Nutraceutical potential and compositional diversity of underutilized Makran Date palm (Phoenix dactylifera L.) cultivars

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Research Article

Keywords: Date Palm, Nutraceutical, Bioactive Compounds, Antioxidant Properties

Posted Date: June 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10082567/v1

Additional Declarations: No competing interests reported.

Abstract

The Makran division of Balochistan, Pakistan possesses a wealth of indigenous date palm (*Phoenix dactylifera* L.) cultivars whose nutraceutical potential and compositional diversity have never been systematically documented, despite their cultural and economic significance. Seven underutilized date palm cultivars: Halinee, Dandari, Shakari, Muzawati, Rabie, Shengeskan, and Zard Irani were investigated. Proximate analysis showed that the highest moisture content (44.80%), ash content (4.40%), and crude protein (4.80%) were observed in Muzawati, while crude lipid (1.73%) and crude fiber (4.00%) were highest in Shengeskan, and total carbohydrates (64.30%) in Shakari. Mineral profiling revealed that all cultivars were rich in essential elements, with Shengeskan showing the highest levels of calcium (789 mg/kg), magnesium (606 mg/kg), and sulfur (782 mg/kg), while Muzawati recorded the highest potassium content (8598 mg/kg). Total phenolic content was highest in Shakari and Muzawati (72.32 and 69.41 mg GAE/100 g, respectively), while Halinee exhibited the highest flavonoid content (0.37 mg QE/100 g). Halinee showed the highest α-tocopherol (52.45 mg/kg), Dandari exhibited the highest β-tocopherol (61.42 mg/kg), and Rabie showed the highest γ-tocopherol (99.57mg/kg). Antioxidant analysis demonstrated significant variation among cultivars ($p < 0.05$), with Shengeskan and Dandari exhibiting the highest DPPH radical scavenging activity (78.90% and 76.60%, respectively). Principal Component Analysis (PCA) further identified Muzawati, Shengeskan, Rabie and Dandari as the most promising cultivars for nutritional and nutraceutical applications. These findings highlight the exceptional nutritional and bioactive potential of Makran date palm cultivars, positioning them as promising candidates for innovation in functional foods, nutraceutical applications, and commercial exploitation. Makran dates inclusion in the global market could enhance dietary diversity and contribute to sustainable food security, warranting further research and investment in their development.

Introduction

The term nutraceutical describes substances that possess both nutritional and pharmaceutical properties. Broadly, nutraceuticals function as food or food components that play a vital role in maintaining human health by supporting normal physiological functions within cells and tissues. A nutraceutical is a substance derived from food or its components that exhibits medicinal or therapeutic properties, including disease prevention and treatment (DeFelice, 2002). Nature has blessed mankind with plant products in their purest form, incorporating all the goodness of nutraceutical components, such as antioxidants, bioactive elements, minerals, and polyunsaturated fatty acids. These natural sources may serve as either supplements or medicine to prevent or cure several health-related conditions, such as cardiovascular diseases, cancer, osteoporosis, arthritis, diabetes, and hypercholesterolemia, with the least non-redundant effects on the overall well-being of consumers. This recognition of food as a source of nutrition with health benefits has cultivated interests in exploring natural nutraceutical sources. This growing interest in nutraceuticals has led to a paradigm shift in the pharmaceutical and wellness sectors, driving the food industry to become more scientifically guided and regulated (Verma and Mishra, 2016). In this regard, efforts have been made to highlight indigenous natural sources with functional health benefits. Among these, date palm (*Phoenix dactylifera* L.) cultivars from Balochistan hold considerable value due to their rich nutritional composition and bioactive compounds (Ayub et al. 2023; Koser et al. 2022). Dates are believed to possess therapeutic qualities in addition to their nutritional properties due to the presence of numerous bioactive compounds. Dates have a long history of being used as an anti-hypertensive component. They can lower hypertension, hypercholesterolemia and oxidation of lipoproteins, thus reducing the series of reactions that could trigger cardiovascular disease initiation and progression (Vayalil, 2002). Dates' intrinsic antioxidants and phenolics make them effective against a cultivar of diseases such as viral and bacterial infections, diabetes, atherosclerosis, and cancer. However, dates' phenolic and antioxidant components may vary (Khalid, 2017). Dates are also a good source of many antioxidants, and the antioxidant properties of dates are due to the presence of phenolic, carotenoids and flavonoids (Al-Farsi and Lee, 2008). According to Sajid et al. (2019), date fruits and seeds are rich sources of bioactive compounds and have great nutritive value along with renowned health benefits. Such compounds can be incorporated as antibiotics in functional foods to improve the health benefits of the food products. In Balochistan, Makran is famous for the production of several date palm cultivars. Makran is a division of the Balochistan province of Pakistan. It covers an area of 23,460 sq mi (60,761 sq km) and consists of the districts of Kech, Gwadar, and Panjgur, administratively, whereas the headquarters of the Makran division is Turbat. In the Makran division, the date farms contain different types of date trees that produce several kinds of dates, such as Mozati, Haleeni, Shakrok, Dandari, Sangeskanz, Rabi and Zard Irani, which are consumed daily by local communities, yet their potential bioactive components, which are capable of imparting both health benefits and possible risks, remain largely unrecognized.

This study aims to investigate the untapped potential of underexplored date palm cultivars native to the Makran, Balochistan focusing on their distinctive nutritional profiles and bioactive compounds. By uncovering the health-promoting properties inherent in these local cultivars, this study also aims to identify natural functional foods that offer significant benefits with minimal and/or with no risk. Given the growing global demand for safe, effective nutraceuticals, this research addresses a critical gap by promoting the value of regional date palms as sustainable sources of functional ingredients. Highlighting their unique nutraceutical attributes not only supports local agriculture but also opens new avenues for health-focused food innovation and market development. This work therefore makes a vital contribution to advancing both nutritional science and regional economic growth.

Materials and Methods

Sample collection and preparation

Date palm cultivars (Dandari, Halinee, Muzawati, Rabie, Shakari, Shengeskan, and Zard Irani) were manually collected from Kech, Panjgur, and Gwadar Districts of the Makran Division, Balochistan Province, Pakistan. Tap water was used to thoroughly wash the collected samples, followed by distilled and deionized water and then dried in an oven at 70ºC for 7–10 hours. The dried samples were manually ground into a fine powder and stored in airtight containers. To ensure a representative sample of each cultivar, twenty date palm fruits were randomly selected from each tree of each cultivar using simple random sampling.

Proximate analysis

Moisture, ash, and lipid content percentages were quantified using standard formulas following the protocols outlined in AOAC (AOAC, 1995). Similarly, crude fiber, crude protein, and total carbohydrate content were quantified using the procedures described in AACC (2000), AOAC (1984) and FAO (2023).

Elemental analysis

A total of sixteen elements were quantified after the elemental composition of the processed samples from each of the seven date palm cultivars was examined.

Organic elemental analyzer (Flash 2000 Thermo-Scientific CHNS-O) was used to measure the amounts of carbon (C), hydrogen (H), and nitrogen (N). Each sample's percentage of nitrogen, hydrogen, carbon, and sulfur was then calculated by generating and processing electrical signals using Eager 300 software. Following samples digestion, the elemental composition was determined with accuracy by using ICP-OES (iCAP 6500, Thermo Scientific, UK) thirteen other elements: aluminum (Al), barium (Ba), calcium (Ca), chromium (Cr), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), nickel (Ni), phosphorus (P), sulfur (S), strontium (Sr), and zinc (Zn) were identified. During elemental analyses, calibration was prepared using diluted stock solutions (1000 mg/l).

Bioactive compound analysis and antioxidant activity

Using the Folin-Ciocalteu method, Total Phenolic Content (TPC) was measured using the gallic acid calibration curve spectrophotometrically at 765 nm (Ainsworth and Gillespie, 2007). Total flavonoid content (TFC) was calculated using the procedure outlined by Kim et al. (2003). A spectrophotometer was used to measure absorbance at 510 nm, and the results were reported as milligrams of quercetin equivalent per 100 grams (mg QEC/100 g). Tocopherol content was analyzed following the method described in IUPAC (1987). The analysis was performed using an HPLC system (Agilent 1100) equipped with a Zorbax NH_2 column (25 cm × 4.6 mm i.d., 5 µm particle size) and a fluorescence detector set at 295 nm and 325 nm. Results are expressed as milligrams of α, β, γ, and δ tocopherols per kilogram of oil and compared with known standards. The antioxidant activity was evaluated using the DPPH radical scavenging assay (Blois, 1958). Absorbance was measured at 517 nm using a UV-Visible spectrophotometer (Shimadzu UV-160) in triplicate. Butylated hydroxytoluene (BHT) was used as a reference standard. The radical scavenging activity was expressed as a percentage inhibition of DPPH radicals.

Statistical analysis

The obtained data were analyzed in triplicate, and results are expressed as means ± standard deviation. Statistical significance among date palm samples was evaluated using analysis of variance (ANOVA) and the least significant difference (LSD) test at $p \leq 0.05$. Principle Component Analysis (PCA) was applied to examine compositional variability among selected date palm cultivars.

Results and Discussion

Nutritional Parameters

The proximate composition of the seven date palm cultivars studied showed significant variation ($p < 0.05$) among all parameters (Table 1). Moisture content ranged from 29.00% to 48.80%, with the highest value observed in Muzawati and the lowest in Shakari. These values were higher than those reported by Parvin

(2015) (15.2–17.1%), possibly due to differences in cultivar, growing conditions, and maturity stage. Ash content, which is used as an index of a food's nutritive value, was recorded in a range of 4.40% (Muzawati) to 1.57% (Shakari), lower than the reported values for other date palm cultivars (Ogungbenle, 2011). Proteins play a crucial role in enzymatic catalysis, cell growth, and differentiation (Whitney and Rolfes, 2022). The crude protein content recorded between 4.80% (Muzawati) to 1.80% (Rabie) among selected cultivars, the obtained result aligning with previously reported values (1.72–4.73%) by Assirey, (2015). Lipid content was measured between 1.73% in Shengeskan to 0.50% in Muzawati and, slightly higher than earlier (0.12–0.72%) reported by Parvin, (2015). Dietary fiber is essential for digestion and may help reduce the risk of certain cancers (Saldanha, 1995; UICC/WHO, 2005). The highest dietary fiber content was recorded in Shengeskan (4.00%), while the lowest was in Shakari (0.90%), comparable to previous findings of Ogungbenl (2011) and Rehman et al. (2001). High-fibre diets are in growing demand due to their cholesterol-lowering effects, which could possibly help to protect against coronary heart disease (Brown et al. 1999). The carbohydrate content was highest in Shakari (64.30%) and lowest in Muzawati (42.00%), which was in a lower in range to that of the previously reported values (80.67%) by Ogungbenle (2011).

Table 1
Proximate composition (g/100g) and energy value (Kcal/ 100g) of selected date palm (*Phoenix dactylifera* L.) cultivars.

Cultivars	Moisture	Ash	Protein	Lipid	Crude Fiber	Carbohydrates
Halinee	29.30 ± 0.01^{f}	2.20 ± 0.01^{c}	3.20 ± 0.20^{cd}	0.87 ± 0.05^{ab}	2.50 ± 00.10^{c}	60.62 ± 1.5^{b}
Dandari	32.5 ± 0.15^{de}	3.16 ± 1.12^{b}	3.60 ± 0.20^{bc}	1.40 ± 0.01^{ab}	1.50 ± 0.30^{d}	56.18 ± 1.0^{c}
Shakari	29.00 ± 0.30^{e}	1.57 ± 0.05^{c}	2.90 ± 0.30^{d}	1.43 ± 0.05^{ab}	0.90 ± 0.17^{e}	64.30 ± 0.95^{a}
Muzawati	44.80 ± 0.05^{a}	4.40 ± 0.00^{a}	4.80 ± 0.40^{a}	0.50 ± 0.10^{b}	3.50 ± 0.20^{b}	42.00 ± 1.00^{f}
Rabie	32.60 ± 0.10^{d}	1.74 ± 0.05^{c}	1.80 ± 0.03^{e}	1.63 ± 0.50^{ab}	1.00 ± 0.10^{e}	60.14 ± 1.01^{b}
Shengeskan	38.20 ± 0.10^{c}	1.60 ± 0.01^{c}	3.90 ± 0.10^{b}	1.73 ± 0.46^{ab}	4.00 ± 0.01^{a}	50.21 ± 0.56^{d}
Zard Irani	42.03 ± 0.05^{b}	2.13 ± 0.05^{c}	3.30 ± 0.30^{cd}	0.90 ± 0.00^{ab}	2.50 ± 0.30^{c}	48.13 ± 1.01^{e}
Mean ± SD, mean with different superscripts differ significantly ($p < 0.05$)						

Mineral Composition

Plants utilize 82 of the 92 naturally occurring elements on Earth in their metabolic processes (Reimann et al. 2001). In the present study, 16 elements were analyzed and categorized into macro- and micronutrients.

Macro Elements

Carbon (C) is vital for photosynthesis, and among the selected date palm cultivars, Dandari exhibited the highest (41.19%), while Muzawati had the lowest C content (39.09%). Hydrogen (H), known for its antioxidant properties (Silva et al. 2015), ranged from 9.93% in Rabie to 9.16% in Muzawati, exceeding previously reported levels quantified by Nwaokobia et al. (2018). Nitrogen (N), essential for amino acids and protein synthesis, ranged from 2.83% (Halinee) to 0.22% (Muzawati), higher than previous findings (1.44%) (Nwaokobia et al. 2018). Potassium (K), a crucial intracellular cation, was highest in Muzawati (8598 mg/kg) from district Kech and which may serve as a nutraceutical, potassium-rich product which could help promote cardiovascular health and overall well-being. According to Codex Alimentarius (Codex Stan 234–1999), the recommended nutrient intake for K is 3510mg/day. A 100g serving would provide approximately 859.8mg of K (8598mg/kg×0.1kg), contributing significantly to daily intake. Calcium (Ca), vital for bone health, was most abundant in Shengeskan (789 mg/kg). Shengeskan from the Turbat district can be utilized in dietary supplements and as a nutraceutical product as it supports overall health and well-being. The present work documented higher values of Ca when compared with the same date palm cultivar (680-460mg/kg) collected from other countries (Parvin, 2015). Phosphorus (P), a key component of DNA and bones, was highest in Dandari (336 mg/kg). The daily recommended intake for (P) according to Codex Alimentarius varies by age and physiological state. A 100g serving of Dandari cultivar could provide approximately 33.6mg of the recommended daily intake. Sulfur (S), important for enzymatic reactions, ranged from 782 mg/kg (Shengeskan) to 468 mg/kg (Muzawati). Magnesium (Mg), essential for enzyme activation, was most abundant in Shengeskan (606 mg/kg) (Belitz et al. 2009).

Micro Elements

In the human body, Aluminum (Al) is involved in about 300 distinct chemical reactions. It plays a role in the nervous system, cardiac functions, protein synthesis, and energy metabolism (Insel et al. 2011). In the present study, Shengeskan had the highest mean Al concentration in fruit samples (54.4 mg/kg) and Zard Irani had the lowest (2.90 mg/kg) (Table 2). In comparison to previously published values, the concentration of Al in Shengeskan was higher (Kursa et al. 2020). Selected date palm fruits had barium (Ba) concentrations ranging from 0.37 mg/kg in Halinee to 0.02 mg/kg in Shengeskan. In order to prevent negative health effects, edible fruits usually have low concentrations of Ba. The date palm samples Ba levels fell between the previously reported range of 0.02 ± 0.07 and 0.10 ± 0.06 mg/kg (Habib and Ibrahim, 2011). The metabolism of lipids, carbohydrates, proteins, and cholesterol depends critically on chromium (Cr) (Anderson., 1993). Only the Muzawati, Dandari, and Rabie cultivars had Cr found in this investigation; concentrations ranged from 1.68 mg/kg to 0.09 mg/kg to 1.68 mg/kg. These values are consistent with the 0.36–0.42 mg/kg Cr concentrations in date samples that have been previously reported Parvin et al. (2015). Haemoglobin in blood and myoglobin in muscle tissue both require iron (Fe). Additionally, it is an essential part of a number of enzymes, such as hydroxylase, flavine, peroxidase, and catalase (Belitz et al. 2009). Muzawati had the highest (7.4.25 mg/kg) in this study, while Shakari had the lowest Fe concentration (1.5.89 mg/kg). Compared to date palm cultivars from Libya (0.03 mg/kg) (Oribi, 2018) and Iraq (0.63–1.96 mg/kg) (Attiya et al. 2020), these values were higher. According to the Codex Alimentarius guidelines, consuming a 100g serving size, the iron content would be approximately 7.424 mg per serving. This value is about 41% of the recommended value (18 mg/day) for adults (CODEX stan 234–1999). In the human body, manganese (Mn) functions as an antioxidant activator and is necessary for blood sugar regulation (Emsley, 2001). According to this study, Dandari had the highest Mn content (7.91 mg/kg), while Halinee had the lowest (1.45 mg/kg). Compared to previously published Mn concentrations (3.37–9.7 mg/kg) (Kursa et al. 2020), these values were higher.

Table 2
Elemental composition of date palm fruit.

Macro-elements								
Sample	**C (%)**	**H (%)**	**N (%)**	**K (mg/kg)**	**Ca (mg/kg)**	**P (mg/kg)**	**S (mg/kg)**	**Mg (mg/kg)**
Halinee	40.04 ± 1.00^{d}	9.83 ± 0.03^{b}	2.83 ± 0.03^{a}	5743 ± 0.65^{f}	581 ± 0.54^{c}	205 ± 2.64^{f}	588 ± 3.61^{d}	457.00 ± 1.51^{b}
Dandari	41.19 ± 0.02^{a}	9.70 ± 0.774^{c}	0.61 ± 0.60^{e}	5785 ± 2.64^{f}	534 ± 1.00^{d}	336.33 ± 2.08^{a}	671 ± 2.08^{c}	591.00 ± 0.55^{a}
Shakari	40.42 ± 0.02^{c}	9.75 ± 0.02^{c}	1.03 ± 0.02^{c}	7447 ± 6.08^{b}	532 ± 2.64^{d}	238 ± 1.24^{e}	563 ± 1.21^{e}	431.00 ± 2.60^{bc}
Muzawati	39.09 ± 0.04^{f}	9.16 ± 0.06^{f}	0.22 ± 0.03^{g}	8598 ± 1.40^{a}	438 ± 1.29^{e}	170 ± 1.58^{g}	468 ± 1.61^{f}	293.00 ± 1.36^{d}
Rabie	39.71 ± 0.02^{e}	9.930.03^{a}	1.62 ± 0.03^{b}	5971 ± 1.78^{e}	729 ± 2.64^{b}	315 ± 3.61^{g}	752 ± 2.08^{b}	574.33 ± 1.16^{a}
Shengeskan	40.71 ± 0.03^{b}	9.58 ± 0.02^{d}	0.90 ± 0.05^{d}	6520 ± 2.64^{c}	789 ± 0.29^{a}	297 ± 1.57^{c}	782 ± 0.08^{a}	606.00 ± 1.20^{a}
Zard Irani	39.71 ± 0.02^{e}	9.27 ± 0.02^{e}	0.37 ± 0.30^{f}	6316 ± 1.14^{d}	342 ± 0.71^{f}	247 ± 1.18^{d}	562 ± 3.61^{e}	404.00 ± 1.57^{c}
Micro-elements								
Sample	**Al (mg/kg)**	**Ba (mg/kg)**	**Cr (mg/kg)**	**Fe (mg/kg)**	**Mn (mg/kg)**	**Ni (mg/kg)**	**Sr (mg/kg)**	**Zn (mg/kg)**
Halinee	10.27 ± 0.67^{d}	0.37 ± 0.67^{a}	ND	2.1.21 ± 0.34^{d}	1.45 ± 0.49^{f}	0.65 ± 0.05^{c}	9.86 ± 0.03^{c}	5.51 ± 1.76^{ab}
Dandari	3.76 ± 0.15^{f}	0.06 ± 0.03^{b}	0.70 ± 0.12^{c}	4.2.47 ± 1.67^{b}	7.91 ± 0.03^{a}	0.65 ± 0.05^{e}	5.97 ± 0.03^{e}	5.12 ± 0.04^{ab}
Shakari	38.90 ± 0.44^{b}	ND	ND	1.5.89 ± 0.04^{f}	4.68 ± 0.04^{bcd}	ND	7.55 ± 0.09^{d}	2.84 ± 0.87^{c}
Muzawati	25.24 ± 0.06^{c}	0.09 ± 0.04^{ab}	0.09 ± 0.04^{b}	7.4.25 ± 0.12^{a}	3.50 ± 0.04^{e}	1.16 ± 0.04^{b}	5.98 ± 0.12^{e}	5.02 ± 0.04^{ab}
Rabie	6.86 ± 0.04^{e}	0.12 ± 0.03^{ab}	1.68 ± 0.03^{a}	2.3.06 ± 0.03^{c}	4.89 ± 0.02^{c}	1.23 ± 0.02^{a}	10.65 ± 0.02^{b}	6.12 ± 0.02^{ab}
Shengeskan	54.47 ± 0.04^{a}	0.02 ± 0.02^{b}	ND	2.0.29 ± 0.04^{de}	5.64 ± 0.04^{b}	0.56 ± 0.04^{d}	16.69 ± 0.04^{a}	4.51 ± 0.04^{b}
Zard Irani	2.90 ± 0.18^{g}	0.04 ± 0.03^{b}	ND	1.9.27 ± 0.06^{e}	4.50 ± 0.05^{d}	ND	3.02 ± 0.07^{f}	3.25 ± 0.04^{c}
Mean ± SD, mean with different superscripts differ significantly (*p* < 0.05), ND (Not Detected)								

Another important micronutrient required for hormone regulation and lipid metabolism is nickel (Ni). It enters the human body through the skin, digestive tract, and respiratory system (Zdrojewicz et al. 2016). Rabie had the highest (1.23 mg/kg) while Shengeskan had the lowest Ni concentration in this study (0.56 mg/kg). These values exceeded the Ni concentrations in date palm cultivars (0.7-0.071mg/kg) that had been previously reported (Abdrabo et al. 2015). Strontium (Sr) is well known for its ability to decrease osteoclast activity while increasing angiogenesis, osteogenesis, and tooth and bone mineralization (Ibrahim et al. 2020). Shengeskan had the highest Sr concentration (16.69 mg/kg), while Zard Irani had the lowest (3.02 mg/kg). These levels exceeded those reported in earlier research (3.3–12.0 mg/kg) (Kuras et al. 2020). Carboxypeptidases A and B, lactate dehydrogenase, glutamate dehydrogenase, carbonic anhydrase, malate dehydrogenase, and alcohol dehydrogenase are among the enzymes that require Zinc (Zn). Enolase, alkaline phosphatase, lecithinase, and dipeptidases are among the enzymes that Zn also activates (Belitz et al. 2009). According to this study, Rabie had the highest concentration of Zn (6.12 mg/kg) and Shakari had the lowest (3.25 mg/kg) (Table 2). Compared to previous studies, these values were significantly higher (0.07–1.78 mg/kg) (Brima, 2019). This implies that these traditional date palm cultivars from Makran, Balochistan, especially Rabie, could be a useful dietary Zn source.

Bioactive compounds and antioxidant activity

The total phenolic content (TPC) of food indicates its antioxidant and nutraceutical potential. Phenolic compounds found in date palm fruit can help prevent heart disease, diabetes, and other illnesses (Droge, 2002). Due to their anti-mutagenic properties, phenols also inhibit cancer development (Mitscher et al. 1996). TPC is highest at the Kamri stage but declines as the fruit ripens to the tamar stage. This study, conducted at the Tamar stage, recorded the highest TPC in Shakari (72.32 mg GAE/100 g) and the lowest in Zard Irani (6.81 mg GAE/100 g). Biglari et al. (2009), reported TPC values in Khalas and Khasa cultivars ranging from 20.24 to 63.41 mg GAE/100 g, which were lower than the values found in the present study. The TPC levels in this study were also higher than those in other fruits such as green grapes (23.20 mg GAE/100 g FW), kiwi (87.54 mg GAE/100 g FW), peach (27.58 mg GAE/100 g FW), lemon (61.47 mg GAE/100 g FW), and avocado (76.07 mg GAE/100 g FW) (Fu L et al. 2011). The total flavonoid content (TFC) was highest in Halinee (0.37 mg QE/100 g) and lowest in Shengeskan (0.02 mg QE/100 g) at the Tamar stage. The TFC values in this study were lower compared to previously reported findings (Amira et al. 2011). In endoperoxide, leading to the termination of inflammation mediators like prostaglandins and thromboxane, the phenolics and flavonoid content could inhibit the formation of prostaglandins (Zhang et al. 2013).

Alpha-tocopherol (α-tocopherols) is a powerful peroxyl radical scavenger that plays a key role in preventing and treating diseases such as heart disease, cancer, and Alzheimer's disease (Tucker and Townsend, 2005). Halinee had the highest α-tocopherol concentration in this study (53.45 mg/kg), while Zard Irani had the lowest (3.32 mg/kg). According to Kornsteiner et al. (2006), the mean α-tocopherol contents in extracted oil of almonds and hazelnuts were 24.2 and 31.4 mg/100 g, respectively, in comparison to other fruits and nuts. The extracted oil content of other fruits, including cranberries, blackberries, and kiwis, was 1.43, 1.31, and 1.23 mg/100 g, respectively (Chun et al. 2006). The α-tocopherol concentrations discovered in date palm fruit in this investigation are still higher than these values. The highest concentration of α-tocopherol in the current study shows its high affinity towards nutraceutical proficiency.

Beta-tocopherol (β-tocopherols), a form of vitamin E, exhibits strong antioxidant activity by scavenging free radicals and reactive oxygen species, thereby protecting cellular components from oxidative damage (Brigelius-Flohé and Traber, 1999). According to the current study, Dandari had the highest β-tocopherol concentration (61.42mg/kg), while Shakari had the lowest (10.49 mg/kg). These values were higher than those reported for fruits such as blackberry and pear, which contained 0.04 and 0.21 mg/100 g extracted oil, respectively (Chun et al. 2006).

Gamma-tocopherol (γ-tocopherol) has been shown to inhibit cancer cell growth by trapping free radicals, including reactive nitrogen species that cause DNA mutations and malignant transformations (Stone et al. 2004). The γ-tocopherol concentration in the present study ranged from 44.20 mg/kg in Dandari to 6.44 mg/kg in Zard Irani. Chun et al. (2006) reported gamma-tocopherol levels in fresh blackberry and grape ranging from 1.39 to 0.33 mg/g and 0.16 to 0.16 mg/g, respectively, which were significantly lower than the values recorded in the present study.

Antioxidants protect the human body against damage caused by free radicals, helping prevent chronic diseases such as ageing-related conditions, cancer, anaemia, cardiovascular disease, and inflammation (Vaibhav et al. 2011). Across all date palm cultivars, DPPH activity declined as the fruit ripened. Date palm fruit contains potent antioxidants that contribute to various health benefits (El Hadrami et al. 2005). The highest was found in Shengeskan (78.90%), followed by Dandari (76.60%), while the lowest radical scavenging activity was observed in Zard Irani (60.32%) at the Tamar stage (Table 3). Eman (2001) reported antioxidant activity levels in Ambarah and Ajwa cultivars ranging from 70.14% to 81.33%, which were in a similar range with the values in the present study. These findings highlight the nutraceutical potential of underutilized date palm cultivars, reinforcing their value as rich sources of bioactive compounds and natural antioxidants.

Table 3
Bioactive compounds and antioxidant activity in date palm fruit.

Sample	Bioactive compounds	Content
Halinee	TPC	19.78 ± 1.75^{c} mg GAE/100 g
	TFC	0.37 ± 0.45^{a} mg QE/100 g
	α tocopherol	53.45 ± 0.9113^{a}mg/kg
	β tocopherol	32.38 ± 1.83^{d}mg/Kg
	γ tocopherol	57.10 ± 0.38^{d}mg/kg
	DPPH	60.32 ± 0.01^{d} %
Dandari	TPC	7.10 ± 0.27^{d} mg GAE/100 g
	TFC	0.06 ± 0.02^{ab} mg QE/100 g
	α tocopherol	46.70 ± 1.50^{b}mg/kg
	β tocopherol	61.42 ± 1.10^{a}mg/kg
	γ tocopherol	17.36 ± 0.32^{a}mg/kg
	DPPH	76.60 ± 1.06^{ab} %
Shakari	TPC	56.18 ± 3.72 mg GAE/100
	TFC	M
	α tocopherol	9.38 ± 0.65^{e}mg/kg
	β tocopherol	10.49 ± 1.07mg/kg
	γ tocopherol	35.35 ± 0.38^{b}mg/kg
	DPPH	70.02 ± 0.01^{c} %
Muzawati	TPC	69.41 ± 1.59^{a} mg GAE/100 g
	TFC	0.09 ± 0.03^{ab} mg QE/100 g
	α tocopherol	27.61 ± 1.16^{c}mg/kg
	β tocopherol	54.50 ± 3.55^{b}mg/kg
	γ tocopherol	8.71 ± 0.39mg/kg
	DPPH	43.07 ± 1.00^{e} %

Mean ± SD, mean with different superscripts differ significantly ($P < 0.05$)

Sample	Bioactive compounds	Content
Rabie	TPC	9.06 ± 0.66^{d} mg GAE/100 g
	TFC	0.11 ± 0.02^{ab} mg QE/100 g
	α tocopherol	21.96 ± 1.66^{d}mg/kg
	β tocopherol	39.09 ± 1.06^{a}mg/kg
	γ tocopherol	99.57 ± 0.39
	DPPH	72.90 ± 0.26^{bc}%
Shengeskan	TPC	72.32 ± 1.76^{b} mg GAE/100 g
	TFC	0.02 ± 0.02^{b} mg QE/100 g
	α tocopherol	22.86 ± 1.87^{d}mg/kg
	β tocopherol	57.10 ± 4.30^{b}mg/kg
	γ tocopherol	20.19 ± 1.39^{c}mg/kg
	DPPH	78.90 ± 0.53^{a}%
Zard Irani	TPC	6.81 ± 1.05^{d} mg GAE/100 g
	TFC	0.04 ± 0.02^{b} mg QE/100 g
	α tocopherol	3.32 ± 0.56^{f} mg/kg
	β tocopherol	31.41 ± 1.26^{d}mg/kg
	γ tocopherol	6.44 ± 0.38^{f}mg/kg
	DPPH	37.17 ± 0.75^{f} %
Mean ± SD, mean with different superscripts differ significantly (P < 0.05)		

Multivariate statistical assessment for identifying Date Palm cultivars with nutraceutical potential using principal component analysis (PCA)

A useful exploratory method for examining multivariate data is Principal Component Analysis (PCA), enabling the identification of hidden patterns within large datasets. This approach enhances the precision of outcome determination. In the present study, the dataset was divided into two groups for PCA analysis.

Multivariate analysis of elemental composition

Principal component analysis (PCA) of elemental composition (C, H, S, N, P, Ca, Mg, Al, Ba, Cr, Fe, K, Mn, Ni, and Zn) revealed significant variability among the studied date palm cultivars. Four principal components

(PCs) with eigenvalues greater than 1 were extracted. PC1, with the highest eigenvalue of 5.68, explained the maximum variability in the dataset, followed by PC2 (3.60), PC3 (2.59), and PC4 (2.48). The total variance was explained by these four principal components in 89.80% of cases, with individual contributions of 35.52%, 22.54%, 16.22%, and 15.52%, respectively. The PCA Euclidean bi-plot illustrates the spatial variability between the elements (independent variables) and the date palm cultivars studied (dependent variables) (Fig. 1). According to PCA variable loadings, PC1 represented a mineral differentiation axis, with positive loadings for Ca, Mg, Zn, Ni, Cr, S and P and negative loadings for K and Fe, indicating separation between cultivars enriched in structural and micronutrients and those associated with potassium and iron. PC2 was mainly influenced by Ba, Ni, Zn and N on the positive side and Mn, C and p on the negative side, reflecting secondary variability in the overall data set. The PCA case scores highlight clear clustering patterns among the cultivars. Rabie and Halinee were positioned along the positive side of PC1 and were strongly associated with mineral elements such as Ca, Mg, Zn and Ni suggesting a mineral rich compositional profile. Shengeskan and Dandari were located in the right lower quadrant and were associated with S, P, C, and Mn, indicating a distinct macro nutrient-dominated profile. In contrast, PC2 scores revealed that Muzawati showed a strong association with K and Fe, highlighting a unique elemental signature. These findings highlighted clear compositional differentiation among cultivars and their potential for targeted nutritional and nutraceutical applications.

Multivariate analysis of proximate and bioactive compounds

Principal component analysis (PCA) revealed clear compositional variability among the studied cultivars. Principal components (PCs) with eigenvalues greater than 1 were extracted. PC1 had the highest eigenvalue (5.35), followed by PC2 (2.28), PC3 (1.81), and PC4 (1.21). Together, these four PCs accounted for 88.84% of the total variance. PC1 explained 44.60% of the variance, PC2 accounted for 19.02%, PC3 explained 15.84%, and PC4 explained 10.07%. A PCA Euclidean biplot was used to show the spatial compositional variability of proximate and bioactive elements among the selected date palm cultivars (Fig. 2). PCA variable loadings showed that PC1 represented a major nutritional gradient, with positive loadings for protein, moisture, ash and crude fiber and negative loadings for total carbohydrates, lipid, γ-tocopherol, and antioxidant activity DPPH. This indicates separation between energy-dense and lipophilic antioxidant-rich cultivars and those characterized by higher protein, moisture, fibre content. PC2 was mainly influenced by positive loadings of TPC and moisture, while α-tocopherol and TFC showed strong negative associations, suggesting contrasting accumulation patterns between phenolic compounds and flavonoid–tocopherol related antioxidants. Based on the case scores, distinct cultivar clustering was evident. Muzawati exhibited a significant association with positive PC1 values and was associated with protein, crude fiber, moisture, and ash contents, indicating superior nutritional quality. Shakari, Zard Irani and Shengeskan showed a close association with TPC and moisture. Rabie was located on the negative side of PC1 and was associated with carbohydrates, γ-tocopherol, and DPPH activity, reflecting higher energy-related compounds and antioxidant scavenging potential. Halinee and Dandari were negatively associated with PC2 and were characterized by elevated α-tocopherol and TFC contents. Overall, these findings support the unique nutritional and bioactive profiles of the date palm cultivars under study by highlighting the notable compositional differences between selected cultivars.

Conclusion

High levels of inflammation and oxidative stress in the human body are the main causes of chronic non-communicable diseases. As a valuable source of bioactive compounds, date palm fruit may have therapeutic and protective effects against such conditions. The present study demonstrated significant variability in the nutritional, elemental and bioactive composition of date palm cultivars from the Makran region of Balochistan. Multivariate analysis further exhibited cultivar-specific compositional patterns, offering a plentiful and easily accessible supply of vital nutrients and highlighting the distinct nutritional signatures of the evaluated cultivars. Among them, the Shengeskan cultivars from the Turbat district in the Makran division and the Rabie cultivar from Panjgur were rich in bioactive and antioxidant compounds, which made them excellent candidates for functional food and nutraceutical applications. The overall results emphasized the nutritional and therapeutic potential of these underutilized cultivars, supporting their role in promoting regional dietary quality and food sources. However, further studies focusing on bioavailability, in vivo efficacy and clinical validation are crucial to further substantiate their potential health benefits. Additionally, a comprehensive evaluation of all parts of traditional date cultivars and advanced phytochemical characterisation could further expand the utilization and commercial value of these cultivars for local communities and global markets.

Declarations

Funding declaration

This research received no specific grant from any funding agency.

Conflicts of interest

The authors declared that there are no conflicts of interest.

Acknowledgements

We are thankful to the Directorate of Agriculture Extension, Quetta and Chemistry Division, Directorate of Science PINSTECH, Islamabad., for its help during the analytical procedures.

Author Contribution

Authors contributions to the manuscript: Conceived and designed the experiments: Kulsoom Baloch1, Ashif Sajjad1*, Shaista Anjum2 Performed the experiments: Kulsoom Baloch1, Munib Ahmed Shafique3, Sidra Nadeem3, Waheed Ahmed Shah4 Analyzed the data: A Ashif Sajjad1*, Shaista Anjum2, Zahoor Ahmed Bazai2Contributed reagents/materials/analysis tools: Waheed Ahmed Shah4, Sohail Ahmed1, Muhammad Javed Khan1 Wrote the paper: Kulsoom Baloch1, Ashif Sajjad1*, Shaista Anjum2

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Figures

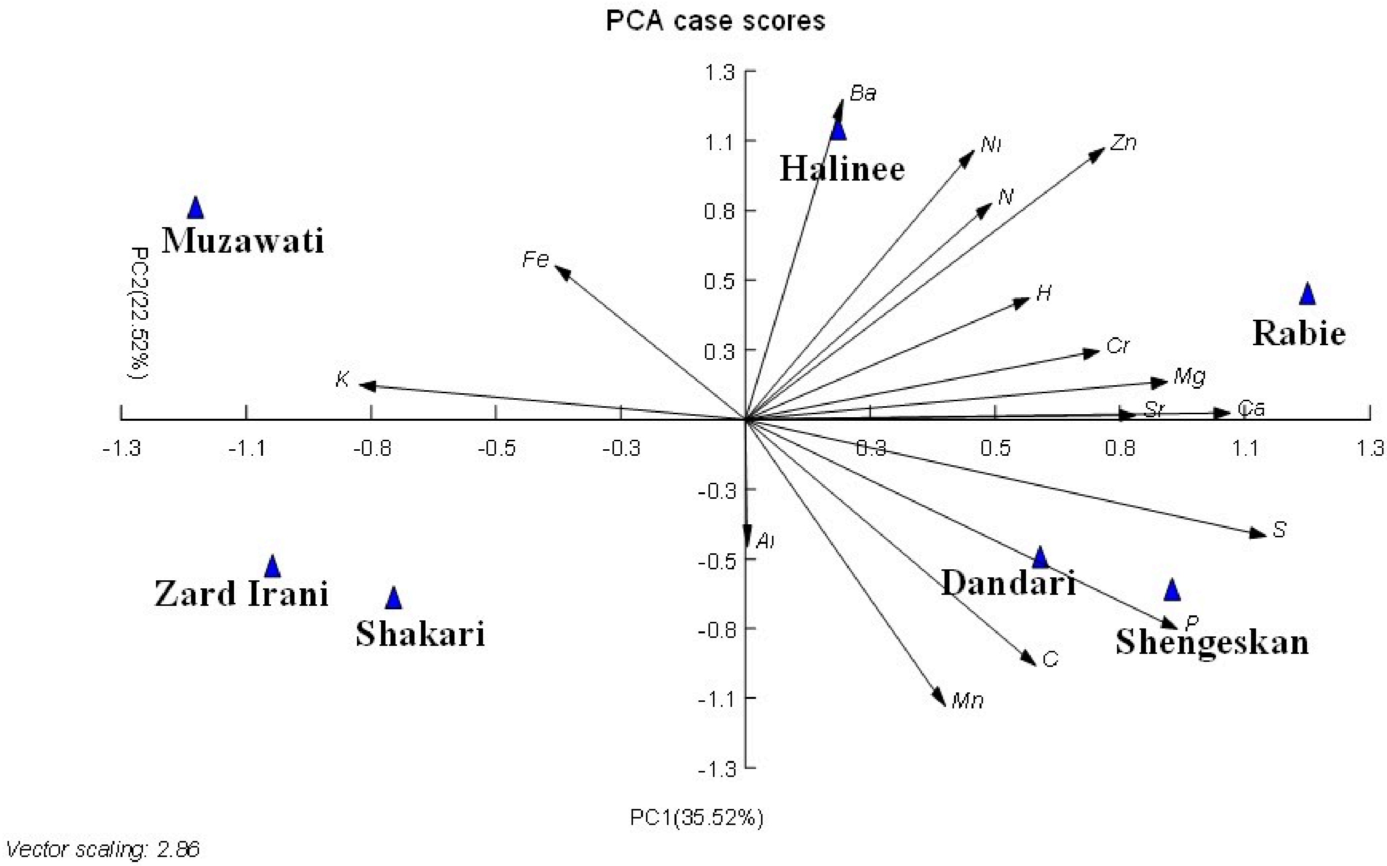

Figure 1

2D Euclidean Biplot of Principal Component Analysis (PCA) showing spatial compositional variability in Elements in selected date palm cultivars grown in the Makran division. Vectors represent elemental variables, while points represent individual cultivars.

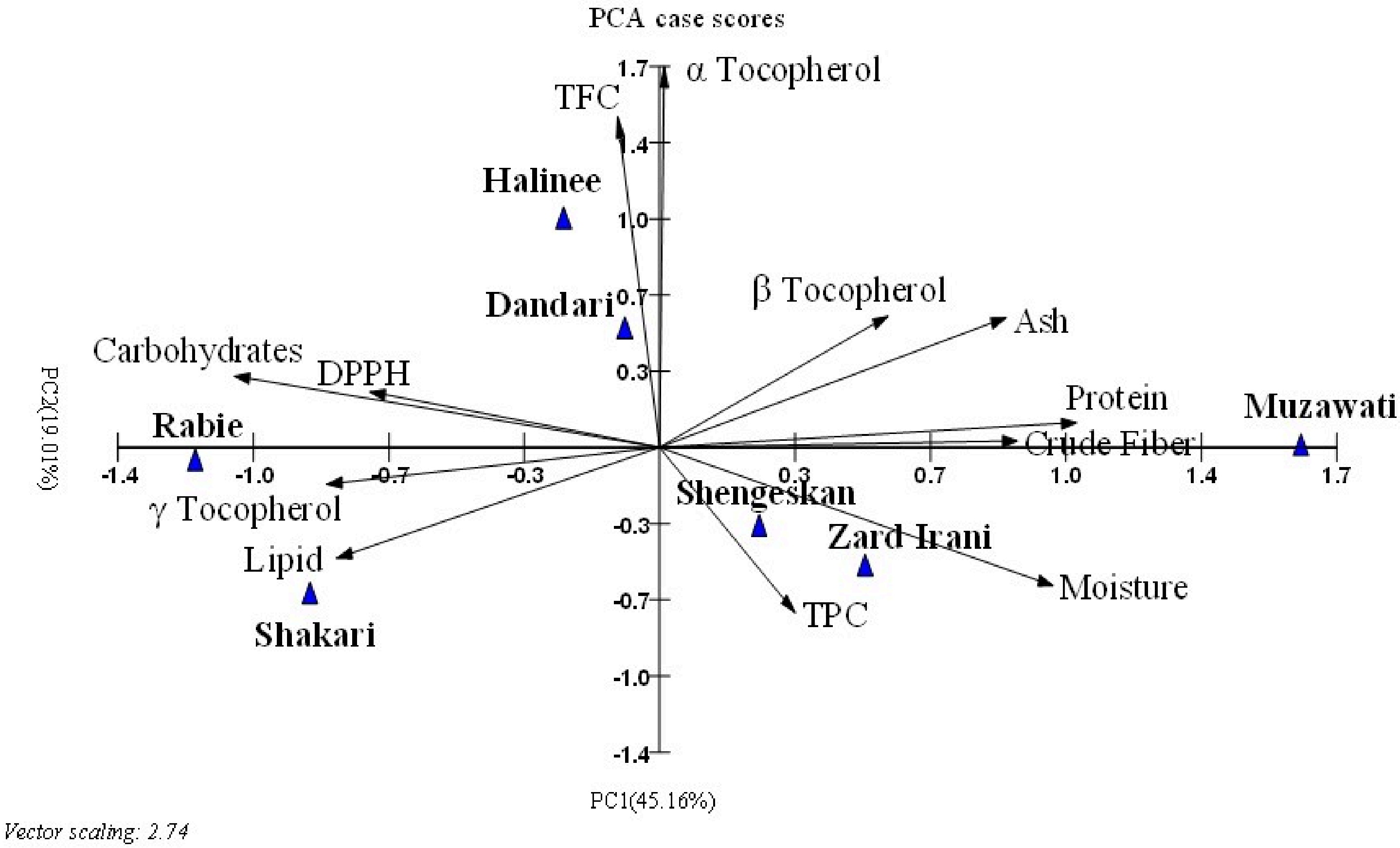

Figure 2

2D Euclidean Biplot of Principal Component Analysis (PCA) showing spatial variability in proximate and bioactive composition in selected date palm cultivars grown in the Makran division. Vectors represent elemental variables, while points represent individual cultivars.