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ORIGINAL PAPER

Nutritional potential of tamarind (*Tamarindus indica* L.) from semi-arid and subhumid zones of Uganda

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Abstract
It has been reported that plants that experience some form of stress while growing tend to accumulate increased levels of nutrients that are useful to humans. We compare the proximate and mineral composition of *Tamarindus indica* leaves, fruit pulp and seeds from Uganda's semi-arid and sub-humid zones with contrasting environmental conditions including temperature, rainfall, soils and geology. Samples were analyzed following standard AOAC procedures. Mineral content was in the order K > Ca > Mg > Na > Fe and K > Mg > Ca > Na > Fe for the semi-arid and subhumid zones respectively. *Tamarindus indica* fruit pulp and leaves from both zones plus seeds from the semi-arid zone contained the Na/K ratio of < 1 recommended by World Health Organisation for prevention and treatment of cardiovascular diseases. Proximate composition for leaves, fruit pulp and whole seeds were in the following ranges: Moisture content (9.83–69.42%), ash (1.93–11.6%), carbohydrate (64.74–88.7%), crude lipid (0.96–3.57%), crude fiber (0.89–14.93%), and crude protein (4.59–14.82%). Leaves contained higher levels of crude protein, crude lipid and crude fibre than fruit pulp. *Tamarindus indica* from the semi-arid zone tends to accumulate nutrients in ways that better promote human health. *Tamarindus indica* from both zones has high potential to provide functional foods and livestock feeds.

Keywords Agro-ecological · Mineral composition · Proximate composition · Semi-arid · *Tamarindus indica* L.

Introduction

Wild and semi wild plant species play an important role in maintaining human and environmental health particularly in relation to global food security and sustainable development [1]. Sub-Saharan Africa has the highest prevalence of undernourishment in the world with at least one in every four persons undernourished [2, 3]. Sub-Saharan Africa is divided into eight agro-ecological zones and Karamoja drylands and Kyoga plains of Uganda where the study was carried out fall under the Tropic-warm semiarid and Tropic-warm subhumid zones respectively [4]. According to the Food and Agriculture Organization (FAO) an agro-ecological zone is a land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use [5].

Tamarind (*Tamarindus indica* L.) is an indigenous fruit tree of the tropics belonging to family Fabaceae (Leguminosae), subfamily Caesalpinioideae [6]. The species has a wide geographical distribution in the subtropics and semi-arid tropics and is cultivated in numerous regions including Africa, Asia and the Americas [6]. It grows both in the wild and on farms and is widely used as a flavouring in foods, sauces and juices due to its unique characteristics [6]. The tree is also valued for wood, aesthetics, shade and other environmental benefits but currently underutilized worldwide [6]. *Tamarindus indica* is indigenous to the semi-arid and subhumid zones of Uganda [7] and is highly valued especially during times of food scarcity [8]. Khairunnuur et al. [9] reported nutritionally useful quantities of protein and carbohydrate in tamarind pulp and seed

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extracts. The phytonutrients in tamarind pulp and seeds extracts are reported to be powerful dietary antioxidants [9, 10]. *Tamarindus indica* fruit pulp is reported to be rich in calcium, phosphorus, potassium with significant amounts of iron, sodium, copper, zinc and nickel [6, 9, 11]. Tamarind leaves are reported to be rich in minerals particularly Phosphorus, Potassium, Calcium and Magnesium [6]. *Tamarindus indica* is highly resilient to disease attacks, is wind resistant and grows under a variety of soil and agro-climatic conditions [6, 12].

Several studies have demonstrated the influence of climatic and other environmental conditions on the nutrient content and levels of plants growing in particular areas [13, 14]. According to FAO [15], besides the mineralogical composition of the parent material, the total amounts of trace elements present in soils depend on the type and intensity of weathering and on climatic and other factors predominating during the process of soil formation. Crosby et al. [16] asserted that the phytochemical profiles of crops are modified by several factors including soil characteristics, fertilization timing/amount and the physiological status of the plant. It has been observed that crops that experience some form of stress while growing tend to accumulate more nutrients useful to man as compared to those growing under less harsh conditions [14]. Semiarid areas such as Karamoja experience harsh environmental conditions including prolonged drought, high temperatures and low humidity and their soils tend to have low humus content due to scanty vegetation cover as compared to the subhumid zone [4, 17]. The study sought to compare nutrient content of *T. indica* growing under the semi-arid conditions with those of *T. indica* growing under subhumid conditions. Although some studies have been carried out on Ugandan tamarinds [18], none has compared the nutrient composition of *T. indica* growing under the harsh semi-arid conditions to that growing under the more conducive subhumid zone. It was therefore pertinent to compare the nutrient composition of *T. indica* from the two zones in order to find out the variations under contrasting environmental conditions. Furthermore this study includes *T. indica* leaves which have not been reported on previously. The study therefore aimed at assessing the variations in nutritional composition of three *T. indica* parts used for food from the semiarid and subhumid zones of Uganda with contrasting environmental conditions including temperature, rainfall, geology and soils. It was hypothesized that given the harsh environmental conditions, *T. indica* from the semi-arid zone accumulates higher levels of nutrients beneficial to human health compared to that from the subhumid zone. The specific objective was to compare the variations in proximate and mineral composition of fruit pulp, leaves and seeds of *T. indica* from semi-arid and subhumid zones of Uganda.

Materials and methods

Background to study areas

Karamoja drylands and Kyoga plains agro-ecological zones are part of the *T. indica* natural range in Uganda [7] and were purposively selected to represent the semi-arid and subhumid zones respectively. The two study areas are among those most affected by food and nutrition insecurity whose severity has been aggravated by climatic fluctuations [17, 19].

Karamoja drylands in North-Eastern Uganda lies between longitudes 33° 38′–34° 46′ E and latitudes 1° 53′–3° 05′ N. It experiences semi-arid type of climate characterized by one rainy season extending from April to September and one dry season from October to March. Temperatures range between 15 and 33 °C [17]. Rainfall is low totaling 400–600 mm annually. Vegetation includes isolated thorny trees and shrubs [20]. The major geological formations are mid-Tertiary alkaline igneous rocks while soils are mostly black clays and dark grey clays, with moderate moisture storage capacity [17].

The Kyoga plains lie between longitudes 33°–34° E and latitudes 0°–1° N. It experiences a sub-humid climate characterized by higher rainfall totals with two rainy seasons. Temperatures range between 15.7 and 30.6 °C. Average annual rainfall is 1495 mm but ranges between 1130 and 1730 mm. Vegetation ranges from medium altitude forests through swamps to savannas. The geology consists largely precambrian rocks of basement complex including a variety of granites, gneisses and quartzites. Soils are ferralitic, mainly sandy loams and largely undifferentiated into horizons [19].

Study sites

Karamoja drylands and Kyoga plains agro-ecological zones were purposively selected to enable comparison of *T. indica* nutritional composition under contrasting climatic and environmental conditions. A list of districts with *T. indica* populations was generated for each zone and two districts were selected randomly from each list. A list of subcounties with tamarind populations within the two selected districts in each zone was then generated and five subcounties were selected randomly from the list. Figure 1 shows the location of study sites.

Sample trees were selected from wild or semi-wild populations. Up to five *T. indica* sample trees were selected per sampling site based on ease of access, presence of good mature pods and absence of obvious signs of pests and diseases.

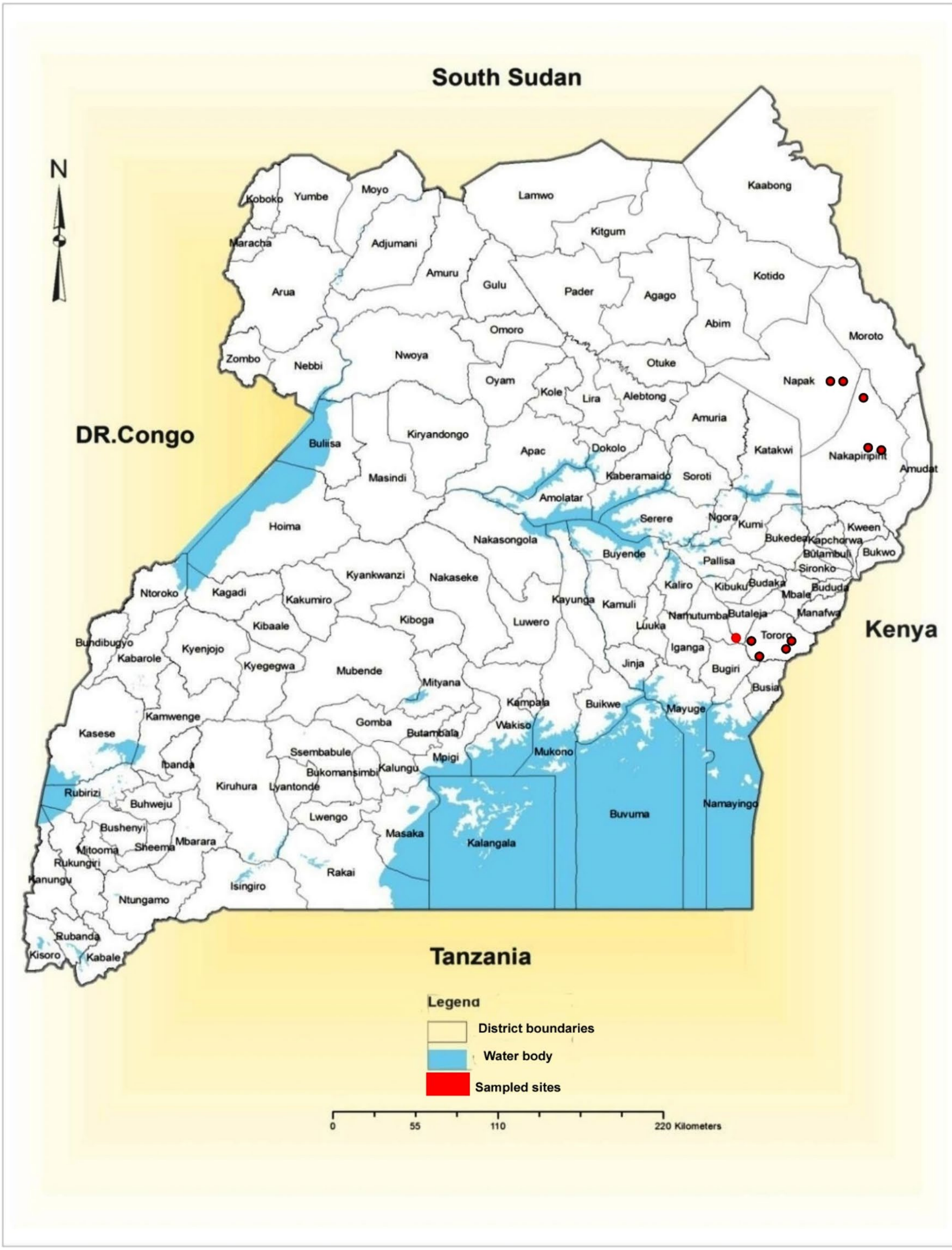

Fig. 1 Map of Uganda showing location of study sites

Sample collection and preparation

For each plant part, equal portions were collected from the five subcounties selected per zone (thus five replicates) and combined to make the bigger sample. Leaves and mature ripe pods were collected from lower, middle and upper parts of selected trees. Mature ripe pods were considered to be those with brown, woody fragile shell containing fruit pulp and seeds [6]. Ladders were used to climb the trees and a sharp knife used to sever the pods and leaves from the stalk. Samples were removed carefully so as to minimize damage to the trees. Leaf samples were transported in a cooler at 10 °C. Pods were carefully broken to expose the fruit pulp which was then carefully removed using a pair of scissors and placed in clean, dry, well-labelled polythene bags. The seeds were obtained manually and placed in clean, dry, well-labelled polythene bags.

Each of the three samples (viz leaves, fruit pulp and whole seeds) from each zone was divided into four portions. One portion of the fresh sample was used for moisture content analysis, while three portions of the fruit pulp and seed samples were dried in an oven (Heraeus D-6450 Hanau) at a temperature of 40–60 °C for three days. The leaf samples were air dried at room temperature for seven days. The dry samples were pulverized in an electric grinder (Brooks Crompton Series 2000, UK) and stored in sealed plastic containers in the laboratory prior to proximate and mineral analysis.

Proximate analyses

Analyses for moisture content, dry matter, ash, organic matter, lipid content and crude fiber were carried out in triplicates according to standard Association of Official Analytical Chemists (AOAC) procedures [21]. Crude protein was determined by the Kjeldahl method (method number 978.04), nitrogen content was converted to protein by multiplying by 6.25 [21]. Carbohydrate content was determined by difference [21]. The sum of percentages of moisture content, fat, ash, crude fiber and crude protein was subtracted from 100 to get the amount of nitrogen free extract also known as carbohydrate as follows:

$$\%\ \text{carbohydrate} = 100 - (\%\ \text{moisture content} + \%\text{fat} + \%\text{ash} + \%\text{crude fiber} + \%\text{crude protein}).$$

All proximate values were expressed as percentage of sample analyzed. Calorific values were estimated (in kcal/g) by multiplying the percentages of crude protein, crude lipid and carbohydrate with the recommended factors (2.44, 8.37 and 3.57 respectively) [10].

Analyses for mineral content

Mineral content of Iron, Potassium, Sodium, Calcium and Magnesium was determined according to standard AOAC procedures [21]. Specified standards were used. All chemicals were of analytical grade. All values were expressed in mg/100 g.

Statistical analysis

All experiments were conducted in triplicate. Proximate and mineral composition data were compared using the Statistical Package for Social Scientists version 16.0 software program (SPSS software, release 16.0, SPSS Inc.). Means, standard deviations were determined, analysis of variance were performed to calculate significant differences in means of proximate and mineral composition data using the Tukey technique. $p < 0.05$ was used for separation of means.

Results

Proximate composition

Moisture, ash, carbohydrate, crude lipid, crude fiber, and crude protein contents for leaves, fruit pulp and whole seeds were in the following ranges: 9.83–69.42%, 1.93–11.6%, 64.74–88.7%, 0.96–3.57%, 0.89–14.93%, 4.59–14.82% respectively. Details of the results for proximate analysis of *T. indica* leaves, fruit pulp and whole seeds are presented in Table 1.

Carbohydrate content recorded the highest values of all the proximates measured. It ranged from 64.74 to 88.7% for leaves, fruit pulp and seeds. High values of crude protein were recorded in whole seeds and leaves. These values lay in a similar range and were more than double the values for fruit pulp. Estimated calorific values for the three plant parts ranged from 266.96 to 342.97 kcal/100 g. Details are shown in Fig. 2.

Ash content is an indicator of mineral content. Ash had the largest ranges between corresponding *T. indica* products as well as among the three edible portions. Moisture content gives an indication of water soluble vitamins present and was highest in leaves.

Mineral composition

Potassium was the most abundant mineral with highest values recorded in fruitpulp from the semiarid zone. Mineral content was in the order K > Ca > Mg > Na > Fe for the semi-arid zone and K > Mg > Ca > Na > Fe for the subhumid zone. The sodium/potassium (Na/K) ratio in the body is important in controlling high blood pressure and a Na/K ratio of < 1 is recommended by WHO for prevention and treatment of cardiovascular diseases [22]. *Tamarindus indica* fruit pulp and leaves from both zones plus seeds from the semi-arid zone contained the WHO recommended Na/K ratio. Detailed results for mineral content are presented in Table 2.

Tamarindus indica leaves recorded consistently higher levels of calcium and magnesium compared to fruit pulp. The richest source of magnesium was leaves at 344.5 mg/100 g and 154.5 mg/100 g for subhumid and semi-arid zones respectively. Iron content was consistently higher in the subhumid zone than semi-arid zone for the three sampled parts. Iron content in leaves, fruit pulp and seeds ranged between 13.25–20.1 and 6.45–11.6 mg/100 g for subhumid and semi-arid zones respectively.

Table 1 Comparison of proximate composition of *T.indica* leaves, fruitpulp and whole seed by agroecological zone

Moisture content and nutrients	Plant part	Semi-arid zone	Subhumid zone
Moisture content (%)	Leaf	69.42 ± 0.54^{a}	66.04 ± 0.21^{b}
	Fruit pulp	25.82 ± 0.43^{b}	28.98 ± 0.07^{a}
	Whole seed	9.83 ± 0.18^{b}	14.63 ± 0.03^{a}
Ash (%)	Leaf	4.65 ± 0.40^{b}	6.22 ± 0.30^{a}
	Fruit pulp	10.98 ± 0.04^{a}	4.81 ± 0.02^{b}
	Whole seed	1.93 ± 0.06^{b}	11.60 ± 0.28^{a}
Crude lipids (%)	Leaf	3.20 ± 0.01^{a}	1.12 ± 0.01^{b}
	Fruit pulp	1.69 ± 0.02^{a}	0.96 ± 0.01^{b}
	Whole seed	3.31 ± 0.02^{a}	3.57 ± 0.26^{a}
Crude fibre (%)	Leaf	14.40 ± 0.01^{a}	14.93 ± 0.03^{a}
	Fruit pulp	0.89 ± 0.13^{a}	0.93 ± 0.01^{a}
	Whole seed	2.96 ± 0.01^{a}	2.95 ± 0.01^{a}
Crude protein (%)	Leaf	13.14 ± 0.50^{a}	11.65 ± 0.19^{b}
	Fruit pulp	4.59 ± 0.20^{a}	4.62 ± 0.33^{a}
	Whole seed	11.08 ± 0.78^{b}	14.82 ± 0.06^{a}
Carbohydrates (%)	Leaf	64.74 ± 0.12^{b}	66.17 ± 0.11^{a}
	Fruit pulp	83.40 ± 0.42^{b}	88.70 ± 0.33^{a}
	Whole seed	81.24 ± 0.01^{a}	68.53 ± 0.06^{b}

Means in rows with the same letter as superscript are not significantly different while means in rows with the different letter as superscript are significantly different at $P < 0.05$

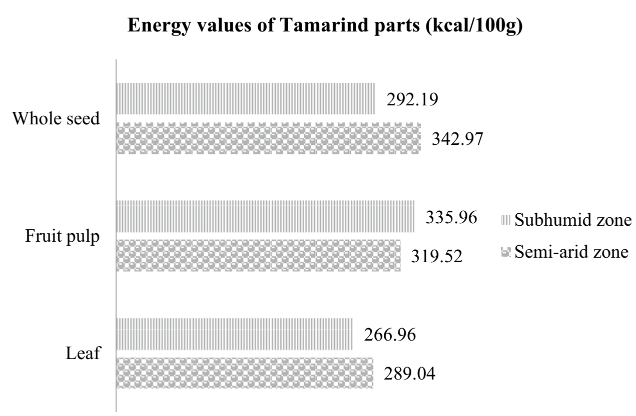

Fig. 2 Comparison of energy values of *T. indica* seeds, fruit pulp and leaves

Discussion

Soil minerals exert significant direct and indirect influences on the supply and availability of most nutrient elements [15]. In this study, ash content had large ranges between plant parts (1.93–11.6%). This observation regarding ash levels is notably a reflection of differences in the way nutrients are stored by plants in the different parts [23]. The large ranges between ash values for corresponding plant parts zones can be attributed to differences in mineral composition of the soils which are a result of variations in rates and types of weathering due to differences in nature of parent rock of the specific locations in which tamarind trees grow and climatic factors especially rainfall and temperature [15, 16]. For instance, at 10.98% ash content for fruit pulp from the semi-arid zone more than doubles that for the subhumid zone at 4.81%. Okello [18] reported a range of 2.2–5.0% ash content for seeds and fruit pulp for Ugandan tamarinds. El-Siddig et al. [6] report a range of 2.1–3.3% for tamarind fruit pulp, [24] report a range of 4.53–7.91% for fruit pulp from Kenyan tamarinds while Yusuf et al. [10] report 7.35% and 9.51% for whole seeds and seeds nuts respectively for Nigerian tamarinds.

According to Crosby et al. [16] mineral nutrients influences phytochemical content both directly and indirectly. Processes that affect the uptake, transport and metabolism of inorganic mineral nutrients thus influence phytochemical profiles. In this study potassium, which influences many Potassium-dependent functions such as transport processes and stress tolerance in plants [15, 16], recorded the highest values of all the minerals analysed.

According to Stenberg et al. [25] 'Soil minerals generally account for half the soil volume. Their type, proportions and concentrations ultimately determine important properties such as texture, structure, and cation exchange capacity.' Zebire et al. [26] assert that the Potassium content of a given soil depends on the climatic condition and degree of soil development, the intensity of cultivation, and the parent materials from which the soil is formed and particle size distribution. Potassium availability for plant uptake is

Table 2 Comparison of mineral composition (mg/100 g, Mean ± SEM) of edible portions of *T. indica* by agroecological zone

Minerals	FAO/WHO RNI†	Plant part	Semi-arid zone	Subhumid zone
Iron (mg)	14 mg†	Leaf	11.60 ± 0.14[b]	13.25 ± 0.35[a]
		Fruit pulp	8.45 ± 0.07[b]	16.75 ± 0.35[a]
		Whole seed	6.45 ± 0.35[b]	20.10 ± 0.14[a]
Calcium (mg)	1000 mg†	Leaf	496.60 ± 0.57[a]	122.75 ± 0.35[b]
		Fruit pulp	113.05 ± 0.21[a]	86.50 ± 0.71[b]
		Whole seed	115.00 ± 0.00[b]	184.75 ± 0.35[a]
Magnesium (mg)	300 mg†	Leaf	154.50 ± 0.71[b]	344.50 ± 0.71[a]
		Fruit pulp	131.50 ± 0.71[b]	324.75 ± 0.35[a]
		Whole seed	149.50 ± 0.71[b]	294.00 ± 1.41[a]
Potassium (mg)	3510 mg‡	Leaf	767.75 ± 0.35[a]	451.50 ± 0.71[b]
		Fruit pulp	1156.50 ± 0.71[a]	1079.50 ± 0.71[b]
		Whole seed	49.20 ± 0.00[a]	32.75 ± 0.35[b]
Sodium (mg)	< 2 mg§	Leaf	33.25 ± 1.06[b]	75.50 ± 0.71[a]
		Fruit pulp	36.50 ± 0.71[b]	65.50 ± 0.71[a]
		Whole seed	16.75 ± 1.06[b]	72.50 ± 0.71[a]
Na/K ratio	< 1§	Leaf	0.044	0.168
		Fruit pulp	0.031	0.061
		Whole seed	0.34	2.212

Means in rows with the same letter as superscript are not significantly different. Means in rows with a different letter as superscript are significantly different at P < 0.05

†[22]

‡[28]

§[29]

†FAO/WHO Recommended nutrient intake (RNI) is the daily intake which meets the nutrient requirements of almost all (97.5%) apparently healthy individuals in an age- and sex-specific population [22]

dependent on its release from the weathering of primary soil minerals [25]. 'Potassium is a vital element for plant and animal health playing an important role as a mineral nutrient in the synthesis and accumulation of other phytochemicals in plants'. [15]. Potassium is essential for controlling the salt balance in human tissue [27]. WHO recommends 3510 mg of Potassium per day for an adult [28] thus consuming 100 g of *T. indica* pulp a day would be adequate. *Tamarindus indica* leaves, fruit pulp and seeds possess a high potential for providing potassium when incorporated in the diet. Findings of this study concur with Brady's observation that Potassium is usually less in seed than in pulp samples due to its use in the different plant functions [23]. Soil Potassium supply and plant uptake are regulated by plant and environmental factors [15].

Sodium levels are of significance given the importance of the Na/K ratio in the body in controlling hypertension [29]. Sodium levels were significantly different in the two zones ($p < 0.05$). The differences could probably be attributed to differences in mineral content of soils in the two zones. Plants derive their minerals from soils whose mineral content is a direct reflection of the geological formation in the area in combination with other factors especially climatic factors [15, 25].

The fact that fruit pulp scored the lowest Na/K ratio in both zones is very significant given that it is the most popular tamarind product [8]. This finding concurs with indigenous knowledge and practice of *T. indica* use in the study areas whereby fruit pulp has traditionally been used to quicken recovery from sickness or stress, boost male sexual potency and mandatory for pregnant mothers and warriors [8].

Tamarindus indica fruit pulp and leaves from both zones plus seeds from the semi-arid zone contained the WHO recommended Na/K ratio [22]. We report this significant finding for the first time in literature. The optimum Na/K ratio of the various *T. indica* products plus the low lipid content of fruitpulp are desirable qualities which make *T. indica* an ideal low cost functional food for addressing hypertension and diabetes, two of the leading non-communicable diseases currently on the increase in Uganda [30].

Of the three edible portions, fruit pulp scored the lowest Na/K ratio in both zones thus most beneficial for health purposes. This finding is significant as it concurs with the popularity of fruit pulp as an ingredient in many traditional food recipes and medicinal preparations in the study area [8]. However the Na/K ratio for whole seeds from the subhumid zone was far above the WHO recommended range and significantly higher than the ratios for the other products thus need for further investigations.

Calcium is essential to bone structure and function [27]. Calcium, magnesium, phosphorus, manganese in conjunction with vitamins A, C, D, and protein are involved in bone formation [15]. *Tamarindus indica* leaves, fruit pulp and seeds can therefore serve as rich sources of minerals involved in bone formation.

100 g of *T. indica* (leaf powder, fruit pulp or seeds) from the subhumid zone is capable of providing adequate levels of iron to meet the RNI of 14 mg per day. The high levels of Iron show potential for addressing anemia, a common problem among pregnant and lactating mothers and children below 5 years [15].

According to Crosby et al. [16], the effects of soil fertility and mineral nutrient supply on yield, carbohydrate and protein content of food crops are well documented and related to soil type. Ben-Shahar and Macdonald [31] found that: 'High protein levels in mopane leaves correlated with elevated levels of nitrogen and phosphorus in the soils.' These differences were evident when comparing mopane plots that were situated more than 30 km apart in northern Botswana. Proteins play a key role in several life processes including catalyzing, regulating, protecting and providing energy and their deficiency can result into growth retardation, wasting of muscles, edema and kwashiorkor. Crude protein content ranged between 4.59 and 14.82% for leaves, fruit pulp and seeds. The values for crude protein were highest in leaves and whole seeds which had similar ranges and were more than double the protein values for the more popular fruit pulp. Both leaves and seeds are currently underutilized in the study areas [8]. *Tamarindus indica* leaves, seeds and fruit pulp thus hold potential to contribute to provision of much needed dietary protein in the study areas.

Crude protein content in fruit pulp from the two zones was not significantly different. Values for fruit pulp were within the range (2.0–9.1%) reported by El-Siddig et al. [6] while leaves and whole seeds recorded higher values (11.08–14.82%) thus indicating a higher potential to provide alternative sources of protein. *Tamarindus indica* fruit pulp, leaves and whole seeds values were all higher than those reported for fruit pulp of Ugandan shea butter tree fruit (*Vitellaria paradoxa*) whose range was 3.1–4.2% [32]. Given that annual fruit yield is estimated at 150–500 kg/tree and with a life span of up to 200 years [12], *T. indica* has great potential to address protein needs in resource poor communities. The high values of crude protein for leaves and whole seeds hold potential for alternative sources of protein for both humans and livestock to supplement traditional sources such as peas and beans.

Crude lipid content was highest in whole seeds. Yusuf et al. [10] recorded higher lipid values for Nigerian tamarind seednuts and whole seeds at 6.94% and 11.43% respectively. *Tamarindus indica* seed oil has been proposed as being suitable for industrial purposes [6, 9] thus could be exploited in the study areas to diversify income. The low lipid content in tamarind fruit pulp combined with an optimum Na/K ratio makes tamarind pulp especially appealing as a raw material for nutraceuticals to address obesity, hypertension and diabetes [33].

Crude fiber assists in maintaining normal peristaltic movement. Diets rich in fiber can minimize occurrence of disorders such as constipation, colon diseases, obesity, diabetes and cardiovascular diseases [33]. There was no significant variation between crude fiber content of corresponding tamarind parts as well as for crude lipids in whole seed ($p < 0.05$). *Tamarindus indica* products from both zones provide a valuable source of crude fiber.

Carbohydrates (sugars and starches) provide energy to cells in the body, particularly the brain, which is a carbohydrate-dependent organ [34]. Carbohydrate content was highest in fruit pulp thus accounting for its popularity as a snack. These values lay in similar ranges for the two zones for fruit pulp and leaves but values for whole seeds from the semi-arid were significantly higher than the subhumid zone. Carbohydrate values for leaves, fruit pulp and whole seeds in this study were in the ranges reported by El-Siddig et al. [6] for dried tamarind fruit pulp (56.7–82.6%) and Chiteva and Kituyi [24] for fruit pulp from Kenya (55.5–71.8%). The values in this study were observed to be much higher than those reported for whole seeds and seed nuts of tamarind from Nigeria (17.1% and 8.9% respectively) [10]. Carbohydrate values in this study are significantly higher than those reported by Okello [18] who recorded a range of 50.1–56.4 and 54.5–61.5 for fruit pulp and seeds respectively for Ugandan tamarinds.

Energy is required to sustain the body's various functions, including respiration, circulation, physical work, and protein synthesis [34]. The ranges for estimated calorific value (266.96–342.97 kcal/100 g) indicate that *T. indica* has potential to contribute significantly to energy needs especially during the lean period when food is scarce yet preparation of gardens involves labor intensive activities. Being a popular snack, *T. indica* fruit pulp contributes significantly to the Estimated Energy Requirement (EER) of 2200 (kcal) [34]. Residents commonly consume at least one pod of fresh ripe sweet tamarind equivalent to approximately to 3–8 teaspoonfuls of fruit pulp daily. *Tamarindus indica* can therefore supplement energy provided by the traditional staples such as millet and sorghum.

The nature of variations observed in proximate values can be attributed to differences in nature and rates of weathering. According to Qafoku [35], accelerated weathering of the rocks and minerals in soils are promoted by higher atmospheric carbondioxide concentrations (≥ 400 ppm) and temperature, intensive rainfall, and heat waves and extended periods of drought. Since temperatures are high in both zones, the higher rainfall in the subhumid zone allows for higher rates of chemical weathering resulting in more nutrients becoming available in soils compared to the semi-arid zone. However the heat waves and extended periods of drought experienced in the semiarid zone encourage physical weathering.

Nutritional potential of underutilized *T. indica* products

In both zones, *T. indica* leaves had significantly higher values of crude fiber, crude protein, and crude lipid compared to the more popular fruit pulp. This implies that a large proportion of consumers are missing out on nutrients that they could potentially get from *T. indica* leaves. Processing of *T. indica* leaves into powder has potential to increase consumption through convenient packaging thus eliminating the tendency to label it 'food for the poor' especially among urban dwellers [36].

This study has revealed that tamarind leaves are in fact more nutritious than the more popular fruit pulp as leaves provide higher levels of nutrients in majority of cases (66.7% and 55.6% for the semi-arid zone and the subhumid zone respectively). Tamarind leaf powder is on 'dry basis' thus certain nutrients may be more concentrated than when leaves are wet. However freshly harvested green tamarind leaves may provide additional nutrients such as vitamins some of which may be lost during drying and grinding thus need for further investigation.

Tamarindus indica fruits ripen during the dry season when food is scarce thus providing an important source of nutrients. In both zones harvesting begins in October and continues up to January thus coinciding with the period of labor-intensive activities such as preparation of gardens for planting. Tamarind fruit can be kept fresh for long periods using simple methods such as baskets thus no need for refrigeration. Simple storage methods are ideal for the peasants and pastoralists in rural resource-poor settings who are in great need of low-cost, low-technology solutions to the challenges they face.

It was hypothesized that given the harsh environmental conditions it experiences while growing, *T. indica* from the semi-arid zone contains higher levels of beneficial nutrients compared to that from the subhumid zone. Generally findings agree with the hypothesis that plants experiencing harsher conditions tend to accumulate nutrients in ways that better promote human health. *Tamarindus indica* leaves and fruit pulp from both zones and seeds from the semi-arid zone meet the WHO recommended Na/K ratio of < 1. The hypothesis that *T. indica* growing under the harsher conditions in semiarid zone of Uganda tends to accumulate nutrients in ways that better promote human health was therefore accepted ($p < 0.05$).

Conclusions and recommendations

Tamarindus indica products from both zones hold great potential to provide food and feed for the people and their livestock given the nutrients they contain. Findings agree with the hypothesis that plants that experience some stress while growing tend to accumulate nutrients in ways that better promote human health. *Tamarindus indica* leaves and fruit pulp from both zones and seeds from the semi-arid zone meet the WHO recommended Na/K ratio of < 1. The fact that *T. indica* products from the semi-arid zone scored consistently lower Na/K ratios compared to corresponding products from the subhumid zone supports the hypothesis. All products from the semiarid zone which experiences harsher environmental conditions scored the WHO recommended Na/K ratio as compared to two-thirds for the subhumid zone.

We document for the first time the proximate and mineral composition of leaves of Ugandan tamarinds which are important during times of scarcity and in ethno-medicinal practices. The study revealed that tamarind leaves have high potential to address food and nutritional security challenges due to high levels of nutrients comparable to and in some cases higher than the more popular fruit pulp. The low lipid content in tamarind fruit pulp combined with the WHO recommended Na/K ratio makes tamarind pulp especially appealing as a raw material for nutraceuticals to address obesity, hypertension and diabetes. Use of *T. indica* products provides an affordable, accessible and culturally acceptable alternative. Given the high nutrient content, currently underutilized *T. indica* products can contribute significantly to addressing food insecurity, malnutrition and poverty.

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Author contributions EEO designed the study, collected and analyzed data and coordinated the write up. DJK designed the study with EEO. PN and DN participated in write up. AM participated in data analysis and write up. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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