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Comparative phytochemical composition and bioactivities of local variety of *Prunus domestica* L. from Northeastern Türkiye

Composición fitoquímica comparativa y bioactividades de la variedad local de *Prunus domestica* L. del noreste de Turquía

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ABSTRACT

The Cancur plum (*Prunus domestica* L.), a local variety grown in Northeastern Türkiye, represents a valuable source of bioactive compounds with potential functional food applications. This study aimed to comprehensively evaluate the phytochemical composition and functional properties of Cancur plum fruits collected from two regions with contrasting climatic conditions: Posof (microclimate, 1260 m) and Çıldır (continental climate, 1585 m). Antioxidant potential was assessed using multiple approaches, including TAC, DPPH, glutathione, SOD, and catalase assays, while the quantities of total phenolics, flavonoids, and anthocyanins were also determined. The characterization of individual phenolic and flavonoid molecules was performed via LC-MS/MS, volatile constituents were profiled through GC-MS, and free sugars were quantified using HPLC. Comparative evaluation showed that the Çıldır vinegars exhibited greater DPPH radical scavenging capacity and elevated catalase activity, whereas the Posof vinegars were richer in total phenolics and glutathione. Despite these differences, both groups displayed a similar overall antioxidant capacity, though mediated by distinct biochemical mechanisms. LC-MS/MS profiling highlighted shikimic, chlorogenic, and p-coumaric acids as the predominant phenolics, with rutin and hesperidin occurring in higher amounts in the Çıldır sample. In terms of aroma-active compounds, acetic acid and acetoin dominated in the Çıldır vinegars, while ethanol and furfural were more pronounced in the Posof samples.Glucose and fructose were identified as the primary sugars, with minor sucrose detected only in Çıldır fruits. Microclimatic differences strongly shape the biochemical and functional profiles of Cancur plum, highlighting its value as a source of antioxidants, flavor compounds, and functional food ingredients.

Key words: Cancur plum; Prunus domestica L.; antioxidant; phenolic profile; volatile compounds

RESUMEN

La ciruela Cancur (*Prunus domestica* L.), una variedad local cultivada en el noreste de Turquía, es una valiosa fuente de compuestos bioactivos con posibles aplicaciones en alimentos funcionales. Este estudio tuvo como objetivo evaluar exhaustivamente la composición fitoquímica y las propiedades funcionales de los frutos de la ciruela Cancur recolectados en dos regiones con condiciones climáticas contrastantes: Posof (microclima, 1260 m) y Çıldır (clima continental, 1585 m). El potencial antioxidante se evaluó mediante diversos enfoques, incluyendo los ensayos de TAC, DPPH, glutatión, SOD y catalasa, mientras que también se determinaron las cantidades de fenoles totales, flavonoides y antocianinas. Los compuestos fenólicos y flavonoides se identificaron mediante LC-MS/MS, los perfiles de volátiles se determinaron mediante GC-MS y el contenido de azúcares libres se analizó mediante HPLC. Los resultados revelaron que las muestras de Çıldır mostraron una actividad de depuración de DPPH y niveles de catalasa significativamente mayores, mientras que las muestras de Posof presentaron un mayor contenido de fenoles totales y concentraciones de glutatión. Ambas muestras mostraron una capacidad antioxidante total comparable, aunque a través de diferentes vías bioquímicas. El análisis LC-MS/MS reveló que los ácidos shikímico, clorogénico y p-cumárico eran los fenólicos predominantes en la muestra de Çıldır, mientras que la rutina y la hesperidina fueron más abundantes. El perfil GC-MS destacó el ácido acético y la acetoína como los principales volátiles en la muestra de Çıldır, mientras que el etanol y el furfural predominaron en la muestra de Posof. La glucosa y la fructosa se identificaron como los azúcares primarios, mientras que solo se detectaron pequeñas cantidades de sacarosa en las frutas de Çıldır. Las diferencias microclimáticas influyen fuertemente en los perfiles bioquímicos y funcionales de la ciruela Cancur, resaltando su valor como fuente de antioxidantes, compuestos de sabor e ingredientes alimentarios funcionales.

Palabras clave: Ciruela cancur; Prunus domestica L.; antioxidante; perfil fenólico; compuestos volátiles

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INTRODUCTION

Increased fruit and vegetable consumption has been linked to a reduced incidence of degenerative diseases due to the high antioxidant potential of these plant foods [1] Epidemiological studies indicate that consumption of fruits and vegetables rich in phenolic compounds provides significant benefits in preventing deaths from cardiovascular and cerebrovascular diseases and some cancers [2]. One of the most effective ways to increase antioxidant intake is to increase the frequency of consumption of fruits and vegetables rich in polyphenols [3]

Plum (*Prunus* spp.) is a stone fruit belonging to the Rosaceae family and is distinguished from other Prunus species (peaches, cherries, etc.) by its morphological characteristics. Despite their low-calorie content, plums have high nutritional value; they contain carbohydrates such as sucrose, glucose, and fructose; organic acids such as citric and malic acids; fiber (pectin); tannins; aromatic compounds; and various enzymes [4]. They are also particularly rich in vitamins A, C, E, B1, and B2, as well as minerals such as potassium, phosphorus, calcium, and magnesium. Because they are high in potassium and low in sodium/potassium, consuming plums appears to be partially beneficial for patients with hypertension. [5].

Plums contain high levels of anthocyanins and other phenolic compounds. These bioactive compounds exhibit higher antioxidant properties compared to oranges, apples, and strawberries. In vitro studies suggest that the high antiradical activity detected in plum extracts is due to the phenolic compounds contained in the fruit. [6].

Besides their health benefits, plums also have potential uses in sustainable livestock feeding and waste reduction. The rising cost of animal feed and the limited availability of natural resources have made it necessary to explore alternative feed sources. In this regard, wastes and by-products from the fruit and vegetable processing industry offer significant potential, as they can help reduce environmental waste and support nutrient recycling. Plum fruits and their processing residues, rich in carbohydrates, fiber, minerals, and antioxidant compounds, can serve as an energy source and functional additive in ruminant diets [6].

Previous studies have shown that adding fruit residues to animal feed at appropriate levels can improve digestibility, lower greenhouse gas emissions, and enhance antioxidant capacity. Therefore, plum-derived materials and other fruit and vegetable by-products may represent valuable feed alternatives for sustainable and environmentally friendly livestock production. Building on these considerations, evaluating the biochemical composition and functional properties of local plum varieties may provide valuable insights into their potential use in both human nutrition and sustainable agricultural practices [7].

This study was designed to investigate the potential of Caucasian plum species native to northeastern Türkiye. This variety, known locally as 'cancur,' is of particular interest due to its unique biochemical properties and potential health benefits. It thrives in diverse climates, particularly in Ardahan's Çıldır (Öncül village; elevation: 1793 m) and Posof (Türkgözü; elevation: 1276 m) [8].

This study aims to comprehensively evaluate the antioxidant capacity, total phenolic and flavonoid content, phenolic and volatile components of the Cancur plum (*Prunus domestica* L.) grown in two different climates in two regions. It was thought that a comprehensive analysis of these species grown in two different climates in the same region would be useful in revealing their potential as a functional food. The study's findings, which are significant for scientific and industrial applications, will enlighten the field and pave the way for the development of innovative functional foods, offering new possibilities for public health.

MATERIALS AND METHODS

Collection of fruit samples

Samples of Cancur plum (*Prunus domestica* L.) fruit were collected from Turkgozu village of Posof/Ardahan (Türkiye) (Altitude: 1260 m, 41° 27' 22''N, 42° 12' 56''E) and from Oncul village of Kurtkale locality of Çıldır/Ardahan (Altitude: 1585 m, 41°14'52.9838''N '' N, 43°8'2.8842''E '' E). The collected samples were washed and cleaned of dust and soil residues and used in analyses.

Posof, one of the districts where plums are harvested, has a microclimate with rainy winters and hot summers. The district of Çıldır, on the other hand, has a continental climate, with harsh, cold winters and warm, rainy summers.

Extraction of plums

Fresh fruits (CP: for Çıldır plum, PP: for Posof plum) were pitted and dried at 40–45°C to constant weight, then ground to obtain a fraction of ≤ 0.5 mm. After weighing approximately 10.0 grams (g) (Mettler Toledo, Switzerland), 200–250 mL of HPLC-grade methanol was added to a Soxhlet flask and extracted for six hours (h). The resulting extract was filtered through a 0.22 µm PTFE filter and transferred to amber vials for analysis. It was used in the analysis of antioxidant and bioactivity parameters.

Total antioxidant capacity and DPPH analyses

A commercial spectrophotometric kit (TAC; Rel Assay Diagnostics) was used to determine the total antioxidant level. For this purpose, ABTS solution was incubated with metmyoglobin (peroxidase) and hydrogen peroxide (H_2O_2) to form the $ABTS^{+}$• radical cation, which is blue-green and exhibits maximum absorption at 660 nm. Measurements were performed spectrophotometrically (Shimadzu Co., Japan) in triplicate, and the results were expressed in Trolox Equivalent (TE). Trolox was used as the reference standard in creating the calibration curve. Analyses were performed in triplicate, and mean values were used.

The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity was determined based on the method developed by Blois [9]. Before the analysis, a fresh stock solution was prepared by dissolving the DPPH radical in methanol at a concentration of 1 mM. After stock solution preparation, 2 mL of DPPH solution and 0.1 mL of the plum extract were mixed, and the mixture was kept in the dark for 30 min. After the incubation, the activity levels were measured using a UV-Vis spectrophotometer (Shimadzu Co., Japan) at 517 nm. Methanol was used as a blank, and 0.1 mL of methanol was added instead of vinegar in the control group. Analyses were performed in triplicate, and mean values were used.

Determination of glutathione

The glutathione (GSH) determination was carried out using its ability to reduce 5,5'-dithiobis-(2-nitrobenzoic acid) (DTNB). During this reaction, the thiol groups in GSH interact with DTNB, generating 2-nitro-5-mercaptobenzoic acid, which gives a yellow coloration. The absorbance of this chromogenic compound was then measured, and GSH levels were expressed as mmol/L [10]. All measurements were conducted in triplicate, and the average values were considered for evaluation.

Determination of antioxidant enzyme activities

Superoxide dismutase (SOD) activity was determined using an ELISA kit that measures the enzyme's ability to reduce superoxide anions generated in a xanthine/xanthine oxidase (XOD) system. In this assay, SOD activity was quantified based on its capacity to inhibit or reduce the formation of a chromogen, allowing for measurement of SOD levels.

Catalase (CAT) activity was assessed by measuring the amount of H_2O_2 remaining after CAT catalysis. The measurements performed by using an ELISA kit and analyses were performed in triplicate, and mean values were used.

Total phenolic content and total flavonoid content

Total phenolic content was determined using the Folin-Ciocalteu method [11]. 200 µL of extract, 1000 µL of Folin-Ciocalteu, and 800 µL (7.5 %) Na_2CO_3 were added to a glass tube, and the mixture was incubated for 2 h at room temperature. After that, absorbance was measured at 750 nm against a 50 % ethanol-water mixture in a spectrophotometer (Shimadzu Co., Japan). The total phenolic content of the samples was determined as milligrams per 100 g using a gallic acid standard. Analyses were performed in triplicate, and mean values were used.

The total flavonoid content was determined according to the method described by Quettier-Deleu *et al*. [12]. One milliliter of the extract was mixed with 1 milliliter of 2 % $AlCl_3$ and incubated for 1 h at room temperature in the dark. The absorbance of the samples was determined using a spectrophotometer at 415 nm and calculated in milligrams per 100 g based on the calibration curve prepared using routine methods. Analyses were performed in triplicate, and mean values were used.

Total anthocyanin content

The total anthocyanin content was determined using the pH differential method [13]. The absorbances of the samples incubated in 0.025 M KCl buffer [pH 1.0] and 0.4 M CH_3COONa buffer were measured at 520 and 770 nm by a spectrophotometer. Analyses were performed in triplicate, and mean values were used.

Phenolic profile screening with LC-MS/MS

Methanol extracts of plum samples were obtained using a simple extraction method. 10 g of partially dried and ground plant samples were shaken with 50 mL of methanol at 100 rpm for 24 h. The solvent in the resulting mixture was removed using a rotary evaporator (SciLogex RE100-Pro). The extracts were frozen and lyophilized for 48 h and stored at +4 °C (Arçelik, Türkiye) until analysis. For analysis, 50 mg of the dry extract was sonicated for 5 min in 1 mL of water-methanol (50:50), filtered through a 0.25 µm PETF filter, and diluted 1:10 with the same solvent mixture before being transferred to vials.

Samples prepared for secondary metabolite analyses were filtered using a PTFE filter (Isolab) with a pore diameter of 0.45 µm and transferred to capped glass vials before analysis. No dilution was applied to the samples.

Qualitative and quantitative analyses of secondary metabolites containing phenolic and flavonoid compounds were performed using liquid chromatography (Spark Holland) and tandem mass spectrometry (AB SCIEX 4000 QTRAP). Chromatographic separation was provided by a C18-type column (Inertsil ODS-3V, 250 mm × 4.6 mm, 5 µm). 0.1 % (v/v) formic acid solution (phase A) and methanol (phase B) were used as mobile phases. The injection volume was 10 µL, the flow rate was 0.700 mL/min, and the column oven temperature was 30 °C. The chromatographic analysis time was determined as 20 min.

Volatile components screening with GC-MS

Analysis of volatile components was carried out using a Gas chromatography and mass spectrometry (GC–MS; QP 2010 Ultra, Shimadzu, Japan) system equipped with a Headspace (HS) unit. A TRB-5MS capillary column (60 m length, 0.25 mm inner diameter, 0.25 µm film thickness) was used in GC analysis. Helium (He) was selected as the carrier gas, and the pressure was set at 164.9 kPa. The column oven was initially kept at 40 °C, then increased to 320 °C at 12 °C/min and held at this temperature for 2 min. The injection temperature was 230 °C, the injection mode was set as "split", and the split ratio was set as 70:1. The total flow rate was 113.8 mL/min, the column flow rate was 1.56 mL/min, and the linear velocity was 31.8 cm/s.

Under headspace conditions, the valve oven temperature was set at 120 °C, the transfer line temperature at 120 °C, and the sample plate temperature at 120°C. The sample plate equilibration time was set at 3 min, and the sample equilibration time at 2 min. The mixer was turned off, the mix level was set at 5, the mix time was set at 5 min, and the stabilization time was set at 0.5 min. Pressurization was set at 10 PSIG for 2 min, the loop fill pressure was set at 5 PSIG, the fill time was set at 2 min, and the injection time was set at 3 min.

Free sugar analysis

Fresh plum fruits collected from two different regions (Posof and Çıldır) were dried in an oven at 40 °C (CTO-10AS VP, Shimadzu, Japan) for three d. A 10 g sample of the dried fruits was weighed, cut into small pieces, and then covered with ~50 mL of distilled water. The samples were extracted at room temperature on a magnetic stirrer for 24 h. The extracts were filtered, and the filtered solutions were transferred to glass petri dishes and dried at 40 °C for another two d. 100 mg of completely dried samples were weighed and dissolved in 1 mL of distilled water, followed by 10 min of sonication and 10 min of vortexing (VELP ZX3, Italy). The solutions were centrifuged (Elektromag M4808 PR, Türkiye) at 25155 g for 15 min. The supernatant was diluted with an equal volume of distilled water and subjected to HPLC analysis.

Analyses were performed using a Shimadzu LC-20AT HPLC system equipped with a SIL-20A HT autosampler, SPD-M20A

diode array detector (DAD), CTO-10AS VP column oven, and LC Solution data analysis software. Separation was performed using a SilUR NH_2 HPLC column (250 × 4.6 mm, 5 µm), and a mixture of acetonitrile and water (80:20, v/v) was used as the mobile phase. The injection volume was 20 µL, the flow rate was 1.0 mL/min, the column temperature was 30 °C, and the analysis time was 35 min.

Statistical analysis

All experiments were conducted in triplicate, and results were expressed as mean ± standard deviation (SD). Statistical analysis was performed using IBM SPSS Statistics version 25.0.

RESULTS AND DISCUSSION

Posof (PP) and Çıldır (CP) samples of Cancur plum were compared in terms of antioxidant capacity (TABLE I). Total antioxidant capacity values were found to be 1513 ± 256 µmol trolox equiv./L in PP and 1590 ± 137 µmol trolox equiv./L in the CP sample. While DPPH radical scavenging activity was 46.98 ± 0.01 % in PP, it was 58.69 ± 0.02 % in the CP sample and was found to be statistically significantly higher ($P < 0.001$). SOD activities, one of the enzymatic antioxidants, were detected at similar levels in both samples. Glutathione level was 2.20 ± 0.02 in PP, while it was lower in CP (1.680 ± 0.005; $P < 0.001$). CAT activity was significantly higher in the CP sample ($P < 0.001$).

TABLE I
Antioxidant Levels of Cancur Plum

	PP	CP
Total Antioxidant Capacity (µmol trolox equiv./L)	1513 ± 256	1590 ± 137
DPPH (%inhibition)	46.98 ± 0.01	58.69 ± 0.02*
Superoxide Dismutase	5.45 ± 0.04	5.39 ± 0.04
Glutathione	2.20 ± 0.02	1.680 ± 0.005*
Catalase	2.48 ± 0.22	5.19 ± 0.22*

*P<0.001 (PP: Posof Plum vs CP: Çıldır Plum)

Plums, especially the Cancur variety, are rich fruits for not only nutrition but also in flavonoids, anthocyanins, carotenes and polyphenolic acids [7]. These compounds affected the high antioxidant capacity of plums, with the CP sample exhibiting superior DPPH radical scavenging capacity and CAT activity. On the other hand, the PP sample comes forward in terms of total phenolics and glutathione levels. This suggests that CP primarily prevents oxidative stress through enzymatic mechanisms, while PP does so through phenolic compounds and glutathione. The similar total antioxidant capacity of both plum samples suggests that they exhibit the same protective activity through different biochemical pathways and thus provide a range of health benefits to consumers.

As seen in TABLE II, when phenolic compounds and other bioactive parameters were evaluated, the total anthocyanin amount was determined as 56.44 ± 2.33 mg/L cyanidin-3-glucoside in the PP sample and 52.21 ± 1.36 mg/L in the CP sample. The total phenolic substance amount was found to be 860.33 ± 14.16 mg/L gallic acid equivalent in the PP sample, which was statistically significantly higher than the CP sample (788.00 ± 2.51 mg/L; $P < 0.05$). On the other hand, the total flavonoid amount was found to be 3.57 ± 0.017 mg/L in the CP sample, which was significantly higher than the PP sample ($P < 0.05$).

TABLE II
Different Bioactivity Levels of Cancur Plum

	PP	CP
Total Antocyanine (Siyanidin-3-glikozit)	56.44 ± 2.33	52.21 ± 1.36
Total Phenolic (mg/L gallic acid)	860.33 ± 14.16	788.00 ± 2.51**
Total Flavonoid (mg/L)	3.47 ± 0.008	3.57 ± 0.017**

** p<0.05 (PP: Posof Plum vs CP: Çıldır Plum)

Flavonoid content was significantly higher in CP, while anthocyanin levels were similar in the two samples. Rop *et al*. [5] also suggested that regional plums had higher phenolic, antioxidant, and mineral contents than common varieties in a study of 12 plum varieties grown in the same region. These differences are believed to be due to genetic variation and adaptation to microclimatic conditions.

Similarly, Rupasinghe *et al*. [6] reported a relatively high correlation between total phenolic and antioxidant activity in European genotypes. The findings confirm the phenolic content-antioxidant activity relationship revealed in the literature and show that Cancur plum varieties have functional food potential for human health and can be valuable resources for breeding new varieties.

When the volatile compound profiles were examined, it was seen that the dominant compounds in the CP sample were acetic acid (48.89 %), 2-butanone-3-hydroxy (acetoin; 19.51 %), and 1,1'-bibicyclo (2.2.2) octyl-4-carboxylic acid (22.54 %). Additionally, ethanol, hexanoic acid, and nonanal were detected at lower levels (TABLE III). In the PP sample, the highest concentrations were ethanol (51.98 %) and 3,3-dimethyl-2-phenyl-2-(1-oxo-1,2,3,4-tetrahydronaphthalen-2-yl) azirane (29.88 %).

Additionally, acetic acid was detected at 10.04 %, furfural at 3.86 %, and nonanal at 1.44 %. Other volatile compounds (e.g., diacetyl, pentanal, hexanal, benzene, acetaldehyde) were recorded at lower percentages (TABLE III). Volatile metabolites are generated both as part of fruit ripening and because of tissue disruption, with some arising from endogenous metabolic pathways and others triggered by cellular injury. Their composition and abundance are strongly influenced by genetic background, environmental conditions, cultivation practices, maturity stage, and postharvest storage [14].

In evaluating the volatiles responsible for fruit aroma, it becomes clear that distinct chemical classes make critical contributions to the perception of flavor and the unique sensory properties of each fruit [15].

The analysis of volatile constituents in Cancur plum vinegars from the Çıldır (CP) and Posof (PP) regions demonstrated that geographical origin markedly influences their flavor attributes. In the CP samples, acetic acid emerged as the dominant compound, imparting the typical sharp and sour character associated with vinegar. Elevated acetoin levels further contributed buttery–creamy notes [14], enhancing mouthfeel smoothness. Conversely, ethanol was the most abundant volatile in the PP samples, arising from fermentation and contributing significantly to flavor balance and aromatic complexity [16].

TABLE III
Volatile Compounds of Cancur Plum

Samples	Aromatic Compounds	Ret. Time	Area	Area %
CP	1,1'-bibicyclo(2.2.2)octyl-4-carboxylic acid	3.582	2013638	22.54
	Ethanol (CAS) Ethyl alcohol	4.030	386400	4.33
	Acetic acid	6.750	4366910	48.89
	2-Butanone, 3-hydroxy- (CAS) Acetoin	8.641	1742699	19.51
	Hexanoic acid (CAS) n-Hexanoic acid	16.819	252052	2.82
	Nonanal	20.311	171019	1.91
PP	3,3-Dimethyl-2-phenyl-2-(1-oxo-1,2,3,4-tetrahydronaphthalen-2-YL) Azirane	3.616	19270443	29,88
	Ethanol (CAS) Ethyl alcohol	4.083	33520578	51,98
	2,3-Butanedione (CAS) Diacetyl	5.162	291829	0,45
	Butanal, 3-methyl-	6.295	104663	0,16
	Pentanal (CAS) n-Pentanal	7.234	49652	0,08
	Hexanal (CAS) n-Hexanal	10.261	150869	0,23
	Acetic acid	10.581	6475089	10,04
	2-Furancarboxaldehyde (CAS) Furfural	11.439	2489100	3,86
	2-Butanone, 3-hydroxy- (CAS) Acetoin	11.720	879230	1,36
	N Heptanal	13.855	77151	0,12
	Octanal	17.954	96153	0,15
	Benzeneacetaldehyde	19.754	151188	0,23
	Nonanal (CAS) n-Nonanal	22.044	930641	1,44

(PP: Posof Plum vs CP: Çıldır Plum)

Additional compounds such as diacetyl, furfural, and several aldehydes enriched the PP profile with fruity and floral nuances [13], leading to a more intricate aromatic composition. In contrast, the CP sample displayed a narrower aldehyde spectrum, represented mainly by nonanal (1.91 %), which pointed to a simpler aroma profile. Collectively, these findings emphasize that climatic and environmental factors specific to each cultivation site are decisive in shaping the volatile composition, thereby conferring distinct sensory characteristics to Cancur plums depending on their region of origin.

The free sugar contents of the Posof and Çıldır samples of the Cancur plum were determined by HPLC (TABLE IV). The most dominant sugar in both samples was glucose, which was 18.88 mg/mL (37.77 g/100 g; 58.01% area ratio) in CP and 19.02 mg/mL (38.05 g/100 g; 61.20 %) in PP. Fructose levels were found to be 13.04 mg/mL (26.09 g/100 g; 41.17 %) in CP and 11.83 mg/mL (23.67 g/100 g; 38.80 %) in PP. However, sucrose was detected at a low level only in the CP sample and was not detected in the PP sample. Other sugar species (turanose, maltose) were not measured in either sample.

Sugar content, type, and ratio play important roles in determining fruit flavor, and their regulation is influenced by various factors, including transcription factors (TFs), epigenetic modifications, phytohormones, and environmental conditions [17].

The results of the study indicate that glucose and fructose are the dominant components in the free sugar composition of Cancur plum. Glucose (37.77 g/100 g) and fructose (26.09 g/100

g) were prominent in the CP, while similar levels of glucose (38.05 g/100 g) but lower fructose (23.67 g/100 g) were found in the PP. This suggests that samples from both regions have similar glucose profiles in terms of sweetness perception, but the difference in fructose levels may contribute to the more intense fruity taste in the Çıldır samples.

Sucrose was detected at low levels (1.14 g/100 g) only in CP samples and was not found in PP samples. This difference may be related to the breakdown of sucrose into glucose and fructose by the invertase enzyme during ripening. Indeed, it has been previously reported that sucrose decreases, and glucose and fructose ratios increase during ripening in various fruits [17, 18]. Therefore, it is likely that sucrose was completely degraded in PP. Sugar composition in fruits varies depending on environmental conditions, genotype, and ripening stage. Ecological factors, particularly temperature and light intensity, have a direct impact on carbohydrate metabolism [18, 19]. In this context, the different microclimatic characteristics of the Çıldır and Posof regions may be one of the main reasons for the differences in fructose levels.

TABLE IV
Free Sugar Levels of Cancur plum by HPLC

Sugar	CP Concentration (mg/mL)	CP g/100 g	CP Area %	PP Concentration (mg/mL)	PP g/100 g	PP Area %
Fructose	13.0471	26.09	41.17	11.8360	23.67	38.80
Glucose	18.8869	37.77	58.01	19.0266	38.05	61.20
Saccarose	0.5679	1.14	0.82	ND	ND	ND
Turanose	ND	ND	ND[d]	ND	ND	ND
Maltose	ND	ND	ND[d]	ND	ND	ND

CP: Çıldır Plum, PP: Posof Plum, ND: not detected

As shown in TABLE V, LC-MS/MS analyses revealed that the phenolic compounds in the PP and CP samples of Cancur plum exhibited both common and distinct characteristics. The most dominant compound in both samples was shikimic acid, which was found to be higher in the PP (392.98 µg/g) than in the CP (355.26 µg/g). Chlorogenic acid, p-coumaric acid, and vanillin were also other significant compounds detected in high amounts in both samples. The amount of p-coumaric acid was higher in the PP than in the CP.

It is noteworthy that some phenolic compounds were found only in certain samples. For example, protocatechuic acid was measured only in the CP at 10.94 µg/g, while in PP, it was below the LOQ. Similarly, hesperetin was detected only in the CP. Caffeic acid was detected in both samples but was found at a higher level in the PP (12.43 µg/g) than in the CP (6.26 µg/g).

TABLE V
Phenolic and Flavonoid Compounds of Cancur Plum

Analytes	Retention Time	R^2	LOQ[e] (ng/mL)	LOD[e] (ng/mL)	Quantification (µg/G extract)	
					CP	PP
Shikimic acid	1.367	0.9985	18.59	7.17	*355,26*	392,98
Gallic acid	3.808	0.9986	13.17	3.16	N.D.[d]	N.D.[d]
Protocatechuic acid	5.554	0.9993	18.59	7.17	10,94	<LOQ
Catechin	6.888	0.9992	7.50	1.71	N.D.[d]	N.D.[d]
Chlorogenic acid	7.396	0.9986	25.90	11.59	225,97	132,57
Hydroxybenzaldehyde	7.767	0.9992	12.87	4.97	N.D.[d]	N.D.[d]
Vanillic acid	7.826	0.9981	724.21	89.04	N.D.[d]	N.D.[d]
Caffeic acid	7.838	0.9985	24.16	6.92	6,26	12,43
Syringic acid	8.396	0.9958	857.34	358.50	N.D.[d]	N.D.[d]
Caffein	8.399	0.9995	15.50	6.81	N.D.[d]	N.D.[d]
Vanillin	8.428	0.9989	40.54	14.59	34.55	38,20
p-coumaric acid	9.410	0.9984	17.54	3.53	156,18	172,16
Salicylic Acid	9.746	0.9983	82.96	47.67	10,33	39,09
Taxifolin	9.768	0.9999	23.51	11.03	N.D.[d]	N.D.[d]
Polydatin	9.772	0.9987	1.84	1.15	N.D.[d]	N.D.[d]

Resveratrol	9.775	0.9989	13.56	4.58	N.D.[d]	N.D.[d]
Trans-ferulic acid	10.096	0.9995	11.53	6.12	N.D.[d]	N.D.[d]
Sinapic acid	10.244	0.9991	4.97	1.94	N.D.[d]	N.D.[d]
Scutellarin	11.054	0.9989	4.00	3.13	N.D.[d]	N.D.[d]
o-coumaric acid	11.506	0.9995	8.00	4.02	N.D.[d]	N.D.[d]
Coumarin	11.510	0.9986	20.70	6.01	N.D.[d]	N.D.[d]
Protocatechuic ethyl ester	11.573	0.9987	24.92	14.56	N.D.[d]	N.D.[d]
Rutin	11.649	0.9995	240.67	59.56	38,35	25,42
Isoquercitrin	11.650	0.9989	11.27	9.94	21,07	10,48
Hesperidin	12.271	0.9979	17.68	4.14	23,96	<LOQ
Quercetin-3-xyloside	12.402	0.9992	69.41	18.71	0,45	N.D.[d]
Kaempferol-3-glucoside	13.072	0.9996	4.52	1.16	0,53	N.D.[d]
Fisetin	13.344	0.9985	44.37	10.90	1,52	N.D.[d]
Baicalin	13.544	0.9996	3.10	0.53	0,50	N.D.[d]
Trans-cinnamic acid	14.325	0.9980	22.03	11.19	N.D.[d]	N.D.[d]
Quercetin	14.841	0.9986	16.91	4.66	5,57	N.D.[d]
Naringenin	14.994	0.9957	0.46	1.37	N.D.[d]	N.D.[d]
Morin	15.681	0.9984	0.53	0.13	0,03	N.D.[d]
Hesperetin	15.684	0.9981	0.65	0.30	2,34	N.D.[d]
Kaempferol	16.377	0.9984	5.40	1.87	N.D.[d]	N.D.[d]
Baicalein	17.150	0.9991	0.96	0.60	N.D.[d]	N.D.[d]
Biochanin A	17.926	0.9993	0.73	0.15	0,04	N.D.[d]
Luteolin	17.967	0.9988	21.45	12.05	N.D.[d]	N.D.[d]
Chrysin	18.002	0.9997	0.13	0.07	N.D.[d]	N.D.[d]

CP: Çıldır Plum, PP: Posof Plum, [d]: not detected

When flavonoid derivatives were examined, it was observed that the amount of rutin was higher in the CP (38.35 µg/g) than in the PP (25.42 µg/g). Isoquercitrin was also found to be significantly higher in the CP than in the PP. Hesperidin was detected at 23.96 µg/g in the CP, while in the PP, it was below the LOQ. In contrast, some flavonoid compounds, such as quercetin, fisetin, and baicalin, were detected in low amounts only in the PP.

The phenolic composition exhibited clear regional differences between the samples. Shikimic acid represented the most abundant constituent in both vinegars, with notably higher levels in the PP. Chlorogenic acid, p-coumaric acid, and vanillin were also present at substantial concentrations in both regions. Among these, p-coumaric acid accumulated more strongly in Posof, whereas rutin and hesperidin were more enriched in Çıldır. Caffeic acid was identified in both samples but predominated in Posof, while protocatechuic acid and hesperetin appeared exclusively in Çıldır. Regarding flavonoid derivatives, rutin, isoquercitrin, and hesperidin were detected in both samples, although their relative proportions varied considerably.

In agreement with these observations, Çelik *et al*. [20] reported that chlorogenic and caffeic acids were the most prominent phenolics in three different plum varieties, alongside rutin, gallic acid, and vanillic acid. They attributed such compositional differences to environmental and genetic influences. The authors also highlighted that flavonol glycosides tend to accumulate in the peel due to light exposure and that climatic conditions exert a major role in phenolic biosynthesis. Overall, the present findings indicate that ecological factors shape the phenolic profile of Cancur plums, thereby influencing their biofunctional potential depending on the region of cultivation.

In addition to these compositional and ecological aspects, the potential utilization of plum-derived materials in livestock systems represents another dimension of their biofunctional value. Plum processing residues, such as pulp and kernels, contain valuable nutrients including protein, fat, and fiber, which may allow their use as feed ingredients in ruminant diets. When properly processed to eliminate cyanogenic compounds, these by-products can contribute to nutrient recycling and sustainable livestock production.

Studies have also indicated that limited inclusion of fruit and vegetable residues in sheep diets can improve digestibility and antioxidant status while reducing methane emissions. However, further studies are needed to evaluate the specific effects of plum-based materials on animal performance and safety [7 , 21].

CONCLUSION

Marked variations were identified in the antioxidant capacity, phenolic composition, volatile profile, and sugar content of Cancur plum vinegars derived from the Çıldır and Posof regions. The Çıldır samples appeared to mitigate oxidative stress predominantly through enzymatic pathways, whereas the Posof samples relied more heavily on phenolic constituents and glutathione. Distinctions in aroma-active volatiles and carbohydrate composition further highlighted the influence of regional microclimates on the biofunctional and sensory characteristics of the product. Collectively, these results underscore the relevance of Cancur plum as a promising functional food and highlight its potential utility as a raw material for innovative applications in the food industry.

Conflict of interests

The authors of this study declare that there is no conflict of interest with the publication of this manuscript.

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