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Proximal characteristics, phenolic compounds profile, and functional properties of *Ullucus tuberosus* and *Arracacia xanthorrhiza*

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Abstract

Aim: The Andean tubers *Ullucus tuberosus* and *Arracacia xanthorrhiza* are of great international importance due to their nutritional value (carbohydrates, fiber), functional and phenolic compounds. This study aimed to determine the proximate composition of the flours of these tubers, their functional properties, and the phenolic profiles of both the skin and the pulp, since the flour used is a mixture of both.

Methods: The proximal characteristics were determined as established by the Association of Official Analytical Chemists (AOAC), the functional properties, water holding capacity (WHC), swelling capacity (SC), and oil holding capacity (OHC); and the profile of phenolic compounds was carried out by high performance liquid chromatography-mass spectrometry (HPLC-MS).

Results: Results revealed that the tubers contain more than 50% carbohydrates, with *U. tuberosus* having 14% fiber and *A. xanthorrhiza* having 4.07% fiber. Notably, they are rich in minerals, such as potassium (K), with levels of 4.12% and 3.32% for *U. tuberosus* and *A. xanthorrhiza*, respectively. In terms of functional properties, *U. tuberosus* exhibited a WHC of 0.78 g water/g dry matter (DM), an SC of 1.42 g water/g DM, and an OHC of 0.44 g oil/g DM. In contrast, *A. xanthorrhiza* showed a WHC of 0.96 g water/g DM, an SC of 3.86 g water/g DM, and an OHC of 0.18 g oil/g DM. Additionally, the study identified various hydroxycinnamic acids, including caffeic acid 4-*O*-glucoside and *p*-coumaroyl glucose, as well as methoxyflavonols, such as 3,7-dimethylquercetin.

Conclusions: These characteristics suggest that the flours could be valuable for the production of bakery products, pastries, pastas, or foods requiring high viscosity. Furthermore, *U. tuberosus* and *A. xanthorrhiza* flours have potential applications in the development of functional foods, thus promoting their use and adding value to these tubers produced in the Andean region.

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Keywords

Starch, minerals, polyphenols

Introduction

The Andean region, extending across countries such as Peru, Ecuador, Bolivia, Venezuela, Chile, Argentina, and Colombia, is renowned for its diverse array of grains, fruits, roots, and tubers. This region encompasses a variety of climates, ranging from droughts to frosts and saline conditions, significantly influencing the agronomic management of crops grown there [1–4]. Among the diverse crops cultivated in the Andean region, certain tubers, such as ulluco (*Ullucus tuberosus*) and arracacha (*Arracacia xanthorrhiza*), have been categorized as marginal due to their ability to thrive under the extreme conditions of the Andes. These unique adaptations suggest that these tubers could play a crucial role in enhancing global food security [1].

Ulluco and arracacha are notable for their pleasant taste and nutritional value. For instance, arracacha provides significant amounts of resistant starches, fructooligosaccharides (FOS), vitamin A, calcium (Ca), phosphorus (P), iron (Fe), niacin, ascorbic acid, proteins, fiber, and carbohydrates [4–8]. Similarly, ulluco is also a significant source of protein, fiber, vitamin C, and betalains. Nonetheless, the nutritional value of both tubers varies depending on the cultivar [4, 9–13].

In addition to their nutritional value, these tubers possess other benefits. They contain phytochemicals, such as carotenoids, anthocyanins, and phenolic acids, which suggest their potential to contribute to the treatment of various health conditions [3, 8]. Extracts from ulluco have shown potential in reducing inflammation and promoting tissue regeneration due to their high starch content (approximately 65%), which is easily digestible and valuable for producing edible films and coatings [4, 9–13]. Various betalains have been identified in ulluco, including betaxanthins (22–96 μg/g) and betacyanins (64 μg/g), without the presence of carotenoids and anthocyanins. Furthermore, ulluco contains phenolic compounds, predominantly hydroxycinnamic acids [14–18]. Likewise, arracacha is rich in phenolic compounds that contribute to its diuretic and antiseptic activities, as well as saponins with anticancer and cholesterol-lowering properties [19, 20]. Additionally, it has been described that this tuber has a lower glycemic index and acts as a substrate for gut microbiota [21]. Consequently, current research efforts have focused on promoting the consumption of these tubers and extracting specific phytochemicals, such as anthocyanins, carotenoids, phenols, and starch [14].

Traditionally, these tubers are consumed as staple foods by rural populations, valued for their high carbohydrate content, particularly starch [5]. However, consumption levels of certain tubers, including mashua (*Tropaeolum tuberosum*), oca (*Oxalis tuberosa*), and ulluco (*U. tuberosus*), remain relatively low, with their use largely confined to local dishes [6, 7]. Despite their potential, these tubers face significant post-harvest losses due to the lack of adequate processing. Their characteristics that would allow for diverse food processing are still unknown. Therefore, the objective of this study was to determine the proximal composition of flours from these tubers, their functional properties, and the phenolic profiles of both the skin and pulp of *U. tuberosus* and *A. xanthorrhiza*, to elucidate potential uses once they are processed.

Materials and methods

Vegetal material

Tubers of ulluco (*U. tuberosus*) and arracacha (*A. xanthorrhiza*) were procured from a market in Popayán City, Colombia. The tubers were then selected and washed to remove any solids and impurities, and subsequently stored at room temperature until further processing.

To produce flour from *U. tuberosus* and *A. xanthorrhiza*, the tubers were thoroughly washed using friction with water. The samples were then chopped and subjected to convection drying at 45°C for 24 hours in a BINDER convection oven, until a moisture content of approximately 8% was achieved. The

dehydrated samples were then ground using an IKA™ mill (basic microfine grinding unit MF10) and sieved to a particle size of 0.5 µm. The resulting flours were stored in zip-lock bags at room temperature.

For species identification and phenolic compound analysis, 0.5 kg of fresh roots were processed. The outer shells were removed using an ILKO vertical vegetable peeler. The shells were then dried at 50°C a BINDER convection oven for 12 hours. These dried samples were used for species identification and phenolic compound extraction. The identification of the tubers was conducted by sequencing the chloroplast genes ribulose-1,5-bisphosphate carboxylase (*rbcL*) and Maturase K (*matK*). For this purpose, the tuber shells were first frozen in liquid nitrogen and then ground to a fine powder for DNA extraction using the DNeasy Mericon kit (Qiagen). The polymerase chain reaction (PCR) reaction was performed in a final volume of 25 µL, containing 12.5 µL of DreamTaq Green PCR Master Mix (2X) (ThermoFisher Scientific), which included DNA polymerase DreamTaq, DreamTaq Green 2X buffer, deoxynucleoside triphosphate (dNTP) and 4 mM $MgCl_2$, and 0.5 µL of each primer at a concentration of 10 mM, 10.5 µL of water, and 1 µL of DNA template (100 µg/µL). For the amplification of the *rbcL* gene, the following primers were used: Rbcla-F 5'-ATGTCACCACACAAACAGAGAGAGACTAAAGC-3' and Rbcla-R 5'-GTAAAATCAAGTCCACCRCG-3'. The PCR conditions were as follows: an initial denaturation at 95°C for 2 minutes, followed by 35 cycles of denaturation at 95°C for 30 seconds, annealing at 55°C for 30 seconds, and extension at 72°C for 1 minute, with a final extension at 72°C for 2 minutes. For the amplification of the *matK* gene, the same reagent concentrations were used. The primers employed were: matK-F 5'-CGTACAGTACTTTTTTGTGTGTTTACGAG-3' and matK-R 5'-ACCCAGTCCATCTGGAAATCTTGGTTC-3'. The PCR conditions included an initial denaturation at 94°C for 5 minutes, followed by 35 cycles of denaturation at 94°C for 30 seconds, annealing at 52°C for 30 seconds, and extension at 72°C for 1 minute, with a final extension at 72°C for 2 minutes. Gel electrophoresis images were captured using a Transilluminator Ultraviolet Spectroline UVP mini Darkroom (Spectroline), with image analysis performed via VisionWorksTMLS software. Sequencing of the amplified DNA fragments was carried out using an Applied Biosystems Model 3730 sequencer (ThermoFisher Scientific), employing the Taq FS Dye Terminator Cycle Sequencing method. All obtained DNA sequences were compared with those in the GenBank database of the NCBI (National Center for Biotechnology Information) using the BLAST tool (Basic Local Alignment Search Tool) to identify highly similar sequences.

Proximal analysis

The physicochemical properties of the two tuber flours were analyzed using standard methods recommended by the Association of Official Analytical Chemists (AOAC, 1990). The analyses included the determination of total dry matter (TDM) and moisture percentage (AOAC method 920.39), total ash content (AOAC method 923.03), fat percentage (AOAC method 920.39), and crude fiber content (AOAC method 985.29). Crude protein content was determined using the Kjeldahl method (AOAC method 962.10), which involves converting nitrogen to ammonium sulfate and applying a conversion factor of 6.25. The carbohydrate content was calculated by difference, following the equation recommended by de Camargo et al. [22] (2014).

Mineral identification and quantification were conducted using the methodology described by Michel-Michel et al. [23] (2020). The analyses were performed with an Epsilon 1 X-ray fluorescence (XRF) spectrometer from Malvern Panalytical, located in Madrid, Spain.

Functional properties

Water holding capacity

Dry powder (1 g) was accurately weighed and transferred into a graduated tube. Subsequently, 10 mL of distilled water was added and thoroughly mixed using a vortex mixer (Labnet). The mixture was allowed to hydrate for 24 hours. Following hydration, the suspension underwent centrifugation at 3,000 *g* for 15 minutes using a Sorvall ST 8R centrifuge (ThermoFisher, Germany), and the volume of the supernatant was measured. Water holding capacity (WHC) was calculated as grams of water per gram of sample [24], using the equation:

$$WHC = \frac{P_1 - P_0}{P_0}$$

Where P_1 is the weight of the sediment, P_0 is the initial weight.

Swelling capacity

This characteristic was determined following the method described by Requena et al. [25] (2016). Dry powder (0.2 g) was accurately weighed and transferred into a graduated tube. The initial volume occupied by the powder was measured. Subsequently, 5 mL of distilled water was added and thoroughly mixed using a vortex mixer (Labnet) and left to hydrate for 24 hours. After hydration, the final volume occupied by the hydrated powder was measured. Swelling capacity (SC) was calculated as milliliters of water per gram of sample [25]:

$$SC = \frac{V_1 - V_0}{Sample\ weight}$$

Where V_1 is the final volume, V_0 is the initial volume.

Oil holding capacity

Dry powder (1 g) was accurately weighed and transferred into a graduated tube. Subsequently, 10 mL of soybean vegetable oil (density = 0.89 g/mL) was added and thoroughly mixed using a vortex mixer (Labnet). The suspension was then centrifuged at 3,000 *g* for 10 minutes at 4°C using the Sorvall ST 8R centrifuge (ThermoFisher, Germany). After centrifugation, the supernatant was carefully removed, and the remaining sediment was weighed. Oil holding capacity (OHC) was calculated as grams of oil per gram of sample [26]:

$$OHC = \frac{V_f - V_i}{Sample\ weight} \times \rho$$

Where V_f is the final volume, V_i is the initial volume, ρ is the density of the oil.

Identification of phenolic compounds by reverse phase-high performance liquid chromatography-electrospray ionization-mass spectrometry

Sample preparation

Ethanolic extracts were prepared by mixing 1 g of sample with 7 mL of solvent (distilled water:absolute alcohol, 1:1). The samples were subjected to ultrasound-assisted extraction for 20 minutes at a frequency of 60 Hz, followed by centrifugation at 420 *g* for 10 minutes to recover the supernatant. The obtained extracts (supernatants) were then filtered using 0.45 µm nylon membranes and transferred into 1.8 mL vials for subsequent analysis.

Reverse phase-high performance liquid chromatography

Phytochemical analyses were conducted using reverse phase-high performance liquid chromatography (RP-HPLC) employing a Varian HPLC system (Palo Alto, USA), which included an autosampler (Varian ProStar 410, USA), a ternary pump (Varian ProStar 230I, Palo Alto, USA), and a photodiode array (PDA) detector (Varian ProStar 330, Palo Alto, USA). Additionally, a liquid chromatograph ion trap mass spectrometer (Varian 500-MS IT Mass Spectrometer, Palo Alto, USA) equipped with an electrospray ion source was utilized. Samples (5 µL) were injected onto a Denali C18 column (150 mm × 2.1 mm, 3 µm, Grace, USA) maintained at 30°C oven temperature.

The mobile phase consisted of formic acid (0.2%, v/v; solvent A) and acetonitrile (solvent B), applied with the following gradient: initial, 3% B; 0–5 min, 9% B linear; 5–15 min, 16% B linear; 15–45 min, 50% B linear. Subsequently, the column was washed and reconditioned. The flow rate was set at 0.2 mL/min, and elution was monitored at 245, 280, 320, and 550 nm.

Electrospray ionization-mass spectrometry

For mass spectrometry (MS) analysis, the entire effluent (0.2 mL/min) was introduced into the MS source without splitting. All MS experiments were conducted in negative ion mode $[M-H]^{-1}$. The nebulizing gas used was nitrogen, while helium served as the damping gas. Specific ion source parameters included a spray voltage of 5.0 kV, and capillary voltage and temperature were maintained at 90.0 V and 350°C, respectively.

Data acquisition and processing were performed using MS Workstation software (Version 6.9). Initially, samples were analyzed in full scan mode over the range of 50–2,000 m/z [27].

Statistical analyses

All experiments were conducted following a randomized complete block design with three replications. Statistical analysis was performed using a two-sample *T* test at a significance level of 5%. Data analysis was conducted using InfoStat software version (2020). In addition, a principal components analysis was carried out, where the species were considered as classification variables, using the OriginPro 2021 software.

Results

Raw material characterization

Upon comparison of the obtained sequences from the *rbcL* (RuBisCo) and *matK* genes of the tubers with sequences deposited in GenBank, it was verified that the tubers used in this study corresponded to *U. tuberosus* (Figure 1A) with 100% identity with sequence HQ620896.1 (*U. tuberosus)* and *A. xanthorrhiza* to (Figure 1B) with 100% similarity with sequence NC-032364.1 (*A. xanthorrhiza*).

Figure 1. Edible Andean tubers used in this research. (A) *U. tuberosus*; (B) *A. xanthorrhiza*

Physicochemical properties

The physicochemical composition of *U. tuberosus* and *A. xanthorrhiza* flours is presented in Table 1, showing percentages of moisture, total ash, lipids, and crude fiber that align with previously reported values for these tubers [12, 28]. Both tubers exhibit starch content exceeding 50%, confirming starch as the predominant carbohydrate in their structure [29, 30]. This characteristic suggests their potential application in the food industry, particularly in baking, where starch serves as a significant energy source [31–33].

Proximate characterization reveals significant statistical differences ($p < 0.05$) in fiber content among tubers, with *U. tuberosus* exhibiting the highest value (14.0%), surpassing reported values for tubers from the Andean region. Lipid content in these tuber flours is notably low (Table 1), consistent with previous

Table 1. Proximate composition of *U. tuberosus* and *A. xanthorrhiza* flours

Variable	*U. tuberosus* (%)	*A. xanthorrhiza* (%)	*p* values
Humidity	5.93 ± 0.05[a]	7.60 ± 0.37[b]	0.025
Fat	0.25 ± 0.00[a]	1.02 ± 0.16[b]	0.022
Fiber	14.0 ± 0.00[b]	4.07 ± 0.09[a]	0.002
Protein	6.28 ± 0.39[a]	9.64 ± 0.25[b]	0.010
Ash	6.25 ± 0.41[a]	5.16 ± 0.24[a]	0.093
Carbohydrates	67.04 ± 0.28[a]	72.28 ± 0.18[b]	0.004

Data represent the mean ± standard deviation of the experiment. In each row, equal letters indicate that the means are not significantly different ($p < 0.05$)

reports ranging from 0.1% to 1% [9–12, 29], making them suitable for developing foods aimed at maintaining healthy cholesterol levels [34].

Mineral content

Potassium (K) is the most abundant mineral in both *U. tuberosus* (4.12%) and *A. xanthorrhiza* (3.32%) (Table 2), likely due to their role as reservoirs for K in flowers, developing fruits, and tubers [35], consistent with findings from other studies [8]. Studies have indicated higher proportions of Ca, P, and K, averaging around 2%, with slightly lower levels observed in *Arracacia*. K plays essential roles in fluid balance, nerve function, and muscle and cardiac contractions [36].

Table 2. Mineral content of *U. tuberosus* and *A. xanthorrhiza* flours

Mineral	*A. xanthorrhiza* (%)	*U. tuberosus* (%)	*p* values
K	3.32 ± 0.01[a]	4.12 ± 0.02[b]	0.010
Mg	1.12 ± 0.01[a]	1.22 ± 0.03[b]	< 0.01
Ca	0.29 ± 0.00[b]	0.15 ± 0.00[a]	< 0.01
P	0.22 ± 0.00[a]	0.32 ± 0.00[b]	< 0.01
S	0.09 ± 0.00[a]	0.15 ± 0.00[b]	< 0.001
Cl	0.06 ± 0.00[a]	0.13 ± 0.00[b]	< 0.001
Fe	0.02 ± 0.00[a]	0.03 ± 0.00[b]	0.012
Mn	0.01 ± 0.00[a]	0.01 ± 0.00[a]	0.312

K: potassium; Mg: magnesium; Ca: calcium; P: phosphorus; S: sulfur; Cl: chlorine; Fe: iron; Mn: manganese. Data represent the mean ± standard deviation of the corresponding experiment. In each row, equal letters indicate no significant differences ($p < 0.05$)

Additionally, both flours exhibit high magnesium (Mg) content (1.22% and 1.12% for *U. tuberosus* and *A. xanthorrhiza*, respectively), followed by Ca, P, sulfur (S), chlorine (Cl), Fe, and manganese (Mn).

Functional properties

The functional properties assessed in tuber flours establish parameters for their diverse applications in food [37]. Parameters such as WHC and SC indicate the flours' ability to retain water or other substances upon partial rehydration [34]. *U. tuberosus* flour exhibited significantly higher WHC compared to *A. xanthorrhiza* flour (see Table 3). Both flours also demonstrated a high capacity to increase volume upon water addition (1.42 and 3.86 g H_2O/g flour for *U. tuberosus* and *A. xanthorrhiza*, respectively), potentially enhancing satiety due to their hydrophilic nature and influencing starch behavior related to water absorption and gelation processes [34]. In terms of OHC, *A. xanthorrhiza* flour exhibited higher values than *U. tuberosus* flour, suggesting its potential in structural interactions within foods, particularly in retaining flavors, aromas, improving quality, and extending shelf life [17].

Principal component analysis

The principal component analysis indicates that the amount of described information is substantial, as the first component represents 87.53% and the second component 6.34%, summing up to a total of 93.87%.

Table 3. Functional properties of *U. tuberosus* and *A. xanthorrhiza* flours

Property	Unit	*U. tuberosus*	*A. xanthorrhiza*	*p* values
WHC	g of water/g of sample	0.78 ± 0.02[a]	0.96 ± 0.00[b]	0.0003
SC	mL of water/g of sample	1.42 ± 0.40[a]	3.86 ± 0.23[b]	0.0001
OHC	g of oil/g of sample	0.44 ± 0.00[b]	0.18 ± 0.04[a]	0.0001

WHC: water holding capacity; SC: swelling capacity; OHC: oil holding capacity. Data represent the mean ± standard deviation of the experiment. In each row, equal letters indicate that the means are not significantly different ($p < 0.05$)

The Biplot displays the grouping of variables and their relationship with each of the tubers, indicating that certain variables are associated with specific species (Figure 2). K, P, Mn, S, Mg, and Cl are the minerals directly associated with *U. tuberosus*. Additionally, the inorganic matter content (ash percentage), oil retention capacity, and fiber content are related to this tuber.

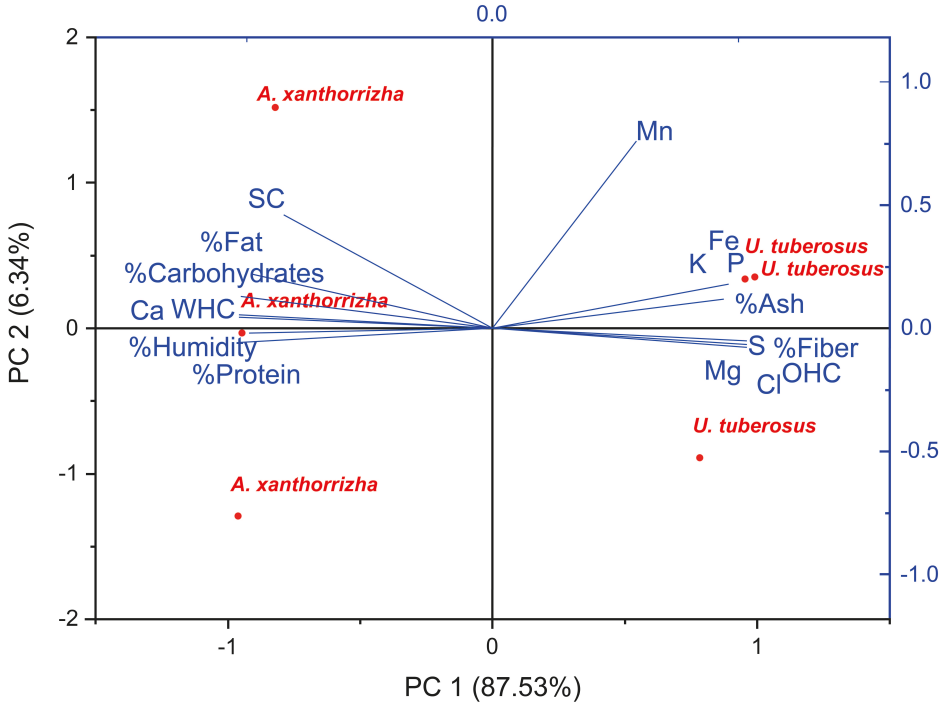

Figure 2. Principal component analysis the Andean tubers and response variables

A. xanthorrhiza is observed to be related to the variables of moisture, carbohydrate content, protein, and fat. Additionally, water retention capacity and SC are related to this tuber. It is important to highlight that the variables associated with *U. tuberosus* and the variables associated with *A. xanthorrhiza* exhibit a negative correlation.

Phenolic compounds profile

Various phenolic compounds were identified in both the skin and flour of *U. tuberosus* and *A. xanthorrhiza* tubers, employing HPLC-MS due to the raw material composition of skin mixed with pulp. Table 4 presents the identified compounds, highlighting hydroxycinnamic acids (caffeic acid 4-*O*-glucoside and *p*-coumaroyl glucose) and methoxyflavonols (3,7-dimethylquercetin), which were consistently found in all samples. *U. tuberosus* also exhibited flavonols (kaempferol 3-*O*-xylosyl-rutinoside) in both peel and flour. In addition, catechol was identified in the peel of *U. tuberosus*, scopoletin and tectorigenin 4'-sulfate were also detected.

For *A. xanthorrhiza*, 1-caffeoylquinic acid was identified in both the peel and flour. Additionally, *d*-viniferin was found in the peel of this tuber, a dihydro derivative of resveratrol with significant implications in the food industry. Also, lignans such as secoisolariciresinol and sesamolinol were identified in *A. xanthorrhiza* flour, while lariciresinol was found in *U. tuberosus* peel.

Table 4. Compounds identified by HPLC-MS in *U. tuberosus* and *A. xanthorrhiza*

RT (min)	m/z	Compound	Family	*U. tuberosus*		*A. xanthorrhiza*	
				Flour	Husk	Flour	Husk
4.39	341.1	Caffeic acid 4-*O*-glucoside	Hydroxycinnamic acids	+	+	+	+
5.22	353.1	1-Caffeoylquinic acid	Hydroxycinnamic acids	-	-	+	+
6.09	110.9	Catechol	Other polyphenols	-	+	-	-
6.23	191.0	Scopoletin	Hydroxycoumarins	-	+	-	-
18.34	380.1	Tectorigenin 4'-sulfate	Flavonols	-	+	-	-
19.13	382.1	Quercetin 3'-sulfate	Flavonols	-	-	+	-
19.56	365.1	Secoisolariciresinol	Lignans	-	-	+	-
20.74	359.0	Lariciresinol	Lignans	-	+	-	-
21.01	371.2	Sesamolinol	Lignans	-	-	+	-
31.34	355.1	Ferulic acid 4-*O*-glucoside	Methoxycinnamic acids	-	+	-	-
32.68	755.1	Quercetin 3-*O*-rhamnosyl-rhamnosyl-glucoside	Flavonols	-	+	-	-
34.90	739.2	Kaempferol 3-*O*-xylosyl-rutinoside	Flavonols	+	+	-	-
35.33	371.2	Sinensetin	Methoxyflavones	+	-	-	-
35.78	385.2	5-5'-Dehydrodiferulic acid	Methoxycinnamic acid dimers	-	-	+	-
36.05	609.1	Quercetin 3-*O*-rutinoside	Flavonols	-	+	-	-
38.10	453.2	*d*-Viniferin	Stilbene dimers	-	-	-	+
40.95	341.1	Tetramethylscutellarein	Methoxyflavones	-	-	+	-
41.24	329.3	3,7-Dimethylquercetin	Methoxyflavonols	+	+	+	+
46.57	325.3	*p*-Coumaroyl glucose	Hydroxycinnamic acids	+	+	+	+
48.41	325.1	Feruloyl tartaric acid	Methoxycinnamic acids	+	-	-	-
49.86	325.2	*p*-Coumaric acid 4-*O*-glucoside	Hydroxycinnamic acids	+	-	-	-
51.81	327.2	*p*-Coumaroyl tyrosine	Hydroxycinnamic acids	-	+	-	-
53.96	311.3	Caffeoyl tartaric acid	Hydroxycinnamic acids	-	-	+	-

Ratio of solid/liquid (1:14, absolute ethanol 50% and water 50%). RT: retention time; HPLC-MS: liquid chromatography-mass spectrometry. +: presence; -: absence

Discussion

Differences in physicochemical properties

Both tubers are known for their high content of resistant starch and FOS [38]. Different rheological studies indicated that *U. tuberosus* starch could serve as an effective thickening or gelling agent in various food and biomaterial applications [14]. Variability in fiber content can be attributed to factors such as variety, geographic location, climate, soil type, and cultivation practices [39]. The fiber contents reported in these tubers typically range from 1% to 9% [9–12, 29]. The fiber content of ulluco and arracacha flours positions them as promising raw materials for food development [40], capable of meeting dietary fiber requirements, moderating glycemic response, and promoting gastrointestinal health due to their association with FOS and prebiotic activity, beneficial to probiotic bacteria [41, 42].

The nutritional composition of these tubers plays a crucial role in conserving Andean tuber biodiversity and promoting their use as novel raw materials for developing functional snacks. This approach not only supports socioeconomic sustainability in the region but also addresses current consumer demands, demonstrating the potential to diversify the utilization of these Andean tubers rich in primary metabolites such as starch, protein, fat, ash, and fiber.

U. tuberosus and *A. xanthorrhiza* are rich in various minerals essential for human nutrition, including Ca, Mg, Cl, P, and sodium (Na), among others. The contribution of K from these flours can meet recommended daily intake levels and benefit individuals with hypertension, as K intake has been linked to reduced blood pressure and antihypertensive effects [23, 43, 44].

Variations in macro and micronutrient content are influenced by soil fertility practices, with organic cultivation typically resulting in higher levels of P, K, Mg, S, Fe, Mn, and Cu, while conventional methods may

yield higher nitrogen and Mn levels. Agroecological conditions also impact mineral absorption and content, as well as the specific plant species [45, 46].

The presence of these minerals in Andean tubers positions them as potential sources for developing functional foods that can promote human health. Ca, for example, exhibits hypoglycemic effects and stimulates insulin secretion, while other minerals contribute to bone health, hormone production, and carbohydrate metabolism, thereby supporting blood sugar regulation and appetite control [12, 34, 47].

The functional properties determined for each of the tubers, the WHC of *U. tuberosus* flour makes it suitable for industrial use as a thickening or gelling agent [14]. This characteristic is attributed to the hydrogen bonding between water molecules and matrix proteins [17].

The SC found in both flours makes them suitable for bakery products, pastries, pastas, or other high viscosity foods [17]. These values contrast with the low swelling power reported for three other Andean tubers [48], and with the negative correlation presented in the principal component analysis. Some authors have reported that when the flour has a lower water retention capacity, it has a greater oil absorption capacity [17].

Based on the results from *U. tuberosus* and *A. xanthorrhiza* flours, the development of foods using these raw materials could offer beneficial effects for human health [34]. Furthermore, promoting their use as novel sources in the food industry is encouraged [49].

Impact of identified phenolic compounds

The hydroxycinnamic acids, methoxyflavonols, and flavonols identified are known for their cardioprotective effects, antioxidant properties, and potential benefits in glycemic control, neuroprotection, anti-inflammatory, antidiabetic, antimicrobial, and anticancer activities. Consumption of these compounds may help reduce the risk of several types of cancer, such as skin, liver, colon, ovarian, pancreatic, and bladder cancers [50, 51].

U. tuberosus, suggesting potential applications in pharmaceuticals, plastics, dyes, and cosmetics. Catechol is recognized for promoting skin wound healing and possessing hydrating and antimicrobial properties due to its physicochemical and biological characteristics [52, 53]. Of the compounds scopoletin and tectorigenin 4'-sulfate are reported to have antioxidant, antidiabetic, hepatoprotective, neuroprotective, and antimicrobial activities mediated through various intracellular signaling mechanisms [54, 55], which enhances the use of these tubers in different industries.

Hydroxycinnamic acids identified in arracacha are beneficial for health as they mitigate oxidative damage by enhancing the endogenous antioxidant system through scavenging free radicals, chelating metals, and modulating enzymatic activity [56]. So far, it has been reported that *d*-viniferin exhibits anticancer, neuroprotective, antioxidant effects, serves as a modulator of lipid and lipoprotein metabolism, functions as a platelet antiaggregant, and shows estrogenic activity [57, 58].

Quercetin, one of the flavonols found in *U. tuberosus* peel and *A. xanthorrhiza* flour, plays a crucial role in human health due to its antioxidant properties, which neutralize free radicals [34]. These flavonols are significant as their consumption has been linked to reduced risks of certain cancers, neuronal damage, and cardiovascular diseases [59]. These findings align with previous research using HPLC-diode array detection (DAD)-electrospray ionization (ESI)/MS on three Andean tubers, which identified flavonols such as quercetin-3-*O*-rutinoside [40.6 μg/g dry matter (DM)], kaempferol-*O*-dirhamnosylhexoside (29.5 μg/g DM), and kaempferol-*O*-dihexoside (46.22 μg/g DM). These tubers are thus suggested as natural antioxidant sources for both food and non-food applications [60].

The lignans can be metabolized by human intestinal microflora, potentially reducing the risk of breast, prostate, and colon cancers due to their (anti)-estrogenic and antioxidant activities [61, 62]. Furthermore, 5-5'-dehydrodiferulic acid, known for its inhibitory effects on P-selectin expression compared to its phenolic precursors, suggests enhanced efficacy in modulating platelet activation through phenolic

compound metabolism [63]. Tetramethylscutellarein, identified for its bioactive role in blood coagulation and anti-inflammatory activity, was also detected [64].

Andean tubers are known for their richness in phytochemicals such as carotenoids, anthocyanins, phenolic acids [14], and glucosinates [9], all of which possess potential antioxidant properties [65]. *U. tuberosus* has been reported to contain betalains in the form of betaxanthins and betacyanins [9, 15], including betanidin- and isobetanidin-5-*O*-(4'-*O*-malonyl-β-glucoside), 2-decarboxyphyllocactin, betanidin- and isobetanidin-6-*O*-(6'-*O*-feruloyl)-β-glucoside (gomphrenin and isogomphrenin III), dehydrophilocactin and isophilocactin, as well as arginine and glycine-betaxanthins (portulacaxanthin III). *A. xanthorrhiza* contains limonene and myrcene [66], yet a comprehensive phenolic profile of these tubers remains to be fully documented. The presence of these diverse compounds underscores Andean tubers' potential as raw materials for developing healthy snacks with functional properties [10, 21, 67–69].

Conclusions

The characterization of flours from two Andean tubers, *U. tuberosus* and *A. xanthorrhiza,* revealed them to be significant sources of starch, dietary fiber, and minerals such as K, Mg, Ca, and P. Moreover, these tubers exhibit functional properties that facilitate their application in both the food and non-food industries. Phenolic compound characterization identified primarily hydroxycinnamic acids, highlighting the potential of these tubers as sources for developing functional foods known for their health-promoting effects. Additionally, their content of FOS, related to fiber and starch structures, suggests potential prebiotic activity, as supported by literature findings.

Abbreviations

AOAC: Association of Official Analytical Chemists

DM: dry matter

ESI: electrospray ionization

FOS: fructooligosaccharides

MS: mass spectrometry

OHC: oil holding capacity

RP-HPLC: reverse phase-high performance liquid chromatography

SC: swelling capacity

WHC: water holding capacity

Declarations

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Author contributions

SSP: Conceptualization, Investigation, Supervision, Writing—original draft. RRH: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Writing—original draft, Writing—review & editing. MdRSS: Methodology, Supervision, Writing—review & editing. LGCM: Formal analysis, Methodology, Validation. ACFG: Investigation, Software, Validation, Writing—review & editing. JFSD: Conceptualization, Funding acquisition, Project administration, Resources. JAAV: Investigation, Software. CMLB: Formal analysis, Methodology, Software, Validation.

Conflicts of interest

The authors declare that they have no financial interests or personal relationships that might appear to influence the work presented in this article.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and materials

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

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References

1. Sáenz-Torres S, López-Molinello A, Prieto-Contreras L, Rodríguez T. El Cubio Como Una Alternativa Productiva Sostenible En Condiciones de Agricultura Urbana de Bogotá. Equidad y Desarrollo. 2019;1: 121–42. Spanish. [DOI]
2. Euder HH. Influencia Del Nitrógeno y Fósforo En El Comportamiento Agronómico Del Frijol Caupí (Vigna Unguiculata L. Walp) En Cieneguillo Centro-Sullana-2019 [dissertation]. São Paulo: Universidad San Pedro; 2021. Spanish.
3. Clavijo Ponce NL. Cultura y Conservación in Situ de Tubérculos Andinos Marginados En Agroecosistemas de Boyacá: Un Análisis de Su Persistencia Desde La Época Prehispánica Hasta El Año 2016. Cuadernos de Desarrollo Rural. ;14:1–19. [DOI]
4. Sanchez-Portillo S, del Rosario Salazar-Sánchez M, Solanilla-Duque JF, Rodríguez-Herrera R. Andean Tubers, Morphological Diversity, and Agronomic Management: A Review. Plant Science Today. 2023; 10:98–105. [DOI]
5. Bonete M, Urquizo C, Guevara R, Yanez P. Estudio De Cuatro Tubérculos Y Raíces Tuberosas No Tradicionales De La Sierra Centro De Ecuador Y Su Potencial de Uso En Platos de Autor. Estudio de cuatro tubérculos y raíces tuberosas no tradicionales. 2016;12:37–67. Spanish.
6. Velásquez-Barreto FF, Bello-Pérez LA, Nuñez-Santiago C, Yee-Madeira H, Velezmoro Sánchez CE. Relationships among Molecular, Physicochemical and Digestibility Characteristics of Andean Tuber Starches. Int J Biol Macromol. 2021;182:472–81. [DOI] [PubMed]
7. Parra-Quijano M, Panda S, Rodríguez N, Torres E. Diversity of *Ullucus Tuberosus* (Basellaceae) in the Colombian Andes and Notes on Ulluco Domestication Based on Morphological and Molecular Data. Genet Resour Crop Evol. 2012;59:49–66. [DOI]

8. Caracterización de las raíces y los tubérculos andinos en la ecoregión andina del Ecuador. In: Barrera VH, Tapia CG, Monteros AR, editors. In: Raíces y Tubérculos Andinos: Alternativas Para La Conservación y Uso Sostenible En El Ecuador. Lima: Centro Internacional de la Papa; 2004. pp. 3–30. Spanish.
9. Campos D, Chirinos R, Gálvez Ranilla L, Pedreschi R. Bioactive Potential of Andean Fruits, Seeds, and Tubers. Adv Food Nutr Res. 2018;84:287–343. [DOI] [PubMed]
10. Galindez A, Daza LD, Homez-Jara A, Eim VS, Váquiro HA. Characterization of Ulluco Starch and Its Potential for Use in Edible Films Prepared at Low Drying Temperature. Carbohydr Polym. 2019;215: 143–50. [DOI]
11. Heil N, Bravo K, Montoya A, Robledo S, Osorio E. Wound Healing Activity of *Ullucus Tuberosus*, an Andean Tuber Crop. Asian Pac J Trop Biomed. 2017;7:538–43. [DOI]
12. Pacheco MT, Hernández-Hernández O, Moreno FJ, Villamiel M. Andean Tubers Grown in Ecuador: New Sources of Functional Ingredients. Food Biosci. 2020;35:100601. [DOI]
13. Repo-Carrasco R. Cultivos Andinos. Importancia nutricional y posibilidades de procesamiento. Cusco: Centro Bartolomé de las Casas; 1988.
14. Pacheco MT, Moreno FJ, Moreno R, Villamiel M, Hernandez-Hernandez O. Morphological, Technological and Nutritional Properties of Flours and Starches from Mashua (*Tropaeolum Tuberosum*) and Melloco (*Ullucus Tuberosus*) Cultivated in Ecuador. Food Chem. 2019;301:125268. [DOI] [PubMed]
15. Campos D, Noratto G, Chirinos R, Arbizu C, Roca W, Cisneros-Zevallos L. Antioxidant Capacity and Secondary Metabolites in Four Species of Andean Tuber Crops: Native Potato (*Solanum* Sp.), Mashua (*Tropaeolum Tuberosum* Ruiz & Pavón), Oca (*Oxalis Tuberosa* Molina) and Ulluco (*Ullucus Tuberosus* Caldas). J Sci Food Agric. 2006;86:1481–8.
16. Goicochea Chuquilin RC, Carolim M, Teodoro J. Propiedades Funcionales de Productos Tradicionales Congelados y Secados al Sol de Oca (Oxalis Tuberosa Molina) y Olluco (Ullucus Tuberosus Caldas): Una Revisión. Puriq. 2020;2:247–63. Spanish. [DOI]
17. González Cabrera MV, Moreno Andrade GI, López Sampedro SE. Caracterización Nutricional y Funcional de La Harina de Mashua. ConcienciaDigital. 2020;3:199–214. Spanish. [DOI]
18. Mosquera N, Cejudo-Bastante MJ, Heredia FJ, Hurtado N. Identification of New Betalains in Separated Betacyanin and Betaxanthin Fractions from Ulluco (*Ullucus Tuberosus* Caldas) by HPLC-DAD-ESI-MS. Plant Foods Hum Nutr. 2020;75:434–40. [DOI] [PubMed]
19. Tribst AAL, de Castro Leite Júnior BR, De Oliveira MM, Cristianini, M. High Pressure Processing of Cocoyam, Peruvian Carrot and Sweet Potato: Effect on Oxidative Enzymes and Impact in the Tuber Color. Innovative Food Sci Emerging Technol. 2016;34:302–9. [DOI]
20. Apak R, Özyürek M, Güçlü K, Çapanoğlu E. Antioxidant Activity/Capacity Measurement. 1. Classification, Physicochemical Principles, Mechanisms, and Electron Transfer (ET)-Based Assays. J Agric Food Chem. 2016;64:997–1027. [DOI] [PubMed]
21. Soriano Sancho RA, Souza JDRP, de Lima FA, Pastore GM. Evaluation of Oligosaccharide Profiles in Selected Cooked Tubers and Roots Subjected to in Vitro Digestion. LWT-Food Science and Technology. 2017;76:270–7. [DOI]
22. de Camargo AC, Vidal CMM, Canniatti-Brazaca SG, Shahidi F. Fortification of cookies with peanut skins: Effects on the composition, polyphenols, antioxidant properties, and sensory quality. J Agric Food Chem. 2014;62:11228–35. [DOI] [PubMed]
23. Michel-Michel MR, Aguilar-Zárate P, Lopez-Badillo CM, Chávez-González ML, Flores-Gallegos AC, Espinoza-Velázquez J, et al. Mineral and Fatty Acid Contents of Maize Kernels with Different Levels of Polyembryony. Cereal Chem. 2020;97:723–32. [DOI]

24. Salas YA, Colque MC, Lazo AB. Obtención y caracterización fisicoquímica y funcional de las fibras dietéticas del níspero común (Mespilus germanica). Revista de la Sociedad Química del Perú. 2008;74: 269–81. Spanish.
25. Requena MC, González CNA, Barragán LAP, Correia T, Esquivel JCC, Herrera RR. Functional and Physico-Chemical Properties of Six Desert-Sources of Dietary Fiber. Food Biosci. 2016;16:26–31. [DOI]
26. Garcia-Ortiz JD, Flores-Gallegos AC, Ascacio-Valdés JA, López-Badillo CM, Nery-Flores SD, Esparza-González SC, et al. Microwave-Ultrasound Assisted Extraction of Red Corn Pigments and Their Effect on Chemical Composition and Tecno-Functional Properties. Food Biosci. 2022;50:102115. [DOI]
27. Ascacio-Valdés JA, Aguilera-Carbó AF, Buenrostro JJ, Prado-Barragán A, Rodríguez-Herrera R, Aguilar CN. The Complete Biodegradation Pathway of Ellagitannins by Aspergillus Niger in Solid-State Fermentation. J Basic Microbiol. 2016;56:329–36. [DOI] [PubMed]
28. Leidi EO, Altamirano AM, Mercado G, Rodriguez JP, Ramos A, Alandia G, et al. Andean Roots and Tubers Crops as Sources of Functional Foods. J Funct Foods. 2018;51:86–93. [DOI]
29. Velásquez-Barreto FF, Bello-Pérez LA, Yee-Madeira H, Velezmoro Sánchez CE. Esterification and Characterization of Starch From Andean Tubers. Starch/Staerke. 2019;71:1800101. [DOI]
30. Chaali N, Ouazaa S, Jaramillo-Barrios CI, Araujo Carrillo GA, Ávila Pedraza EÁ. Edaphoclimatic Characterization and Crop Water Requirement of Arracacha (*Arracacia Xanthorrhiza* Bancroft) Roots in Upland Production Areas. Sci Hortic. 2020;272:109533. [DOI]
31. Luo X, Cheng B, Zhang W, Shu Z, Wang P, Zeng X. Structural and Functional Characteristics of *Japonica* Rice Starches with Different Amylose Contents. CYTA-Journal of Food. 2021;19:532–40. [DOI]
32. Ojeda L, Claramonte M, Rey J, Trestini C, Useche M, Zambrano N, et al. Effect of the Freezing and Thawing Processes on Starches in a Corn-Based Food. Revista Chilena de Nutricion. 2018;45:310–5. Spanish. [DOI]
33. Scortegagna ML, de Oliveira VR, Pasini I, Silva M, de Oliveira Rios A, Doneda D. Low Phenylalanine Breads as an Alternative for Patients with Phenylketonuria. British Food Journal. 2020;122:26–35. [DOI]
34. del C. Coutiño Laguna B, Flores Gallegos AC, Ascacio Valdés JA, Iliná A, Galindo AS, Castañeda Facio AO, et al. Coutiño Laguna B, Flores Gallegos AC, Ascacio Valdés JA, Iliná A, Galindo AS, Castañeda Facio AO, et al. Physicochemical and Functional Properties of the Undervalued Fruits of Cactus *Cylindropuntia Imbricate* ("Xoconostle") and Antioxidant Potential. Biocatal Agric Biotechnol. 2022;39:102245. [DOI]
35. Kant S, Kafkafi U. Absorcion de potasio por los cultivos endistintos estadios fisiologicos. Potasio en plantas animales [Internet]. 2006 [cited 2022 Nov 23]. Available from: https://www.ipipotash.org/uploads/udocs/Sesion%20V.pdf
36. Perasso Padilla CS. Investigación Del Procedimiento Óptimo Para La Disminución de La Concentración de Potasio En Patata, Zanahoria y Yuca Sometidas a Cocción [dissertation]. Quito: Universdad Central Del Ecuador; 2019. Spanish.
37. Ana Cruz Morillo C, Yacenia Morillo C, Leguizamo MF. Caracterización Morfológica y Molecular de Oxalis Tuberosa Mol. En El Departamento de Boyacá. Rev Colomb Biotecnol. 2019;21:18–28. [DOI]
38. Lovera M, Pérez E, Laurentin A. Digestibility of Starches Isolated from Stem and Root Tubers of Arracacha, Cassava, Cush–Cush Yam, Potato and Taro. Carbohydr Polym. 2017;176:50–5. [DOI] [PubMed]
39. Andrade-Mahecha MM, Tapia-Blácido DR, Menegalli FC. Physical-Chemical, Thermal, and Functional Properties of Achira (*Canna Indica* L.) Flour and Starch from Different Geographical Origin. Starch/Staerke. 2012;64:348–58. [DOI]
40. Salazar Rodríguez Y, Alfonso Martinez J, Gallardo Cruz A. Biostimulants. An Alternative for Cuban Agroecological Development. Ecovida. 2021;11:225–49. Spanish.

41. Fabersani E, Grande MV, Coll Aráoz MV, Zannier ML, Sánchez SS, Grau A, et al. Metabolic Effects of Goat Milk Yogurt Supplemented with Yacon Flour in Rats on High-Fat Diet. J Funct Foods. 2018;49: 447–57. [DOI]
42. Padilha VM, Andrade SAC, Valencia MS, Stamford TLM, Salgado SM. Optimization of Synbiotic Yogurts with Yacon Pulp (*Smallanthus Sonchifolius*) and Assessment of the Viability of Lactic Acid Bacteria. Food Science and Technology. 2017;37:166–75. [DOI]
43. Espín S, Villacrés E, Brito B. Caracterización Físico-Química, Nutricional y Funcional de Raíces y Tubérculos Andinos. In: Barrera VH, Tapia C, Monteros y A, editors. Raíces y Tubérculos Andinos: Alternativas para la conservación y uso sostenible en el Ecuador. Quito: INIAP/CIP/COSUDE; 2004. pp. 91–116. Spanish.
44. Carlos Zehnder B. Sodio, Potasio e Hipertensión Arterial. Revista Médica Clínica Las Condes. 2010;21: 508–15. [DOI]
45. Sawicka B, Hulail Noaema A, Seead Hameed T, Skiba D. Genotype and environmental variability of chemical elements in potato tubers. Acta Sci Pol Agricultura. 2016;15:79–91.
46. Soares JC, Santos CS, Carvalho SMP, Pintado MM, Vasconcelos MW. Preserving the Nutritional Quality of Crop Plants under a Changing Climate: Importance and Strategies. Plant Soil. 2019;443:1–26. [DOI]
47. Renee Vidal A, Zaucedo-Zuñiga AL, de Lorena Ramos-García M. Nutrimental properties of the sweet potato (*Ipomoea batatas* L.) and its benefits in human health. Revista Iberoamericana de Tecnología Postcosecha. 2018;19:2. Spanish.
48. Valcárcel-Yamani B, Rondán-Sanabria GG, Finardi-Filho F. The Physical, Chemical and Functional Characterization of Starches from Andean Tubers: Oca (*Oxalis Tuberosa* Molina), Olluco (*Ullucus Tuberosus* Caldas) and Mashua (*Tropaeolum Tuberosum* Ruiz & Pavón). Brazilian Journal of Pharmaceutical Sciences. 2013;49:453–64. [DOI]
49. Torres-León C, Rojas R, Serna-Cock L, Belmares-Cerda R, Aguilar CN. Extraction of Antioxidants from Mango Seed Kernel: Optimization Assisted by Microwave. Food and Bioproducts Processing. 2017; 105:188–96. [DOI]
50. Chaves WF. Exposição materna à dieta hipercalórica e hiperlipídica e administração neonatal de Kaempferol: aspectos somáticos, bioquímicos e do comportamento alimentar [dissertation]. Recife: Universidad federal de pernambuco; 2020. Spanish.
51. Imran M, Salehi B, Sharifi-Rad J, Gondal TA, Saeed F, Imran A, et al. Kaempferol: A Key Emphasis to Its Anticancer Potential. Molecules. 2019;24:2277. [DOI] [PubMed] [PMC]
52. Chumillas S, Palomäki T, Zhang M, Laurila T, Climent V, Feliu JM. Analysis of Catechol, 4-Methylcatechol and Dopamine Electrochemical Reactions on Different Substrate Materials and PH Conditions. Electrochim Acta. 2018;292:309–21. [DOI]
53. Conejo-Cuevas G, Ruiz-Rubio L, Sáez-Martínez V, Pérez-González R, Gartziandia O, Huguet-Casquero A, et al. Spontaneous Gelation of Adhesive Catechol Modified Hyaluronic Acid and Chitosan. Polymers. 2022;14:1209. [DOI] [PubMed] [PMC]
54. Lim HS, Kim YJ, Kim BY, Park G, Jeong SJ. The Anti-Neuroinflammatory Activity of Tectorigenin Pretreatment via Downregulated NF-KB and ERK/JNK Pathways in BV-2 Microglial and Microglia Inactivation in Mice with Lipopolysaccharide. Front Pharmacol. 2018;9:462. [DOI] [PubMed] [PMC]
55. Sakthivel KM, Vishnupriya S, Chandramani L, Dharshini P, Rasmi RR, Ramesh B. Modulation of Multiple Cellular Signalling Pathways as Targets for Anti-Inflammatory and Anti-Tumorigenesis Action of Scopoletin. J Pharm Pharmacol. 2022;74:147–61. [DOI] [PubMed]
56. Abramovič H. Antioxidant Properties of Hydroxycinnamic Acid Derivatives: A Focus on Biochemistry, Physicochemical Parameters, Reactive Species, and Biomolecular Interactions. In: Preedy VR, editor. Coffee in Health and Disease Prevention. San Diego: Academic Press; 2015. pp. 843–52. [DOI]

57. Vitelli-Storelli F, Zamora-Ros R, Molina AJ, Fernández-Villa T, Castelló A, Barrio JP, et al. Association between Polyphenol Intake and Breast Cancer Risk by Menopausal and Hormone Receptor Status. Nutrients. 2020;12:994. [DOI] [PubMed] [PMC]
58. Zamora-Ros R, Andres-Lacueva C, Lamuela-Raventós RM, Berenguer T, Jakszyn P, Martíez C, et al. Concentrations of resveratrol and derivatives in foods and estimation of dietary intake in a Spanish population: European Prospective Investigation into Cancer and Nutrition (EPIC)-Spain cohort. Br J Nutr. 2008;100:188–96. [DOI] [PubMed]
59. Robles Solano E. Caracterización de Compuestos Fenólicos En Extractos de Origen Vegetal [dissertation]. Jaén: Universidad de Jaén; 2021. Spanish.
60. Pacheco MT, Escribano-Bailón MT, Moreno FJ, Villamiel M, Dueñas M. Determination by HPLC-DAD-ESI/MSn of Phenolic Compounds in Andean Tubers Grown in Ecuador. J Food Compos Anal. 2019;84: 103258. [DOI]
61. Fuentalba Carrasco CV. Determinación de la bióaccesibilidad de lignanos de linaza mediante una simulación in vitro del proceso digestivo [dissertation]. Santiago: Universidad de Santiago de Chile; 2015. Spanish.
62. Rojas Muñoz FS. Revisión bibliográfica de compuestos fenólicos, su efecto en la salud, métodos de encapsulación y digestión simulada in vitro. [dissertation]. Santiago: Universidad de Chile; 2021. Spanish.
63. Baeza G, Bachmair EM, Wood S, Mateos R, Bravo L, De Roos B. The Colonic Metabolites Dihydrocaffeic Acid and Dihydroferulic Acid Are More Effective Inhibitors of in Vitro Platelet Activation than Their Phenolic Precursors. Food Funct. 2017;8:1333–42. [DOI] [PubMed]
64. Pandith H, Zhang X, Thongpraditchote S, Wongkrajang Y, Gritsanapan W, Baek SJ. Effect of Siam Weed Extract and Its Bioactive Component Scutellarein Tetramethyl Ether on Anti-Inflammatory Activity through NF-KB Pathway. J Ethnopharmacol. 2013;147:434–41. [DOI] [PubMed]
65. Duque L, Bravo K, Osorio E. A Holistic Anti-Aging Approach Applied in Selected Cultivated Medicinal Plants: A View of Photoprotection of the Skin by Different Mechanisms. Ind Crops Prod. 2017;97: 431–9. [DOI]
66. Leonel M, do Carmo EL, Franco CML, Fernandes AM, Garcia EL, dos Santos TPR. Peruvian Carrot (*Arracacia Xanthorrhiza* Bancroft) as Raw Material for Producing Special Native Starches. Aust J Crop Sci. 2016;10:1151–7. [DOI]
67. Chacón Orduz G, Muñoz Rincón A, Quiñónez Mosquera GA. Descripción Del Mercado de Los Snacks Saludables En Villavicencio, Meta. Libre Empresa. 2017;14:33–45. [DOI]
68. Coyago E. Estudio Sobre El Contenido En Carotenoides y Compuestos Fenólicos de Tomates y Flores En El Contexto de La Alimentación Funcional [dissertation]. San Fernando: Universidad de Sevilla; 2017. Spanish.
69. Márquez Fernández PM, Fer M, Nández DM. Functional Foods: Current Issues and Trends. Vitae. 2019; 26:6–7. [DOI]