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Nutritional evaluation of *Colocasia esculenta* (L.) Schott leaves and corms from KwaZulu-Natal, South Africa

Zwelonke Beato [a,*], Lucy N. Gitonga [b], Eric O. Amonsou [c], Viloshanie Reddy [d]

[a] Department of Horticulture, Durban University of Technology, 41/43 M L Sultan Road, Greyville, Durban 4001, KwaZulu Natal, South Africa
[b] School of Animal, Plant and Environmental Sciences, University of the Witwatersrand, Private Bag 3, Johannesburg WITS 2050, South Africa
[c] Department of Biotechnology and Food Science and Technology, Durban University of Technology, 41/43 M L Sultan Road, Greyville, Durban 4001, KwaZulu Natal, South Africa
[d] Tissue Culture Section, Production and Display Division, Parks, Recreation and Culture Unit, eThekwini Municipality, 70 St. Thomas Road, Botanic Gardens, P.O Box 3740, Durban 4000, KwaZulu Natal, South Africa

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A B S T R A C T

Green leafy vegetables (GLVs) are good sources of vital nutrients for human health sustenance. In this study, the nutrient compositions of *Colocasia esculenta* L. (Schott) leaves and corms from both Southern and Northern locations of KwaZulu-Natal province were investigated. Total, soluble, and insoluble oxalates and soil minerals were analysed to establish nutrient-plant organ correlations. Substantial variations were observed in nutrient contents among plant parts and locations. Young leaves in both locations showed higher phosphorus content and the northern location had the highest potassium levels in both young and mature leaves. Zinc and copper contents of leaf tissues were relatively low, ranging from 1.9 to 4.7 mg/100 g and 0.48–1.46 mg/100 g FW, respectively, whereas manganese (2–64 mg/100 g FW) and iron (13 – 88 mg/100 g FW) showed higher variability. While oxalate levels showed minimal location effects, corms had more than double the total oxalate content (35–39 g/100 g FW) of leaf tissues. Despite variations in mineral profile, Colocasia esculenta leaves can serve as a valuable source of essential micronutrients to address micronutrient needs in vulnerable communities.

1. Introduction

Global food systems rely on the consumption of a limited number of species. Cassava, millet, sorghum, wheat, rice, sugar, and maize are critical human calorie sources contributing about 70–90% (Clapp and Cohen, 2009). Global food security is at risk due to the decreasing diversity of crop species and hence a decline in genetic heterogeneity (Khoury et al., 2014). In addition, a combination of different economic, political, and environmental crises has led to increased poverty, and hence food insecurity, particularly among rural communities in Sub-Saharan Africa including South Africa (Abukutsa-Onyango et al., 2010; Seekings and Nattrass, 2015).

Although South Africa is food secure at a national level, food insecurity at the household level is imminent. About 20% of South African households had inadequate or severely inadequate access to food in 2017 (STATS, 2019). This situation has recently been aggravated by the coronavirus pandemic (STATS, 2020). Food insecurity is defined as a situation where an individual or household has limited access to enough, safe and nutritious food or consumes food that falls below 80% of the daily minimum recommended allowance of caloric intake for normal growth and development (Mohamed, 2017). Food insecurity and hidden hunger affect poorer households a hundred times more than their wealthier counterparts (Schönfeldt et al., 2010).

Vitamin A-rich vegetables are the least consumed by South African adults (Labadarios et al., 2011). Moreover, 64% of 1- to 9-year-old children are vitamin A deficient, 28% are anemic, 13% have poor iron levels, and 45% have low zinc levels. Green leafy vegetables (GLVs) are abundantly high in minerals such as Ca, Fe, Cu, P, Cl, Na, and Zn (Kumar et al., 2020). Some of these nutrients enhance the absorption of other nutrients in the body (Melse-Boonstra, 2020). GLVs also form the cheapest and most readily available sources of important fibers, vitamins, and essential amino acids and are the only natural source of folic acid (Randhawa et al., 2015). They are low in lipids and hence ideal for weight management (Kumar et al., 2020). GLVs are also an excellent source of antioxidants (Odhav et al., 2007), with beta-carotene being the most crucial pro-vitamin. Hence diets supplemented with GLVs have the

* Correspondence to: Department of Horticulture, Durban University of Technology, 41/43 M. L. Sultan Road, Greyville, Durban 4001, South Africa.
E-mail address: zwelonke.beato@outlook.com (Z. Beato).

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potential to not only improve nutritional security (Toledo & Burlingame, 2006) but also boost immunity (Ghosh, 2019; Kumar et al., 2020).

Colocasia esculenta (L.) Schott commonly known as taro is an emergent, semi-perennial, aquatic, and semi-aquatic stemless herbaceous plant cultivated for its starchy corms. It belongs to the Araceae family of which about 140 genera and about 3750 extensively distributed species are known (Christenhusz and Byng, 2016). The species is allogamous and polymorphic (Rashmi et al., 2018). The corm is a reliable source of starch (70–80 g/100 g dry weight), fiber (0.80%), ash (1.2%), and fat (0.20%) but low in protein (1.5%) similar to many other tuber crops (Rashmi et al., 2018). The leaves are rich in nutritional and phytochemical compounds, however, they are greatly underutilized. Numerous studies depict that leaves of taro have a high nutritional composition in comparison to green leafy vegetables generally consumed by masses regularly (Table S2). They're also an essential source of thiamine, riboflavin, iron, phosphorus, and zinc and an exceptionally good source of vitamin B6, vitamin C, niacin, potassium, copper, and manganese (Magbalot-Fernandez and Umar, 2018).

Taro *Colocasia esculenta* (L.) Schott, is an archaic crop cultivated in the tropical and subtropical regions of the world, particularly in the Pacific and Caribbean islands, parts of Central and South America, and in isolated regions of the United States (Quero-Garcia et al., 2010). Taro is a widely cultivated root crop in 50 countries worldwide. Nigeria is the largest producer of taro, followed by Cameroon, China, and Ghana, and collectively, they account for over half of the global taro production. In 2021, global taro production reached 12,396,248.5 tons, with Africa contributing 76.8% of the total output. Asia contributed 19.3%, while Oceania and the Americas contributed 3.3% and 0.5%, respectively (FAOSTAT, 2023). In South Africa, taro is mainly grown as a subsistence starchy staple. The main growing areas include KwaZulu Natal, Mpumalanga, Eastern and Western Cape provinces, where it is popularly known as *amadumbe*, *madumbis, mufhongwe, taro, and dasheen* (Louw, 2022; Shange, 2004).

Although grown for its corm, all other parts of the plant including the leaves, petiole, and flowers are edible (Chivenge et al., 2015) and have antioxidant, anticancer, and antidiabetic activity (Mitharwal et al., 2022). However, according to (FAOSTAT, 2023) South Africa's taro production is minor compared to other major African taro producers. It is therefore postulated that the promotion of consumption of leaves as a green leafy vegetable in South Africa will supplement and complement the nutrients available in the corms. Consequently, provincial and national subsistence farmers can grow and use a*madumbe* leaves as a 'complete' food source to alleviate food insecurity. However, the complete nutritional information must be known before the crop can be promoted as a green leafy vegetable (Maseko et al., 2017).

Typical of the Aroid family (Kumar et al., 2017), all parts of taro contain needle-like calcium oxalate crystals or raphides (Du Thanh et al., 2017). These crystals produce a sharp irritation and burning sensation in the mouth and throat resulting in low preference and consumption of this crop (Du Thanh et al., 2017). Oxalates occur in plants in either soluble or insoluble forms, each of which impacts differently when consumed (Holmes and Assimos, 2004; Nakata, 2012). Because *amadumbe* in South Africa is grown under different growing conditions with different soil types, this may subsequently influence the nutrient uptake and nutritional (including antinutritional) quality of the harvested crop (Raju & Byju, 2018).

The objectives of the current study, therefore, were: 1: to determine the nutritional quality of leaves (young and mature) and compare them to that of the corms of the same plants 2: to compare the nutritional quality of two landraces collected from two regions in KwaZulu Natal province of South Africa, 3: to assess the correlation between soil nutrient status and nutritional quality of the plant tissues for the two landraces and 4: to assess the level of oxalates in young and mature leaves and compare to that of the corms.

2. Materials and methods

2.1. Study sites

Two different sites located in eThekwini Municipality in the KwaZulu-Natal province of South Africa were used for the study: Snembe farms (29° 34' 48'' S; 31° 7′ 12'' E) in Tongaat located in North Coast, about 40 km north of Durban, and farms in Umbumbulu (29° 59' 0" S; 30° 42' 0" E) about 45 km south-west of Durban (Fig. 1). They use the upland (non-flooded) growing system. Five farms were randomly selected from the two sites and 20 plants were randomly collected along a transect in each farm.

2.2. Chemical and plant materials

Three types of tissues were analyzed: young newly emerged succulent leaves of approximately 20 cm × 10 cm, mature fully expanded leaves of about 50 cm × 25 cm, and mature corms were prepared for nutrient analysis. Farms were visited regularly in the autumn (April – May 2018) season during leaf growth. Young and mature leaves (excluding the petiole) were harvested from the plant using a pair of scissors. Corms were harvested from the ground and the soil debris was removed using Bunty's Dish Cloth – Honey-Comb DC. For each farm, all mature leaves were pooled together to make a composite sample from which 20 random samples were drawn for analysis. This was repeated for young leaves and corms. Samples were packed in Leo Manilla Plain Wage Gummed C4 envelope 297 mm × 210 mm and immediately transported to Cedara College of Agriculture and Rural Development, Kwa-Natal, South Africa for nutritional analysis (mineral content and proximate composition). Another 20 random samples from the same composites were sent to Standard Global Services (SGS) Agriculture and Food Division, Maitland, Cape Town for vitamin A, vitamin C, and beta-carotene analyses. Analytical reagents (AR) were supplied by Merck Sigma-Aldrich, South Africa, all AR grade (≥99.5%). No additional purification was undertaken in any reagents.

2.3. Soil sampling technique

Soil samples from the same five farms in Umbumbulu and Snembe sites were also collected for soil nutrient and pH analysis. All soil sample collection was carried out during the autumn-winter period and soil was collected between the rows of a*madumbe* plants in a *zig-zag* pattern across the farm to ensure homogeneity. Samples from each farm were independently homogenized for analysis. The surface was cleared of all the litter using a Lasher 26 – Tooth Steel Garden Rake and a Stainless-Steel Soil Sampler Probe 25 cm × 52 cm (Johnson Soil Augers, Johannesburg, South Africa) was driven to a plow depth of 30 cm.

Fifteen samples were collected from each sampling unit and placed in a high-density polyethylene bucket (HDPE) 25 L, and all foreign materials such as decomposing leaves, leaf stalks, and stones were removed before covering the bucket with a lid. The procedure was repeated for each farm in the two sites and all samples were labeled and immediately transported to the South African Sugar Research Institute (SASRI) for analysis of pH, macronutrients, and micronutrients.

2.4. Mineral analysis

Analysis of the mineral elements calcium, magnesium, potassium, phosphorus, copper, iron, manganese, and zinc content followed (Allen et al., 1974). Pieces of leaf samples were chopped using an Eiger - Bruno 4PC Stainless Steel Knife Set EG-SKKS01 (Yangjiang Smartwife Kitchenware Manufacturing Co. LTD, Yangjiang, China) and acid digested using nitric (HNO_3), sulphuric (H_2SO_4), and perchloric ($HClO_4$) acid mixtures (5:1:0.1). A 0.5 g of sample mixed with 6.5 ml acid mixture was digested on the digital hotplate E-PT1000–23 (Masiye Labs, Johannesburg, South Africa), at 80 °C and gradually increased to 250 °C

Fig. 1. Map showing selected sampling sites in Snembe and Umbumbulu in eThekwini Municipality in KwaZulu-Natal.
Source: Shih (2017).

until it turned into thick viscous material. After cooling, the volume was raised to 20 ml using 0.2 N nitric acid, and the contents were filtered (Whatman No. 42) and analysed with a flame through an atomic absorption spectrophotometer (Shimadzu, Kyoto, Japan) for elements Ca, K, P, Cu, Fe, Mn, and Zn. The instrument was calibrated by a series of standard solutions including a blank, prepared for each nutrient.

2.5. *Proximate composition*

2.5.1. *Moisture content*

Moisture content (%) was determined according to the method by (Osborne and Voogt, 1978). The porcelain crucibles were thoroughly scrubbed and allowed to dry in an air oven at 110 °C for 10 min to obtain a constant weight. The crucibles were subjected to cooling in a desiccator for 30 min, labeled, and weighed (W_1). A 2.0 g of each plant tissue sample was precisely weighed in the crucibles and re-weighed (W_2). The crucibles containing the samples were placed in an oven maintained at 105 °C for 14 hrs. The crucibles were removed and transferred to desiccators to cool and obtain the final weight (W_3). The percentage of weight loss between the wet weight and dry weight of samples was calculated.

2.5.2. *Protein content*

Protein analysis followed the Dumas method (Simonne et al., 1994) of total combustion using the LECO- Trumac instrument model FP – 528 (Leco, St Joseph, USA). The plant tissue samples, leaves (young and mature), and corms were isolated. The samples were then dried in an air-forced oven (G.C.A. Corporation, Chicago, USA) at 70 °C for 72 h and ground in a Wiley mill (Arthur H. Thomas Co., Philadelphia, USA) to pass through a 20-mesh screen. A 0.2 g of dry tissue was wrapped in tin foil, weighed, and introduced into the induction furnace of an FP-428 N Analyzer (LECO Inc., St Joseph, USA). Nitrogen oxide gas (NO_2) formed during combustion was reduced to N_2, which was then quantified by thermal conductivity. Nitrogen (N_2) was calculated by dividing protein by 6.25 and expressed directly as g N/100 g of dry matter (% N).

2.5.3. Fat content

Fat content was determined using the ether extraction Soxhlet method (Nielsen, 1998). Two grams (2 g) of sample pre-dried at 100 °C to constant weight under pressure was weighed into a pre-dried extraction thimble, ensuring porosity permits a rapid flow of ethyl ether. The sample in the thimble was then covered with glass wool. The pre-dried boiling flask was weighed, and anhydrous ether was added to the boiling flask. The boiling flask, Soxhlet flask, and condenser were assembled simultaneously. The extract was removed at a rate of six drops per second by condensation for about 4 h by heating the solvent in a boiling flask. The boiling flask with extracted fat was air dried in an oven at 100 °C for 30 min, thereafter, cooled in a desiccator and weighed. Fat was calculated with the following formula:

$$\%Fat \quad on \quad a \quad dry \quad weight \quad basis = \frac{g \quad of \quad fat \quad in \quad sample}{g \quad of \quad dried \quad sample} x100$$

2.5.4. Ash content

The determination of ash content followed the AOAC method (Horwitz, 1980). The porcelain crucibles were thoroughly washed with distilled water and dried in an oven to a constant weight at 110 °C for 10 min. The crucibles were cooled in a desiccator and weighed (W_1). A 2.0 g of each plant tissue was weighed into the crucibles and reweighed (W_2). The crucibles containing the samples were transferred into a muffle furnace set at 550 °C for 8 h to ascertain adequate ashing. The crucibles were removed and allowed to cool in desiccators and weighed (W_3). The percentage of ash was calculated.

2.5.5. NDF and ADF content

Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined using (Goering & Van Soest, 1970). A 0.5 g of air-dried sample was ground to a fine powder to allow passing through a 1 mm mesh into a beaker of the refluxing apparatus. A 100 ml cold (room temperature) neutral detergent solution was added to the beaker, 2 ml decahydronaphthalene, and 0.5 g of sodium sulphite using a calibrated measuring instrument. The solution was heated to boiling for 10 min and intermittently reduced the heat to prevent foaming. The solution was adjusted to a constant boiling temperature and refluxed for 6 min. The tared Gooch crucibles were placed on filter manifolds while simultaneously swirling the beaker to suspend solids and fill crucibles. The sample was rinsed with 100 °C hot water, filtered the liquid, and duplicate the washing procedure. Wash twice with acetone and dry the crucible at 100 °C for 8 h and weigh. NDF was calculated by subtracting the weighted value from 100. The residue was ashed for 3 h at 500 °C, weighed, and presented as insoluble NDF.

ADF was repeatedly washed with acetone until no color was removed. The remaining lumps were broken to permeate the contact of particles of the fiber with the solvent. Suck the ADF and dry at 100 °C for 8 h and weigh. ADF was calculated using the following equation:

$$\text{ADF} = \frac{W0 - W1}{S} x100$$

Where, W_0 = Weight of oven dry crucible including fiber;.

W_1 = Tared weight of the oven-dry crucible;.

S = Oven dry sample weight.

2.6. Determination of oxalate content

Oxalates analysis was conducted at the Department of Chemistry Laboratory at the Durban University of Technology, Kwa-Zulu Natal, South Africa. Leaves and corms were oven-dried at 60°C for 48 h and powdered separately in a 1.5 L, 400 W blender (Sunbeam, Florida, USA). To determine total oxalate and soluble oxalate, 36 Erlenmeyer (100 ml) flasks were first rinsed with distilled water. A 0.5 g of powdered leaf powder sample was weighed into each of the 18 Erlenmeyer flasks and 0.5 g of powdered corm was weighed into the other eighteen Erlenmeyer flasks. Total oxalates were extracted by diluting the powdered leaf or corm samples with 50 ml of distilled water. The flasks were placed in a shaking water bath at 80ºC for 30 min. After filtration using 90 mm Whatman filter paper, the extracts were diluted with 50 ml of distilled water.

From each diluted extract, 25 ml aliquots were titrated with standard 0.02 mol^{-1} of potassium permanganate solution standardized against calcium oxalate. To acidify the extracts dissolved in distilled water (soluble oxalate), 20 ml of 0.02 mol^{-1} sulphuric acid was added to the solutions. Titrations were performed in triplicate at 50°C using a hot-plate KT6301–56 (Science Lab, Navasota, USA) and the titration endpoint of the solution was considered when the colorless solution turned pink for more than 30 s. The insoluble oxalate content was calculated by the difference between the total oxalate and soluble oxalate. Oxalate concentrations were expressed as g/100 g dry matter.

2.7. Soil analysis

2.7.1. Extraction procedure and analysis

The soil was collected from the northern and southern regions of KwaZulu-Natal. The soil was air-dried and sieved (2 mm). 10 g samples of soil were weighed into 250 ml conical flasks and 20 ml of AB-DTPA solution was added. The flasks were shaken for 15 min at 180 rpm, then filtered through 2.5 μm filter paper (Whatman grade 42, Sigma Aldrich) and diluted 1:1 using distilled water. The samples were spiked with known concentrations of analytes to test the recoveries of the required elements. The samples and spiked samples were loaded on the SPS 4 autosampler for analysis. Calibration standards for all the required elements were prepared using Agilent single-element standards (1000 mg/l). The standards were diluted using the AB-DTPA extraction solution to ensure matrix matching. Linear calibrations were obtained for all analytes and wavelengths, with calibration coefficients greater than 0.999. The samples were analysed by ICP-OES for elements, potassium, calcium, magnesium, zinc, copper, manganese, and iron. Phosphorus was determined using the Resin ion exchange method, the ion exchange membrane simulates the interaction between the plant roots and a soil/water mixture.

2.8. Data analysis

All plant nutrient (antinutrient) data for the three distinct types of plant tissue collected from the two sites were subjected to R Statistics R version 4.0.0 (Auckland, New Zealand). Two-way analysis of variance (ANOVA) and the means for all analyses of variance were further separated using Tukey's posthoc HSD (honestly significant difference) test. Soil nutrient data were independently analyzed using the T-Test MS XLX statistical analysis to determine the means, S±D, and p values. The significant differences were determined at $p < 0.05$.

3. Results and discussion

3.1. Macronutrient content

Young and mature leaves from Umbumbulu and Snembe did not differ significantly in calcium and magnesium content, but young leaves contained significantly higher ($p < 0.05$) phosphorus and potassium than mature leaves in Umbumbulu and Snembe, respectively, (Table 1). All macronutrient content in young and mature leaves was significantly higher than in corms from both sites. The insignificant differences in the macronutrient content of calcium and magnesium in both young and mature leaves indicate that the maturity of leaves has no significant impact on the availability of the two macronutrients. Since young leaves had significantly higher phosphorus and potassium content than mature leaves, the maturity of leaves needs to be considered when harvested as a GLV.

The high phosphorus concentration in young and mature leaves from both cultivation sites indicates higher sources of nutritional phosphorus that can supplement the low phosphorus content in the corms from Umbumbulu and Snembe, respectively (Table 1). *Colocasia* leaves have the potential to meet the recommended daily allowance of 1.250 mg/day (Table S4) (IM, 1997) if adequate servings of 300 g per person/day are consumed providing a minimum of 72% and (>100%) of the RDA of this mineral. The results indicated a higher phosphorus content compared to spinach (32.59 mg/100 g), mustard (71.62 mg/100 g), fenugreek (53.05 mg/100 g), amaranth (73.22 mg/100 g), and bathua (37.55 mg/100 g) leaves (Table S4) (Longvah et al., 2017; USDA, 2021).

Potassium content was significantly higher ($p < 0.05$) in young and mature leaves (Table 1) from the Snembe population, contrarily young and mature leaf tissues from Umbumbulu showed no significant difference ($p > 0.05$), (more than double) compared to the corms (Table 1). The abundance of potassium in leaves is similar to the study by (Azubuike et al., 2018) who also found potassium to be the most abundant mineral in fresh leaves of *Colocasia*. A high intake of dietary K potentially reduces the risk of coronary heart disease and other chronic illnesses (Asyira et al., 2016). Young leaves alone from the Snembe population could be sufficient for satisfying the maximum recommended daily allowance of 3.400 mg/day per 100 g servings (Table S4) (IM, 1997; Sawka, 2005) of 100 g portions per person contributing (>100%) of the RDA of potassium.

Young leaves from Umbumbulu had a lower calcium content compared to mature leaves from the same site. Similarly, Snembe had a higher content of calcium in mature than in young leaves. In both population sites, leaf tissues indicated no significant difference ($p > 0.05$) in calcium content. Moreover, corm tissues displayed no significant difference ($p > 0.05$) and contained the lowest calcium concentration compared to leaf tissues. Young and mature leaves from Umbumbulu and Snembe have the potential to supply 1.4 – 1.5 g/100 g and 1.2 – 1.3 g/100 g, respectively, (Table 1).

Contrarily, corms contain 0.08 – 0.09 g/100 g of calcium requiring a colossal intake of 1.700 g of the starchy corm to satisfy recommended daily allowance. The maximum recommended daily intake of calcium is 1.300 mg/day (Table S4) (IM, 1997; Sawka, 2005), and about 100 g of *Colocasia* leaves can potentially provide a complete nutritional value to satisfy the RDA (Ross et al., 2011) if sufficient portions are consumed contributing (>100%) of RDA of calcium. Calcium improves bone health, facilitates growth and development, and maintains the human skeletal system and supporting structure (Flynn, 2003; Sicinska et al., 2020). Magnesium plays a protective role against cardiovascular diseases, strokes, and diabetes (Barbagallo et al., 2021).

Young and mature leaves from both sites had a high magnesium content (Table 1). Young and mature leaves from Umbumbulu indicated no significant difference ($p > 0.05$), both sites showed no significant difference ($p > 0.05$), except mature leaves from Umbumbulu with a higher concentration (0.48 g/100 g). While corms from Umbumbulu and Snembe had a lower concentration ($p < 0.05$) (Table 1). The highest daily requirement for magnesium is 360 mg (Table S4) (IM, 1997; Sawka, 2005) which can be satisfied by consuming 100 g of *Colocasia* leaves per person contributing > 100% of RDA indicating that *Colocasia* leaves can be considered a high-content source of magnesium.

According to (Longvah et al., 2017), numerous other commonly consumed green leafy vegetables such as *Amaranth*, *Spinacea*, *Brassica,* and *Trigonella* contain considerably lower magnesium content in leaves (Table S2). (Jalali & Fakhri, 2021) discovered that fresh wild edible plants, *Taraxacum vulgar* and *Fumaria parviflora* supplied between 146.9 and 203.9 $mg/100^{-1}$ g of Mg, providing 10–14%, thus none of the WEPs can be considered a good source of Mg. (Longvah et al., 2017) reported Mg concentrations of *Spinacea oleracea*, *Brassica juncea*, and *Chenopodium gangeticus* as 24%, 14%, and 13% indicating the superiority of *Colocasia* leaves as a contributor of Mg (Table S2).

3.2. Micronutrient content

Leaves had higher levels of the micronutrients Zn, Cu, and Mn than the corms in both sites, with young leaves containing higher micronutrient concentrations (Table 2). In both sites, although Zn content was higher in younger leaves, there was no significant difference ($p > 0.05$) in Zn content for the young and mature leaves, and hence both can be good sources of nutritional zinc. Both population sites showed no significant differences ($p > 0.05$) in zinc concentration in corms.

The RDA of Zn is 11 and 9.0 mg/day (Trumbo et al., 2001b) for adult males and females, respectively. Studied *Colocasia* leaves can potentially contribute 3–4% of the RDA, suggesting that leaves are a poor source of Zn. To satisfy daily Zn rations about 2.100 g (> 2 kg) of portions must be consumed. Furthermore, supplementation is required for pregnant women of up to 11 mg/day (Table S3) (Carducci et al., 2021; Silva et al., 2019).

Unlike the Snembe population which showed no significant differences in micronutrient content between young and mature leaves, young leaves from the Umbumbulu population were significantly higher in copper ($p < 0.05$) and manganese ($p < 0.05$) content compared to mature leaves (Table 2). Since copper is essential for several physiological processes, it is needed in human diets. Both young and mature leaves from the Umbumbulu population contained adequate concentrations, whilst the corms retained considerably low concentrations (Table 2). The consumption of leafy parts of *Colocasia* has the potential to contribute effective copper concentrations if portions of 100 g are served. The RDA of Cu is (0.9 mg) and (1.3 mg) for pregnant and lactating females (USDA, 2014). *Colocasia* leaves can supply a maximum of 15% of the RDA of Cu. (Jalali and Fakhri, 2021) indicated the leaves could contribute 14% of the RDA of Cu.

Manganese is essential for bone development and amino acids, lipid, protein, and carbohydrate metabolism and is also needed for the proper functioning of several metalloenzymes (Islam et al., 2023). Young and mature leaves from Umbumbulu contained Mn in significantly high amounts ($p < 0.05$), in contrast, leaf organs from Snembe exhibited no significant difference ($p > 0.05$), respectively, compared to corms from

Table 1
Macronutrient content in the tissue of *amadumbe* plants collected in Umbumbulu and Snembe sites.

	Umbumbulu			**Snembe**		
Macronutrients (g/100 g FW)	*Young*	*Mature*	*Corms*	*Young*	*Mature*	*Corms*
Phosphorus (P)	0.43 ± 0.02^{c}	0.30 ± 0.09^{b}	0.14 ± 0.02^{a}	0.43 ± 0.02^{c}	0.42 ± 0.02^{c}	0.24 ± 0.01^{b}
Potassium (K)	3.5 ± 0.09^{b}	3.7 ± 0.25^{b}	2.2 ± 0.11^{ab}	5.1 ± 0.24^{d}	4.5 ± 0.32^{c}	2.0 ± 0.11^{a}
Calcium (Ca)	1.4 ± 0.02^{bc}	1.5 ± 0.21^{c}	0.08 ± 0.01^{a}	1.2 ± 0.08^{b}	1.3 ± 0.18^{bc}	0.09 ± 0.03^{ab}
Magnesium (Mg)	0.40 ± 0.03^{bc}	0.48 ± 0.09^{c}	0.15 ± 0.02^{ab}	0.36 ± 0.02^{b}	0.39 ± 0.05^{bc}	0.14 ± 0.01^{a}

Mean ± Standard Deviation, n = 5 farms per site. Values followed by the same letter in a row are not significantly different at $p < 0.05$.

Table 2
Micronutrient content in the tissue of *amadumbe* plants collected in Umbumbulu and Snembe sites.

Micronutrients (mg/100 g)	Umbumbulu			Snembe		
	Young	*Mature*	*Corms*	*Young*	*Mature*	*Corms*
Zinc (Zn)	4.7 ± 2.7^{b}	3.7 ± 20^{ab}	1.9 ± 1.5^{a}	5 ± 4.5^{b}	5.1 ± 7^{b}	4 ± 21.5^{ab}
Copper (Cu)	1.46 ± 0.89^{d}	1.16 ± 3.1^{c}	0.62 ± 0.45^{ab}	0.78 ± 0.45^{b}	0.82 ± 0.45^{b}	0.48 ± 0.45^{a}
Manganese (Mn)	64 ± 73^{d}	45 ± 158^{c}	3 ± 6^{ab}	14 ± 40^{b}	17 ± 39^{b}	2 ± 2.5^{a}
Iron (Fe)	24 ± 120^{a}	13.4 ± 26^{a}	48 ± 170^{b}	23 ± 105^{a}	13 ± 11^{a}	88 ± 149^{c}

Mean ± Standard Deviation, n = 5 farms per site. Values followed by the same letter in a row are not significantly different at $p < 0.05$.

both sites ($p < 0.05$) (Table 2). The Mn in leaves may supply from 71% - (>100%) of the RDA. The RDA is 2 mg/day (Trumbo et al., 2001a) for adults, rations of 100 g/day may provide the necessary daily allowance to avoid toxicity.

The excessive amounts of Mn in leaves would be expected to cause manganese toxicity (He et al., 2022). However, since no evidence of manganese toxicity from dietary Mn intake has been documented (Evans and Masullo, 2020; Finley et al., 2003; Greger, 1998) and further, humans can maintain stable tissue levels of Mn through homeostatic control of both its absorption and excretion, this ensures only a small percentage of dietary manganese is absorbed and the excess is excreted very rapidly into the gut via bile (Silva et al., 2019). Hence, the high concentrations of Mn reported for leaves or corms in this study may not have negative health implications if consumed.

Iron content in leaves showed no significant difference ($p > 0.05$) for young and mature leaves from Umbumbulu, similarly with Snembe leaf tissues ($p > 0.05$). However, young leaves contain more iron than mature leaves since they have double the iron content of mature leaves. Iron content in leaves (Table 2) may potentially provide about 13–30% of the required RDA 600–1.800 g of servings for males (8 mg) and females (18 mg) of all ages, respectively (Piskin et al., 2022). Jalali and Fakhri (2021) studied *Allium ampeloprasum* and *Taraxicum vulgare* and discovered that these wild edible plants (WEPs) supply approximately 29% and 47% of the RDA for males and 13% and 21% for females, respectively. Additionally, (Longvah et al., 2017) documented potential RDA values of *Colocasia esculenta* (3.41 mg/100 g), *Spinacea oleracea* (2.95 mg/100 g), and *Brassica juncea* (2.84 mg/100 g) as 43%, 37%, and 36% for males and 19%, 16%, and 16% for females respectively.

Interestingly, unlike other microelements, the corms from both sites had higher iron content ($p < 0.05$) (Table 2) than leaves with an excess of four times that of leaves and therefore would be a better source of iron to meet the RDA, more especially for pregnant women who require at least 27 mg/100 g in their daily diet (Muriuki et al., 2014). Iron is essential for DNA synthesis and the production of hemoglobin, necessary for oxygen transport, and therefore necessary for preventing anemia (Abbaspour et al., 2014).

Iron transportation within various parts of the plant is linked to different complex biochemical processes, genetic codes, and protein mechanisms (Kobayashi and Nishizawa, 2012). The higher Fe concentration in corms than in leaves is possibly linked to Heat Shock Cognate Protein B (*At*HSCB) which regulates iron translocation from roots to shoots (Upadhyay, 2022). Overexpression of *At*HSCB causes over-accumulation of Fe in roots than in leaves (Mahawar et al., 2022). It is therefore possible that the corms have a higher concentration of *At*HSCB, or the protein could be overexpressed.

These results showed leaves to have significantly higher proportions of macro and micronutrients than reported for exotic leafy vegetables like cabbage or spinach (Butnariu and Butu, 2015; Bwembya et al., 2018; Hussain et al., 2009; Lewu and Kambizi, 2015).

3.3. Effect of harvesting of leaves on corm production

Colocasia leaves have the immense potential to contribute to alleviating micronutrient deficiencies and hence the overall mitigation of food insecurity. However, when utilizing *Colocasia esculenta* leaves as a green leafy vegetable premature harvesting of the leaves must take place. (Shields and Wyman, 1984) determined that defoliation of the upper leaves of 'Superior' and 'Russet Burbank' cultivars potatoes during full bloom resulted in significant yield loss while 10% of lower leaf loss during full bloom on 'Russet Burbank' plants resulted in tuber yield loss. (Dukuh, 2011) examined the effect of defoliation on *Ipomoea batatas* L. sweet potato tubers and found a significantly high effect on tuber sprouting in the field. The number of days of defoliation also had an immense impact on increasing tuber sprouting.

Other studies have also shown that increasing the frequency of *Ipomoea batatas* var. Bophelo vine harvesting improved leaf yield, but total storage root yield decreased (Dukuh, 2011; Gomes and Carr, 2003; Gomes and Carr, 2001). Further, Nyathi et al. (2019) investigated the effect of vine harvesting on the storage root yield of orange-fleshed sweet potato and found that vine harvesting reduced storage root yield and reduced micronutrients such as zinc and iron concentrations in the storage root thus decreasing the potential of utilizing the orange-fleshed sweet potato as a dual-purpose food crop for commercialization. However, on a subsistence scale, dual-purpose food crop practice is recommended as the availability of edible nutritious leaves would supplement micronutrients that are low in the starchy underground storage roots. Therefore, the harvesting of young and mature leaves of *Colocasia esculenta* may potentially reduce underground production of root crops, but improve nutritionally balanced diets for impoverished communities.

3.4. Proximate composition

Moisture content in young and mature leaves from Umbumbulu did not differ significantly ($p > 0.05$), but young leaves had a higher moisture content than the corms from Snembe ($p < 0.05$) (Fig. 2a). High moisture content is indicative of freshness but is also associated with low shelf life (Gogo et al., 2017). The high moisture content observed in *amadumbe* tissues is within the range documented for taro (60 – 83%) and comparable to other leafy vegetables (Azubuike et al., 2018; Temesgen and Retta, 2015).

Young and mature leaves from both populations contained significantly higher amounts of protein than corms ($p < 0.05$) (Fig. 2b). Proteins facilitate the body to combat infections and are a major energy supplier (Temesgen and Retta, 2015). Temesgen and Retta (2015) showed that the essential amino acids, methionine, lycine, cystine, phenylalanine, and leucine are relatively more abundant in the leaves than in the corms. The results of this study demonstrated that leaves have higher protein content than the previously cited amount in taro (23%) (FAO, 1999). Communities consuming both the leaves and corms will ideally receive higher protein compared to people including only corms in their diets.

Mature leaves from both populations had significantly ($p > 0.05$) higher fat content than young leaves (Fig. 2c). Further, compared to other organic components, the percentage of fat was also significantly ($p < 0.05$) lower in both the leaves and corms (Fig 3c). The low-fat content in the leaves is advantageous for people suffering from obesity (Lewu et al., 2009). The mature leaves from the Umbumbulu population

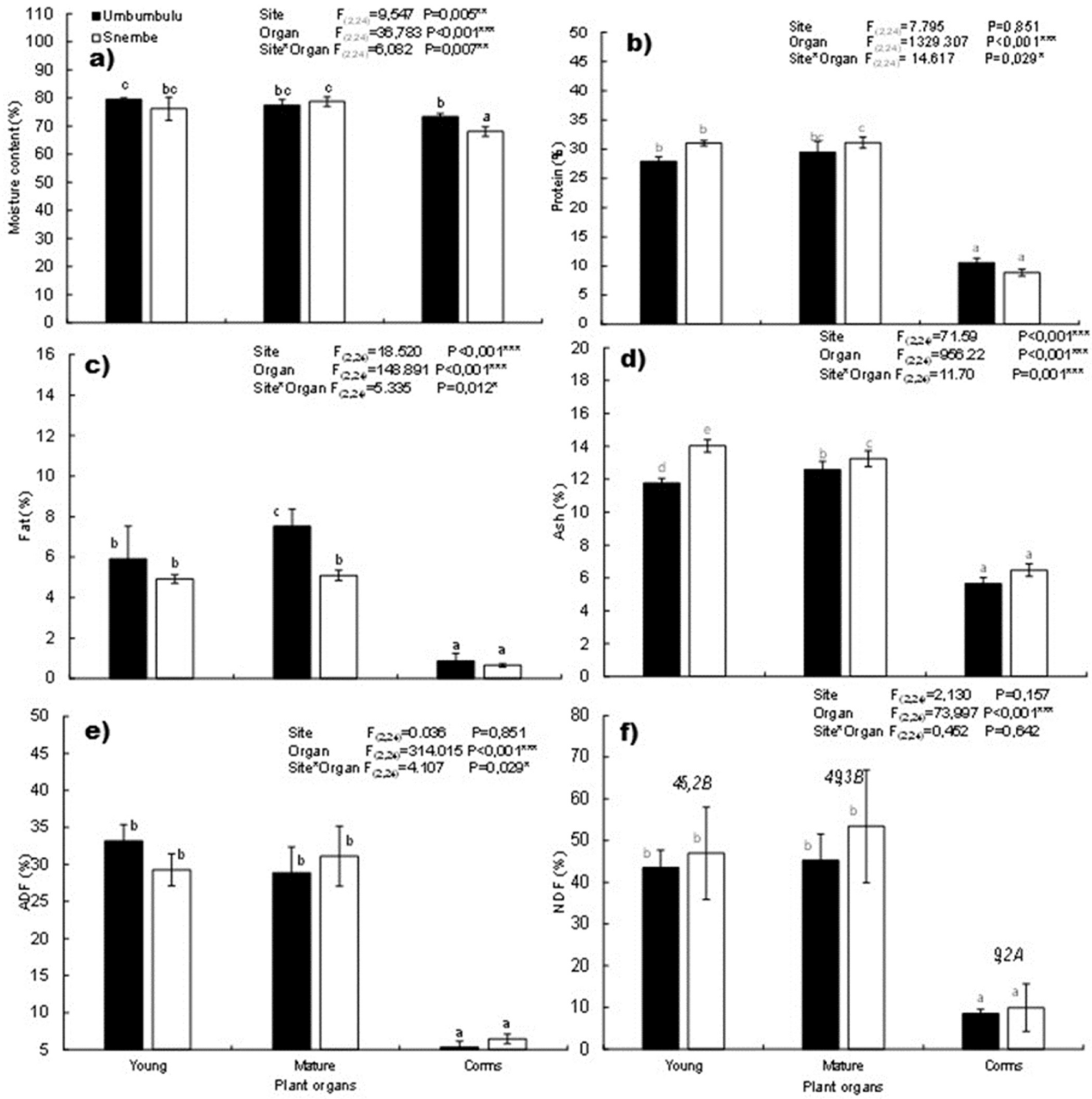

Fig. 2. Proximate composition of different tissues of *Colocasia esculenta* from Umbumbulu and Snembe sites of KwaZulu-Natal province of South Africa. A) Moisture content in leaf and corm tissues; B) Protein content availability in *Colocasia* leaves and corms; C) Fat concentrations in leaves and corm tissues; D) Ash content; E) ADF content; F) NDF content. Bars represent mean ± standard error. Different letters denote significantly different means at $p < 0.05$ using Tukey HSD.

had significantly ($p < 0.05$) higher ash content than young leaves, but the opposite was true for the Snembe population (Fig. 2d). Ash content is directly correlated to mineral content and therefore mature leaves from the Umbumbulu generally contained higher mineral content than young leaves, contrary to the young leaves from the Snembe population (Fig. 2d; Table 1; 2). The ash content of the leaves is above previously documented ranges for *C. esculenta* tissues (3.5 – 7.8%) (Temesgen and Retta, 2015), confirming their suitability as a mineral-rich leafy vegetable.

Young and mature leaves from both the Umbumbulu and Snembe populations showed no significant differences ($p < 0.05$) in ADF (Fig. 2e) and NDF (Fig. 2f). However, ADF and NDF content was significantly lower in corms than in leaves from both populations. ADF and NDF values are inversely related to digestibility (Stergiadis et al., 2015); therefore, leafy vegetables with low ADF concentrations are usually more digestible thus releasing more nutrients. Further, NDF and ADF digestibility depends on the age of the organ (Salama, 2019). According to (Van Soest et al., 1991), NDF increases as forage matures. While the results conform to (Van Soest et al., 1991) in NDF, these values are not significantly different between young and mature leaves and are even lower than previously cited levels of 38% (Giang et al., 2010). Hence both young and mature leaves indicate similar and appreciable digestibility. However, corms would be more digestible than leaves based on their low ADF and NDF values. In addition to aiding in digestion, leaves have been found to support the growth of beneficial gut and intestinal microbes such as *Escherichia coli* and *Lactobacillus acidophilus*, that help digestion and fight against harmful microbes (Saenphoom et al., 2016).

3.5. Oxalate content

Young and mature leaves from both sites showed no significant difference in total oxalate content (Table 3). The total oxalate content in leaves from both sites was significantly lower ($p < 0.05$) than in corms, with corms from the Umbumbulu site having more than two times higher oxalate content and corms from the Snembe site having up to three times more oxalate than leaf oxalate content (Table 3). Similarly, for insoluble oxalate content, no significant differences ($p > 0.05$) were observed in young and mature leaves from both sites. Leaves contained lower amounts of insoluble oxalate compared to corms with more than five times higher concentrations. Soluble oxalates were lowest in the corms. No significant differences were observed for soluble oxalates in leaf and corm tissue except for corms from Snembe that contained significantly ($p > 0.05$) lower soluble oxalates (Table 3).

The presence of oxalates in food is considered antinutritional due to its negative effects on the consumer after consumption (Samtiya et al., 2020). Oxalates are present in almost all plants as a natural defense mechanism against grazing animals by producing acridity, causing lip and mouth swelling (Mitharwal et al., 2022). Total oxalate is always the sum of both dietary soluble and insoluble oxalates. Soluble oxalates bind with minerals such as K^+, and Na^+ rendering them unabsorbed through the intestinal wall into the bloodstream. Hence excessive intake of soluble oxalates can lead to the formation of kidney stones (Mitharwal et al., 2022; Savage and Dubois, 2006).

Insoluble oxalates however occur as salts of CaOx, MgOx, and FeOx which are usually excreted, and therefore more preferred than soluble oxalates. The results indicated that both young and mature leaves had significantly lower total and insoluble oxalates than corms from both sites and indeed lower than in spinach which is among leafy vegetables with the highest oxalate content of 658 mg/100 g; (Bargagli et al., 2009). These results also corroborate those of Mitharwal et al. (2022) who observed higher total and insoluble oxalate content in corms than in leaves. Cooking and other processing methods have been used to reduce the negative effects of oxalates in corms e.g., boiling taro corm at 90°C for 30 min and steeping in water at 30°C for 24 h can reduce the oxalate-salt content to 32.7% and 56.7%, respectively, of its original content (Temesgen and Retta, 2015). Similarly, boiling the leaves was found to significantly reduce oxalate content (Du Thanh et al., 2017).

3.6. Plant-soil interactions

The pH of the soil from the Snembe site was 5.42, significantly ($p < 0.05$) higher than the soil pH of 4.76 at the Umbumbulu site. Apart from magnesium which was significantly ($p < 0.05$) higher in Umbumbulu, Snembe soil was significantly higher in all other macronutrients (Table 4). While a higher level of nutrients in the Snembe soil appeared to correspond to higher nutrient levels in the plant tissues for some elements, in others there was no clear direct relationship. For example, phosphorus was 6 times higher in the Snembe soil corresponding to significantly higher levels of phosphorus specifically in mature leaves and corms, compared to mature leaves and corms from the Umbumbulu site.

Potassium was 2.5 times higher in the Snembe soil and this corresponded to a significantly higher content of potassium in both young and mature leaves but not in the corm (Table 1; Table 4). However, calcium was 1.8 times and magnesium was 0.4 times more abundant in the Snembe soil, significant differences ($p < 0.05$) were observed in the magnesium content in the plant tissues from both sites. Nutrient uptake and translocation are influenced by several factors (Malik, 2009). While nutrients may be abundant in the soils they must be in a readily absorbable form (Bhatla & Lal, 2018). In addition, several mechanisms enable plants to maximize their nutrient acquisition from the soil and at the same time also protect against the accumulation of these nutrients at toxic levels (Osvalde, 2011). These mechanisms are influenced by factors such as soil properties (e.g., structure, composition, pH), plants' characteristics (e.g., root structure, high or low-affinity transport systems), microorganisms (e.g., symbiotic bacteria, mycorrhiza), and the presence of synergistic or antagonistic minerals (Osvalde, 2011).

Similarly for micronutrients, despite Zn being exceptionally higher (28-fold) in the Snembe soil than in the Umbumbulu soil, this only resulted in slightly higher but insignificant differences in Zn content in young and mature leaves from the Snembe site. Copper was also significantly ($p < 0.05$) higher in Snembe soil, but plant tissues showed significantly lower levels compared to the same tissues collected from Umbumbulu (Tables 1 and 4). An exception was in manganese concentration which was significantly higher in the Umbumbulu soil and appeared to directly influence significantly higher levels of manganese in both young and mature leaves from Umbumbulu. Manganese solubility in soil solution is dependent on pH, organic matter, and the presence of antagonistic minerals (Ghasemi-Fasaei and Ronaghi, 2008). Acceptable pH ranges for Mn availability in the soil are 5 – 6.5. Lower ranges such as 4.76 that of soil in Umbumbulu promote excessive Mn^{2+} availability.

The significantly ($p < 0.05$) higher iron concentration in the Snembe soil did not appear to cause significant differences in leaf tissue iron content but resulted in considerably high amounts of iron in corms (Table 1) collected from Snembe. Iron uptake from the soil and translocation from the corm to the leaves may be linked to Heat Shock Cognate Protein B (*At*HSCB) (Leaden et al., 2016) and hence higher soil iron levels in Snembe may have translated to the high iron levels in Snembe corms.

Table 3
Oxalate content in tissues of *amadumbe* plants from Umbumbulu and Snembe sites.

	Umbumbulu			**Snembe**		
	Young	*Mature*	*Corms*	*Young*	*Mature*	*Corms*
Oxalate (g/100 g)						
Total	15 ± 0.70^{ab}	18 ± 1.8^{b}	38 ± 2.5^{c}	11 ± 1.6^{a}	12 ± 3.3^{ab}	39 ± 1.8^{c}
Insoluble	10 ± 0.60^{a}	14 ± 2.6^{a}	35 ± 3.6^{b}	7 ± 1.5^{a}	8 ± 3.1^{a}	37 ± 21.7^{b}
Soluble	5 ± 0.80^{b}	5 ± 0.80^{b}	3 ± 0.80^{ab}	4 ± 0.20^{b}	4 ± 0.3^{b}	2 ± 0.3^{a}

Mean ± SD, n = 5 farms per site. Values followed by the same letters in a row are not significantly different at ($p < 0.05$).

Table 4
Soil nutrient content in Umbumbulu and Snembe sites.

Parameters (mg/kg)	**Umbumbulu**	**Snembe**
P	69 ± 24^{a}	412 ± 80^{b}
K	1521 ± 336^{a}	3785 ± 231^{b}
Ca	18694 ± 4451^{a}	33301 ± 6056^{b}
Mg	6315 ± 984^{a}	2556 ± 371^{b}
Zn	20 ± 8^{a}	553 ± 104^{b}
Cu	97 ± 10^{a}	166 ± 39^{b}
Mn	154 ± 28^{a}	108 ± 16^{b}
Fe	2467 ± 308^{a}	3475 ± 213^{b}

Mean±SD, n = 5 farms per site. Values followed by the same letters in a row are not significantly different at ($p < 0.05$).

4. Conclusions

Establishing the nutrient profile is essential due to the importance of green leafy vegetable consumption in the human diet and the impact on disease prevention. Our findings strongly suggest that the plant parts are promising sources of essential nutrients. Specifically, potassium (K), calcium (Ca), manganese (Mn), and iron (Fe) were the most abundant among both macro and microelements. *Colocasia* leaves can contribute significantly to meeting the requirements for potassium and calcium, manganese, and iron, respectively, provided that factors such as oxalates are processed thoroughly to avoid mineral binding and unavailability. Suitable cooking methods that would minimize excessive leaching of minerals should be adopted. The consumption of green leafy vegetable species can potentially provide health benefits owing to their nutritional profile. These vegetables offer a cost-effective source of nutrition, particularly for rural communities. Since taro is a minor crop in South Africa, and production is mainly subsistence, interval harvesting of leaves is not recommended for commercial production but rather supported for small-scale self-sustenance farmers to balance trade-offs.

CRediT authorship contribution statement

Zwelonke Beato: Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing, Visualization. **Lucy N. Gitonga**: Conceptualization, Supervision, Writing – review & editing, Visualization. **Eric Amonsou**: Validation, Supervision, Funding acquisition, Resources. **Viloshanie Reddy**: Supervision, Writing – review & editing, Resources, Visualization.

Declaration of Competing Interest

"None."

Data availability

The data that has been used is confidential.

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Authors Statement

I declare that an accurate description of my work has been provided and that I am a sole contributor where necessary and I have acknowledged all parties involved.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jfca.2023.105831.

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