ssetyabule' having the highest tannins content of 4.06 mg TA/g and peeled NASPOT 8 having the lowest of 0.52 mgTA/g. However, the tannins content obtained in OFSP varieties in this study (0.52–1.36 mg TA/g) are comparable to values of 0.4–1.3 mg/g (Abong' et al., 2020), and 0.74–1.08 mg/g (Haile et al., 2015) reported in Kenyan and Ethiopian OFSP varieties respectively.

3.1.7. Total monomeric anthocyanin content

The interaction effect between variety and peel condition for total anthocyanins was insignificant ($P = 0.291$). However, the individual factors were significant at $P<0.001$ for both variety and peel condition. The mean anthocyanin content for the unpeeled sweetpotato samples was significantly higher than for peeled (4.83 versus 2.65 mg/g; $P<0.001$). Fig. 2 shows the effect of variety on anthocyanin content.

The anthocyanin content of PF-167, the purple-fleshed, was significantly higher (15.29 mg/g; $P<0.001$) than the other varieties, which ranged between 0.86 mg/g for 'Ssetyabule' to 2.44 mg/g for NAROSPOT 1. The anthocyanin content of PFSP varieties is reported to widely vary between 0.32–13.90 mg/g and is dependent on the varietal and environmental factors, as well as extraction and quantification methods, such as spectrophotometry or HPLC (Xu et al., 2015). Anthocyanin level in PF-167 was comparable to two PFSP varieties that have been reported to have high levels of anthocyanins. The two varieties, GZ9 and P40 were bred in China and the United States and have anthocyanin content of 15 mg/g and 14 mg/g respectively (Liao et al., 2019; Xu et al., 2015).

Research into anthocyanin pigments, their sources, uses, and effects are gaining attention as evidence grows on their potential health benefits. Such benefits include high antioxidant activity, cancerous cells inhibition, promotion of brain function, hypoglycaemic effects, reduction

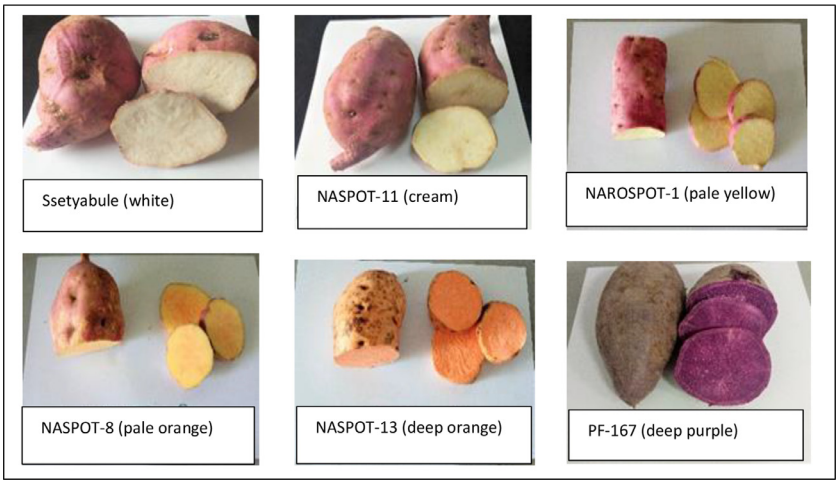

Fig. 1. Sweetpotato varieties with different storage root flesh colours used for this study.

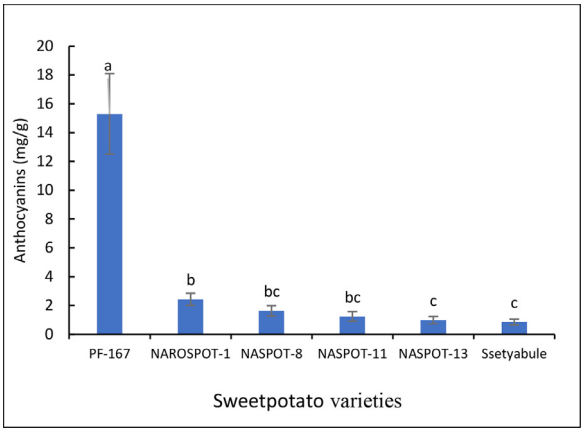

Fig. 2. Total anthocyanin content of sweetpotato storage roots.
Bars are means ± SD of three independent biological replicates ($n = 3$). Different letters on top of bars represent statistical differences in the varieties at $P < 0.001$.

Table 3
Antioxidant activities of sweetpotato storage roots as influenced by variety and peel condition.

Variety	Peel	ABTS(μg AAE/g)	FRAP(μg AAE/g)
'Ssetyabule'	WP	227.52 ± 24.89^{a}	64.95 ± 7.46^{b}
	WTP	103.62 ± 24.84^{c}	29.51 ± 1.30^{e}
NASPOT 11	WP	189.97 ± 34.36^{b}	44.55 ± 8.24^{d}
	WTP	159.66 ± 22.12^{b}	25.32 ± 3.79^{e}
NAROSPOT 1	WP	59.91 ± 5.83^{de}	66.18 ± 4.76^{ab}
	WTP	34.78 ± 2.42^{e}	47.51 ± 4.35^{d}
NASPOT 8	WP	62.68 ± 6.18^{de}	60.08 ± 7.40^{bc}
	WTP	39.77 ± 4.79^{e}	44.44 ± 2.56^{d}
NASPOT 13 O	WP	91.71 ± 9.21^{cd}	75.86 ± 9.52^{a}
	WTP	53.30 ± 3.13^{e}	53.44 ± 1.89^{cd}
PF-167	WP	103.05 ± 17.57^{c}	50.14 ± 2.68^{cd}
	WTP	66.41 ± 10.21^{de}	30.45 ± 1.12^{e}
P-value		0.002	0.015

All values are on a dry weight basis. Values are means ± SD of three independent biological replicates ($n = 3$). Means in the same column with different superscripts are significantly different ($P < 0.05$). WP=with peel; WTP=without peel; ABTS=ABTS radical scavenging antioxidant activity; AAE=ascorbic acid equivalent; FRAP=ferricyanide reducing antioxidant potential.

of insulin resistance, and promotion of gut health through prebiotic-like activity (Zhang et al., 2015, 2013). In addition, the anthocyanins from PFSP roots have shown higher antioxidant and antimutagenic activity when compared with other foods like purple asparagus, eggplant, and red onion, which are also highly pigmented. This is because the PFSP anthocyanins occur primarily as acylated forms with many phenolic compounds, making them more stable to changes in pH, heat and light (Li et al., 2012; Xu et al., 2015).

In addition to these potential health benefits from consuming PF-167 and other PFSP varieties, it could also be promoted as a colourant for the food, pharmaceutical and cosmetic industries (Alvarez-Suarez et al., 2021). NAROSPOT 1, NASPOT 8, NASPOT 11, and 'Ssetyabule', although not purple-fleshed had reddish-purple peels (Fig. 1) that may have resulted in their observed anthocyanin contents. Thus, recipes for sweetpotato with peels should be encouraged in SSA.

3.2. Antioxidant activity

The antioxidant activities of the six sweetpotato varieties were measured by ABTS radical scavenging activity and FRAP (Table 3).

ABTS varied significantly ($P = 0.002$) with variety and peel condition, ranging from 34.78 μg AAE/g for peeled NAROSPOT 1 to 227.52 μg AAE/g for unpeeled 'Ssetyabule'. Significant ($P = 0.015$) variations between variety and peel condition also existed for FRAP, ranging from 25.32 μgAAE/g for peeled NASPOT 11 to 75.86 μgAAE/g for unpeeled NASPOT 13 O. 'Ssetyabule', NASPOT 11 and PF-167, with high phenolics content showed higher ABTS values. In contrast, NASPOT 13 O, with the highest carotenoids content showed the highest FRAP value.

These results bolster the assertion that different bioactive compounds react differently to different antioxidant assays (Tang et al., 2015), but more so, that phenolic compounds and carotenoids could both have high antioxidant activities. Considering the means of unpeeled and peeled samples of each variety, the ABTS values were in decreasing order NASPOT 11 > 'Ssetyabule' > PF-167 > NASPOT 13 O > NASPOT 8 > NAROSPOT 1. The FRAP values were in the order NASPOT 13 O > NAROSPOT 1 > NASPOT 8 > 'Ssetyabule' > PF-167 > NASPOT 11. The higher antioxidant activities in the unpeeled compared with the peeled samples, for both ABTS and FRAP reflect the higher content of bioactive compounds in sweetpotato with peel.

Since different bioactive compounds have varied affinities for each assay for antioxidant activity, the sensitivity and specificity of one assay do not provide a complete representation of all antioxidants in a particular sample (Tang et al., 2015). Moreover, the common methods for evaluating antioxidant activity are based on different reaction mechanisms such as hydrogen atom transfer, reducing power, metal chelation, and radical scavenging ability (Shahidi and Zhong, 2015). Hence, it is appropriate to use a combination of two or more tests as a reliable assessment to provide a complete profile of antioxidant activity.

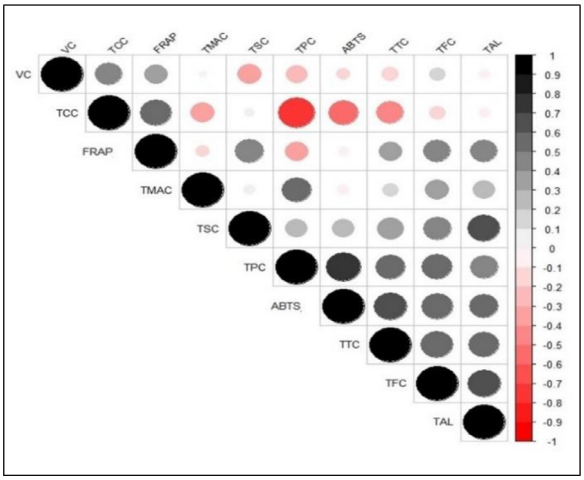

Fig. 3. Correlation matrix showing the correlations between each pair of variables (bioactive compounds and antioxidant activities) of sweetpotato varieties. An increasing degree of redness represents an increasing negative correlation and an increasing degree of blackness represents an increasing positive correlation. VC=vitamin C; TCC=total carotenoids content; FRAP=ferricyanide reducing antioxidant potential; TMAC=total monomeric anthocyanin content; TSC=total saponins content; TPC=total phenolic compounds; ABTS=ABTS radical scavenging antioxidant potential; TTC=total tannins content; TFC=total flavonoids content; TAL=total alkaloids content.

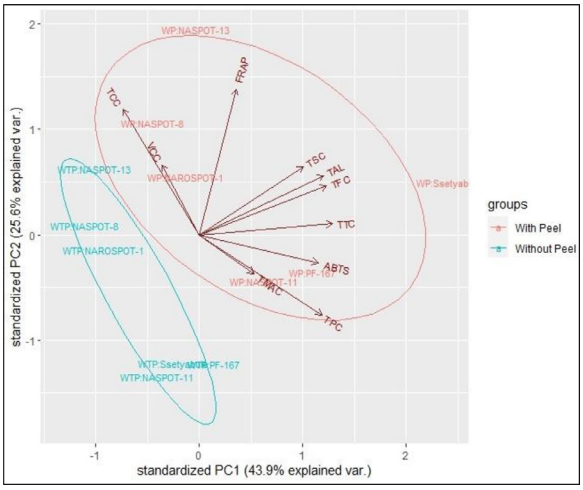

Fig. 4. PCA biplot showing the interrelationships amongst the individual bioactive compounds and antioxidant activities of sweetpotato varieties on the axes of Principal Components 1 (x-axis) and 2 (y-axis).
TCC=total carotenoids content; VCC=vitamin C content; FRAP=ferricyanide reducing antioxidant potential; TMAC=total monomeric anthocyanin content; TSC=total saponins content; TPC=total phenolic compounds; ABTS=ABTS radical scavenging antioxidant potential; TTC=total tannins content; TFC=total flavonoids content; TAL=total alkaloids content.

Notably, free radicals or reactive oxygen species are generated in the human body through various biological processes including aerobic metabolism, pathogenic defence mechanisms, and external exposures such as pollutants and radiation. Natural antioxidant enzymes remove these free radicals in healthy individuals (Pokorny et al., 2001). However, dietary antioxidants are necessary because they assist the body in neutralising the free radicals and reducing the harmful effects of oxidation, hence the importance of consuming a diet rich in antioxidants (Teow et al., 2007).

3.3. Relationships between the bioactive compounds content and antioxidant activities

The correlations between bioactive compounds and antioxidant activities are presented in the heat map in Fig. 3.

Significant ($P<0.05$) positive correlations existed between the ABTS antioxidant activity and total phenolics, tannins, flavonoids, and alkaloids. About 53%, 41%, 32% and 25% of the variation observed in ABTS antioxidant activity was associated with total phenolics, tannins, flavonoids, and alkaloids respectively. This suggests that total phenolics could account for about half the variation observed in ABTS antioxidant activity. Also, significant positive correlations were observed between the FRAP antioxidant activity and total carotenoids, saponins, flavonoids, and alkaloids. About 31%, 23%, 19% and 18% of the variation observed in FRAP was associated with total carotenoids, saponins, flavonoids and alkaloids respectively. This suggests that total carotenoids had more influence on FRAP.

Total flavonoids and alkaloids contents of the evaluated sweetpotato varieties were associated with both ABTS and FRAP antioxidant tests. Thus, total phenolics and tannins contents could be used as indicators in assessing ABTS antioxidant activity, while total carotenoids content could aid in predicting the FRAP antioxidant activity. Therefore, if time is a constraining resource during the screening phase, sweetpotato breeders could conduct either of these phytochemical tests to assess the antioxidant activities of the genotypes under evaluation.

The strongest negative correlation was between total phenolics and total carotenoids content ($r= -0.77$; $P<0.001$), consistent with the earlier observation that the WFSP and PFSP had higher phenolics and lower carotenoids compared with the OFSPs that had lower phenolics and higher carotenoids.

Fig. 4 illustrates the PCA biplot for this dataset, explaining the interrelationships amongst the individual bioactive compounds and antioxidant activities. The first and second principal components (PC) cumulatively explained 69.5% of the total variation in the dataset. The acute angles observed between total phenolics, anthocyanins, tannins and the ABTS antioxidant activity showed the close relationship of those bioactive compounds with ABTS rather than FRAP. In a study evaluating bioactive compounds in medicinal plants and their relationships with antioxidant activity, PCA revealed a close relationship between total phenolics, tannins and DPPH antioxidant activity (Oualcadi et al., 2020). This is a radical scavenging antioxidant assay similar to the ABTS in our study. On the other hand, total carotenoids and vitamin C content were more closely associated with FRAP than ABTS.

However, saponins, alkaloids, and flavonoids were associated with both ABTS and FRAP antioxidant activities. These three (3) phytochemicals showed similar vector directions, indicating a strong relationship. This implies that evaluating the content of any one of the total saponins, flavonoids, or alkaloids in the sweetpotato varieties could indicate the amounts of the other two. This information could be useful in biofortification strategies and in selection procedures where breeders deal with many genotypes. The opposite directions of the vectors for phenolics and carotenoids contents illustrate an inverse relationship between those two bioactive compounds. This supports the observation that the yellow- and orange-fleshed varieties rich in carotenoids had lower phenolics. The unpeeled sweetpotato samples were strongly associated with all the bioactive compounds and antioxidant activities evaluated, contributing to a greater variation in the data than the peeled samples.

3.4. Colour properties

The L*a*b* colour values in the sweetpotato roots varied significantly ($P<0.001$) with both variety and peel condition (Table 4).

Unpeeled PF-167 presented as the darkest colour, with the L* value (59.18; $P<0.001$) significantly lower than the other varieties. PF-167, compared with the other varieties also had significantly higher ($P<0.001$) a* values and lower b* values in both peeled and unpeeled forms. This suggests a more reddish (higher a*) and more

Table 4
L*a*b* colour values of sweetpotato roots as influenced by variety and peel condition.

Variety	Peel	L*	a*	b*
'Ssetyabule'	WP	79.06 ± 1.84^{a}	2.48 ± 0.33^{de}	12.93 ± 1.39^{de}
	WTP	69.66 ± 1.51^{cd}	1.14 ± 0.15^{gh}	11.75 ± 0.78^{ef}
NASPOT 11	WP	77.61 ± 1.31^{ab}	2.14 ± 0.29^{ef}	14.47 ± 1.07^{c}
	WTP	65.60 ± 1.44^{def}	0.98 ± 0.17^{h}	16.06 ± 0.83^{b}
NAROSPOT 1	WP	81.64 ± 0.51^{a}	1.89 ± 0.15^{f}	14.09 ± 0.18^{cd}
	WTP	63.05 ± 6.90^{fg}	1.24 ± 0.27^{gh}	10.37 ± 1.56^{g}
NASPOT 8	WP	79.98 ± 0.61^{a}	2.25 ± 0.20^{ef}	16.37 ± 0.62^{b}
	WTP	68.81 ± 11.65^{cde}	1.44 ± 0.18^{g}	13.72 ± 1.63^{cd}
NASPOT 13 O	WP	80.51 ± 0.35^{a}	3.44 ± 0.64^{c}	18.39 ± 0.90^{a}
	WTP	72.59 ± 13.01^{bc}	2.82 ± 0.75^{d}	16.07 ± 3.45^{b}
PF-167	WP	59.18 ± 1.08^{g}	12.09 ± 0.84^{b}	10.53 ± 0.41^{fg}
	WTP	63.96 ± 1.42^{efg}	13.25 ± 0.43^{a}	9.41 ± 0.73^{g}
P-value		<0.001	<0.001	<0.001

Values are means ± SD of nine individual measurements (n = 9). Means in the same column with different superscripts are significantly different (P < 0.05). WP=with peel; WTP=without peel.

bluish (lower b*) hue, resulting in its dark purple colouration (Fig. 1). Truong et al. (2010), in their characterisation of anthocyanins in PFSP, reported that peonidin and cyanidin, the pigments that impart the reddish and bluish hues respectively, are the significant contributors to the anthocyanin pigment colour found in PFSP. Furthermore, the relatively high levels of phenolic compounds in PF-167 (Table 2) may have caused enzymatic browning from polyphenol oxidase during processing, resulting in the darker colour (Ebrahimi and Lante, 2021).

In contrast, the yellowness (higher b*) of unpeeled NASPOT 13 O was significantly higher (18.39; P<0.001) than all the varieties, reflecting its orange flesh and cream peel colour. These colour differences between the sweetpotato varieties result from diverse biosynthetic pathways (Johnson et al., 2021). Significant differences in L*a*b* colour values have been observed in other studies comparing sweetpotato varieties of various flesh and peel colours (Ooi et al., 2021; Tang et al., 2015). Although beyond the scope of this study, colour is an essential sensory attribute that may influence consumer acceptability of sweetpotato (Tomlins et al., 2007). Consumer preference for vitamin A-enriched root crops may be higher than other varieties due to their bright yellow or orange colour (Bechoff et al., 2018). On this basis, PF-167 may be less acceptable to consumers than the other varieties such as NASPOT 13 O, which has a brighter colour, whether peeled or unpeeled.

4. Conclusions

Although sweetpotato is an important staple in Uganda, and in SSA, not much research on this food crop has paid attention to its bioactive compounds content, hence its potential as a functional food. This study showed that the six (6) varieties of sweetpotato evaluated had appreciable amounts of bioactive phytochemicals that varied significantly with flesh colour. While the white, cream and purple-fleshed contained more phenolic compounds than the yellow and orange-fleshed varieties, the white-fleshed, in addition, had higher levels of alkaloids, saponins and tannins. Total carotenoids were higher in yellow and orange-fleshed roots. Peeling sweetpotato roots significantly reduced the levels of the content of bioactive compounds. Therefore, the results provide information on which varieties to consume to benefit from a particular bioactive compound. Antioxidant activities observed in the sweetpotato varieties may be due to the synergistic effect of all the phytochemicals evaluated.

The sweetpotato roots we studied were uncooked. However, postharvest processing and heating generally applied to many foods before consumption may cause changes to their bioactive compounds. Therefore, to fully appreciate sweetpotato as a functional food, future research should investigate how common postharvest processes such as storage time and conditions, and cooking methods may influence the retention of the inherent bioactive compounds.

Ethical statement

This research did not involve any animals or human subjects.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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