Measurement: Food 20 (2025) 100258

Contents lists available at ScienceDirect

Measurement: Food

journal homepage: www.elsevier.com/locate/meafoo

Nutritional and mineral composition, metal bioaccumulation, and health risk assessment of *Diospyros mespiliformis* Hochst. Ex A.DC., *Ficus thonningii* Blume, and *Strychnos spinosa* Lam.: Implications for food security and public health

Sinorita Chauke [a], Maropeng Erica Matlala [a], Wilfred Otang-Mbeng [a], Bongisiwe Gladys Shelembe [b], Peter Tshepiso Ndhlovu [a,*]

[a] *School of Biology and Environmental Sciences, University of Mpumalanga, Private Bag X11283, Mbombela 1200, South Africa*
[b] *Agricultural Research Council, Vegetable, Industrial and Medicinal Plants, Private Bag X293, Pretoria 0001, South Africa*

ARTICLE INFO

Keywords:
Bioaccumulation
Elemental analysis
Food insecurity
Food security
Health risk assessment
Mineral composition
Proximate analysis
Wild fruits

ABSTRACT

Food insecurity continues to pose a significant challenge in developed and developing nations, prompting the need to identify alternative, nutrient-dense food sources. This study examines the nutritional profile of the fruits of *Diospyros mespiliformis* Hochst. Ex A.DC., *Ficus thonningii* Blume, and *Strychnos spinosa* Lam., emphasising their potential as underutilised yet valuable food resources. In addition, the mineral composition of both leaves and fruits was assessed, alongside bioaccumulation factors (BAFs), to evaluate the extent of mineral uptake from the soil. A health risk assessment was also conducted to determine the safety for human consumption. Nutritional analysis revealed that *F. thonningii* had the highest moisture (82.07%) and crude fat (3.92%), while *S. spinosa* seeds were notably rich in crude protein (31.20%). Fibre content was higher in the peels across all species, with *S. spinosa* peel containing 44.21%. The pulp of *D. mespiliformis* had the highest carbohydrate content (86.02%) and energy value (391.38 Kcal/100 g). Elemental analysis demonstrated significant levels of essential minerals, including calcium (Ca), iron (Fe), and magnesium (Mg), with *S. spinosa* leaves particularly high in manganese (Mn) content (1728 mg/Kg). Leaves of *D. mespiliformis* and *F. thonningii* showed efficient zinc (Zn) accumulation with BAFs of 1.25 and 1.58, respectively. *S. spinosa* exhibited a notably high BAF of 25.08 for Mn. The carcinogenic risk factors for arsenic (As), cadmium (Cd), and chromium (Cr) in all the fruit samples exceeded the established safety thresholds. The highest risk was associated with *F. thonningii* fruit, presenting a carcinogenic risk factor of 0.008 for Cr. While these fruits offer promising nutritional benefits, their potential toxicological risks underscore the need for further safety assessments.

1. Introduction

There is a declining trend in global food security, particularly in developing nations that struggle to meet the growing demand for safe, affordable, and nutritious food [63,82]. Nearly half of the global population cannot afford a healthy diet, reflecting the instability and inefficiency of current food systems [104]. This crisis is driven by multiple factors, including climate change, rapid population growth [61,70], and the recent global health emergencies such as the COVID-19 pandemic [5]. Armed conflicts, notably the Palestine-Israel and Russia-Ukraine wars, have further exacerbated the situation, disrupting global food and nutrition security through their socio-economic impacts [40,54,85]. Southern Africa remains particularly vulnerable due to its susceptibility to climate-related threats [70]. Food security is defined as consistent access to sufficient, safe, and nutritious food for maintaining an active and healthy life. In contrast, nutrition security encompasses access to healthy foods and their role in supporting overall well-being, including the prevention and management of diet-related diseases [93]. A balanced diet is therefore essential for promoting health, nutrition, and the prevention of chronic diseases [37].

Food insecurity is closely linked to various forms of malnutrition, particularly undernutrition resulting from inadequate dietary intake,

---

* Corresponding author.
E-mail address: Tshepiso.Ndhlovu@ump.ac.za (P.T. Ndhlovu).

https://doi.org/10.1016/j.meafoo.2025.100258
Received 20 December 2024; Received in revised form 25 September 2025; Accepted 11 October 2025

and overnutrition, which stems from excessive food intake [94,99]. Nutritional deficiencies can manifest as inadequate levels of energy, protein, vitamins, and trace elements [30]. Previous studies have indicated that food insecurity contributes to both obesity [13] and undernutrition [39,55]. In South Africa, malnutrition remains a significant contributor to the disease burden [63]. Adequate nutrition is thus fundamental for maintaining health, as demonstrated by conditions such as Kwashiorkor, which results from severe deficiencies in calories and protein [78].

Fruits are widely recommended as part of a healthy diet due to their nutritional density [29] and are considered essential components of a balanced diet [105].

Wild fruits, in particular, are rich in nutrients, vitamins, and minerals vital for human health, offering potential benefits in disease prevention and alleviating food insecurity [2]. Mytton et al. [71] emphasise the protective role of fruit consumption against numerous diseases and advocate for public health strategies to increase intake. The Mpumalanga Province of South Africa is home to various wild fruit species traditionally utilised for their nutritional value, including *Diospyros mespiliformis* Hochst. Ex A.DC., *Strychnos spinosa* Lam., and *Ficus thonningii* Blume [19]. This study, therefore, investigates the proximate and elemental composition of selected wild fruits from Mpumalanga Province to evaluate their potential contributions to food and nutrition security. Additionally, the study assesses the bioaccumulation of metals in the leaves and fruits of these species to evaluate possible health risks. This study provides a unique contribution by focusing on underutilised indigenous wild fruits collected from the Bushbuckridge Local Municipality in Mpumalanga Province, South Africa, where many rural households depend on natural resources for food and nutrition. By analysing both the proximate and elemental composition of these species and assessing potential metal bioaccumulation, the research highlights their nutritional value while also addressing safety concerns. This integrated perspective offers important insights into how climate-resilient wild fruits from Bushbuckridge can be harnessed to strengthen sustainable food systems and improve food and nutrition security locally and globally.

2. Materials and methods

2.1. Sample collection and preparation

Leaves and ripe fruit samples of *D. mespiliformis, S. spinosa*, and *F. thonningii*, along with their corresponding soil samples, were collected from various villages (Table 1) within the Jurisdiction of the Mnisi Tribal Council, Bushbuckridge Local Municipality, Mpumalanga Province, South Africa. Ethical approval for the study was obtained from the University of Mpumalanga Ethics Committee (Ethics Reference: UMP/Chauke/230,013,937/MSC/2024). Permission for plant sample collection was granted by local village leaders, the Mnisi Tribal Council, and the Mpumalanga Tourism and Parks Agency (Permit Number: MPB. 1465). Plant species identification was verified at the University of Mpumalanga. Voucher specimens were prepared and deposited in the Indigenous Flora Research Laboratory, University of Mpumalanga, under the codes: *S. spinosa* (SC001), *F. thonningii* (SC003), and *D. mespiliformis* (SC004). Fruits of *D. mespiliformis* and *S. spinosa* were manually separated into peel, pulp, and seeds, whereas *F. thonningii* fruits were used whole due to their small size. Leaf samples were rinsed with distilled water, air-dried at room temperature, and ground into a fine powder. Soil samples were air-dried and sieved through a 2 mm mesh to remove stones and debris before further analysis (Table 2).

2.2. Proximate analysis

2.2.1. Moisture content

Moisture content was determined using the oven-drying method described by Jacob et al. [44]. A mass of 5 g of each fruit sample was weighed in triplicate and placed into pre-weighed crucibles. The samples were dried in an oven (Memmert, Germany) at 60 °C until a constant weight was obtained. After drying, crucibles were transferred to a desiccator, cooled to room temperature, and reweighed. The moisture content was calculated using Eq. (1).

$$\%\ Moisture\ content = \frac{W_2 - W_3}{W_2 - W_1} \times\ 100 \tag{1}$$

Where:

W_1 = mass of the empty crucible (g)
W_2 = mass of the crucible with the fresh sample (g)
W_3 = mass of the crucible with the dried sample (g)

2.2.2. Ash content

Ash content was determined following the dry ashing method outlined by Jacob et al. [44]. A 5 g portion of each fruit sample was weighed into pre-dried, pre-weighed crucibles (W_1) and reweighed with the sample (W_2). The crucibles were placed in a muffle furnace (Nabertherm, Germany) and incinerated at 500 °C for three hours until a greyish ash residue was obtained. Crucibles were then cooled in a desiccator and weighed again (W_3). The percentage ash content was calculated using Eq. (2).

$$\%\ Ash = \frac{W_3 - W_1}{W_2 - W_1} \times\ 100 \tag{2}$$

2.2.3. Crude fat

The crude fat content was determined using Soxhlet extraction with the analytical reagent (AR) n-hexane (Labchem, South Africa), as described by Jacob et al. [44] with slight modifications. Round-bottom flasks (500 mL) were oven-dried at 105 °C for 30 min, cooled in a

Table 2
Certified and found values of certified reference material (strawberry leaves).

Elements	Wavelength (λ)	Measured	Certified
Cr	283.563	1.94	**2.15±0.34**
Cu	324.752	10.73	**10**
Cd	228.8	0.204 ±0.29	0.17 ±0.04
Zn	213.857	39.07	**24±5**

Table 1
Dates of collection of the samples that were collected and analysed for nutritional and elemental content.

Plant species	Sample	Month of collection	Season	Name of village	GPS coordinates of villages
Diospyros mespiliformis Hochst. ex A.DC.	Soil	August	Winter	Gottenburg	−24.6293° S, 31.3802° E
	Leaves				
	Fruit	May	Autumn		
Strychnos spinosa Lam.	Soil	August	Winter	Welverdiend	−24.5679° S, 31.3459° E
	Leaves				
	Fruit	May	Autumn		
Ficus thonningii Blume.	Soil	August	Winter	Seville	−24.6691° S, 31.4167° E
	Leaves				
	Fruit	May	Autumn		

desiccator, and weighed. A mass of 2 *g* of each sample (W_1) was placed into labelled extraction thimbles, which were lightly plugged with cotton wool. Each round-bottom flask was filled with 300 mL of hexane. The thimbles were inserted into the Soxhlet extraction units, and the system was allowed to reflux for eight hours at a controlled temperature of 50–55 °C. After extraction, the thimbles were removed, and the hexane was evaporated under reduced pressure. The flasks were then oven-dried at 105 °C for 1 h to ensure complete removal of residual solvent, cooled in a desiccator, and weighed (W_2). The percentage fat content was calculated using Eq. (3).

$$\%\,Fat = \frac{W_1 - W_2}{W_1} \times 100 \tag{3}$$

2.2.4. Crude fibre

Crude fibre was determined using a sequential acid-base digestion method as described by Jacob et al. [44]. A 2 g portion of defatted sample (W_s) was weighed into a 250 mL conical flask, and 200 mL of 1.25 % (v/v) sulfuric acid (H_2SO_4) (AR, Labchem, South Africa) was added. The mixture was heated for 30 min and then filtered through poplin cloth using a Büchner funnel. The residue was washed thoroughly with hot distilled water until no acidic trace was detected using pH litmus paper.

The residue was transferred back to the same conical flask, and 200 mL of 1.25 % (w/v) sodium hydroxide (NaOH) (AR, Rochelle chemicals, South Africa) solution was added. The mixture was heated again for 30 min, filtered, and washed repeatedly with hot water until the filtrate was neutral, as confirmed by litmus paper. The residue was transferred into a pre-weighed crucible, dried in a hot air oven, cooled in a desiccator, and weighed (W_{cd}). The crucible was placed in a muffle furnace and heated to 500 °C for a period of six hours. After cooling in a desiccator, the crucible was reweighed (W_{ca}). Eq. (4) was used to calculate the percentage of fibre.

$$\%\,Fibre = \frac{W_{cd} - W_{ca}}{W_s} \times 100 \tag{4}$$

2.2.5. Protein

The nitrogen content was estimated using the Kjeldahl method described by Jacob et al. [44]. A mass of 1 *g* of each sample was weighed and transferred into a Kjeldahl digestion flask (Thermo Fisher Scientific, USA). Two selenium catalyst tablets (Thermo Fisher Scientific, USA) and 12 mL of concentrated H_2SO_4 (AR, Labchem, South Africa) were added. The mixture was heated until a clear solution was obtained. After cooling, the digest was transferred to a 50 mL volumetric flask and made up to volume with distilled water. A 10 mL aliquot of the digest was mixed with 10 mL of 40 % (w/v) NaOH (AR, Rochelle chemicals, South Africa) in the Kjeldahl distillation unit. A receiving flask containing 5 mL of a 2 % (w/v) boric acid (AR, Sigma-Aldrich, Germany) solution and three drops of a mixed indicator (Lab grade, Labchem, South Africa) was positioned under the condenser outlet. During distillation, ammonium ions in the digest were converted to ammonia gas, which was captured in the boric acid solution. The nitrogen content in the distillate was determined by titration with 0.01 M hydrochloric acid (HCl) (AR, Labchem, South Africa). The endpoint was indicated by a colour change from green to pink. Eq. (5) was used to estimate the % of nitrogen, and Eq. (6) to calculate the % of crude protein.

$$\%\,N = \frac{(S - B) \times N_{acid} \times 0.014 \times D}{Weight\ of\ sample \times V} \times 100 \tag{5}$$

$$\%\,Crude\ protein = 6.25^{*} \times \%N(*Correction\ factor) \tag{6}$$

Where:

S= sample titration reading; *B*=blank titration reading; *N*= normality of HCL; *D*= Dilution of sample after digestion; V volume taken for distillation; 0.014= milliequivalent weight of nitrogen.

2.2.6. Carbohydrate

The carbohydrate estimate was calculated using Eq. (7) [44].

$$\%Carbohydrate = 100 - (\%Ash + \%Protein + \%\,Fat + \%\,Fibre) \tag{7}$$

2.2.7. Energy value (Ev)

The energy/calorific value of fruit samples, expressed in kilocalories, was calculated as Jacob et al. [44] described. The values of crude protein, crude fat, and available carbohydrates were multiplied by 4.00, 9.00, and 4.00 Kcal/g, respectively, and summed to obtain the total energy value, as shown in Eq. (8).

$$Ev\,(Kcal/100g) = (Protein \times 4) + (Fat \times 9) + (Available\,carbohydrate \times 4) \tag{8}$$

Available carbohydrates refer to digestible carbohydrates, primarily sugars and starches, that are absorbed in the small intestine, which excludes crude fibre. In contrast, total carbohydrate content includes both digestible (sugars and starches) and non-digestible (fibre) components [32].

2.3. Elemental analysis

Mineral content was determined using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), following microwave-assisted acid digestion as described by Shelembe [96]. A mass of 0.5 *g* of each dried sample was weighed and transferred into ceramic digestion vessels. A volume of 10 mL of 70 % (v/v) AR nitric acid (HNO_3) (Labchem, South Africa) was added, and the samples were allowed to pre-digest for 1 hr at room temperature before sealing. Microwave (CEM MARS 6 One Touch, USA) digestion was performed in a closed-vessel system at 500 W for 30 min, followed by 650 W for an additional 15 min. After digestion, the vessels were cooled using forced ventilation for 15 min. The digested samples were filtered through 0.45 μm filters into 50 mL volumetric flasks, made up to the mark with double-distilled water. The filtrates were transferred to polyethylene bottles for mineral analysis. Elemental analysis was performed using ICP-OES (PerkinElmer, USA). The following elements were quantified: arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), calcium (Ca), copper (Cu), manganese (Mn), magnesium (Mg), iron (Fe), lead (Pb), selenium (Se), and zinc (Zn). Analytical wavelengths were selected based on minimal spectral interference and optimal analytical sensitivity. The three most sensitive lines were initially considered for each element, and the line with the least interference was selected for quantification.

2.3.1. Quality assurance

The validity of the mineral analysis was assessed using certified reference material (CRM: strawberry leaves, LGC-7162; Community Reference Bureau, Commission of the European Communities, Brussels, Belgium), following the protocol described by Shelembe [96]. The emission wavelengths that yielded optimal results for CRM, defined by high signal intensity and minimal spectral interference, were selected for each element. Calibration standards for all target elements were prepared from 1000 mg/L single-element stock solutions (Fluka Analytical, Sigma-Aldrich, Switzerland) using double-distilled water and 70 % HNO_3 to minimize matrix effects. Five-point calibration curves were constructed for each element within the expected concentration range. The linear regression models providing the best fit were used for quantification. Reagent blanks and all sample solutions were prepared and analysed under identical conditions. CRM samples were analysed in triplicate to confirm the accuracy and precision of the method. Method accuracy was evaluated by comparing the mean experimental values to the certified values for each analyte using a two-sample *t*-test (assuming equal variances). No statistically significant differences were observed between the means ($p > 0.05$), indicating acceptable accuracy. Method precision was assessed by calculating the relative standard deviation (% RSD) of the replicate CRM measurements. A %RSD $\leq$ 20 % was considered acceptable. Additionally, the experimental values fell within the 95 % confidence interval of the certified values, confirming the method's precision and reliability.

2.4. Bioaccumulation factors (BAF)

The BAF was used to evaluate the ability of plant tissues to absorb and retain heavy metals from the surrounding soil. The BAF was calculated as the ratio of the metal concentration in plant tissues (leaves or fruits) to that in the corresponding soil samples, as expressed in Eq. (9).

$$BAF = \frac{[metal]_{\frac{leaves}{fruit}}}{[Metal]_{soil}} \tag{9}$$

A BAF value equal to 1.00 suggests that the plant can take up metals from the soil but does not accumulate them in its tissues over time. Conversely, a BAF value greater than 1.00 indicates a potential for metal accumulation within plant tissues [43].

2.5. Human health risk assessment

2.5.1. Estimated daily intake (EDI) indices

The EDI of elements through the consumption of wild fruits was calculated based on the concentration of each component of the fruit (mg/Kg), the average daily fruit intake (DI), and the average adult body weight (BW), following the method described by Kavcar et al. [47]. The calculation is expressed in Eq. (10).

$$EDI = \frac{C \times \mathrm{DI}}{\mathrm{BW}} \tag{10}$$

Where:
C = concentration of the element in the fruit (mg/Kg)
DI = 0.4 Kg/day [60]
BW = 70 Kg [107]

2.5.2. Target hazard quotient (THQ)

The potential non-carcinogenic health risk associated with consuming wild fruits was assessed using the THQ, calculated according to Eq. (11).

$$THQ = \frac{EDI}{R_f D} \tag{11}$$

Where:
EDI = estimated daily element intake (mg/Kg body weight/day).
R_fD = oral reference dose for the element (mg/Kg/day), as provided in Table 3.

A THQ value of less than 1 indicates that exposure is unlikely to cause adverse health effects. In contrast, a THQ value greater than 1 suggests a potential risk of non-carcinogenic health effects in the exposed population [1].

Table 3
The oral toxicity reference dose (R_fD) of toxic minerals [1].

Mineral	R_fD (mg/Kg/day)
As	0.0003
Co	0.0003
Cd	0.00005
Cr	0.003
Cu	0.04
Fe	0.7
Mn	0.14
Zn	0.3

2.5.3. Target carcinogenic risk (TCR)

The potential carcinogenic health risk associated with consuming wild fruits was evaluated using the TCR, which estimates the probability that an individual will develop cancer over their lifetime due to exposure to specific carcinogenic elements. The TCR was calculated using Eq. (12).

$$TCR = \mathrm{SF} \times \mathrm{CDI} \tag{12}$$

Where:
SF = oral slope factor $(\mathrm{mg/Kg/day})^{-1}$
CDI = chronic daily intake (mg/Kg/day)

The slope factors used in this study were obtained from the U.S. Environmental Protection Agency (USEPA, 2015) and other recent literature: As = 1.7, Cd = 0.38, Cr = 0.5 [1]. The slope factor converts chronic exposure into a risk estimate of cancer incidence.

TCR values were not calculated for Co, Cu, Fe, Mn, and Zn because these elements are not classified as carcinogenic [49]. TCR value above 1.0×10^{-4} represents a potential carcinogenic risk [1].

2.6. Statistical analysis

All data were expressed as the mean ± standard error (SE) of three independent replicates. Statistical analyses were performed using version 30.0.0 of the Statistical Package for the Social Sciences (SPSS). Correlation coefficients (r) ranged between −1 and +1, where values $\geq +0.8$ indicated a strong positive relationship and $P \leq -0.8$ indicated a strong negative relationship. Significant differences between means were determined using Tukey's Honestly Significant Difference (HSD) and Least Significant Difference (LSD) post hoc tests, with statistical significance set at $p < 0.05$.

3. Results

3.1. Proximate analysis

The proximate analysis of the three fruit species revealed notable variations in nutritional composition across different fruit structures (Table 4). Moisture content was highest in the whole fruit of *F. thonningii* (82.07 %), followed by the pulp of *S. spinosa* (76.33 %) and *D. mespiliformis* (59.13 %). The highest ash content was recorded in the pulp of *S. spinosa* (5.87 %). Crude fat was most abundant in the fruit of *F. thonningii,* with the pulp of *D. mespiliformis* ranking second (2.50 %). Crude fibre content was significantly higher in the fruit peels than pulp and seeds, with the *S. spinosa* peel exhibiting the highest value (44.21 %), followed by *D. mespiliformis* peel (31.23 %). The lowest crude fibre level was observed in the pulp of *D. mespiliformis* (2.95 %). Crude protein was most concentrated in *S. spinosa* seeds (31.20 %), followed by its pulp (23.62 %) and the whole fruit of *F. thonningii* (20.60 %). Carbohydrate content was highest in the pulp, seeds, and peel of *D. mespiliformis.* In terms of energy values, the pulp of *D. mespiliformis* had the highest energy content, whereas *S. spinosa* peel had the lowest.

3.2. Elemental analysis

3.2.1. Mineral composition

Elemental analysis (Table 5) revealed significant variation in mineral concentrations across soil and plant samples. As levels were significantly higher (p < 0.001) in soils compared to plant tissues of *D. mespiliformis* and *S. spinosa*. In *F. thonningii*, the content was comparable between fruit and leaves (0.2 mg/Kg). Cd concentrations showed no significant difference (p = 1.00) between soils from sites A and B and the leaves of *D. mespiliformis*. The highest Ca content was observed in *S. spinosa* leaves (17,240 mg/Kg), far exceeding the Ca concentration in the Ca-rich soils of Site A (1502 mg/Kg). Cu was most concentrated in *D. mespiliformis* leaves from Site A and in the fruit of *F. thonningii.* Co was undetectable in *D. mespiliformis* but was highest in the leaves and fruit of *S. spinosa*. Cr

Table 4

Nutritional composition of wild fruits harvested from the Mpumalanga Province.

Plant name	Proximate analyses (%)							
	Fruit part	Moisture	Ash	Crude fat	Crude fibre	Protein	Carbohydrates	Energy value (Kcal/100 g)
D. mespiliformis	Peel	38.13±1.03^{a}	**2.93±0.07**^{ab}	1.73±0.03^{ab}	**31.23±0.58**^{e}	2.37±1.02^{a}	61.78±2.09^{c}	**272.13±2.83**^{c}
	Pulp	**59.13±0.59**^{c}	2.21±0.13^{ab}	**2.5 ± 0.25**^{bc}	2.95±0.20^{a}	**6.20±0.29**^{b}	**86.02±0.41**^{a}	**391.38±2.25**^{a}
	Seeds	37.73±1.13^{a}	3.41±0.46^{bc}	1.13±0.12^{ab}	11.40±0.05^{bc}	5.37±0.63^{b}	**78.70±1.18**^{b}	**346.39±2.27**^{b}
S. spinosa	Peel	39.93±2.74^{a}	2.98±0.13^{ab}	1.47±0.03^{ab}	**44.21±0.33**^{f}	8.83±0^{c}	42.95±1.17^{e}	**218.61±1.97**^{d}
	Pulp	**76.33±0.18**^{d}	**5.87±0.93**^{c}	0.25±0.75^{a}	10.30±0.15^{b}	23.62±1.04^{d}	59.55±0.51^{c}	342.55±0.55^{c}
	Seeds	51.27±1.87^{b}	3.55±0.06^{bc}	1.63±0.37^{ab}	13.13±0.43^{c}	**31.20±0.29**^{e}	51.85±1.9^{d}	**341.45±0.05**^{b}
F. thonningii	Whole fruit	**82.07±1.75**^{d}	1.2 ± 0.2^{a}	**3.92±0.42**^{c}	17.55±0.30^{d}	20.60±1.47^{f}	55.16±1.02^{cd}	346.68±2.18^{b}

The results are expressed as the mean of three replicates ± standard error (SE). Statistical analyses were performed separately for each nutrient. Identical superscript letters within the same column indicate no significant difference ($p > 0.05$). The analyses were conducted using Post Hoc's Tukey tests, with the significant difference determined at $p < 0.05$.

Table 5

Elemental analysis of the fruit and leaf samples of selected plant species and the soil samples from their respective sites.

Elements	Wavelength (λ)	Concentration (mg/Kg)								
		D. mespiliformis			*F. thonningii*			*S. spinosa*		
		Soil (Site A)	Leaves	Fruit	Soil (Site B)	Leaves	Fruit	Soil (Site C)	Leaves	Fruit
As	228.81	0.4 ± 0.01^{f}	0.2 ± 0.01^{d}	0.1 ± 0.00^{b}	0.3 ± 0.01^{e}	0.2 ± 0.01^{d}	0.2 ± 0.02^{c}	0.2 ± 0.01^{d}	BDL	BDL
Cd	228.80	0.3 ± 0.01^{b}	0.3 ± 0.02^{b}	**0.2** ± 0.01^{a}	0.3 ± 0.01^{b}	0.2 ± 0.01^{a}	**0.2** ± 0.01^{a}	0.2 ± 0.01^{a}	0.2 ± 0.01^{a}	0.2 ± 0.02^{a}
Ca	315.89	1502 ± 2.08^{e}	2 793 ± 0.58^{f}	395.9 ± 2.09^{c}	753 ± 0.50^{d}	**12 190** ± 0.44^{h}	**4 933** ± 3.00 ^{g}	247.9 ± 0.46^{a}	**17240 ± 2.00**^{i}	**388.2 ± 0.09**^{b}
Cu	224.7	9.7 ± 0.09 *g*	9.3 ± 0.02^{f}	3 ± 0.03^{a}	6.6 ± 0.03^{d}	6.1 ± 0.08^{c}	7 ± 0.01^{e}	4.8 ± 0.02^{b}	6 ± 0.01^{c}	3.1 ± 0.00^{a}
Co	228.62	2.6 ± 0.05^{f}	BDL	BDL	1.5 ± 0.01^{e}	0.1 ± 0.00^{a}	BDL	1 ± 0.00	0.4 ± 0.00^{c}	0.2 ± 0.01^{b}
Cr	205.56	**26.6** ± 0.02^{h}	3 ± 0.03^{c}	2.2 ± 0.01^{a}	**6.5 ± 0.09**^{f}	4 ± 0.27^{d}	2.8 ± 0.00^{bc}	**8.1** ± 0.07 ^{g}	4.6 ± 0.03^{e}	2.7 ± 0.00^{b}
Fe	239.56	1 948 ± 0.57^{i}	91.5 ± 0.27^{d}	21.1 ± 0.50^{a}	1 647 ± 2.00^{h}	330.5 ± 0.05^{f}	157.6 ± 0.06^{e}	1 195 ± 1.00 *g*	31.9 ± 0.08^{c}	28.6 ± 0.00^{b}
Pb	217.00	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Mg	285.21	1 026 ± 0.29^{d}	1 149 ± 0.11^{e}	483.1 ± 0.56^{c}	445.5 ± 0.69^{b}	1 896 ± 0.56^{h}	1 555 ± 5.03 ^{g}	213.5 ± 0.27^{a}	1 508 ± 0.55^{f}	455.3 ± 0.44^{b}
Mn	260.57	72 ± 0.20 *g*	9.4 ± 0.10^{b}	2.1 ± 0.10^{a}	73.6 ± 0.10 *g*	43.5 ± 0.20^{e}	16.9 ± 0.10^{c}	68.9 ± 0.10^{f}	1 728 ± 3.00^{h}	21.3 ± 0.10^{d}
Se	196.03	2.2 ± 0.10^{b}	4.9 ± 0.06^{e}	4.5 ± 0.08^{d}	3.2 ± 0.01^{c}	6.4 ± 0.07^{h}	6 ± 0.03 ^{g}	1.8 ± 0.04^{a}	5.7 ± 0.00^{f}	1.8 ± 0.01^{a}
Zn	213.86	45 ± 0.00^{e}	56.3 ± 0.10^{h}	27.8 ± 0.01^{b}	20.7 ± 0.01^{a}	32.7 ± 0.00^{c}	53.3 ± 0.62^{f}	44.9 ± 0.03^{e}	40.8 ± 0.00^{d}	55 ± 0.06 *g*

BDL= Beyond detection limit. The results are presented as the mean of three independent replicates (n) ± standard deviation (SD). Significant differences among the samples were assessed using the Tukey test at a significance level of $p < 0.05$. Identical superscript letters within a row denote no significant difference ($p > 0.05$) between the samples, while differing letters indicate a significant difference.

concentration in site C soil differed significantly ($p < 0.001$) from that in *S. spinosa* leaves and fruit. In contrast, no significant difference ($p = 1.00$) was observed between Cr levels in the pulps of *D. mespiliformis* and *F. thonningii.*

Iron (Fe) was the most dominant mineral across all samples, with the highest levels detected in the leaves and fruit of *F. thonningii.* Pb was not detected in any sample. Mg was particularly high in *F. thonningii* leaves (1896 mg/Kg) and dominant in the fruit of both *F. thonningii* and *S. spinosa.* Mn was present in high concentrations, especially in *S. spinosa*, whose fruit had the highest (1728 mg/Kg) Mn content among the species.

Selenium (Se) levels were highest in the leaves of *S. spinosa*, while Zn concentrations varied by species and tissue type, with the highest levels observed in the leaves of *D. mespiliformis* and fruit of *S. spinosa*. Overall, these results emphasise the nutritional and elemental richness of the studied fruit species.

Correlation analysis of the proximate composition and elemental content in *D. mespiliformis, F. thonningii*, and *S. spinosa* revealed a range of relationships (Tables 6–8). Proximate-to-proximate correlations within the fruit showed notable trends. Fat content demonstrated a perfect positive correlation with energy in *D. mespiliformis* and *F. thonningii* ($r = 1$, $p = 0.017$), indicating a substantial contribution of fat to the overall energy content in these fruits. Conversely, fat showed a strong negative correlation with ash content in both species ($r = -0.999$, $p = 0.033$), suggesting an inverse relationship between these parameters. Fibre content positively correlated with moisture in *D. mespiliformis* and *F. thonningii* ($r = 1$). Protein displayed a strong negative correlation with fibre ($r = -0.874, p = 0.324$) and energy ($r = -0.989, p = 0.096$) in the same species, though these relationships were not statistically significant.

In *S. spinosa*, protein exhibited a weak positive correlation with energy ($r = 0.142$, $p = 0.909$), while fibre had a moderate negative correlation with moisture ($r = -0.787$, $p = 0.423$); both associations were also insignificant. Moisture content exhibited a perfect positive

Table 6

Correlation coefficients (r) and significance levels (p) between the elemental and proximate components of *D.mespiliformis* fruit, along with the elemental composition of the soil where the fruits were harvested.

Relationship	Correlation coefficient (r)	Significance (p)
Fat(F) vs energy(F)	1	0.017
Fat(F) vs ash(F)	−0.999	0.033
Fibre(F) vs moisture(F)	1	
Protein(F) vs fibre(F)	−0.874	0.324
Protein(F) vs energy(F)	−0.989	0.096
Moisture(F) vs carbohydrates(F)	1	
Moisture(F) vs energy(F)	−1	
Protein(F) vs Zn(F)	0.983	0.118
Fibre(F) vs Mg(F)	0.994	0.072
Fat(F) vs Cd(F)	−0.583	0.604
Fibre(F) vs Se(F)	0.858	0.343Fe
Fe(S) vs Zn(S)	−0.543	0.634
Cu(S) vs Cu(F)	0.999	0.022
Fe(S) vs Fe(F)	0.999	0.020
Cd(S) vs Cd(F)	−0.990	0.091
Cr(S) vs Cd(F)	−0.990	0.091
Cr(S) vs Cr(F)	−0.581	0.606

Sample types: Fruit= *F*; Soil= *S*. Elements: Cadmium= Cd; Chromium=Cr; Copper= Cu; Iron=Fe; Magnesium= Mg; Selenium= Se; Zinc= Zn. **Correlation coefficient (*r*):** Strong correlation $r > 0.7$ or $r < 0.7$; Moderate correlation $0.3 < r < 0.7$ **or** $-0.7 < r < -0.3$; Weak correlation $r < 0.3$ **or** $r > -0.3$. **Significance level (*p*):** Significant $p < 0.05$ or not significant $p \geq 0.05$.

Table 7
Correlation coefficients (r) and significance levels (p) between the elemental and proximate components of *F. thonningii* fruit, along with the elemental composition of the soil where the fruits were harvested.

Relationship	Correlation coefficient (r)	Significance (p)
Fat(F) vs energy(F)	1	0.017
Fat(F) vs ash(F)	−0.999	0.033
Fibre(F) vs moisture(F)	1	
Protein(F) vs fibre(F)	−0.874	0.324
Protein(F) vs energy(F)	−0.989	0.096
Moisture(F) vs carbohydrates(F)	1	
Moisture(F) vs energy(F)	−1	
Protein(F) vs Zn(F)	0.983	0.118
Fibre(F) vs Mg(F)	0.994	0.072
Fat(F) vs Cd(F)	−0.583	0.604
Fibre(F) vs Se(F)	0.858	0.343
Fe(S) vs Zn(S)	−0.543	0.634
Cu(S) vs Cu(F)	0.999	0.022
Fe(S) vs Fe(F)	0.999	0.020
Cd(S) vs Cd(F)	−0.990	0.091
Cr(S) vs Cd(F)	−0.990	0.091
Cr(S) vs Cr(F)	−0.581	0.606

Sample types: Fruit= *F*; Soil= *S*. Elements: Cadmium= Cd; Chromium=Cr; Copper= Cu; Iron=Fe; Magnesium= Mg; Selenium= Se; Zinc= Zn. **Correlation coefficient (r):** Strong correlation $r > 0.7$ or $r < 0.7$; Moderate correlation $0.3 < r < 0.7$ **or** $-0.7 < r < -0.3$; Weak correlation $r < 0.3$ **or** $r > -0.3$. **Significance level (p):** Significant $p < 0.05$ or not significant $p \geq 0.05$.

Table 8
Correlation coefficients (r) and significance levels (p) between the elemental and proximate components of *S. spinosa* fruit, along with the elemental composition of the soil where the fruits were harvested.

Relationship	Correlation coefficient (r)	Significance (p)
Fat(F) vs energy(F)	−0.995	0.061
Fat(F) vs ash(F)	0.954	0.194
Fibre(F) vs moisture(F)	−0.787	0.423
Protein(F) vs fibre(F)	−0.047	0.970
Protein(F) vs energy(F)	0.142	0.909
Moisture(F) vs carbohydrates(F)	−0.432	0.716
Moisture(F) vs energy(F)	0.096	0.939
Protein(F) vs Zn(F)	0.920	0.256
Fibre(F) vs Mg(F)	−0.850	0.353
Fat(F) vs Cd(F)	−0.756	0.454
Fibre(F) vs Se(F)	−0.982	0.121
Fe(S) vs Zn(S)	0.835	0.371
Cu(S) vs Cu(F)	−0.993	0.075
Fe(S) vs Fe(F)	0.487	0.676
Cd(S) vs Cd(F)	−0.500	0.667
Cr(S) vs Cd(F)	0.655	0.454
Cr(S) vs Cr(F)	0.915	0.265

Sample types: Fruit= *F*; Soil= *S*. Elements: Cadmium= Cd; Chromium=Cr; Copper= Cu; Iron=Fe; Magnesium= Mg; Selenium= Se; Zinc= Zn. **Correlation coefficient (r):** Strong correlation $r > 0.7$ or $r < 0.7$; Moderate correlation $0.3 < r < 0.7$ **or** $-0.7 < r < -0.3$; Weak correlation $r < 0.3$ **or** $r > -0.3$. **Significance level (p):** Significant $p < 0.05$ or not significant $p \geq 0.05$.

correlation with carbohydrates in *D. mespiliformis* and *F. thonningii* ($r = 1$), while its relationship with energy was perfectly negative ($r = -1$); however, these correlations lacked statistical significance. These findings highlight the interdependence of proximate parameters within each fruit species, with fat, fibre, and moisture emerging as key contributors to compositional variability.

Element-to-element correlations between soil and fruit were assessed to evaluate the influence of soil mineral composition on fruit mineral uptake. A perfect positive correlation was observed between Cu concentrations in fruit and soil for both *D. mespiliformis* and *F. thonningii* ($r = 0.999$, $p = 0.022$), as well as between Fe in fruit and soil in *D. mespiliformis* ($r = 0.999$, $p = 0.020$); both correlations were statistically significant. In contrast, *S. spinosa* showed a strong negative correlation between Cu in fruit and Cu in soil ($r = -0.993$, $p = 0.075$), although this relationship was not statistically significant. Cd in fruit exhibited a strong negative correlation with Cd in soil in both *D. mespiliformis* and *F. thonningii* ($r = -0.990$, $p = 0.091$), while in *S. spinosa*, the Cr in fruit exhibited a strong positive correlation with Cr in soil ($r = 0.915$, $p = 0.265$); however, neither correlation reached statistical significance.

Further analysis revealed several associations between proximate and elemental compositions within the fruit. Zn displayed a strong positive correlation with protein content in *D. mespiliformis* and *F. thonningii* ($r = 0.983, p = 0.118$), and Mg was strongly correlated with fibre ($r = 0.994$, $p = 0.072$). Although both trends were notable, they were not statistically significant. In *S. spinosa*, fibre had a strong negative correlation with Se ($r = -0.982, p = 0.121$), and fat showed a moderate negative correlation with Cd in *D. mespiliformis* and *F. thonningii* ($r = -0.583$, $p = 0.604$). Element-to-element correlations within the soil itself exhibited weaker associations. For example, Fe and Zn showed a moderate negative correlation in the soils of sites A and B ($r = -0.543$, $p = 0.634$), which was not statistically significant.

3.3. *Bioaccumulation factor*

The BAF analysis (Table 9) revealed species- and tissue-specific differences in metal uptake. In *D mespiliformis*, leaves demonstrated the ability to bioaccumulate Zn, while the fruit exhibited BAF values below 1.0 for all tested metals, indicating limited accumulation potential. *F. thonningii* leaves also showed effective Zn bioaccumulation, while its fruit accumulated both Cu and Zn, with BAF values above 1.0. Notably, *S. spinosa* leaves exhibited a high BAF for Mn (25.08), suggesting strong accumulation capacity. Additionally, *S. spinosa* fruit showed moderate Zn bioaccumulation, with a BAF of 1.22.

3.4. *Health risk assessment*

3.4.1. *Target hazard quotient/non-carcinogenic risk and carcinogenic risk*

The THQ and non-carcinogenic risk assessment (Table 10) indicated elevated health risks associated with consuming the studied fruit species. *D. mespiliformis* fruit exhibited the highest THQ values for Cd (22.86), followed by Cr (4.19) and As (1.90). Similarly, *F. thonningii* fruit

Table 9
Bioaccumulation factors of toxic and microminerals in the leaves and fruit of wild fruits.

Plant species	Element	Concentration (mg/Kg)			Bioaccumulation factor	
		Soil	leaves	Fruit	Leaves	Fruit
D. mespiliformis	As	0.4	0.2	0.1	0.5	0.25
	Cd	0.3	0.3	0.2	1	0.67
	Cr	26.6	3	2.2	0.11	0.08
	Co	2.6	BDL	BDL	BDL	BDL
	Cu	9.7	9.3	3	0.96	0.31
	Fe	1 948	91.5	21.1	0.05	0.01
	Mn	72	9.4	2.1	0.13	0.03
	Zn	45	56.3	27.8	1.25	0.62
F. thonningii	As	0.3	0.2	0.2	0.67	0.67
	Cd	0.3	0.2	0.2	0.67	0.67
	Cr	6.5	4	2.8	0.62	0.43
	Co	1.5	0.1	BDL	0.07	BDL
	Cu	6.6	6.1	7	0.92	1.06
	Fe	1 647	330.5	157.6	0.20	0.10
	Mn	73.6	43.5	16.9	0.59	0.23
	Zn	20.7	32.7	53.3	1.58	2.57
S. spinosa	As	0.2	BDL	BDL	BDL	BDL
	Cd	0.2	0.2	0.2	1	1
	Cr	8.1	4.6	2.7	0.57	0.33
	Co	1	0.4	0.2	0.4	0.2
	Cu	4.8	6	3.1	1.25	0.65
	Fe	1 195	31.9	28.6	0.03	0.02
	Mn	68.9	1 728	21.3	25.08	0.31
	Zn	44.9	40.8	55	0.91	1.22

BDL: Beyond detection limit.

showed elevated THQ values for Cd (22.86), Cr (5.33), As (3.81), Fe (1.29), and Zn (1.02). *S. spinosa* fruit contained excessively high levels of Co (51.43), in addition to Cd (22.86) and Zn (1.05), all exceeding the safe threshold (THQ > 1), suggesting potential non-carcinogenic health risks.

The TCR assessment (Table 10) further highlights potential long-term health concerns associated with As, Cd, and Cr in the fruit samples. In *D. mespiliformis* fruit, Cr presented the highest carcinogenic risk factor (0.006), followed by As (0.0017) and Cd (0.0004). For *F. thonningii*, Cr showed the highest carcinogenic risk (0.008). In *S. spinosa* fruit, Cr had a risk factor of 0.0005, which was greater than that of Cd (0.0004). These values exceed the acceptable risk threshold of 1.0×10^{-4}, indicating a potential cancer risk associated with the regular consumption of these fruits.

4. Discussion

4.1. Proximate analysis

4.1.1. Moisture content

The results of this study revealed that *F. thonningii* whole fruit exhibited the highest water content (82.07 %), followed by the pulp of *S. spinosa* (76.33 %) and *D. mespiliformis* (59.13 %). According to Haggag et al. [38], fruit moisture content is highly influenced by species type, seasonal variation, and the developmental stage of the fruit, with ripening typically associated with increased moisture content. In contrast, Jacob et al. [44] reported significantly lower moisture levels in the pulp of *D. mespiliformis* (6.89 %) and *S. spinosa* (7.12 %), highlighting potential differences in environmental conditions, methodologies, or maturity stages at harvest. However, a recent study by Akweni et al. [3] reported a moisture content of 76.4 % for *S. spinosa* pulp, which closely aligns with the present findings. Generally, fruits contain a high water content ranging between 55 % and 85 % [81]. Due to this high water content, various ethnobotanical reports show that wild fruits have traditionally been consumed as natural thirst quenchers by local communities [24,64,65,91]. Nevertheless, a higher moisture content is associated with greater perishability, limiting fruit shelf life [76]. For example, papaya is highly perishable, with moisture-driven post-harvest losses of up to 25 % [62]. Ramjan and Ansari [83] further emphasised that moisture content is a critical determinant of fruit longevity. Therefore, the high water content observed in the fruits studied may indicate a relatively short shelf life. As suggested in previous research, harvesting fruits before they are fully ripe and controlling the surrounding carbon dioxide levels can help reduce post-harvest spoilage.

Table 10
Health risk assessment of toxic elements detected in wild fruit plants' edible parts (Pulp).

Plant species	Elements	Fruit (mg/Kg)	Estimated daily intake	Target hazard quotient	Carcinogenic risk
D. mespiliformis	As	0.1	0.001	1.9	0.0017
	Cd	0.2	0.001	22.86	0.0004
	Cr	2.2	0.012	4.19	0.006
	Co	BDL	BDL	BDL	
	Cu	3	0.017	0.43	
	Fe	21.1	0.121	0.17	
	Mn	2.1	0.012	0.09	
	Zn	27.8	0.159	0.53	
F. thonningii	As	0.2	0.001	3.81	0.0017
	Cd	0.2	0.001	22.86	0.0004
	Cr	2.8	0.016	5.33	0.008
	Co	BDL	BDL	BDL	
	Cu	7	0.040	1	
	Fe	157.6	0.900	1.29	
	Mn	16.9	0.100	0.69	
	Zn	53.3	0.305	1.02	
S. spinosa	As	BDL	BDL	BDL	BDL
	Cd	0.2	0.001	22.86	0.0004
	Cr	0.2	0.001	0.38	0.0005
	Co	2.7	0.015	51.43	
	Cu	3.1	0.018	0.44	
	Fe	28.6	0.163	0.23	
	Mn	21.3	0.122	0.87	
	Zn	55	0.314	1.05	

BDL: Beyond detection limit. The carcinogenic risk of Co, Cu, Fe, Mn, and Zn was not calculated since they are not carcinogenic.

4.1.2. Ash content

Ash content represents the inorganic residue remaining after the complete combustion of organic matter in plant tissues and reflects the total mineral content of the sample [41,103]. The ash composition is influenced by the plant species and the specific plant part analysed [10]. In support of this, Zeng et al. [106] reported variations in ash content across different parts of the Masson pine tree. Similarly, Bakker and Elbersen [11] observed that wetland species typically exhibit higher ash content than C4 plants, suggesting that water uptake plays a key role in determining ash levels. This relationship is supported by the strong positive correlation between moisture and ash content observed in the current study (Table 6), which is consistent with the findings of Dagnew et al. [22]. Additionally, soil properties, such as type and texture, may influence ash content [11].

Among the analysed samples, *S. spinosa* fruit pulp exhibited the highest ash content of 5.87 %, followed by the seeds (2.98 %) and peel (3.55 %). This finding is consistent with those of Mbhele et al. [59], who reported ash content values as high as 5.83 % in specific morphotypes of *S. spinosa*, which closely matches the present study. The authors further suggested that *S. spinosa* could serve as a valuable dietary source of minerals to combat nutritional deficiencies. In contrast, Jacob et al. [44] reported lower ash content in *S. spinosa* pulp (3.86 %) and slightly higher levels in *D. mespiliformis* pulp (4.66 %). In the present study, the ash content in *D. mespiliformis* varied by plant part: pulp (2.21 %), seeds (3.41 %), and peel (2.93 %). In contrast, Magaji [56] reported an ash content of 2.02 g/100 g in the pulp. Notably, *F. thonningii,* which had the highest moisture content (82.07 %), also exhibited the lowest moisture content (1.2 %), corroborating the inverse relationship between moisture and ash content discussed by Mbhele et al. [59]. These findings underscore that ash content varies among species and different anatomical parts of the same fruit (Table 4). Therefore, such fruits could be important in addressing human mineral requirements through dietary inclusion.

4.1.3. Crude fat

The results revealed a strong negative correlation between crude fat and ash content ($r = -0.999$), consistent with the findings of Ugese et al. [102]. Furthermore, a statistically significant relationship was observed between ash and crude fat content ($p = 0.033$), suggesting that mineral composition may influence lipid accumulation in plant tissues. Fat serves three essential functions as a nutrient: it is a dense energy source, facilitates the absorption of fat-soluble vitamins, and provides essential fatty acids that the human body cannot synthesize. Additionally, dietary fat facilitates the transport of lipophilic bioactive compounds, including phytoestrogens and carotenoids. Fatty acids are also vital for cellular structure formation and serve as precursors for biologically active molecules, such as prostaglandins [90]. Among the analysed samples, *F. thonningii* exhibited the highest oil content of 3.92 %. Table 4 shows notable variations in crude fat content across the peel, pulp, and seeds of *D. mespiliformis* and *S. spinosa*. Specifically, the fat content of *D. mespiliformis* peel and pulp was 1.73 % and 2.5 % respectively. These values are comparable to those reported by Muhammad et al. [68], who found fat contents of 1.76 % (peel) and 2.89 % (pulp).

In contrast, Ebbo et al. [31] reported substantially lower fat levels of 0.45 % and 0.11 % for the peel and pulp, suggesting that environmental and physiological factors may account for the observed discrepancies. Figueiredo et al. [34] emphasised that factors such as environmental conditions (climate, pests and diseases, and pollution), geographic variations (soil type), and physiological variations (seasonality, type of plant organ, development stage, secretory structure, and injuries) influence the biosynthesis and accumulation of essential oils. These factors may explain the variability in oil content and quality even within the same species [108]. For example, Hubai and Kováts [42] reported that exposure to heavy metal stress can stimulate essential oil production, while other studies noted that high levels of organic matter content enhance oil biosynthesis [89]. Similarly, water stress has been shown to increase or decrease essential oil production depending on the species involved [36]. Wild-growing plants are often recognised for their capacity to produce essential oils with potent biological activity. Moreover, some wild fruits have been identified as sources of edible oils rich in crucial saturated and unsaturated fatty acids [57]. Despite these benefits, the overall fat content of fruits remains generally low, as confirmed by the present findings (Table 4) and consistent with previous reports [90].

4.1.4. *Crude fibre*

The peel of *S. spinosa*, which is non-edible, exhibited the highest crude fibre content at 43.85 %. The high crude fibre concentration suggests its potential suitability as a feed ingredient for ruminants, whose digestive systems are adapted to efficiently break down high-fibre diets typically ranging from 40 % to 100 % [6]. Among the edible portions of the three analysed fruits, *F. thonningii* pulp contained the highest crude fibre content(17.55 %), surpassing the values recorded for the pulps of *S. spinosa* and *D. mespiliformis*. Crude fibre content is generally estimated based on the proportion of indigestible plant components such as cellulose, pentosans, lignin, and related compounds [72]. Dietary fibre, or crude fibre [23], includes soluble and insoluble fractions [66]. Insoluble fibres are not digested but facilitate gastrointestinal motility, while soluble fibres absorb water and ease waste excretion [100]. The RDA of fibre for adult men and women is 38 and 25 g/day [92]. Dietary fibres provide multiple health benefits, including cholesterol reduction, blood glucose regulation, and improved gut function due to prebiotic properties [66]. As such, fibre is crucial in digestive health and alleviating constipation [23].

4.1.5. *Protein*

The protein content of *D. mespiliformis* pulp was 6.20 % which closely aligns with the 6.01 g/100 g reported by Magaji [56]. Similarly, the protein content of *D. mespiliformis* seeds was 5.37 %, comparable to the 5.47 % reported by Ezeagu et al. [33]. The fruit peel had the lowest protein concentration (2.37 %) among the analysed parts. However, literature shows some variation: Muhammad et al. [68] reported a higher protein content of 6.86 %, whereas Nyambe et al. [74] reported a lower value of 1.6 %.

The fruit of *F. thonningii* contained a substantial protein content of 20.60 % (Table 4), higher than that reported for *F. thonningii* seeds by Muhammad and Oluwaniyi [67]. The pulp of *S. spinosa* exhibited a protein content of 23.62 %, which is notably higher than the values reported by Lockett et al. [53] 11.70 %, Amarteifio and Mosase [7] 3.3 %, and Mbhele et al. [59] 9.19 %. The seed of *S. spinosa* had the highest protein content (31.20 %) among the studied samples. However, this is slightly lower than the 36.40 % protein content reported for *Phoenix dactylifera* L. (date plum) seeds by Bouaziz et al. [16].

According to Satter et al. [92], the RDA for protein is 34 g for children, 56 g for adult men, and 46 g for adult women. In this study, the pulp of *S. spinosa* (23.62 %) and the fruit of *F. thonningii* (20.60 %) contained significant protein levels, indicating their potential to contribute meaningfully to daily protein requirements, particularly in children. Proteins are essential macronutrients that supply amino acids, some of which are essential and must be obtained from the diet. They serve as fundamental structural components of cells and are vital for tissue growth and repair, as they synthesise enzymes and biologically active molecules. Proteins also play critical roles in immune function, blood clotting, and overall metabolic regulation. While fruits generally contain low levels of nitrogenous compounds (0.1–1.5 %) and are therefore not considered primary protein sources, some fruits, such as berries, cherimoya, and avocados, are recognised for having relatively higher protein content [90].

4.1.6. *Carbohydrates*

The carbohydrate content exhibited a strong positive correlation with moisture, fibre, fat, and energy value, and a weak negative correlation with protein (Table 6). Among the studied samples, the pulp of *D. mespiliformis* contained the highest carbohydrate content (86.02 %), followed by the seeds (78.70 %) and peel (61.78 %). The carbohydrate content of the pulp in this study (Table 4) is higher than values previously reported by Magaji [56] 56.55 g/ 100 g, Jacob et al. [44] 60.47 %, and Aremu et al. [8] 79.68 g/100 g. However, it closely aligns with the 86.56 % reported by Muhammad and Oluwaniyi [67]. Similarly, the carbohydrate content of *D. mespiliformis* seeds (78.70 %) is consistent with the 77.21 % reported by Ezeagu et al. [33].

For *S. spinosa,* the pulp contained 59.55 % carbohydrates, which is slightly lower than the 62.47 % recorded by Jacob et al. [44], but notably higher than the range (37.88–40.77 %) reported by Mbhele et al. [59] across thirty-two *S. spinosa* morphophytes. Additionally, the pulp had higher carbohydrate content than the seeds and peel (Table 4). The fruit of *F. thonningii* contained 55.16 % carbohydrates, exceeding the 40.02 % reported for the seeds by Muhammad and Oluwaniyi [67]. According to Satter et al. [92], the RDA for carbohydrates is 130 g/day for both adult men and women. All three fruits analysed in the present study, especially the pulp of *D. mespiliformis,* can be considered good sources of carbohydrates. Carbohydrates are the primary energy source in the human diet, and the energy derived from their metabolism can be used immediately or stored as fat for future energy needs [79,90].

4.1.7. *Energy value*

The present findings indicate a perfect inverse relationship between energy value and moisture content, which agrees with observations by Torrens Zaragozá [101]. Among the studied fruits, *D. mespiliformis* pulp exhibited the highest energy value (391.38 Kcal/100 g), which exceeds the 348.86 Kcal/100 g reported by Jacob et al. [44]. For *S. spinosa*, the pulp had the highest energy content (342.55 Kcal/100 g), followed by the seeds and peel. This value is also higher than the 303.38 Kcal/100 g recorded by Jacob et al. [44]. In the case of *F. thonningii,* the whole fruit had an energy value of 346.68 Kcal/100 g, which is lower than the 382.93 Kcal/100 g reported for the seeds by Muhammad and Oluwaniyi [67].

Energy value refers to the amount of energy provided per unit weight of food and plays a critical role in dietary energy intake. Consuming larger portions of low-energy-dense foods, such as fruits, contributes to satiety while reducing total caloric intake, thus making it less likely to exceed energy requirements. As such, fruits contribute to reduced meal energy density and may assist with body weight regulation [25]. Unlike high-energy-dense foods such as refined grains and added sugars, often associated with obesity, fruit consumption has not been linked to increased risk of obesity [28].

4.2. *Elemental analysis*

The detection of As is consistent with previous findings by Rehman et al. [86], who noted that As is a geogenic carcinogen commonly present in soils, with its concentrations influenced by both parent rock composition and anthropogenic activities. Although the effects of chronic As exposure may take months or years to manifest, they are known to be detrimental to the endocrine, nervous, cardiovascular, hepatic, haematological, renal, dermal, and respiratory systems [86,88].

Cadmium (Cd) was also present in all soil samples examined. As Kubier et al. [48] highlighted, Cd accumulation in soil can be attributed to various sources, including rock weathering, sewage sludge, landfills, vehicular emissions, industrial activities, and mining operations. Furthermore, Cd is known to compete with and displace Zn [77]. The present study observed a weak negative correlation between Cd and Zn ($r = -0.804$), suggesting potential antagonistic interactions. Cd levels were consistent in the fruits of *D. mespiliformis, F. thonningii*, and *S. spinosa*, each containing 0.2 mg/Kg. However, the leaves of *D. mespiliformis* exhibited a slightly higher Cd concentration (0.3 mg/Kg), aligning with the levels detected in the corresponding soil. Given its high toxicity, Cd poses significant health risks even at low concentrations. The potential health risks include carcinogenicity, renal dysfunction, cardiovascular complications, hormonal imbalances, and, in extreme cases, death [95].

Soil from site A exhibited a high Ca content (1502 mg/Kg), with a moderate positive correlation between soil and fruit Ca concentrations ($r = 0.511$). The Ca content is influenced not only by parent material but also by biological weathering [27], agricultural practices, and water movement [14]. In the current study, the fruit of *D. mespiliformis* contained 395.9 mg/Kg of Ca, notably lower than the 69.44 g/100 g reported by Magaji [56]. In *F. thonningii*, Ca levels were highest in the leaves (12,190 mg/Kg) compared to the fruit (4933 mg/Kg), aligning with the findings of Muhammad and Oluwaniyi [67], who reported 2067.5 mg/100 g in the seeds. Across all three species, Ca concentrations were consistently higher in the leaves than in the fruit, with *S. spinosa* exhibiting the highest leaf Ca content (Table 5). Ca plays a vital role in various physiological functions, including skin health, cell differentiation, and the maintenance of the epidermal barrier [50,52]. Disruption of Ca homeostasis has been associated with dermatological conditions such as atopic dermatitis and psoriasis [87].

The Cu content in *D. mespiliformis* was 3 mg/Kg (Table 5), markedly lower than the 30.3 g/100 g reported by Magaji [56]. In *F. thonningii*, Cu concentrations were 6.1 mg/Kg in the leaves and 7 mg/Kg in the fruit. At the same time, Muhammad and Oluwaniyi [67] reported a significantly higher concentration of 57.4 mg/100 g in the seeds. For *S. spinosa*, Cu levels were 6 mg/Kg in the leaves and 3.1 mg/Kg in the fruit, which compares closely with the 2.70 mg/100 g reported by Mbhele et al. [59]. A strong positive correlation was observed between soil and the fruit Cu concentrations ($r = 0.999$, $p = 0.022$), suggesting efficient uptake of Cu from the soil into the edible parts of the plant.

Cobalt (Co) was detected only in the leaves of *F. thonningii* at 0.1 mg/Kg. This is lower than the concentration reported by Muhammad and Oluwaniyi [67] reported, who found 1.2 mg/100 g in the seeds. In *S. spinosa*, Co levels were 0.4 mg/kg in the leaves and 0.2 mg/Kg in the fruit. These findings fall within the expected range of Co uptake in plants, which generally accumulate between 0.1 and 2.0 mg/Kg in their tissues [35].

Chromium (Cr) was detected in all soil samples at varying concentrations (Table 5). Cr is a notable environmental contaminant, commonly present in water, rocks, sediments, and mineral deposits [26]. Biologically, Cr is essential in enhancing insulin activity and metabolising proteins, fats, and carbohydrates [20]. However, despite its physiological importance, exposure to high concentrations of Cr poses a significant carcinogenic risk (Table 10).

All the soil samples in the current study had high Fe levels, with a statistically significant and strong positive correlation ($p = 0.020$, $r = 0.999$) between soil Fe concentrations and those in the fruit. According to Bartholomeus et al. [12], Fe content indicates soil fertility and its potential for cultivation. In this study, the Fe content in *D. mespiliformis* pulp was 21.1 mg/Kg, substantially lower than the 9.88 g/100 g reported by Magaji [56]. In *F. thonningii,* Fe concentrations were higher in the leaves (330.5 mg/Kg) than in the fruit (157.6 mg/Kg), while seeds were reported to contain 434.1 mg/100 g in a study by Muhammad and Oluwaniyi [67]. For *S. spinosa,* Fe concentrations were 31.9 mg/Kg in the leaves and 28.6 mg/Kg in the fruit, compared to 4 mg/100 g in the fruit reported by Mbhele et al. [59].

Lead (Pb) levels were below detection limits in all fruit, leaves, and soil samples, contrary to findings by Magaji [56], who reported 5.06 g/100 g in *D. mespiliformis* pulp.

Magnesium (Mg) levels were higher in site A soil compared to sites B and C. While Mg is essential for plant development, excessive concentrations can become phytotoxic, degrading soil quality [80]. In this study, *D. mespiliformis* pulp contained 483.1 mg/Kg of Mg, significantly lower than the 24 g/100 g reported by Magaji [56]. The leaves and fruit of *D. mespiliformis* showed Mg concentrations of 1.896 mg/Kg and 1.555 mg/Kg, respectively, whereas Muhammad and Oluwaniyi [67] recorded 1.184.10 mg/100 g in the seeds. Mg plays a pivotal role in numerous enzymatic reactions, and deficiencies may disrupt Ca and potassium homeostasis, which is critical for maintaining skin integrity [4]. In *S. spinosa,* Mg levels in the fruit were 455.3 mg/Kg in the current study, compared to a range of 9–69 mg/100 g reported by Mbhele et al. [59].

The Mn content in *F. thonningii* was 43.5 mg/Kg in the leaves and 16.9 mg/Kg in the fruit. Mn is an essential trace element required for normal physiological function, and its deficiency has been linked to skin lesions [21]. In comparison, the Mn concentration in *S. spinosa* fruit in the current study was 21.3 mg/Kg, which markedly exceeds the levels (0.10–2.43 mg/100 g) reported by Mbhele et al. [59] across various *S. spinosa* morphotypes.

Selenium (Se) was detected in low concentrations in all soil, leaf, and fruit samples. According to Brodowska et al. [17], elevated Se levels are typically associated with soils rich in Fe and organic matter. In contrast, low Se levels may result from acidic soil conditions or geologies dominated by magmatic rocks. A moderate positive correlation ($r = 0.513$, $p = 0.657$) was observed between Se and Fe in the fruit of *D. mespiliformis* and *F. thonningii.* In contrast, a moderate negative correlation was observed in the soil samples ($r = -0.890$, $p = 0.301$), suggesting differential Se-Fe interactions between plant and soil matrices.

Zinc (Zn) concentrations varied across the different sites, with soils from Sites A and C exhibiting higher Zn levels compared to Site B. While Zn is an essential micronutrient, excessive accumulation can be toxic. It may interfere with the uptake or function of other minerals such as Mn and Fe [77]. A moderate inverse correlation ($r = -0.543$) between Zn and Fe further supports the antagonistic relationship between these elements. In *F. thonningii,* Zn levels reached 32.7 mg/Kg in the leaves and 53.3 mg/Kg in the fruit, comparable to the 63.6 mg/100 g reported in the seeds by Muhammad and Oluwaniyi [67]. In this study, the Zn content in *S. spinosa* fruit was 55 mg/kg, substantially higher than the 0.10–0.80 mg/100 g range reported by Mbhele et al. [59] in different morphotypes.

4.3. Bioaccumulation of metals across soil, leaves, and fruit

Fruits can naturally accumulate metals from the soil during growth and post-harvest processing. These metals are non-biodegradable and can persist in ecosystems, potentially entering the food chain and posing health risks [59]. Although certain metals serve as essential micronutrients, their accumulation at elevated concentrations may harm human health. Increasing environmental contamination with heavy metals has been linked to rising dietary intake and subsequent health concerns, including organ damage and chronic diseases [84]. Plant metal uptake is governed by multiple factors, including soil metal concentrations, pH, cation exchange capacity, organic matter, plant species, cultivar, and developmental stage [45]. The solubility of metal oxides, which depends on factors such as particle size, composition, surface area, and associated impurities, is crucial to bioavailability. Soil pH is particularly influential; for example, hydrolysable metals such as Cd, or those forming insoluble sulfide or phosphate precipitates, tend to become immobilised in near-neutral soils.

In contrast, metals with low ionic potentials remain more soluble and bioavailable. Additionally, soil microorganisms contribute to metal mobility by secreting soluble ligands that form metal–ligand complexes. Metals with higher ionic potentials also interact with inorganic ligands such as carbonate and sulfate, further affecting their solubility and plant availability [18].

The current study (Table 9) revealed distinct patterns of metal bioaccumulation across different plant parts. In *D. mespiliformis*, the BAF for all tested elements progressively decreased from leaves to fruits, indicating a declining translocation efficiency. A similar trend was observed in *F. thonningii*, where BAF values generally decreased from leaves to roots, except for Cd and As, which maintained a consistent BAF of 0.67 between leaves and fruits. Notably, Cu and Mn in *F. thonningii* exhibited increasing BAFs from leaves to fruits, suggesting preferential translocation to edible tissues. In *S. spinosa*, the BAF for Cd remained constant (1.0) in both leaves and fruits, while Zn showed increased accumulation in fruits.

Overall, the majority of elements exhibited higher bioaccumulation in leaves than in fruits, consistent with previous findings suggesting that roots often act as selective barriers, while leaves, being directly exposed to atmospheric deposition, tend to accumulate higher metal concentrations [43,109]. Particularly noteworthy was the exceptionally high BAF of 25.08 for Mn in *F. thonningii* leaves, a trend corroborated by earlier studies [9,46,69]. This significant Mn accumulation highlights the species' strong phytoremediation potential for Mn-contaminated environments.

These findings suggest that *D. mespiliformis* is a strong accumulator of Zn in leaves, while *F. thonningii* effectively accumulates Cu in fruits and Zn in both leaves and fruits. *S. spinosa,* by contrast, demonstrated high accumulation of Mn in leaves and Zn in fruits. The presence of BAF values greater than one for these elements confirms the phytoremediation potential of all three species, positioning them as promising candidates for targeted remediation of metal-contaminated soils [51].

4.4. Health risk assessment

4.4.1. Target hazard quotient/non-carcinogenic risk and carcinogenic risk

The presence of toxic elements in the environment poses a growing global concern due to their persistence, bioaccumulation, and harmful effects on ecosystems and human health. Contamination of air, water, and soil facilitates the uptake of these elements by plants, primarily through polluted soils, often due to anthropogenic activities and natural geochemical processes that elevate concentrations beyond safe limits [98]. Even at trace levels, toxic elements such as Cd, As, and Cr pose significant risks to public health [88].

In the present study (Table 10), fruit samples from the investigated species revealed elevated concentrations of harmful elements. *D. mespiliformis* fruit contained unacceptable levels of Cd, followed by Cr and As. Similarly, *F. thonningii* exhibited elevated concentrations of Cd, Cr, As, Fe, and Zn. *S. spinosa* showed particularly high levels of Cd and Zn. Notably, Co was undetectable in both *D. mespiliformis* and *F. thonningii fruits*. The accumulation of these elements in edible tissues poses a potential health risk to consumers, particularly when the THQ exceeds 1.0, indicating possible non-carcinogenic effects from prolonged exposure.

Furthermore, carcinogenic risk assessment showed that As, Cd, and Cr concentrations surpassed the acceptable threshold of 1.0×10^{-4}, underscoring the need for stringent consumption regulation and continuous environmental monitoring [1]. These findings are particularly concerning in the Mpumalanga Province, where active gold and coal mining operations are prevalent. The region is known for its coal-fired power stations, which, along with mining activities, significantly contribute to the contamination of water and soil with heavy metals [58]. Open-cast and underground mining degrade biodiversity and contaminate surface and groundwater, increasing the risk of heavy metal accumulation in local flora [97]. Given these environmental conditions, the presence of toxic metals in the analysed fruits may reflect broader regional contamination. Bioremediation has been identified as an effective and low-cost method for mitigating soil contamination using plants, microbes, and microbial enzymes [73]. Ongoing rehabilitation efforts in Mpumalanga to restore metal-contaminated ecosystems further support the urgent need for integrated environmental and public health strategies [15,75].

5. Conclusion

The nutritional and elemental analysis of *D. mespiliformis, F. thonningii*, and *S. spinosa* demonstrates their potential as sources of essential nutrients and minerals, supporting food security and human health. Each species showed distinct profiles, with notable levels of protein, fibre, Ca, Fe, and Zn, and high accumulation of Zn and Mn in certain plant parts, indicating nutraceutical potential. However, elevated levels of toxic metals, including Cd, As, and Cr, likely linked to local mining activities, highlight safety concerns, particularly for fruit consumption. Limitations of this study include its focus on selected species from a single region, limited generalisability, the absence of direct dietary intake assessments, and potential variations in nutrient and metal content due to seasonal or environmental factors. Future research should develop strategies to mitigate health risks and safely integrate these wild fruits into local and global food systems.

Ethical approval

Ethics approval for the study was granted by the University of Mpumalanga's Ethics Committee (Ethics Reference: UMP/Chauke/230,013,937/MSC/2024). Permission to collect plant species in the area was granted by the village leaders, the Tribal Council, and the Mpumalanga Tourism and Parks Agency (Permit Number: MPB. 1465).

Data availability statement

All data related to the current study can be obtained from the corresponding author.

Funding

The study was funded by the National Research Foundation (NRF) postgraduate general Master's bursary (grant number PMDS22060719860) and the Water Research Council (grant number 2023/2024-01331), the NRF Thuthuka grant (grant number 138298), and the University of Mpumalanga for funding the APC.

CRediT authorship contribution statement

Sinorita Chauke: Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Maropeng Erica Matlala:** Writing – review & editing, Investigation, Formal analysis. **Wilfred Otang-Mbeng:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Bongisiwe Gladys Shelembe:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Peter Tshepiso Ndhlovu:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

The authors sincerely appreciate the Mnisi Tribal Council for permitting the collection of plant samples and the University of Mpumalanga and the University of KwaZulu-Natal for offering the facilities necessary to carry out this research. We thank Mr. Kenneth Maduna for protein analysis and Ms. Valentine Uwumubyeyi for elemental analysis.

References

[1] A.A. Adeagbo, O.O. Ogunlaja, H.O. Johnson, M.O. Akinseye, S.O. Oni, Human health risk assessment of trace elements in commonly consumed herbs in Ibadan, Nigeria, J. Food Compos. Anal. 126 (2024) 105838.

[2] J.M. Aguilera, T. Toledo, Wild berries and related wild small fruits as traditional healthy foods, Crit. Rev. Food Sci. Nutr. 64 (2024) 5603–5617.

[3] A.L. Akweni, S. Sibanda, G.E. Zharare, C. Zimudzi, Deriving biomass allocation and carbon stocks in fruit components of *Strychnos madagascariensis* (Poir.) and *Strychnos spinosa* (Lam.) in South Africa, Int. J. Fruit Sci. 22 (2022) 1–16.

[4] F.S. Al-Fartusie, S.N. Mohssan, Essential trace elements and their vital roles in human body, Indian J. Adv. Chem. Sci. 5 (2017) 127–136.

[5] M.O. Alabi, O. Ngwenyama, Food security and disruptions of the global food supply chains during COVID-19: building smarter food supply chains for post COVID-19 era, Br. Food J. 125 (2023) 167–185.

[6] N. Almassri, F.J. Trujillo, N.S. Terefe, Microencapsulation technology for delivery of enzymes in ruminant feed, Front. Vet. Sci. 11 (2024) 1352375.

[7] J. Amarteifio, M. Mosase, The chemical composition of selected indigenous fruits of Botswana, J. Appl. Sci. Environ. Manag. 10 (2006) 43–47.

[8] M.O. Aremu, D.S. Aboshi, A. David, I.J.H. Agere, S.S. Audu, B.Z. Musa, Compositional evaluation of bitter melon (*Momordica charantia*) fruit and fruit pulp of ebony tree (*Diospyros mespiliformis*), Int. J. Sci. 8 (2019) 80–89.

[9] R.B. Assoumou, N.O.Z. Abaga, M. Tayebi, Comparative assessment of the state of growth and bioaccumulation of manganese in Poaceae growing on the Mbembele manganese mine in Gabon, in: Proceedings of the BIO Web of Conferences, EDP Sciences, 2024 06005.

[10] J. Babayemi, K. Dauda, D. Nwude, A. Kayode, Evaluation of the composition and chemistry of ash and potash from various plant material- A review, J. Appl. Sci. 10 (2010) 1820–1824.

[11] R.R. Bakker, H. Elbersen, Managing ash content and quality in herbaceous biomass: an analysis from plant to product, in: Proceedings of the 14th European Biomass Conference, 2005, p. 21.

[12] H. Bartholomeus, G. Epema, M. Schaepman, Determining iron content in Mediterranean soils in partly vegetated areas, using spectral reflectance and imaging spectroscopy, Int. J. Appl. Earth Obs. Geoinf. 9 (2007) 194–203.

[13] M. Bateson, G.V. Pepper, Food insecurity as a cause of adiposity: evolutionary and mechanistic hypotheses, Philos. Trans. R. Soc. B 378 (2023) 20220228.

[14] D.J. Beerling, J.R. Leake, S.P. Long, J.D. Scholes, J. Ton, P.N. Nelson, M. Bird, E. Kantzas, L.L. Taylor, B. Sarkar, Farming with crops and rocks to address global climate, food and soil security, Nat. Plants 4 (2018) 138–147.

[15] F. Blum, Evaluation of Nature Based Materials for the Remediation of AMD Water, Swedish University of Agricultural Sciences, 2025.

[16] M.A. Bouaziz, S. Besbes, C. Blecker, B. Wathelet, C. Deroanne, H. Attia, Protein and amino acid profiles of Tunisian Deglet Nour and Allig date palm fruit seeds, Fruits 63 (2008) 37–43.

[17] M.S. Brodowska, M. Kurzyna-Szklarek, M. Haliniarz, Selenium in the environment, J. Elem. 21 (2016) 1173–1185.

[18] D. Cataldo, R. Wildung, Soil and plant factors influencing the accumulation of heavy metals by plants, EHP 27 (1978) 149–159.

[19] S. Chauke, B.G. Shelembe, W. Otang-Mbeng, P.T. Ndhlovu, Ethnobotanical appraisal of wild fruit species used in Mpumalanga Province, South Africa: a systematic review, S. Afr. J. Bot. 171 (2024) 602–633.

[20] S. Chowdhury, K. Pandit, P. Roychowdury, B. Bhattacharya, Role of chromium in human metabolism, with special reference to type 2 diabetes, JAPI 51 (2003) 701–705.

[21] J. Crossgrove, W. Zheng, Manganese toxicity upon overexposure, NMR Biomed. 17 (2004) 544–553.

[22] A. Dagnew, W. Assefa, G. Kebede, L. Ayele, T. Mulualem, A. Mensa, D. Kenbon, E. Gabrekirstos, M. Minuye, A. Alemu, Evaluation of banana (*Musa* spp.) cultivars for growth, yield, and fruit quality, Ethiop. J. Agric. Sci. 31 (2021) 1–25.

[23] F.J. Dai, C.F. Chau, Classification and regulatory perspectives of dietary fiber, J. Food Drug Anal. 25 (2017) 37–42.

[24] A. Das, Ethnobotanical uses of wild fruits of *Santal paraganas* (Jharkhand), IJMFMAP 4 (2018) 31–38.

[25] M.C. De Oliveira, R. Sichieri, R.V. Mozzer, A low-energy-dense diet adding fruit reduces weight and energy intake in women, Appetite 51 (2008) 291–295.

[26] S.R. Dey, M. Sharma, P. Kumar, Effects and Responses of Chromium on Plants, Chromium in Plants and Environment, Springer, 2023, pp. 385–427.

[27] F.A. Dijkstra, N. Van Breemen, A.G. Jongmans, G.R. Davies, G.E. Likens, Calcium weathering in forested soils and the effect of different tree species, Biogeochemistry 62 (2003) 253–275.

[28] A. Drewnowski, N. Darmon, The economics of obesity: dietary energy density and energy cost, AJCN 82 (2005) 265–273.

[29] G. Duarte, L.O. Barbosa, M.E.A. Rosa, The management of psoriasis through diet, Psoriasis Auckl (2012) 45–53.

[30] R. Dupont, M. Longué, A. Galinier, C.C. Frais, C. Ingueneau, L. Astudillo, P. Arlet, D. Adoue, L. Alric, G. Prévot, Impact of micronutrient deficiency and malnutrition in systemic sclerosis: cohort study and literature review, Autoimmun. Rev. 17 (2018) 1081–1089.

[31] A.A. Ebbo, D. Sani, M.M. Suleiman, A. Ahmed, A.Z. Hassan, Phytochemical composition, proximate analysis and antimicrobial screening of the methanolic extract of *Diospyros mespiliformis* Hochst Ex a. Dc (Ebenaceae), ISTJN 11 (2019) 2–11.

[32] M. Elia, J. Cummings, Physiological aspects of energy metabolism and gastrointestinal effects of carbohydrates, Eur. J. Clin. Nutr. 61 (2007) 40–74.

[33] I.E. Ezeagu, C.C. Metges, J. Proll, K.J. Petzke, A.O. Akinsoyinu, Chemical composition and nutritive value of some wild-gathered tropical plant seeds, FNB 17 (1996) 1–4.

[34] A.C. Figueiredo, J.G. Barroso, L.G. Pedro, J.J. Scheffer, Factors affecting secondary metabolite production in plants: volatile components and essential oils, Flavour Fragr. J. 23 (2008) 213–226.

[35] J. Gál, A. Hursthouse, P. Tatner, F. Stewart, R. Welton, Cobalt and secondary poisoning in the terrestrial food chain: data review and research gaps to support risk assessment, Environ. Int. 34 (2008) 821–838.

[36] P. García-Caparrós, M.J. Romero, A. Llanderal, P. Cermeño, M.T. Lao, M. L. Segura, Effects of drought stress on biomass, essential oil content, nutritional parameters, and costs of production in six Lamiaceae species, Water 11 (2019) 573.

[37] Y. Gelaye, Quality and nutrient loss in the cooking vegetable and its implications for food and nutrition security in Ethiopia: a review, Clin. Nutr. Suppl. 15 (2023) 47–61.

[38] L. Haggag, M. Shahin, E. Genaidy, A.A. Fouad, Changes in fruit weight, dry matter, moisture content and oil percentage during fruit development stages of two olive cultivars, Middle East J. 2 (2013) 21–27.

[39] M.M. Hasan, A. Kader, C.A.A. Asif, A. Talukder, Seasonal variation in the association between household food insecurity and child undernutrition in Bangladesh: mediating role of child dietary diversity, MIYCN 19 (2023) 13465.

[40] A. Hassoun, K. Al-Muhannadi, H.F. Hassan, A. Hamad, K. Khwaldia, M. Buheji, A. Al Jawaldeh, From acute food insecurity to famine: how the 2023/2024 war on Gaza has dramatically set back sustainable development goal 2 to end hunger, Front. Sustain. Food Syst. 8 (2024) 1402150.

[41] M. Hitzl, A. Corma, F. Pomares, M. Renz, The hydrothermal carbonization (HTC) plant as a decentral biorefinery for wet biomass, Catal. Today 257 (2015) 154–159.

[42] K. Hubai, N. Kováts, Interaction between heavy metals posed chemical stress and essential oil production of medicinal plants, Plants 13 (2024) 2938.

[43] M.S. Islam, M.K. Ahmed, A.M. Idris, K. Phoungthong, M.A. Habib, R.A. Mustafa, Geochemical speciation and bioaccumulation of trace elements in different tissues of pumpkin in the abandoned soils: health hazard perspective in a developing country, Toxin. Rev. 41 (2022) 1124–1138.

[44] J.O. Jacob, A. Mann, O.I. Adeshina, M.M. Ndamitso, Nutritional composition of selected wild fruits from Minna area of Niger state, Nigeria, Int. J. Nutr. Food Eng. 10 (2016) 37–42.

[45] M.C. Jung, Heavy metal concentrations in soils and factors affecting metal uptake by plants in the vicinity of a Korean Cu-W mine, Sensors 8 (2008) 2413–2423.

[46] A.K.I. Kamal, M.R. Islam, M. Hassan, F. Ahmed, M.A.T. Rahman, M. Moniruzzaman, Bioaccumulation of trace metals in selected plants within Amin Bazar landfill site, Dhaka, Bangladesh, Environ. Process. 3 (2016) 179–194.

[47] P. Kavcar, A. Sofuoglu, S.C. Sofuoglu, A health risk assessment for exposure to trace metals via drinking water ingestion pathway, Int. J. Hyg. Environ. Health 212 (2009) 216–227.

[48] A. Kubier, R.T. Wilkin, T. Pichler, Cadmium in soils and groundwater: a review, Appl. Geochem. 108 (2019) 104388.

[49] V. Kumar, Going, toll-like receptors in skin inflammation and inflammatory diseases, EXCLI J. 20 (2021) 52–79.

[50] S.E. Lee, S.H. Lee, Skin barrier and calcium, Ann. Dermatol. 30 (2018) 265–275.

[51] B. Li, D. Chen, Y. Yang, X. Li, Effects of soil properties on accumulation characteristics of copper, manganese, zinc, and cadmium in Chinese turnip, Plant Divers. 41 (2019) 340–346.

[52] S. Lin, J. Li, X. Hu, S. Chen, H. Huang, Y. Wu, Z. Li, Potential dietary calcium supplement: calcium-chelating peptides and peptide-calcium complexes derived from blue food proteins, Trends Food Sci. Technol. 145 (2024) 104364.

[53] T. Lockett, C.C. Calvert, L.E. Grivetti, Energy and micronutrient composition of dietary and medicinal wild plants consumed during drought. Study of rural Fulani, Northeastern Nigeria, Int. J. Food Sci. Nutr. 51 (2000) 195–208.

[54] Z. Lu, The impact of the Israeli–Palestinian conflict on food and economy in Gaza, ICIHCS 1 (2024) 1–4.

[55] C.W. Lye, S. Sivasampu, T. Mahmudiono, H.A. Majid, A systematic review of the relationship between household food insecurity and childhood undernutrition, J. Public Health 45 (2023) 677–691.

[56] S. Magaji, Study on the chemical composition of jackal berry (*Diospyros mespiliformis*) fruit edible part, Fudma J. Sci. 3 (2019) 576–580.

[57] R. Maikhuri, D.S. Parshwan, P. Kewlani, V.S. Negi, S. Rawat, L. Rawat, Nutritional composition of seed kernel and oil of wild edible plant species from Western Himalaya, India, Int. J. Fruit Sci. 21 (2021) 609–618.

[58] J.H. Mathebula, Determinants of Household Participation in Agricultural Production in Shatale region of the Bushbuckridge Local Municipality, Mpumalanga Province, University of Limpopo, 2015.

[59] Z. Mbhele, G.E. Zharare, C. Zimudzi, C.N. Mchunu, N.R. Ntuli, Variation in nutritional composition of *Strychnos spinosa* Lam. morphotypes in KwaZulu-Natal, South Africa, Genet. Resour. Crop Evol. 72 (2024) 359–373.

[60] F. Mehri, A. Heshmati, E.T. Ghane, T. Mahmudiono, Y. Fakhri, Concentration of heavy metals in traditional and industrial fruit juices from Iran: probabilistic risk assessment study, Biol. Trace Elem. Res. 11 (2024) 5296–5305.

[61] I.J. Mirón, C. Linares, J. Díaz, The influence of climate change on food production and food safety, Environ. Res. 216 (2023) 114674.

[62] B.B. Mishra, S. Gautam, R. Chander, A. Sharma, Characterization of nutritional, organoleptic and functional properties of intermediate moisture shelf stable ready-to-eat *Carica papaya* cubes, Food Biosci. 10 (2015) 69–79.

[63] X. Mkhize, B.E. Mthembu, C. Napier, Transforming a local food system to address food and nutrition insecurity in an urban informal settlement area: a study in Umlazi township in Durban, South Africa, J. Agric. Food Res. 12 (2023) 100565.

[64] D.M. Motlhanka, S.W. Makhabu, Medicinal and edible wild fruit plants of Botswana as emerging new crop opportunities, J. Med. Plant Res. 5 (2011) 1836–1842.

[65] M. Muchuweti, A.R. Ndhlala, A. Kasiyamhuru, Estimation of the degree of polymerization of condensed tannins of some wild fruits of Zimbabwe (*Uapaca kirkiana* and *Ziziphus mauritiana*) using the modified vanillin-HCl method, J. Sci. Food Agric. 85 (2005) 1647–1650.

[66] D. Mudgil, The interaction between insoluble and soluble fiber. Dietary Fiber for the Prevention of Cardiovascular Disease, Elsevier, 2017, pp. 35–59.

[67] H. Muhammad, O. Oluwaniyi, Proximate, phytochemicals, minerals, and antinutritional contents of *Ficus thonningii* seed, JOTCSA 9 (2022) 793–800.

[68] H.S. Muhammad, M.K. Atiku, I.K. Zubairu, S.M. Muhammad, Nutritional and phytochemical evaluation of Kanya (*Diospyros mespiliformis*) juice: a potential functional beverage for enhanced food security, UMYU Sci. 3 (2024) 114–126.

[69] C. Mulenga, C. Clarke, M. Meincken, Bioaccumulation of Cu, Fe, Mn and Zn in native *Brachystegia longifolia* naturally growing in a copper mining environment of Mufulira, Zambia, Environ. Monit. Assess. 194 (2022) 8.

[70] C.S. Mutengwa, P. Mnkeni, A. Kondwakwenda, Climate-smart agriculture and food security in Southern Africa: a review of the vulnerability of smallholder agriculture and food security to climate change, Sustainability 15 (2023) 2882.

[71] O.T. Mytton, K. Nnoaham, H. Eyles, P. Scarborough, C. Ni Mhurchu, Systematic review and meta-analysis of the effect of increased vegetable and fruit consumption on body weight and energy intake, BMC Public Health 14 (2014) 1–11.

[72] M. Nembang, Development and Quality Evaluation of Blended Wheat Flour by Incorporating Brewer's Spent Grain, Tribhuvan University, 2023.

[73] N.D. Nnaji, H. Onyeaka, T. Miri, C. Ugwa, Bioaccumulation for heavy metal removal: a review, SN Appl. Sci. 5 (2023) 125.

[74] M.M. Nyambe, H. Hakwenye, M. Benyamen, Nutritional and anti-nutritional composition of *Diospyros mespiliformis* and *Hyphaene petersiana* fruits from Namibia, ISTJN 13 (2019) 2–11.

[75] Oberholster, P.J., De Klerk, A., Chamier, J., Cho, M., Crafford, J., De Klerk, L., Dini, J., Harris, K., Holness, S., Le Roux, W., 2016. Assessment of the ecological integrity of the Zaalklapspruit wetland in Mpumalanga (South Africa) before and after rehabilitation: the Grootspruit case study. WRC Report No. 2230/2/16.

[76] A.O. Omolola, A.I. Jideani, P.F. Kapila, Quality properties of fruits as affected by drying operation, Crit. Rev. Food Sci. Nutr. 57 (2017) 95–108.

[77] M.G. Palmgren, S. Clemens, L.E. Williams, U. Krämer, S. Borg, J.K. Schjørring, D. Sanders, Zinc biofortification of cereals: problems and solutions, Trends Plant Sci. 13 (2008) 464–473.

[78] N. Piccardi, P. Manissier, Nutrition and nutritional supplementation: impact on skin health and beauty, Dermatoendocrinology 1 (2009) 271–274.

[79] M.E. Posthauer, M. Banks, B. Dorner, J.M. Schols, The role of nutrition for pressure ulcer management: national pressure ulcer advisory panel, European pressure ulcer advisory panel, and pan pacific pressure injury alliance white paper, Adv. Skin Wound Care 28 (2015) 175–188.

[80] M. Qadir, S. Schubert, J.D. Oster, G. Sposito, P.S. Minhas, S.A. Cheraghi, G. Murtaza, A. Mirzabaev, M. Saqib, High-magnesium waters and soils: emerging environmental and food security constraints, Sci. Total Environ. 642 (2018) 1108–1117.

[81] K.R. Rahman, S. Ramdhani, V.G. Sanyoto, Z. Nawareza, Smart packaging innovation for food: enhancing shelf life and quality of perishable goods, AJSEM 3 (2024) 133–140.

[82] T.U. Rahman, S. Shah, S. Hassan, S. Fahad, Food security challenges and adaptation strategies in China amidst global climate change, J. Umm Al-Qura Univ. Appl. Sci. (2025) 1–14.

[83] M. Ramjan, M.T. Ansari, Factors affecting of fruits, vegetables and its quality, J. Med. Plants Stud. 6 (2018) 16–18.

[84] S.S. Randjelovic, D.A. Kostic, G.S. Stojanovic, S.S. Mitic, M.N. Mitic, B.B. Arsic, A. N. Pavlovic, Metals content of soil, leaves and wild fruit from Serbia, Cent. Eur. J. Chem. 12 (2014) 1144–1151.

[85] A. Raposo, R.P. Zandonadi, R.B.A. Botelho, Challenging the Status Quo to Shape Food Systems Transformation from a Nutritional and Food Security Perspective, MDPI, 2023, p. 1825.

[86] M.U. Rehman, R. Khan, A. Khan, W. Qamar, A. Arafah, A. Ahmad, A. Ahmad, R. Akhter, J. Rinklebe, P. Ahmad, Fate of arsenic in living systems: implications for sustainable and safe food chains, J. Hazard. Mater. 417 (2021) 126050.

[87] M. Rinnerthaler, M.K. Streubel, J. Bischof, K. Richter, Skin aging, gene expression and calcium, Exp. Gerontol. 68 (2015) 59–65.

[88] M. Rokonuzzaman, W.C. Li, C. Wu, Z. Ye, Human health impact due to arsenic contaminated rice and vegetables consumption in naturally arsenic endemic regions, Environ. Pollut. 308 (2022) 119712.

[89] M. Rostaei, S. Fallah, A. Carrubba, Z. Lorigooini, Organic manures enhance biomass and improve content, chemical compounds of essential oil and antioxidant capacity of medicinal plants: a review, Heliyon 10 (2024) 36693.

[90] C. Sánchez-Moreno, S. De Pascual-Teresa, B. De Ancos, M.P. Cano, Nutritional values of fruits, in: Y.H. Hui, J. Barta, M.P. Cano, T.W. Gusek, J.S Sidhu, N. K. Sinha (Eds.), Handbook of Fruits and Fruit Processing, Blackwell Publishing, USA, 2006, pp. 29–43.

[91] R. Sathyavathi, K. Janardhanan, Wild edible fruits used by Badagas of Nilgiri District, Western Ghats, Tamilnadu, India, J. Med. Plant Res. 8 (2014) 128–132.

[92] M.M.A. Satter, M.M.R.L. Khan, S.A. Jabin, N. Abedin, M.F. Islam, B. Shaha, Nutritional quality and safety aspects of wild vegetables consume in Bangladesh, Asian Pac. J. Trop. Biomed. 6 (2016) 125–131.

[93] H.K. Seligman, R. Levi, V.O. Adebiyi, A. Coleman-Jensen, J.F. Guthrie, E. A. Frongillo, Assessing and monitoring nutrition security to promote healthy dietary intake and outcomes in the United States, Annu. Rev. Nutr. 43 (2023) 409–429.

[94] R. Serra, N. Ielapi, A. Barbetta, S. de Franciscis, Skin tears and risk factors assessment: a systematic review on evidence-based medicine, Int. Wound J. 15 (2018) 38–42.

[95] H. Sharma, N. Rawal, B.B. Mathew, The characteristics, toxicity and effects of cadmium, IJNN 3 (2015) 1–9.

[96] B.G. Shelembe, Phytochemical and elemental studies of two indigenous medicinal plants of South Africa. Bridelia Micrantha and Sideroxylon Inerme, University of KwaZulu-Natal, 2014.

[97] G.B. Simpson, J. Badenhorst, G.P. Jewitt, M. Berchner, E. Davies, Competition for land: the water-energy-food nexus and coal mining in Mpumalanga Province, South Africa, Front. Environ. Sci. 7 (2019) 86.

[98] D. Sinha, S. Datta, R. Mishra, P. Agarwal, T. Kumari, S.B. Adeyemi, A. Kumar Maurya, S. Ganguly, U. Atique, S. Seal, Negative impacts of arsenic on plants and mitigation strategies, Plants 12 (2023) 1815.

[99] E. Spoede, M.R. Corkins, B.A. Spear, P.J. Becker, S.G. Bellini, M.K. Hoy, T. A. Piemonte, M. Rozga, Food insecurity and pediatric malnutrition related to under-and overweight in the United States: an evidence analysis center systematic review, JAND 121 (2021) 952–978.

[100] K.M. Stadler, J.C. Elledge, Eating high fiber foods, HNFE (2004) 348–929.

[101] F. Torrens Zaragozá, Classification of fruits proximate and mineral content: principal component, cluster, meta-analyses, Nereis 7 (2015) 39–50.

[102] F.D. Ugese, P.K. Baiyeri, B.N. Mbah, Nutritional composition of shea (*Vitellaria paradoxa*) fruit pulp across its major distribution zones in Nigeria, Fruits 63 (2008) 163–170.

[103] A. Vermani, P. Navneet, A. Chauhan, Physico-chemical analysis of ash of some medicinal plants growing in Uttarakhand, India, Nat. Sci. 8 (2010) 88–91.

[104] J. Von Braun, K. Afsana, L.O. Fresco, M.H.A. Hassan, Science and Innovations for Food Systems Transformation, Springer Nature, 2023.

[105] T.C. Wallace, R.L. Bailey, J.B. Blumberg, B. Burton-Freeman, C.O. Chen, K. M. Crowe-White, A. Drewnowski, S. Hooshmand, E. Johnson, R. Lewis, Fruits, vegetables, and health: a comprehensive narrative, umbrella review of the science and recommendations for enhanced public policy to improve intake, Crit. Rev. Food Sci. Nutr. 60 (2020) 2174–2211.

[106] W.S. Zeng, S.Z. Tang, Q.H. Xiao, Calorific values and ash contents of different parts of Masson pine trees in Southern China, J. For. Res. 25 (2014) 779–786.

[107] A. Zergui, M.A. Kerdoun, S. Boudalia, Trace elements in tea in Ouargla, Algeria and health risk assessment, Food Addit. Contam. (2024) 1–12.

[108] T. Zhang, Y. Zheng, C. Fu, H. Yang, X. Liu, F. Qiu, X. Wang, Z. Wang, Chemical variation and environmental influence on essential oil of *Cinnamomum camphora*, Molecules 28 (2023) 973.

[109] S. Zhao, L. Duo, Bioaccumulation of cadium, copper, zinc, and nickel by weed species from municipal solid waste compost, Pol. J. Environ. Stud. 24 (2015) 413–417.