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NUTRITIONAL PROFILING AND ANTIOXIDANT POTENTIAL OF KANDHARI AND BADANA POMEGRANATE (PUNICA GRANATUM L.) PEELS AND SEEDS

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Abstract

Pomegranate (Punica granatum L.) is worldwide recognized as a functional fruit with notable nutritional as well as therapeutic potential. Nevertheless, a significant portion of the fruit, chiefly the peel and seeds, remains underutilized in spite of their richness in bioactive components. The current study was planned to assess and compare the nutritional composition along with antioxidant potential of two cultivars; Kandhari and Badana, considering on both peels and seeds. Results illuminated significant differences ($p < 0.05$) between cultivars and fruit fractions (peel & seed). Peels of both cultivars displayed higher moisture, ash, crude-fiber, minerals, and phenolic content than seeds, however seeds exhibited greater amounts of crude-protein, -lipid, and phenolic acids. The total phenolic content varied from 73.79 to 287.79 mg GAE/g, whereas total flavonoid content changed between 119.78 to 151.85 mg QE/g. Further, antioxidant assays affirmed that peel extracts encompass stronger radical-scavenging capacities than seed extracts, associating positively with phenolic contents. HPLC analysis recognized gallic acid, ferulic acid, chlorogenic acid, quercetin, & vitamin C as leading bioactive compounds, with maximum concentrations identified in seeds. In conclusion, the varieties of Badana and Kandhari presented distinctive yet abundant nutritional characteristics. The results demonstrate the perspectives of pomegranate seeds and peels as accessible, sustainable sources of bioactive substances, biological antioxidants, and beneficial components for culinary and nutraceutical purposes.

Keywords:
Pomegranate; Kandhari; peel; phenolic compounds; Badana; antioxidant activity; seed; HPLC profiling.

INTRODUCTION

One of the ancient known edible fruit plants, the pomegranate (Punica granatum L.), originates to the Punicaceae family and is valued by people from all over the globe for its exceptional nutritional and therapeutic qualities. Its Latin identity, “Malum granatum”, implies "granular apple" and is where its name stems from. Initially from the Middle East and the Indo-Pak subcontinent, it has since been grown all over the world, even in regions of the Americas, India, Iran, Pakistan, and the Mediterranean. Polyphenols, flavonoids, anthocyanins, tannins, and organic acids constitute the fruit's concentrated biologically active components that lead to its strong cardioprotective, anti-inflammatory, and antioxidant capabilities, which are responsible for its growing recognition as a functional food (Liu et al., 2025). India was the world's leading producer of pomegranates in 2017 with an anticipated 2.84 million metric tons output out of almost 3.8 million metric tons commercially produced pomegranate covering an area of 234,000 hectares (Valero-Mendoza et al., 2023). Notwithstanding its regular consumption, pomegranate has gained importance in the nutraceutical and healthcare sectors owing to the medicinal efficacy of its secondary metabolites.

Although pomegranate juice has usually been the subject of commercial processing, nearly 50 to 60% of the fruit weight, comprises skin and seeds, is discarded as waste during juice extraction. These remains, nevertheless are usually neglected but they are abundant in minerals & phytochemicals. The peels that make up to 40 to 50% of the pomegranate fruit have considerable contents of polyphenols, hydrolysable tannins; punicalagin & ellagitannins, gallic acid, and flavonoids connected with strong antioxidant and antimicrobial aspects (Al-Baidhani et al., 2024; Singh et al., 2018). The seeds, which consists 10 to 15% of the fruit, are pool of protein, fiber, fat, and phenolic acids including chlorogenic, gallic, and ferulic acids. Punicic acid which is a conjugated linolenic acid is abundant in seed oil but associated with promising hypolipidemic and anti-carcinogenic properties (Wang et al., 2024; Younas et al., 2022). Due to limited phyto-screening of these left overs, they are often thrown away which are now prime ecological pollution and inadequate resources utilization. Based on the cultivars, the cultivation methods, origin, and abiotic factors including types of soil, temperature, and ripening stage, the chemical constituents in pomegranate fluctuates greatly. That’s the reason, the biochemical ingredients in prevalent cultivars such as Wonderful, Ganesh, Mollar de Elche, and Acco Multiple differed greatly as assessed by earlier investigations with special focus on antioxidant and phenolics (Salem et al., 2022). Unfortunately, comparative study on locally available cultivars like Badana and Kandhari is still limited. Although both cultivars are abundantly grown in Pakistan and Afghanistan but varied in their sensory profile, outer peel shade, and seed rigidity. Regarding morphological characters, badana fruits have soft arils and thinner peels, however kandhari variety are characteristically deep red in hue with thick peels and somewhat hard seeds. These morphological differences may be linked to different metabolic and phytochemical profiles.

Pomegranate peels and seeds have nutritional potential since they can deliver a variety of secondary metabolites that serve as natural antioxidants while contributing important macro- and micronutrients. It has been discovered that phenolic substances including quercetin, gallic acid, ellagic acid, and chlorogenic acid can capture free radicals, avert lipid peroxidation, and boost cellular defenses against oxidative stress (de Oliveira et al., 2020; Saparbekova et al., 2023). These substances offer significant oxidative stability by functioning in collaboration with vitamin C and other hydrophilic antioxidants. Furthermore, peels' high dietary fiber level and essential minerals (such as calcium, magnesium, potassium, and iron) encourage their eventual usage as food supplements with supplementary nutrients (Abbas et al., 2025). Similarly, the seeds' considerable protein and lipid content makes them beneficial for developing functional ingredients like vitamins, supplements, and emulsifiers in food sector.

Global curiosity in bio-waste valorization and sustainable nutrition has currently intensified efforts to utilize fruit by-products as functional components. The reutilization of such by-products into the food chain offers environmental, economic, and health advantages, line up with circular economy principles (Campos et al., 2020). However, the success of these previous studies based on a detailed understanding of the compositional variations among cultivars and fruit portions. To date, there still remains a clear knowledge gap regarding the simultaneous assessment of both peels and seeds of Kandhari and Badana pomegranates, predominantly in terms of their proximate composition, mineral profile, total phenolics, flavonoids, and bioactive components calculated through chromatographic profiling.

Given these considerations, the instant study was planned to conduct a comprehensive nutritional as well as antioxidant profiling of Kandhari and Badana pomegranate peels and seeds. The research intended to evaluate and compare their proximate composition, minerals, total phenolic & flavonoid concentrations, antioxidant potential, and HPLC-based phenolic components screening. Through this comparative approach, the study pursues to provide evidence-based perceptions into the comparative nutritional and functional advantages of the two cultivars and their fruit fractions. The outcomes are expected to fill a critical research gap and proposed a scientific foundation for the valorization of pomegranate processing by-products as possible sources of natural antioxidants, dietary fibers, and functional bioingredients.

MATERIALS AND METHODS

Sample Collection and Preparation

Mature Kandhari pomegranate (Punica granatum L.) fruits were taken locally from the market of Faisalabad, Pakistan. Fruits were carefully cleaned under running tap water to eliminate surface impurities and air-dried. The peel & seeds were manually separated from the arils, washed again, and oven-dried at 45 ± 2 °C until a constant weight was achieved. The dried materials were ground separately into fine powders using a stainless-steel grinder, sieved through a 60-mesh screen, and stored in airtight containers at 4 °C until further analysis.

Nutritional profiling of pomegranate peel and seed powder

Pomegranate peel and seed powder were examined for moisture, crude-protein, -crude fat, crude -fiber, ash and nitrogen free extract according to protocols defined in AOAC (2019).

Moisture content

The moisture content of the powdered pomegranate peels and seeds was calculated by using a hot air oven (Memmert 200, Germany). A total of 10 g of the sample was added to a pre-weighed China plate. The sample was left at 100–105°C for almost 24 hours. The sample was then taken out of the oven. After obtaining a constant weight, the material was cooled in a desiccator and re-weighed. The following formula was used to determine the moisture content.

$$\text{Moisture content (\%)} = \frac{\text{Weight of original sample (g)} - \text{Weight of dried sample (g)}}{\text{Weight of original sample (g)}} \text{X } 100$$

Crude Protein

According to AACC (2010) method 984.13, crude protein was studied for each sample using the Kjeldahls technique (Kjeltech Apparatus, Technik GmbH D40599, Behr Laboratories, Germany). The sample was put into the digesting tube after it had been weighed (3g). Afterwards, 40 milliliters of 98% concentrated sulfuric acid and 5 grams of the digestion mixture were put into the digestion tube for three to four hours. It was cooled to room temperature and then diluted with distilled water to make a total volume of 250 mL. In another beaker containing a 4% boric acid solution colored with methyl red indicator, trapped ammonia gas was released during distillation using a 40% NaOH solution. The mixture was then titrated against a 0.1N H_2SO_4 solution.

$$\text{Nitrogen (g)} = \frac{\text{Volume of 0.1 NH2SO4} \times 0.0014 \times \text{Volume of dilution (250ml)}}{\text{Weight of original sample (g)} \times \text{Volumeof distillation used in ml}}$$

Using a conversion factor i.e. 6.25, % of protein was calculated, multiplying it to nitrogen content.

% Crude protein= Nitrogen (g) × 6.25

Crude fat

The soxhlet apparatus was used to calculate the crude fat content of pomegranate peel and seed powder using method 920.39, in accordance with the guidelines provided by AOAC (2019). After enclosing a 2 g sample in thimble, it was placed in the extraction tube of the soxhlet apparatus. The heater's temperature (40–60 ºC) was changed so that ether drips continuously fall onto the sample. Almost six syphons were finished by following this procedure. The sample was transferred to a dried, pre-weighed china dish. The dried sample was then weighed and placed inside a desiccator.

$$\text{Crude fat (\%)} = \frac{\text{Weight of residue (g)}}{\text{Weight of sample (g)}} \times 100$$

Crude fiber

The crude fiber content of the sample was determined by digesting each 2g fat-free sample with 1.25 percent sulfuric acid and sodium hydroxide separately, in accordance with the guidelines of the AOAC (2019, method 978.10) using Labconco-Fiber tech (Labconco Corporation, Kansas, USA). For digestion, 2 g sample was placed in a flask containing 25 mL of 1.25% H_2SO_4 solution, diluted to 200 mL, and heated for 30 minutes followed by filtration. Afterwards, similar process was conducted using 25 milliliters of 1.25% NaOH solution. The digested sample was placed in a muffle furnace and heated to between 550 and 650 ºC for three to five hours, or until a gray or white ash began to form. The percentage of crude fiber was calculated using a formula:

$$\text{Crude fiber (\%)} = \frac{\text{Reduction in weight on ignition (g)}}{\text{Weight of sample (g)}} \times 100$$

Total Ash

Total ash content of each sample was assessed using muffle furnace (PCSIR, PAKISTAN MF-1/02) at 550°C for 5 to 6 continuous hours until the it turned grey using AACC (2010) method 942.05. The ash percentage was computed using the formula below.

$$\text{Ash (\%)} = \frac{\text{Reduction in weight on ignition (g)}}{\text{Weight of sample (g)}} \times 100$$

Nitrogen free extent

NFE % was measured by the use of following expression:

NFE % = 100 – (% moisture content + % crude protein content + % crude fat content + % crude fiber content + % ash content)

Mineral analysis

As per AOAC's (2019) guidelines, all samples were wet digested and their mineral content was assessed through the Atomic Absorption Spectrophotometer (AAS). The following minerals; calcium, potassium, magnesium, iron, and zinc were quantified by taking 0.5g of the sample in a conical flask on a hot plate followed by heating between 600-700°C for a duration of 20 minutes. Afterwards, HNO_3 (10mL/100mL) was added as a digestion solvent. Following that, 5 mL of $HClO_4$ was gradually added until the contents become transparent. A volumetric flask (100 mL) containing digested sample was diluted with distilled water and filtered. For the preparation of standard curves of each mineral, various formulations were made with known concentration. Employing a spectrophotometer, the mineral concentration was calculated by recording light absorption. Calibration line was plotted to determine the content of unknown minerals in sample.

Preparation of peel and seed extracts

The seed and peel extracts were prepared by using binary solvent; ethanol and water (80:20). Purposely, 10g of sample was soaked in respective solvent and agitated for 3 to 4 hours using a mechanical shaker. The sample was then centrifuged for 15 to 20 minutes at 7000 rpm. The collected supernatant was filtered through Whatman No. 1 filter paper and kept for solvent and supernatant separation were separated in a rotary vacuum evaporator (EYELA, N-N series, Japan) at 50°C.

Phytochemical screening and antioxidant potential

Total Phenolic Content

The total phenolic content of the all pomegranate samples was determined as per the procedures of Jalal et al. (2021). To quantify phenolics, 1 mL of each prepared sample extract was added in a test tube containing 1.5 mL of 20% sodium carbonate along with 6.9 mL of distilled water. The mixture was incubated at 40 °C after stirring for 30 minutes. A blank sample was also prepared, devoid of sample extract but containing other reagents. To plot a calibration curve, 1 mL aliquots of gallic acid of different strength; 0, 30, 25, 20, 15, 10, and 0.05 mg/mL, were made in ethanol. The sample was run at 760 nm to determine the total phenolic content and expressed as milligrams of gallic acid equivalents per gram of material. The phenolics were calculated as:

$$\text{Total phenolic content (mg GAE/g)} = \frac{\text{C} \times \text{V}}{\text{M}} \times 100$$

Here,

The V stands for sample volume; C is the concentration of gallic acid (mg/mL) while M is the weight of the methanolic extract sample.

Total Flavonoid Content

The $AlCl_3$ colorimetric method was employed for quantification of flavonoids in accordance with the methods of Jalal et al. (2021). The flavonoids were calculated using the quercetin reagent as a standard. To make the stock quercetin solution, 5 milligrams of quercetin were dissolved in 1 milliliter of ethanol solvent. Various dilutions ranging from 5 to 200 g/mL were prepared. For sample preparation, 6 mL of the sample was mixed with 6 mL of the 2% AlCl3 solution. Afterwards, the mixture was left to stand at room temperature for around 60 minutes. The absorbance of the sample as well as standard was then measured using a spectrophotometer set to 420 nm. Total flavonoids were expressed as quercetin equivalent to mg/g.

DPPH

The antioxidant capacity of sample was determined using DPPH radical scavenging activity (Gulcin & Alwasel, 2023). To conduct assay, 5 mL of a 0.1 mM ethanolic solution of DPPH was added to 100 µL of every extract, and then, the tubes were shaken vigorously. A positive control (ethanol instead of the sample) was prepared, and used to zero the spectrophotometer. The tubes were allowed to stand at room temperature for about 30 min. The change of absorbance was measured at 517 nm. Radical scavenging capacity was estimated as percent of DPPH and expresses as a function of the sample concentration using the following formula:

$$\text{DPPH inhibition (mg TEAC/g)} = \frac{\text{AC} - \text{AS}}{\text{AC}} \times 100$$

Where,

AC = absorbance of the control containing DPPH

AS = absorbance of extract in the presence of DPPH

HPLC analysis of phenolic compounds

High-performance liquid chromatography (HPLC) was performed for quantitative analysis of phenolic components. Purposely, extracts were screened via a 0.45 µm membrane filters followed by injecting sample. Separation was achieved using HPLC system connected with a C18 reverse-phase column (250 × 4.6 mm, 5 µm). The mobile phase contained methanol:water:tetrahydrofuran:acetic acid (22 : 76 : 1 : 1), at a flow rate of 1 mL/min. Identification was carried out at 280 nm (El-Hamamsy & El-Khamissi, 2020).

Statistical Analysis

The results for all parameters were expressed as mean ± standard deviation (SD). Data were statistically analyzed using one-way analysis of variance (ANOVA) followed by Tukey's post hoc test to determine significant

differences among means ($p < 0.05$). Statistical interpretation was executed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Proximate Composition

The statistical analysis revealed that all proximate components of pomegranate peels and seed varied momentously ($p < 0.05$) within and across both pomegranate varieties as displayed in Table 1. Moisture content ranged between 5.8 ± 0.48% and 8.3 ± 0.76%, with higher values observed in peels than in seeds. Ash content also changed considerably, being maximum in Kandhari peel (6.46 ± 0.37%) and Badana peel (5.68 ± 0.77%), though minimum was documented in Badana seed (1.90 ± 0.70%) and Kandhari seed (2.45 ± 1.76%). Crude fat content showed the inverse relation, with seeds containing evidently higher values, 24.50 ± 0.59% in Badana and 22.70 ± 1.93% in Kandhari compared to 4.27 ± 0.63% and 3.82 ± 0.48% in Badana and Kandhari peels, correspondingly. Crude fiber content ranged from 11.60 ± 0.68% to 17.90 ± 0.65%, where both peels exhibited higher values (Kandhari 17.90 ± 0.65%; Badana 17.30 ± 0.85%) than seeds (Kandhari 11.70 ± 0.43%; Badana 11.60 ± 0.68%). Protein levels also differed significantly, with seeds showing maximum concentrations compared to peels. The nitrogen-free extract (NFE), showing the crude carbohydrate fraction, was higher in peels, extending from 59.85 ± 0.61% in Kandhari to 61.69 ± 0.56% in Badana, while seeds showed lower values (51.42 ± 1.10% in Kandhari; 49.72 ± 1.09% in Badana).

Table 1: Proximate analysis of two pomegranate cultivars; Kandhari and Badana peels and seeds

Components (%)	Badana Pomegranate Seeds (BPS	Kandhari Pomegranate seeds (KPS)	Kandhari Pomegranate peel (KPP)	Badana Pomegranate peel (BPP)
Moisture	6.3 ± 0.31b	5.8 ± 0.48b	8.3 ± 0.76a	8.2 ± 0.29a
Ash	1.90 ± 0.70c	2.45 ± 1.76b	6.46 ± 0.37a	5.68 ± 0.77ab
Crude fat	24.5 ± 0.59a	22.7 ± 1.93a	3.82 ± 0.48b	4.27±0.63b
Crude Fiber	11.6 ± 0.68b	11.7 ± 0.43b	17.9 ± 0.65a	17.3± 0.85a
Crude Protein	7.1±0.21a	6.34 ±0.92a	3.79 ±0.50b	3.50 ± 0.39b
NFE	49.72 ± 1.09b	51.42 ±1.10ab	59.85 ± 0.61ab	61.69 ± 0.56a

Mineral profiling

The mineral profile of Kandhari and Badana pomegranate peels and seeds is illustrated in Table 2, displaying significant difference ($p < 0.05$) among all samples. The concentrations of iron (Fe), potassium (K), magnesium (Mg), calcium (Ca), and zinc (Zn) differed remarkably between cultivars and fruit fraction. Iron content was highest in Kandhari seed (8.90 ± 0.22 mg/100 g), followed by Badana seed (8.29 ± 0.17 mg/100 g), Kandhari peel (7.28 ± 0.23 mg/100 g), and Badana peel (5.82 ± 0.18 mg/100 g). Magnesium contents were also evidently higher in peels than in seeds, with Badana peel scoring the highest value (156.53 ± 0.42 mg/100 g), trailed by Kandhari peel (144.59 ± 0.37 mg/100 g), Badana seed (103.98 ± 6.13 mg/100 g), and lastly Kandhari seed (98.58 ± 0.29 mg/100 g). Potassium content ranged between 167.52 ± 0.38 mg/100 g and 450.49 ± 0.48 mg/100 g, being highest in Kandhari seed (450.49 ± 0.48 mg/100 g), closely followed by Badana seed (434.76 ± 0.55 mg/100 g), while lower levels were found in Kandhari peel (167.52 ± 0.38 mg/100 g) and Badana peel (185.55 ± 0.48 mg/100 g). Calcium concentration showed a contrasting trend, with peels exhibiting substantially higher values 352.82 ± 0.60 mg/100 g in Kandhari and 330.78 ± 0.61 mg/100 g in Badana compared to seeds (141.66 ± 0.25 mg/100 g in Kandhari; 131.76 ± 0.91 mg/100 g in Badana). Zinc levels remained relatively low across all samples, with alike concentrations of 6.00 ± 0.003 mg/100 g in both seed types, whereas peel samples contained 1.35 ± 0.015 mg/100 g in Kandhari and 2.55 ± 0.051 mg/100 g in Badana.

Figure 1. Mineral analysis (mg/100 g dry weight) of two pomegranate cultivars; Kandhari and Badana peels and seeds

Phytochemical screening and antioxidant activity

Total phenolics and flavonoids

The total phenolic content (TPC) and total flavonoid content (TFC) of Kandhari and Badana pomegranate peels and seeds are illustrated in Table 2. Significant differences ($p < 0.05$) were found among all samples regarding cultivars- and fruit portion (peel & seed). The TPC of the samples ranged from 73.79 ± 0.74 mg GAE/g to 287.79 ± 0.55 mg GAE/g. The highest phenolic concentration was recorded in Kandhari peel (287.79 ± 0.55 mg GAE/g), followed by Badana peel (253.74 ± 0.65 mg GAE/g), whereas markedly lower levels were detected in Kandhari and Badana seeds (73.79 ± 0.74 and 76.81 ± 0.66 mg GAE/g, correspondingly). The TFC also disclosed significant differences ($p < 0.05$), ranging from 119.78 ± 0.64 mg QE/g to 151.85 ± 0.69 mg QE/g. Among all samples, Badana peel revealed the highest flavonoid content (151.85 ± 0.69 mg QE/g), trailed by Kandhari peel (135.89 ± 0.91 mg QE/g), Kandhari seed (121.66 ± 1.11 mg QE/g), and Badana seed (119.78 ± 0.64 mg QE/g).

DPPH Radical Scavenging Activity

The DPPH radical scavenging activity of Kandhari and Badana pomegranate peel and seed extracts is presented in Table 2. All samples showed antioxidant potential, with significant variations observed among them ($p < 0.05$). The scavenging activity ranged from 0.62 ± 0.001 to 0.77 ± 0.002 mg TEAC/g, with Badana peel presenting the highest value (0.77 ± 0.002 mg TEAC/g), followed closely by Kandhari peel (0.62 ± 0.001 mg TEAC/g), whereas the seeds exhibited relatively higher than peel but consistent values (Kandhari seed 2.15 ± 0.017 mg TEAC/g; Badana seed 2.00 ± 0.001 mg/g as TEAC equivalents).

Table 2: Phytochemical screening and antioxidant potential of two pomegranate cultivars; Kandhari and Badana peels and seeds

Components	Badana Pomegranate Seeds (BPS)	Kandhari Pomegranate seeds (KPS)	Kandhari Pomegranate peel (KPP)	Badana Pomegranate peel (BPP)
Total phenols (mg GAE/g)	76.81 ± 0.66b	73.79 ± 0.74c	287.79 ± 0.55a	253.74 ± 0.65ab
Total flavonoids (mg QE/g)	119.78 ± 0.64d	121.66 ± 1.11c	135.89±0.91b	151.85±0.69a
Antioxidant (mg TEAC/g)	2.0 ± 0.001a	2.15 ± 0.017a	0.62 ± 0.001b	0.77 ± 0.002ab

HPLC Phytochemical Profiling

The HPLC analysis of Kandhari & Badana pomegranate peels as well as seeds probed several phenolic and bioactive ingredients, comprising chromatotropic acid, gallic acid, quercetin, ferulic acid, chlorogenic acid & vitamin C. The concentrations of these components (mg/L) are summarized in table 3 and figure 2 & 3, displaying significant differences among the four samples ($p < 0.05$).

The concentration of chromatotropic acid ranged between 17.59 ± 0.49 mg/L and 115.66 ± 0.34 mg/L, with the highest level observed in Badana seed (115.66 ± 0.34 mg/L), followed by Kandhari seed (85.62 ± 0.29 mg/L), Kandhari peel (19.10 ± 0.41 mg/L), and Badana peel (17.59 ± 0.49 mg/L). Quercetin content varied between 3.74 ± 0.44 mg/L and 13.02 ± 0.40 mg/L, being highest in Kandhari seed (13.02 ± 0.40 mg/L), followed by Badana seed (11.61 ± 0.35 mg/L), Kandhari peel (4.58 ± 0.43 mg/L), and Badana peel (3.74 ± 0.44 mg/L). The gallic acid concentration ranged from 101.66 ± 0.47 mg/L to 175.60 ± 0.43 mg/L, with the highest value found in Kandhari seed (175.60 ± 0.43 mg/L), followed closely by Badana seed (171.67 ± 0.44 mg/L), while lower concentrations were recorded in Kandhari peel (102.69 ± 0.54 mg/L) and Badana peel (101.66 ± 0.47 mg/L). For chlorogenic acid, values ranged from 33.02 ± 0.39 mg/L to 81.55 ± 0.43 mg/L, with Kandhari seed exhibiting the highest (81.55 ± 0.43 mg/L), followed by Badana seed (80.51 ± 0.41 mg/L), Kandhari peel (34.60 ± 0.30 mg/L), and Badana peel (33.02 ± 0.39 mg/L).

The content of ferulic acid also presented prominent variation among samples, fluctuating from 22.75 ± 0.44 mg/L to 60.84 ± 0.61 mg/L. The highest concentration was detected in Kandhari seed (60.84 ± 0.61 mg/L), followed by Badana seed (59.98 ± 0.60 mg/L), Kandhari peel (23.37 ± 0.28 mg/L), and Badana peel (22.75 ± 0.44 mg/L). The vitamin C content ranged between 16.91 ± 0.33 mg/L and 28.53 ± 0.29 mg/L, being highest in Kandhari seed (28.53 ± 0.29 mg/L) and lowest in Badana peel (16.91 ± 0.33 mg/L). Generally, all quantified compounds exhibited statistically significant differences ($p < 0.05$) among the pomegranate samples, with maximum concentrations of notable phenolic compounds quantified in the seed fractions in contrast to the peels.

Table 3: Phytochemical profiling (mg/L) of Badana and Kandhari pomegranate peel and seed extracts using HPLC

Components (mg/L)	Badana Pomegranate Seeds (BPS)	Kandhari Pomegranate seeds (KPS)	Kandhari Pomegranate peel (KPP)	Badana Pomegranate peel (BPP)
Chromatotrophic acid	115.66 ± 0.34a	85.62 ± 0.29b	19.10 ± 0.41c	17.59 ± 0.49c
Quercetin	11.61 ± 0.35ab	13.02 ± 0.40a	4.58 ± 0.43b	3.74± 0.44c
Gallic acid	171.67 ± 0.44a	175.60 ± 0.43a	102.69±0.54b	101.66±0.47b
Caffeic acid	15.82 ± 0.57b	17.78± 0.63a	15.78± 0.50b	15.77± 0.50b
Chlorogenic acid	80.51 ± 0.41a	81.55 ± 0.43a	34.60 ±0.30b	33.02± 0.39b
Syringic acid	5.87 ± 0.66b	7.32±0.50a	6.85± 0.36ab	5.70 ± 0.56b
p-coumeric acid	8.58±0.37ab	9.31±0.56a	1.70±0.20b	1.46±0.19c
m-coumeric acid	14.86±0.55a	14.76±0.54a	3.65±0.38b	3.38±0.23b
Ferulic acid	59.98±0.60a	60.84±0.61a	23.37±0.28b	22.75±0.44b
Vitamin C	27.71±0.47a	28.53±0.29a	16.99±0.46b	16.91±0.33b

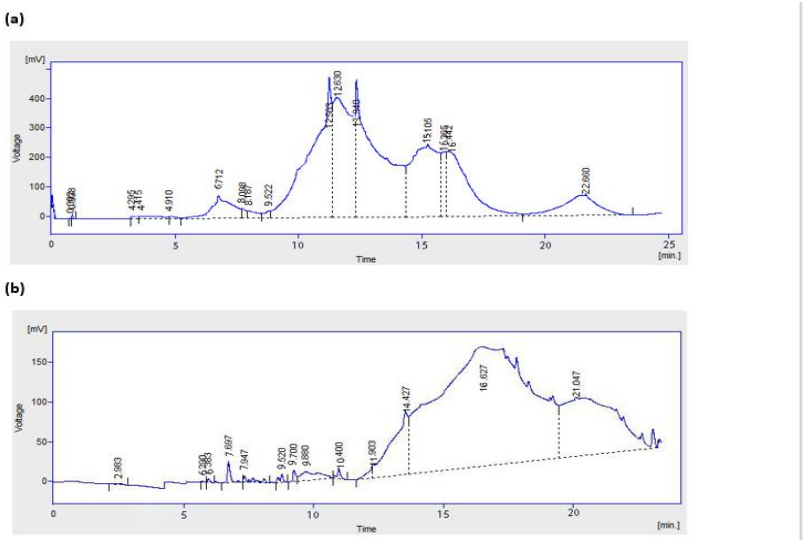

Figure 2: HPLC chromatogram of phytochemicals from (a) Kandhari and (b) Badana pomegranate peel

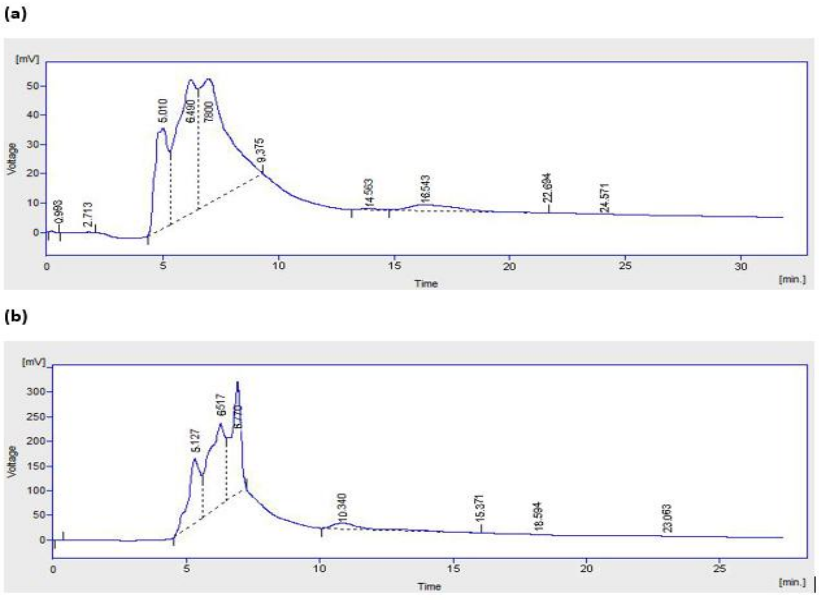

Figure 3: HPLC chromatogram of phytochemicals from (a) Kandhari and (b) Badana pomegranate seed

DISCUSSION

The compositional data for Kandhari and Badana pomegranate fractions disclosed a consistent division of macronutrients as well as phytochemicals that mirrors the discrete biological roles of peel & seed tissues and clarified their differing antioxidant capacities. Seeds function as nutrient assets for the embryo, which accounts for their considerably higher crude fat (14.17 to 29.60%) and protein contents (9.10-13.66%) compared with peels; these storage composites, dominated by conjugated linolenic acids such as punicic acid, gathered during maturation and deliver metabolic energy and membrane precursors (Liu et al., 2025; Wang et al., 2024). The peels, being protective tissues, showed higher fiber, ash, and carbohydrate contents, consistent with a cell-wall-rich matrix of cellulose, hemicellulose, and pectins. Alike patterns were studied previously by Khalil (2016) and Xiong et al. (2023), who also accredited inter-varietal variations to genotype and environmental factors. The slightly higher moisture recorded in Kandhari peel (8.3%) compared with Badana peel (8.2%) is in line with Khalil (2016), who found 8.88 % and 5.43 % moisture in the same cultivars, correspondingly.

Protein and lipid dissimilarities between fractions shows tissue physiology as protein predominates in enzymatically active seed tissues, whereas lipid accumulation results from triacylglycerol biosynthesis through maturation (Alves et al., 2021; JAMRA, 2021). The high ash content in peels specifies strong mineral storage, an attribute confirmed by the current mineral data and by Sharma and Akansha (2018), who stated elevated iron & calcium in Kandhari peel and higher magnesium, potassium, and zinc in Badana peel. Former work by Mirdehghan and Rahemi (2007) confirmed that mineral composition alters with season and ripening phase, illuminating the cause of the variation in instant results.

The antioxidant and phytochemical fallouts corroborate these compositional patterns. Antioxidant activity (stated as mg TEAC/g) was highest in seeds (2.15 for Kandhari and 2.00 for Badana) and slightly lower in peels, where Badana (0.77) surpassed Kandhari (0.62). Comparable cultivar variances were defined by Khalil (2016), who calculated higher DPPH radical-scavenging activity in Badana peel extracts than in Kandhari. The underlying mechanism includes polyphenols donating electrons or hydrogen atoms to nullify free radicals (Sihag et al., 2022), elucidating the observed correspondence between phenolic content and antioxidant indices (Ashraf et al., 2016).

Total phenolic content (TPC) and total flavonoid content (TFC) affirmed clear cultivar and tissue trends. Kandhari peel exhibited the highest TPC (287.79 mg GAE/g) trailed by Badana peel (253.74 mg GAE/g), while seeds exposed much lower values (nearly 74 to 77 mg GAE/g). These outcomes mirror those of Khalil (2016), who documented 259 mg GAE/g in Kandhari peel and 220 mg GAE/g in Badana peel, and they exist within the range described by Ardekani et al. (2011) (98–250 mg GAE/g) and Pande and Akoh (2009) (311 mg GAE/g in peel vs. 89 mg GAE/g in seeds). Likewise, TFC raised to 151.85 mg QE/g in Badana peel and 135.89 mg QE/g in Kandhari peel, line up with the values specified by Kafeel et al. (2023) and the general reflection of Salim (2024) that fruit peels gather higher phenolic and flavonoid levels owed to their revelation to oxidative and microbial stress. The higher phenolic and flavonoid concentrations in peels consequently justify their stronger antioxidant potential, however the smaller, more soluble phenolic acids in seeds contribute equivalently more to TEAC reactivity (Ashraf et al., 2017).

HPLC profiling recognized chromatotropic acid, gallic acid, quercetin, ferulic acid, chlorogenic acid, and vitamin C, verifying earlier characterizations by Mansour (2018) and Ullah et al. (2025). The dominance of gallic and chlorogenic acids in seeds (approximately 170 to 176 mg/L and 80–82 mg/L, correspondingly) supports their comparatively high TEAC values: these low-molecular-weight acids own strong single-electron-transfer capacity and high solubility, which improve assay reactivity. Conversely, the high polymeric tannin content of peels primarily punicalagin and ellagitannins testified by Khalil (2016) and Kafeel et al. (2023) increases overall TPC nevertheless contributes less per unit mass to some assays due to steric hindrance and measured diffusion kinetics.

The biochemical theory underlying these distributions is clear as phenylpropanoid pathway activity is concerted in outer tissues to deliver photoprotection and pathogen defense, though seeds allocate metabolic energy to lipid & protein storage. Ecological and agronomic factors such as soil mineral availability, temperature, irrigation, and harvest maturity additional modulate metabolite synthesis (Adiba et al., 2025; Moradinezhad & Ranjbar, 2024). Methodological assays also affect result differences across studies such as particle size, extraction solvent, and drying temperature modify phenolic yields henceforth comparisons must be made vigilantly.

Overall, these outcomes confirm that both Kandhari and Badana cultivars constitute valued natural sources of nutrients and antioxidants nevertheless with discrete strengths. Peels are richer in structural polysaccharides, minerals, and polymeric phenolics suitable for fiber and antioxidant applications, however seeds are concentrated in protein, oil, and low-molecular-weight phenolic acids appropriate for nutraceutical development. Such complementarity highlights the potential for full fruit consumption and supports the sustainable valorization of pomegranate by-products in food as well as health industries.

CONCLUSION

In current study, both Kandhari and Badana pomegranate peels & seeds confirmed significant nutritional and antioxidant potential, with peels richer in minerals, fiber, and phenolics, and seeds ample in fats, proteins, and bioavailable phenolic acids. Kandhari peel displayed the highest total phenolic content, whereas Badana peel confined higher flavonoid and mineral contents, revealing varietal and environmental variations. These outcomes

highlight the potential of both cultivars as natural bases of functional components for food & nutraceutical industries. Forthcoming research should emphasize on assessing the stability, bioavailability, and in vivo efficacy of these bioactive ingredients, as well as emerging sustainable extraction and formulation approaches to fully utilize the value of pomegranate by-products.

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