Heliyon 9 (2023) e19137

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Valorisation of *Zingiber officinale* Roscoe postharvest residues as byproducts with antioxidant capacity

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ARTICLE INFO

Keywords:
Agroindustry
Bioactive compounds
Infrared spectrophotometry
Scanning microscopy
Waste utilisation

ABSTRACT

During the postharvest phase of ginger, 2.6%–5% by weight of ginger rhizome residues are generated, which are disposed in landfills and constitute a continuous source of organic contamination causing serious environmental problems. The objective of this study was to valorise ginger postharvest residues (shoot, finger, slice, trunk, root, and rootles) from district Pichanaki (Peru) as dry powdered byproducts with an antioxidant capacity similar to that of rhizome. The nutrition composition, phenolic compounds, such as total phenolic content, total flavonoid content, 6-gingerol content, and 6-shogaol content, antioxidant capacity expressed by ferric reducing antioxidant power and IC_{50} of 2,2-diphenyl-1-picrylhydrazyl radical, surface changes, and structural morphology were evaluated. In addition, the dependent variables were correlated using the Pearson's matrix and principal component analysis (PCA). The results for shoot, finger, slice, and trunk residues showed similar phenolic compound contents and antioxidant capacities to those of rhizome, but similar results were not obtained for root and rootlet residues. These results were corroborated by analyses of surface and structural morphologies. The Pearson's matrix showed that the content of phenolic compounds correlated with the antioxidant capacity and carbohydrate content for the rhizome and residues, except for the root. The PCAshowed that residues that exhibited higher contents of starch grains with reserve functions such as shoot, finger, slice, and trunk were correlated with higher contents of phenolic compounds with antioxidant capacity, while residues with higher contents of crude fibre and ash with a support function exhibited a low antioxidant capacity. Thus, the shoot, finger, slice, and trunk residues, from district Pichanaki (Peru), can be valorised and reincorporated as byproducts in the ginger value chain. They are important for the food, cosmetic, and pharmaceutical industries.

1. Introduction

Ginger (*Zingiber officinale* Roscoe) is a herbaceous plant whose edible fraction is rhizome, a marketed product. Since ancient times, it has been used as a medicinal plant for its pharmacological properties as hypoglycemic, antilipidemic, cardiovascularly protective, immunosuppressive, hepatoprotective, antimicrobial, antiinflammatory, antiproliferative, and antioxidative [1–3]. This plant is grown in more than forty countries. 4.4 million tons were produced worldwide in 2020 [4]. During the postharvest stage's washing, cutting, and sorting, residues that were a part of the rhizome are generated. These residues represent 2.6%–5% of the initial weight,

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https://doi.org/10.1016/j.heliyon.2023.e19137
Received 13 June 2023; Received in revised form 4 August 2023; Accepted 14 August 2023
Available online 15 August 2023

which would generate 114 thousand tons of residues per year worldwide. Thus, in the Peruvian jungle's Junín region, this plant was cultivated, and, by 2020, 48,800 tons were produced, generating 1269 tons of waste in that year [4]. Currently, ginger waste is not valued. Thus, its pharmacological properties such as the antioxidant capacity should be identified to evaluate its incorporation into the value chain as a byproduct and ingredient for the food, pharmaceutical, and cosmetic industries.

Bioactive compounds in ginger rhizome include phenolic compounds (9.19–27.4 mg gallic acid equivalent per gram dry matter (GAE/g dm)) [5,6], flavonoids (1.52–11.02 mg quercetin equivalent (QE)/g dm) [7,8], mono- and sesquiterpenes (17.85%–30.26% as zingiberene) [8], and polysaccharides (39.4%–71.5% as carbohydrates) [2], which have antioxidant capacity [2,9,10]. In addition, in the rhizome, the content of 6-gingerol is notable, in the range of 0.53–8.72 mg/g dm. 6-Shogaol is also present with a content of 0.04–7.66 mg/g dm [6,11], as well as paradoles, gingerdiols, 1-dehydrogingerdiones, diarylheptanoids, and zingerone. Thus, 6-gingerol is most abundant [12]. During the rhizome drying process, the gingerols are transformed into their respective shogaols, through the elimination reaction by dehydration of the hydroxyl group and in the presence of an acid catalyst (H^+) and subsequent formation of a double bond in the alkyl tail. Thus, the shogaols exhibit stronger antiinflammatory and antioxidant properties than their corresponding gingerols by the double bond in the alkyl tail [11,12]. Studies by various authors have demonstrated ranges of ferric reducing antioxidant power (FRAP) of 0.2–0.89 mmol Fe^{2+}/g dm [6,13] and half-maximal inhibitory concentration (IC_{50}) of 2, 2-diphenyl-1-picrylhydrazyl radical (DPPH) of 4.3–16.69 mg dm/mL [7,14] for samples of different ginger varieties. These methods are generally used to evaluate the antioxidant capacity.

The objective of this study was to valorise shoot, finger, slice, trunk, root, and rootlet ginger postharvest residues as dry powdered byproducts with an antioxidant capacity similar to that of rhizome. Their nutritional compositions (ash, crude fibre, crude protein, ethereal extract, and carbohydrates), phenolic compound contents (total phenol content (TPC), total flavonoid content (TFC), 6-gingerol (6-G) content, and 6-shogaol (6-S) content), antioxidant capacities (FRAP and IC_{50} of DPPH), and changes in structure and morphology on the surface were evaluated. In addition, Pearson correlation matrix and principal component analyses of the evaluated dependent variables were carried out.

2. Materials and methods

2.1. Plant material and reagents

Fresh samples of rhizome and postharvest residues of ginger including shoot, finger, slice, trunk, root, and rootlet were obtained from a postharvest plant Elisur Organic S.A.C., located in the district of Pichanaki (10°55′29″S 74°52′36″W), Junín, Peru. The collection was carried out on March 22 and 24, 2021. Samples were taken from each lot and homogenised using the coning and quartering technique [15]. 6-G and 6-S standards were purchased from TRC (ON, CAN) and ChromaDex (CA, USA), respectively. The reagent Folin-Ciocalteu, 2,4,6-tripyridyl-*s*-triazine (TPTZ), DPPH, L-ascorbic acid, gallic acid, and quercetin were purchased from Sigma-Aldrich (MO, USA). Methanol and acetonitrile (high performance liquid chromatography grade) were acquired from J. T. Baker (NJ, USA). All other chemicals and reagents were of analytical grade.

2.2. Nutritional composition

The results were calculated in dry matter (g/100 g). The ash, ethereal extract, and crude protein contents were determined using the Association of Official Analytical Chemists methods nos. 930.05, 922.06, and 978.04 respectively. The crude fibre content was determined by the Peruvian Technical Standard no. 205.003. The carbohydrate content was determined by difference.

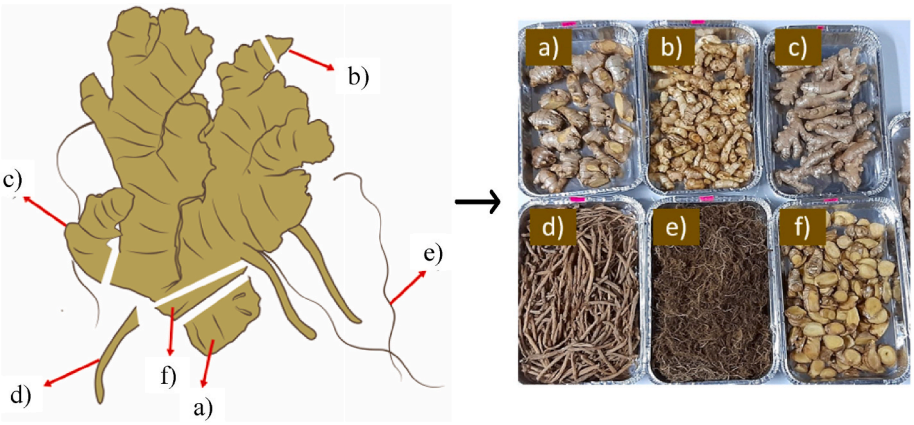

Fig. 1. Ginger residues generated in the postharvest process: a) trunk, b) shoot, c) finger, d) root, e) rootlet, and f) slice.

2.3. Sample treatment

Fresh ginger rhizome samples and postharvest residues (Fig. 1) were washed, cut, oven-dried at 40 °C (UF160, Memmert, DUE), ground, and sieved with a 0.25-mm mesh. Phenolic compounds from the dried samples were extracted by refluxing (FA-46, MRC, ISR) at a loading of 3.125 mg/mL in methanol at 85 °C for 1 h [16]. At the end of the process, two fractions were obtained, a solid fraction (extracted mass), from which changes in surface and structural morphology were analyzed, and liquid fraction (extract), and their volumes were quantified. The extracts were concentrated by nitrogen gas to dryness, which yielded a viscous appearance, and dissolved again in methanol to a concentration of 2 mg/mL. They were denoted as concentrated extracts and stored at 4 °C until the analysis of the phenolic compound content and antioxidant capacity.

2.4. Analysis of surface and structural morphologies

The dried rhizome sample and samples extracted from the rhizome, shoot, finger, slice, trunk, root, and rootlet were treated to dryness with a silica gel and vacuum for 48 h. For a microscopic analysis, the samples were covered with a gold film. For imaging, scanning electron microscopy (SEM; Q250 Analytical, Thermo Fisher Scientific, WI, USA) with an acceleration voltage of 20 kV and magnifications of 120 and 600 was used. For the analysis of the changes in the chemical structures of the samples, Fourier-transform

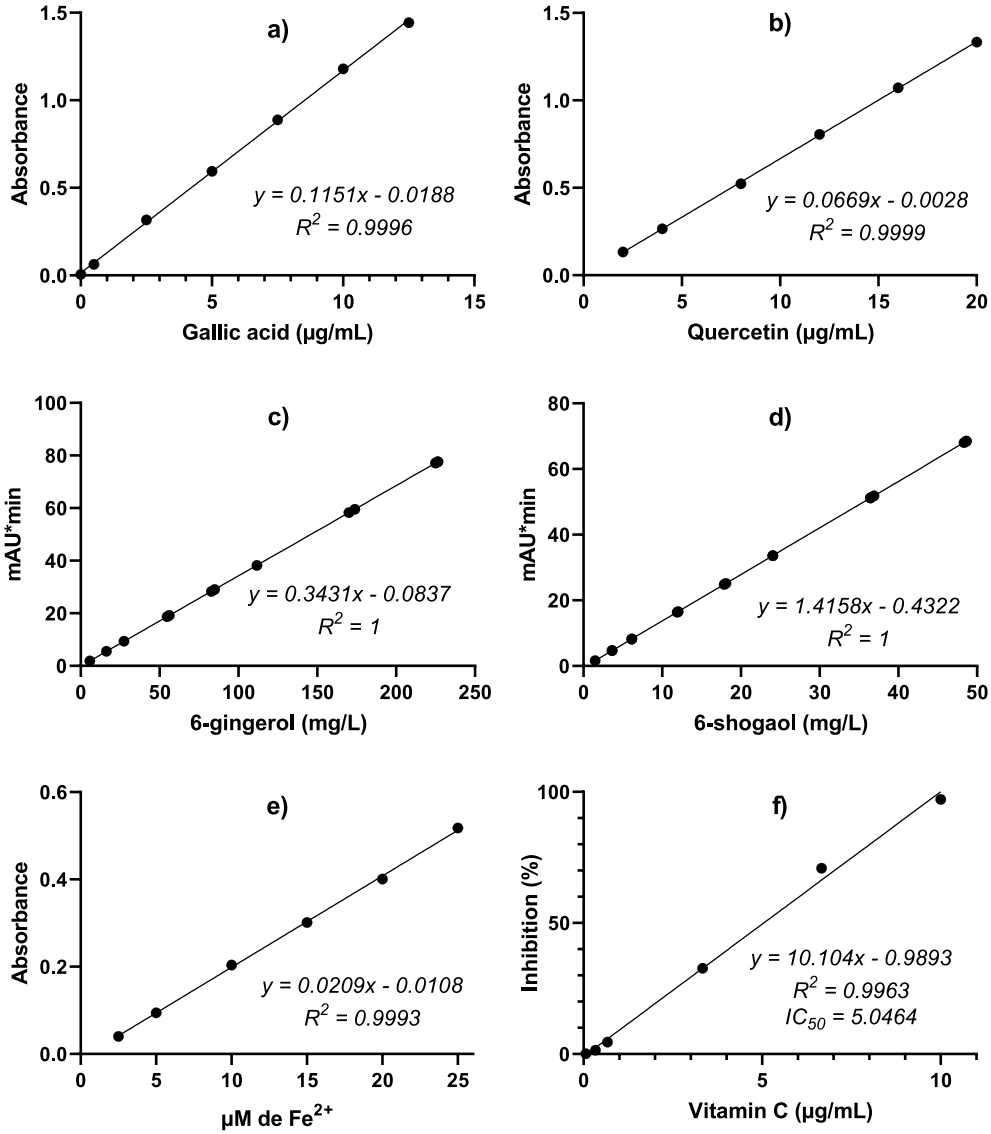

Fig. 2. Calibration curves of a) TPC expressed in gallic acid, b) TFC expressed in quercetin, c) 6-G, d) 6-S, e) FRAP expressed in Fe^{2+}, and f) DPPH radical inhibition expressed in vitamin C.

infrared (FTIR) spectrophotometry (Nicolet iS10, Thermo Fisher Scientific, WI, USA) in a range of 700–4000 cm^{-1} was used [16,17].

2.5. Determination of phenolic compounds

The method to determine phenolic compounds is described in detail in our previous report [16]. The absorbance readings were carried out at 765 nm in an ultraviolet (UV)-visible spectrophotometer (Evolution 300, Thermo Fischer Scientific, WI, USA). The standard curve was obtained with a 0.5–12.5 μg/mL solution of gallic acid in methanol (Fig. 2a), proceeding similarly to the sample described in detail in our previous report [16]. The TPC was expressed as mg gallic acid equivalent per gram of dry matter (mg GAE/g dm).

The method described by Pourmorad et al. [18] was used to determine total flavonoids. $AlCl_3$ (0.1 g/mL), CH_3COOK (1 M), and water were added to the concentrated extract in a ratio of 1:1:28 (mL:mL:mL). The reaction was carried out for 30 min at room temperature. Absorbance readings were carried out at 415 nm using the same spectrophotometer described above. The standard curve was obtained with a 5–20 μg/mL quercetin solution in methanol (Fig. 2b), proceeding similarly to the sample. The TFC was expressed as mg quercetin equivalent per gram of dry matter (mg QE/g dm).

The quantification of 6-G and 6-S was performed using the method proposed by Vipin et al. [19], described in detail in our previous report [16]. The absorbance reading was performed at 230 nm. Calibration curves of 6-G and 6-S were obtained in the ranges of 5.7–85.6 μg/mL and 1.2–17.6 μg/mL, respectively (Fig. 2c and d). The 6-G and 6-S contents were expressed as mg/g dm.

2.6. Determination of antioxidant capacity

The FRAP method is described in detail in our previous report [16]. Absorbance readings were carried out at 593 nm using the same spectrophotometer described above. The standard curve was obtained with a 2.5–25 μM Fe^{2+} ferrous sulphate solution (Fig. 2e), proceeding similarly to the sample described in detail in our previous report [16]. The results are expressed in mmol of Fe^{2+}/g dm.

The DPPH uptake method is described in detail in our previous report [16]. Absorbance readings were performed at 518 nm using the same spectrophotometer describe above. The results are expressed by the ability to scavenge 50% of free radicals (IC_{50}) in mg dm/mL.

In both cases, vitamin C was used as a positive control. For the FRAP assay, a value of 17 mmol Fe^{2+}/g was obtained, similar to that reported by Al-Laith et al. [20] (11.5 mmol Fe^{2+}/g) (Fig. 2e). For the DPPH assay, a value of 5.1 μg/mL IC_{50} was obtained (Fig. 2f), similar to that reported by Ahmad et al. [21] (8.84 μg/mL).

2.7. Statistical analysis

All tests were performed in triplicates. The mean value and its standard deviation are reported. The Grubbs test was applied to eliminate outliers. The normal distribution of the values was checked by the mean of the Jarke–Bera test. A one-way analysis of variance and Duncan's multiple range test were used to compare individual means. The Pearson's correlation matrix was used to evaluate correlations between nutritional composition, phenolic compounds, and antioxidant capacity. The principal component analysis (PCA) was used to evaluate correlations between dependent variables (nutritional composition, phenolic compounds, and antioxidant capacity) and active observations (rhizome, shoot, finger, slice, trunk, and rootlet). The software XLSTAT version 2023.1.6 (Addinsoft, NY, USA) was used, with a significance level of 5% in all cases.

3. Results and discussion

3.1. Nutritional composition

The results obtained for the nutritional composition of the rhizome and residues are presented in Table 1. The results show significant differences ($p < 0.05$) in nutrient content between the rhizome and residues shoot, finger, slice, trunk, root, and rootlets. The shoot exhibited the highest values for the ethereal extract and carbohydrates, similar protein content, and lowest value for fibre

Table 1
Nutritional compositions of rhizome and ginger residues. The data are expressed by mean ± standard deviation, $n = 3$.

	Ash	Crude fibre	Crude protein	Ethereal extract	Carbohydrates
	g/100 g dry matter				
Rhizome	9.68 ± 0.10^{e}	16.33 ± 0.17^{c}	6.18 ± 0.25^{c}	2.25 ± 0.29^{b}	65.56 ± 0.49^{c}
Shoot	10.65 ± 0.30^{d}	10.61 ± 0.25^{f}	6.03 ± 0.28^{c}	3.47 ± 0.05^{a}	69.23 ± 0.78^{a}
Finger	10.44 ± 0.18^{d}	14.04 ± 0.27^{d}	5.59 ± 0.24^{d}	2.12 ± 0.12^{b}	67.81 ± 0.24^{b}
Slice	12.19 ± 0.16^{c}	11.41 ± 0.35^{e}	9.90 ± 0.09^{b}	2.14 ± 0.14^{b}	64.35 ± 0.12^{d}
Trunk	12.81 ± 0.14^{b}	14.05 ± 0.08^{d}	10.40 ± 0.06^{a}	3.61 ± 0.20^{a}	59.14 ± 0.14^{f}
Root	9.87 ± 0.29^{e}	25.13 ± 0.34^{b}	2.13 ± 0.11^{f}	2.00 ± 0.06^{b}	60.87 ± 0.25^{e}
Rootlet	17.69 ± 0.26^{a}	29.20 ± 0.10^{a}	3.04 ± 0.18^{e}	1.63 ± 0.09^{c}	48.44 ± 0.45^{g}

Different letters in the same column imply statistical difference ($p < 0.05$) according to the Duncan's multiple range test.

compared to the rhizome, while the root exhibited the lowest value for the crude protein. The rootlet exhibited the highest values for ash and fibre, and lowest for the ethereal extract and carbohydrates compared to the rhizome and other residues.

The ash contents for the rhizome and shoot, finger, slice, trunk, and root residues (9.68–12.81 g/100 g dm) were within the range of 0.16–13.1 g/100 g dm. The rootlet residue (17.69 g/100 g dm) exhibited a higher value than those reported for ginger rhizome by Shukla et al. [8] and Yeh et al. [14]. It is important to consider that the presence of rootlets is a strategy of the plant to absorb more minerals from the soil. Therefore, rootlets continuously grow to cover new areas and effectively absorb minerals [22]. Consequently, the rootlets exhibited a higher content of ash, or minerals, as they expanded in the soil and fulfilled their absorption function.

The content of crude fibres, providing a support of the plant, in the rhizome and shoot, finger, slice, and trunk residues (10.61–16.33 g/100 g dm) were within the range of 1.01–17.94 g/100 g dm, while the root and rootlet residues (25.13–29.20 g/100 g dm) exhibited higher values than those reported for ginger rhizome by Shukla et al. [8] and Yeh et al. [14]. On the other hand, the rhizome stores nutrients for vegetative reproduction, while the root absorbs water and nutrients, providing the plant with a support and fixation to the soil [22]. In this sense, for the root and rootlet to fulfil their function, they must have a higher fibre content in their composition.

The crude protein contents of the rhizome and residues (2.13–10.40 g/100 g dm) and ethereal extract contents of the rhizome and

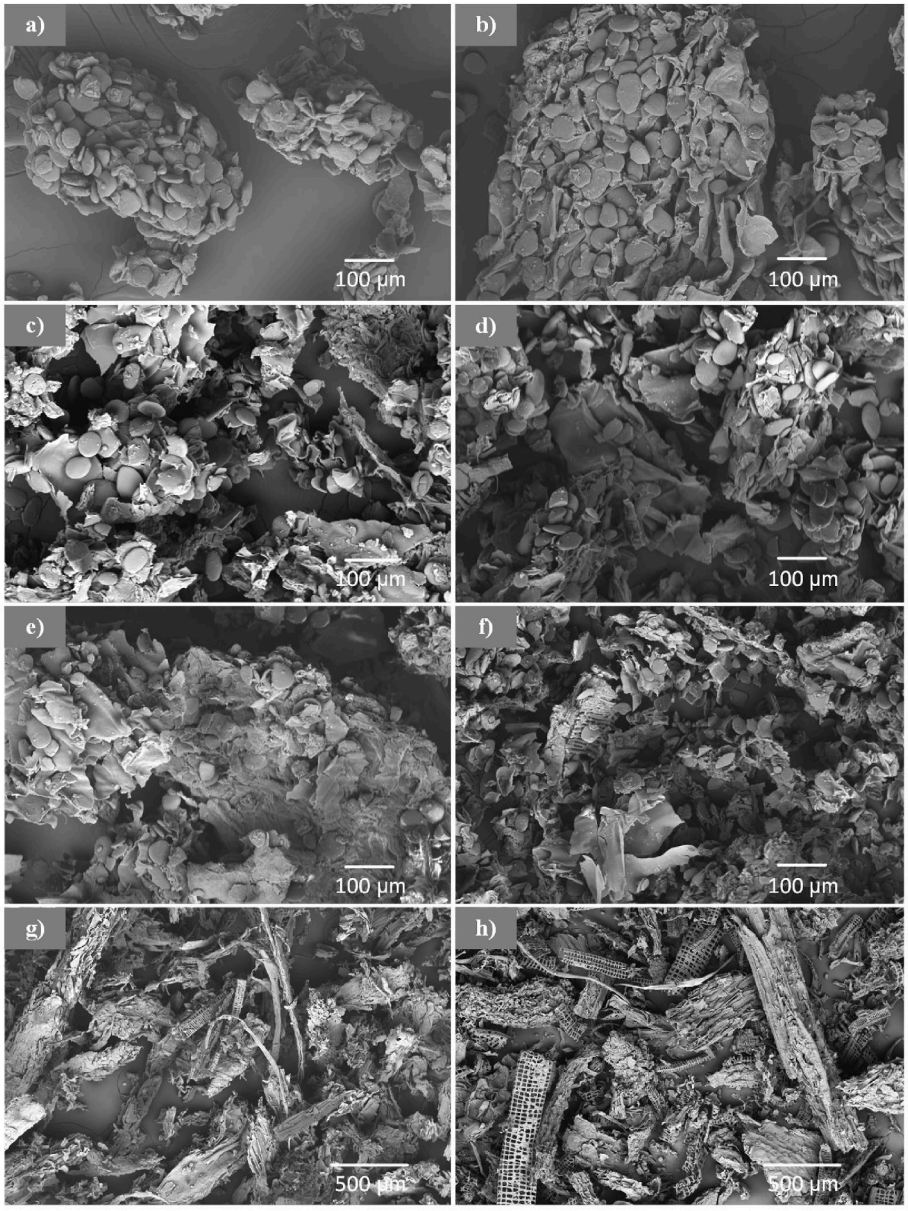

Fig. 3. SEM images before extraction for a) rhizome and after extraction for b) rhizome, c) shoot, d) finger, e) slice, f) trunk, g) root, and h) rootlet.

residues (1.63–3.61 g/100 g dm) were within the expected ranges of 0.93–16.98 g/100 g dm and 0.52–6.48 g/100 g dm, respectively, presented for ginger rhizome by Ogbuewu et al. [23], Shukla et al. [8], and Yeh et al. [14]. The crude protein contents for rhizome and residues were close to and below the values reported for other medicinal and aromatic plants (MAPs) of 10.5–15.0 g/100 g [24]. Although the values for root and rootlets were within the range for protein content, they were lowest relative to the ginger rhizome and other residues, as well as the rootlets for the ethereal extract content, due to the specific function they serve, as described above.

The carbohydrate contents for rhizome and shoot, finger, slice, trunk, and root residues (59.14–69.23 g/100 g dm) were within the expected range of 58.43–97.26 g dm. However, the rootlet (48.44 g/100 g dm) exhibited a lower value than those reported by Shukla et al. [8] and Yeh et al. [14] due to its higher ash and crude fibre contents described above.

Ginger rhizome reproduces vegetatively by seeds, and by hypogeal germination [25], formed from the buds on the fingers of the rhizome. Thus, the apical meristem of the seed contains hundreds of initial cells that undergo successive divisions forming the shoot. With this mechanism, the development and cell growth are achieved, and the new seedling becomes an adult plant [26]. Therefore, the shoot exhibited higher contents of carbohydrates and ethereal extract and similar crude protein content to that of the rhizome, nutrients necessary for conversion to an adult plant.

3.2. SEM analysis

In the SEM images of the rhizome before and after extraction and shoot, finger, slice, and trunk residues, starch grains and very small amount of fibres were visualised (Fig. 3a–f). In contrast, the SEM images of the root and rootlets showed fibres, but no starch grains (Fig. 3g and h). Fig. 3a shows that, in the rhizome before the extraction, there was an alteration of the parenchyma structure, a product of the drying and crushing processes. Discoidal and ovoid-shaped starch grains, 22.2 ± 3.8 μm long, 14.2 ± 2.5 μm wide and 4 μm thick, were kept together. In contrast, in the images after the extraction of rhizome and shoot, finger, slice, and trunk residues (Fig. 3b–f), damages to parenchyma cells and cell walls and dispersion of starch grains in the tissue due to the effects of temperature and pressure generated during extraction were observed [27,28]. The dispersion of starch grains is due to the rupture of the amyloplasts containing them and, possibly, due to the damage of the lamellae covering them. Moreover, at 85 °C, the starch grains of the slice residue underwent an additional gelatinisation (Fig. 3e). According to Kuk et al. [29], ginger starch grains gelatinise at a temperature of 88 °C. However, this process did not influence the content of their phenolic compounds or their antioxidant capacity.

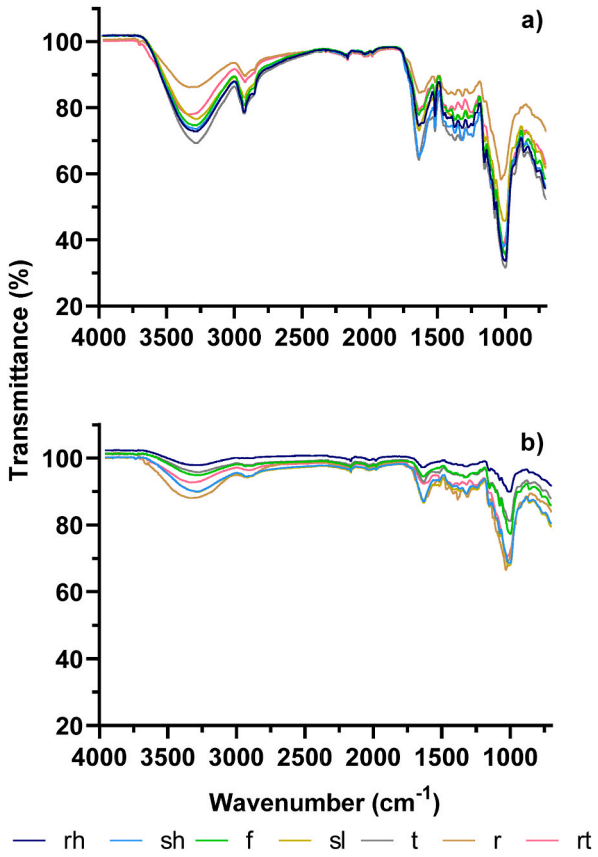

Fig. 4. FTIR spectra a) before and b) after extraction; rhizome (rh), shoot (sh), finger (f), slice (sl), trunk (t), root (r), and rootlet (rt).

3.3. FTIR spectroscopy analysis

The FTIR absorption spectra of the rhizome and residues of ginger are presented in Fig. 4, where the functional groups increased their transmittance or disappeared after the extraction process, which indicates that the rhizome and residues underwent structural changes after the extraction process.

In the spectrum in Fig. 4a, the peak at 3280 cm^{-1} belongs to the *O*–H bond vibrations and hydrogen bonds originating from phenolic compounds (6-G, 6-S), cellulose, hemicellulose, and lignin. The peaks at 2851 and 2932 cm^{-1} belong to the C–H bond vibrations of CH_2 and CH_3 groups of simple phenols (6-S, 6-G) and flavonoids. The peak at 1635 cm^{-1} is attributed to the H–O–H bond of the water molecule. The peak at 1516 cm^{-1} corresponds to the C═C bond of the aromatic rings of lignin and phenolic compounds such as gingerols, shogaols, and flavonoids. The peak at 1002 cm^{-1} belongs to the C–O and C–C bonds of cellulose and hemicellulose. The peaks at 861 and 930 cm^{-1} belong to the C–O–C and C–O–H bonds, respectively, from starch [28,30].

After the extraction, the FTIR spectra of the rhizome and ginger residues (Fig. 4b) show an increase in the transmittance percentage of the mentioned peaks, due to the extraction of phenolic compounds such as gingerols, shogaols, flavonoids, and other compounds related to the solvent methanol. This is verified by the disappearance of the peaks at 2932, 2851, and 1516 cm^{-1} corresponding to the alkyl chain (CH_2, CH_3 groups) and aromatic rings of the phenolic compounds such as gingerols, shogaols, and flavonoids described above.

Therefore, by surface and structural analyses by SEM and FTIR spectroscopy, respectively, it can be confirmed that the extraction caused both physical and chemical modifications in the rhizome and ginger residues favouring the extraction of phenolic compounds such as gingerols and shogaols.

3.4. Phenolic compounds

The TPC, TFC, 6-G, and 6-S results are presented in Table 2, where significant differences ($p < 0.05$) were observed in the comparison of rhizome and residues values.

The TPCs for the rhizome and shoot, finger, and slice residues (26.54–37.00 mg GAE/g dm) were higher than the expected range of 9.19–27.4 mg GAE/g dm, whereas the trunk and root residues (16.46–26.54 mg GAE/g dm) were within that range. The rootlet residues (1.87 mg GAE/g dm) exhibited the lowest value compared to those reported by Ghafoor et al. [5] and Li et al. [6]. Although the rootlet exhibited a lower value, it was close to that reported by Vipin et al. [19] (1.85 mg GAE/g of dry extract) for rhizome. These values were close and lower than the values reported for other MAPs (35.01–54.38 mg GAE/g dm) [24], but higher than those of the residues of *Ziziphus lotus* (L.) Lam. almonds (5.13–10.33 mg GAE/g dm) [31]. In addition, the starch grains observed in the SEM images and lower fibre contents in the rhizome, shoot, finger, slice, and trunk are related to the higher TPC than that observed in the root and rootlet.

The TFCs (Table 2) for the rhizome and shoot, finger, slice, trunk, and root residues (13.88–20.89 mg QE/g dm) were higher than the reported value of 11.02 mg QE/g dm, while the residue rootlet (1.65 mg QE/g dm) exhibited a lower value than that reported by Samappito et al. [7]. The rootlet value is similar to that reported by Shukla et al. [8] (1.52 mg QE/g dm). These values were below the TFCs reported for other MAPs (56.05–93.41 mg QE/g dm) [24], but higher than those of the residues of *Ziziphus lotus* (L.) Lam. almonds (8.25–12.66 mg QE/g dm) [31]. On the other hand, there is an evidence that the higher TFC in the root is due to flavonoids accumulating in this part of the plant to promote nodule formation and symbiosis with endophytic fungi [32]. Thus, the root exhibited a higher TFC among the residues.

The TPC and TFC results are variant because the various plant parts exhibit different concentrations of their phenolic compounds [33,34].

The 6-G contents for the rhizome and shoot, finger, slice, trunk, and root residues (9.66–27.47 mg/g dm) (Table 2) were above the expected range of 2.04–8.72 mg/g dm, while the residue rootlet (1.16 mg/g dm) exhibited a value below this range [6], originating from methanolic extracts of rhizome obtained with ultrasound and with different drying methods. Although the rootlet exhibited a lower value among the residues, it was higher than the values of 0.53 and 0.84 mg/g, reported by Ko et al. [11], originating from

Table 2
Contents of total phenols, total flavonoids, 6-gingerol and, 6-shogaol of rhizome and ginger residues. The data are expressed by mean ± standard deviation, $n = 3$.

	TPC [a]	TFC [b]	6-G	6-S	6-G/6-S
	(mg/g dry matter)				
Rhizome	36.44 ± 2.54^{a}	20.89 ± 1.78^{a}	27.43 ± 0.92^{a}	0.85 ± 0.06^{c}	32.27
Shoot	37.00 ± 0.80^{a}	17.22 ± 0.69 ^{b}	27.47 ± 0.38^{a}	0.95 ± 0.02 ^{b}	28.92
Finger	31.49 ± 2.03 ^{b}	15.21 ± 2.39 ^{b,c}	23.56 ± 0.75 ^{b}	0.76 ± 0.03 ^{d}	31.00
Slice	30.26 ± 1.87 ^{b}	14.55 ± 0.82^{c}	18.54 ± 0.26 ^{d}	0.72 ± 0.02^{e}	25.75
Trunk	26.54 ± 1.77^{c}	13.88 ± 2.27^{c}	21.11 ± 0.48^{c}	0.84 ± 0.03^{c}	25.13
Root	16.46 ± 1.26 ^{d}	20.09 ± 0.39^{a}	9.66 ± 0.28^{e}	1.30 ± 0.06^{a}	7.43
Rootlet	1.87 ± 0.15^{e}	1.65 ± 0.15 ^{d}	1.16 ± 0.08^{f}	0.16 ± 0.02^{f}	7.25

Different letters in the same column imply statistical difference ($p < 0.05$) according to the Duncan's multiple range test.
[a] Gallic acid equivalent.
[b] Quercetin equivalent.

methanolic extracts in a water bath at 60 °C for rhizome skin and fresh rhizome pulp, respectively. On the other hand, during the drying, crushing, and extraction processes, it is possible to obtain a higher 6-G content [27]. Thus, in this study, the 6-G content was higher in the rhizome, shoot, finger, slice, and trunk than in the root and rootlets, which had the lowest values. The higher 6-G content is directly related to the presence of starch grains observed in the SEM images (Fig. 3). On the contrary, higher fibre contents were observed in the SEM images of the root and rootlets, confirmed by their nutritional compositions and lower 6-G contents, due to their absorption, support, and holding function.

Regarding the 6-S concentration (Table 2), the values for the rhizome and all residues (0.16–1.30 mg/g dm) were within the range of 0.07–7.66 mg/g dm reported by Li et al. [6], originating from methanolic extracts of rhizome obtained with ultrasound and with different drying methods.

Ko et al. [11] reported lower values than 0.04 mg/g dm for the fresh rhizome from methanolic extracts in a water bath at 60 °C. The highest values of 6-S were observed for the root and shoot residues, while the lowest value was observed for the rootlet residue, due to its higher fibre concentration than those of the rhizome and other residues.

As 6-G and 6-S are mayor components of different gingerols and shogaols in the ginger rhizome, they are responsible for the purgative taste. 6-S is more purgative than 6-G [19]. Moreover, 6-G is transformed to 6-S during thermal processing and in the presence of an acid catalyst (H^+), which is a reversible reaction under certain conditions and endothermic [19]. Through this mechanism, 6-G dehydrates and loses the β-hydroxy-keto group from the alkyl tail and forms a double bond, transforming into 6-S. 6-S exhibits a higher antioxidant capacity than its predecessor by the double bond [11,12].

When the 6-G/6-S ratio tends to 1, it is a relative indication of a higher antioxidant capacity [11]. In this study, the 6-G/6-S ratio for the rhizome and residues was higher than 1 (Table 2), which would be interpreted as a low antioxidant capacity. However, IC_{50} of DPPH and FRAP of the rhizome and shoot, finger, slice, and trunk residues showed good antioxidant capacities similar to reported values [6,35]. Thus, the antioxidant capacity is also related to the presence of various phenolic compounds, mono- and sesquiterpenes, polysaccharides, etc. [2,9,10], which together may provide such capacity.

The range of values for phenolic compounds is wide, as it depends on the drying method [5] and extraction yield, which, in turn, depends on the solvent and extraction method [11,12,36]. In addition, the nutritional composition of ginger rhizome depends on the variety, state of the fresh or dry sample, soil quality, agroclimatic conditions, place of origin, stages of maturity, adaptive metabolism of the plant, etc. [2,9,10].

3.5. Antioxidant capacity

The antioxidant capacity of the rhizome and residues was determined by FRAP and IC_{50} of DPPH. These results showed significant differences ($p < 0.05$) (Table 3). The FRAP antioxidant capacities for the rhizome and shoot, finger, slice, and trunk residues (0.51–0.72 mmol of Fe^{2+}/g dm) were within the range of 0.46–0.89 mmol of Fe^{2+}/g dm reported by Li et al. [6] and higher than 0.20 mmol of Fe^{2+}/g dm reported by Embuscado [13], including the value for the root (0.28 mmol of Fe^{2+}/g dm). These values were within the expected range of 0.18–2.77 mmol of Fe^{2+}/g dm reported for spices and herbs [13]. In addition, the rootlet residue (0.05 mmol of Fe^{2+}/g dm) exhibited a lower value than those of the rhizome and other residues, but similar to values reported for acetone/acetic acid extracts of fruits such as strawberries, blackberries, and black mulberries of 0.07, 0.08, and 0.02 mmol of Fe^{2+}/g dm, respectively [37]. In this regard, the results obtained in this study indicate that rhizome and ginger residues have a good potential to reduce the ferric tripyridyltriazine complex to ferrous tripyridyltriazine by electron donation [38] through the content of their phenolic compounds, such as 6-S able to donate an electron from the double bond of the alkyl tail [16].

Regarding the values for DPPH, they are reported as IC_{50}, which is the concentration of the extract that provides 50% inhibition of the DPPH radical. Consequently, a lower IC_{50}, implies a higher antioxidant capacity and therefore higher FRAP. The IC_{50} values for rhizome and residues (0.16–3.39 mg/g dm) (Table 3) were close to the value reported by Samappito et al. [7] (16.69 mg dm/mL) for a methanolic extract for ginger rhizome.

According to Fidrianny et al. [35], DPPH $IC_{50} < 50$ μg/mL is considered as a potent antioxidant capacity. With the increase in the value, the capacity decreases. Values in the range of 50–100 μg/mL are high, those of 101–150 μg/mL are medium, and those >150 μg/mL are low for ginger extracts. Thus, in this study, the IC_{50} values of the rhizome extract and finger, shoot, slice, and trunk residues are considered to reflect high antioxidant capacities, whereas the root extract and rootlet residues are considered to have medium and low antioxidant capacities, respectively (Table 3).

Table 3
Antioxidant capacities expressed by FRAP and IC_{50} of DPPH of the rhizome and ginger residues. The data are expressed by mean ± standard deviation, $n = 3$.

	FRAP (mmol Fe^{2+}/g dm)	DPPH (IC_{50} mg dm/mL)	DPPH (IC_{50} μg extract/mL)
Rhizome	0.71 ± 0.01^{a}	0.17 ± 0.01^{c}	32.05 ± 3.26^{c}
Shoot	0.72 ± 0.03^{a}	0.16 ± 0.01^{c}	36.93 ± 2.81^{c}
Finger	0.60 ± 0.03^{b}	0.21 ± 0.01^{c}	31.88 ± 5.88^{c}
Slice	0.60 ± 0.02^{b}	0.19 ± 0.01^{c}	44.60 ± 2.01^{c}
Trunk	0.51 ± 0.01^{c}	0.22 ± 0.01^{c}	41.04 ± 3.02^{c}
Root	0.28 ± 0.03^{d}	0.44 ± 0.03^{b}	99.07 ± 14.83^{b}
Rootlet	0.05 ± 0.01^{e}	3.39 ± 0.38^{a}	858.95 ± 157.66^{a}

Different letters in the same column imply statistical difference ($p < 0.05$) according to the Duncan's multiple range test.

The phenolic compounds in plant extracts can donate hydrogen atoms to stabilise free radicals [6] such as DPPH. Thus, phenolic compounds of a ginger extract, such as the β-hydroxy keto group of the 6-G alkyl tail, can donate hydrogen [12].

In both methods, the results of the antioxidant capacity in the shoot residue were similar to those of the rhizome. The same result was obtained with the values of the analyzed compounds TPC, 6-G, and 6-S. In the last case, it was superior. Thus, the shoot residue exhibited similar and better phytochemical and nutritional characteristics than the rhizome. The high content of phenolic compounds in the shoot may be an essential component in the protection against pathogens during its development [39]. Moreover, these phenolic compounds are important for the development and growth of a new plant [40].

In addition, the finger residue is a branching formed by secondary and tertiary structures that extend the rhizome below the soil (hypogeal) [41]. Similarly, the trunk residue forms the junction of ginger branches, and the slice residue is generated from small cuts during rhizome profiling, a form of hand, during postharvest processing. In this regard, these residues exhibited IC_{50} values as those of the rhizome, reflecting the potent antioxidant capacity. On the contrary, the root residue exhibited a medium antioxidant capacity, but the contents of its TF and 6-S compounds were similar and higher than those of the rhizome, respectively.

The root has the function of absorbing minerals from the soil such as iron and copper that are transported to different parts of the plant. Different studies on ginger rhizome demonstrated iron values of 1.5–53.5 mg/100 g and copper values of 0.46–0.75 mg/100 g [42,43]. The contents of these minerals are important as they enhance the prooxidant activity of phenolic compounds and flavonoid quercetin [44]. Thus, the higher contents of 6-S and TFC in the root and in the presence of transition metals such as iron and copper probably interfered with the expression of their antioxidant capacity.

The rootlet residue exhibited the lowest antioxidant capacity in both methods and lowest content of phenolic compounds compared to the rhizome and other residues. However, this residue is notable for its high fibre and ash contents due to its specific function of nutrient and water absorption, plant support, and subjection, described above.

3.6. Multivariate analysis of nutrient content, phenolic compounds and antioxidant capacity

The Pearson's coefficient was used to analyse the correlation between selected dependent variables of phenolic compound content (TPC, TFC, 6-G, and 6-S), antioxidant capacity (FRAP and IC_{50} of DPPH), and nutritional composition (ash, crude fibre, crude protein, ethereal extract, carbohydrates) of rhizome and shoot, finger, slice, trunk, and rootlet residues. Table 4 shows that the strongest positive associations were obtained for TPC, TFC, 6-G, 6-S, FRAP, and carbohydrates. On the contrary, the most important negative correlations were obtained for IC_{50} of DPPH, ash, and crude fibre. Similar results of correlations were reported by other studies [24].

The positive correlation between FRAP and TPC, TFC, 6-G, and 6-S occurred because the chemical structures of these phenolic compounds can scavenge free radicals. In the case of TPC, 6-G, and 6-S, they contain OH groups and double bonds, while, in the case of TFC, they contain a higher amount of OH groups at C3' and C4' [35]. On the other hand, the correlations between FRAP, TPC, TFC, 6-G and 6-S are attributed to the activation of enzymes involved in the biosynthesis of flavonoid and phenolic compounds [24].

Likewise, a strong negative correlation was observed between phenolic compound variables and antioxidant capacity expressed by IC_{50} of DPPH. The negative values are obtained because the lower IC_{50} represents a higher antioxidant capacity, and is inversely proportional to the higher content of phenolic compounds. Alsataf et al. [45] and Fidrianny et al. [35] obtained similar results relating the antioxidant capacity to the TPC in ginger and pomegranate extracts, respectively.

Furthermore, the Pearson's correlation coefficient for FRAP and IC_{50} of DPPH showed a strong negative correlation, with a good antioxidant capacity as FRAP had a high value and IC_{50} of DPPH had, a low value. Other studies demonstrated a strong positive correlation between the antioxidant capacities expressed by FRAP and DPPH, expressed as percentage inhibition [45].

In this investigation, a strong positive correlation was obtained between the content of phenolic compounds and antioxidant capacity for rhizome and shoot, finger, slice, trunk, and rootlet residues, except for the root. Therefore, the results for the root were not included in the multivariate analysis because there was no direct relationship between the content of its phenolic compounds, such as TFC and 6-S, and its antioxidant capacity.

Using PCA, the response patterns in the factor space of the transformed values of the nutritional contents, phenolic compounds, and

Table 4
Pearson correlation matrix between the variables of phenolic compounds (TPC, TFC, 6-G, 6-S), antioxidant capacity (FRAP, IC_{50} of DPPH), and nutritional composition of rhizome and ginger residues (shoot, finger, slice, trunk, rootlet).

Variable	TPC	TFC	6-G	6-S	FRAP	IC_{50} of DPPH	Ash	Crude fibre	Crude protein	Ethereal extract
TPC	**1**									
TFC	**0.977**	**1**								
6-G	**0.982**	**0.973**	**1**							
6-S	**0.961**	**0.932**	**0.973**	**1**						
FRAP	**0.999**	**0.977**	**0.976**	**0.957**	**1**					
IC_{50} of DPPH	**−0.958**	**−0.926**	**−0.938**	**−0.962**	**−0.956**	**1**				
Ash	**−0.985**	**−0.979**	**−0.983**	**−0.927**	**−0.980**	**0.924**	**1**			
Crude fibre	**−0.913**	**−0.825**	**−0.864**	**−0.924**	**−0.915**	**0.954**	**0.844**	**1**		
Crude protein	0.421	0.410	0.366	0.526	0.435	−0.623	−0.304	−0.625	**1**	
Ethereal extract	0.499	0.427	0.558	0.704	0.492	−0.560	−0.406	−0.630	0.507	**1**
Carbohydrates	**0.959**	**0.891**	**0.929**	**0.889**	**0.954**	**−0.895**	**−0.955**	**−0.897**	0.253	0.420

Values in bold are different from 0 with a significance level alpha = 0.05.

antioxidant capacity of the rhizome and ginger residues were examined (Fig. 5). The selected dependent variables are the nutrient contents (ash, crude fibre, ethereal extract, crude protein, and carbohydrates), phenolic compounds (TPC, TFC, 6-G, and 6-S), and antioxidant capacity (FRAP and IC_{50} of DPPH), while the active observations were the rhizome and shoot, finger, slice, trunk, and rootlet residues. We considered eleven dependent variables mostly distributed in the factorial spaces F1 (82.50%) and F2 (10.58%).

In the F1 factor space, the rhizome and shoot, finger, slice, and trunk residues correlated positively with phenolic compounds, antioxidant capacity expressed as FRAP, and carbohydrate content, while the rootlet residue correlated positively with the antioxidant capacity through IC_{50} of DPPH, ash content, and crude fibre (Table 5). This correlation occurred as the rhizome and shoot, finger, slice, and trunk residues have the function of reserve, so that, in their structure, they have a higher content of starch grains, where the phenolic compounds with antioxidant capacity are probably located. In contrast, the root and rootlet residues have the function of a support and absorption of nutrients, which have a higher content of crude fibre and ash. The F2 factor correlates with the nutritional contents of crude protein and ethereal extract. The ethereal extract is also distributed in the F1 factor space, correlating with the antioxidant capacity [2].

In the biplot of the principal components (Fig. 5), the positive zone of factor F1 is integrated by the phenolic compounds (TPC, TFC, 6-G, and 6-S), antioxidant capacity (FRAP), and nutritional compound (carbohydrates); in addition, it is integrated by the rhizome and shoot, and finger residues. Thus, the rhizome, shoot, and finger exhibited similar contents of phenolic compounds, nutritional compounds, and antioxidant capacity. The carbohydrate content in the starch grains is directly related to the antioxidant capacity, similar to that reported by other authors [9,10]. On the other hand, the negative zone of factor F1 is integrated by the antioxidant capacity (IC_{50} of DPPH) and nutritional content (ash and crude fibre); near these scores, the presence of rootlet residue is observed. Thus, the rootlet exhibited the highest content of these nutrients compared to the rhizome and other residues. This agrees with the results of the nutritional composition (Table 1) and is supported by the lower antioxidant capacity (by DPPH), with the higher IC_{50}.

4. Conclusions

Ginger postharvest residues, shoot, finger, slice, and trunk can be valorised as dry powdered byproducts with antioxidant capacity as they exhibit contents of phenolic compounds such as TPC, TFC, 6-G, and 6-S as well as antioxidant capacity similar to those expected for the rhizome. Therefore, it is recommended that these residues are reincorporated as byproducts in the ginger value chain, considering their importance for the food, cosmetic, and pharmaceutical industries. According to the interpretation of the results obtained in this study, there is a strong correlation between the content of phenolic compounds and antioxidant capacity. Likewise, the higher contents of both variables correlated with the higher content of nutrients such as carbohydrates, as well as with the lower amounts of ash and fibre in the rhizome and postharvest residues.

Author contribution statement

Paola Aurelia Jorge Montalvo: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Carlos Vílchez-Perales: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data. Lizardo Visitación-Figueroa: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

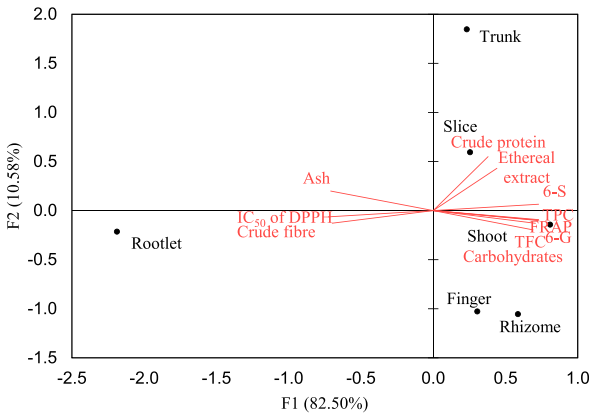

Fig. 5. PCA biplot of phenolic compounds, antioxidant capacity, and nutritional composition of rhizome and ginger residues (shoot, finger, slice, trunk, rootlet).

Table 5
PCA of phenolic compounds (TPC, TFC, 6-G, 6-S), antioxidant capacity (FRAP, IC_{50} of DPPH), and nutritional composition (ash, crude fibre, crude protein, ethereal extract, carbohydrates) variables.

Variable	F1	F2
TPC	0.990	−0.134
TFC	0.957	−0.175
6-G	0.978	−0.137
6-S	0.987	0.088
FRAP	0.988	−0.125
IC_{50} of DPPH	−0.981	−0.087
Ash	−0.960	0.269
Crude fibre	−0.946	−0.174
Crude protein	0.514	0.744
Ethereal extract	0.596	0.583
Carbohydrates	0.935	−0.266
Cumulative variance (%)	82.504	93.088

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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.

Acknowledgements

The authors thank Engineer Luis Angulo from the company Elisur Organic S.A. and Ph.D. Sylvia Alcazar from the research office, Universidad Nacional Agraria La Molina. The authors were supported by the Center for Research in Chemistry, Toxicology and Environmental Biotechnology, Department of Chemistry, Universidad Nacional Agraria La Molina.

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