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Advancing sustainable practices based on UV-C radiation for valorising downgraded date fruit residues from date syrup production

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ABSTRACT

Date fruit pomace from syrup production represent a significant by-product with potential for valorization. This study investigated the physicochemical and functional properties of residues generated through microwave-assisted (MWR), ultrasound-assisted (USR), and water bath (WBR) extraction methods. Additionally, the dates pomaces remaining after green extractions (MWR, USR and WBR) were irradiated with ultraviolet C (UV-C) (5, 10, 20 and 40 min). The effects of these UV-C treatments on soluble carbohydrates, polyphenol profile, and antioxidant capacity were thoroughly examined. Microwave-assisted extraction retained the highest amounts of insoluble dietary fiber (24.31 g/100 g) and total dietary fiber (29.22 g/100 g). The ratio of insoluble to soluble dietary fiber was the closest to the optimum (3:1) in USR (2.96), compared to WBR (2.85) and MWR (4.95). Carbohydrate content was highest in WBR (50.23 g/100 g), followed by MWR (44.43 g/100 g) and USR (34.32 g/100 g), and remained largely unaffected under UV-C treatment. Regarding polyphenol profile, the UV-C irradiation of date syrup residues for 20 min optimally enhanced these compounds, with MWR yielding the highest content, followed by WBR and USR. Total polyphenol content assessed using both the Fast Blue and Folin-Ciocalteu methods, significantly increased after UV-C treatment. While ferric reducing antioxidant power and oxygen radical absorbance capacity remained relatively unchanged. However, the half maximal effective concentration required to inhibit 50 % of the 2,2-diphenyl-1-picrylhydrazyl radical was augmented. Summarizing, date syrup pomace is a valuable source of dietary fiber and polyphenols, and UV-C irradiation appears to be a promising method for preserving and enhancing their nutritional and functional properties, offering potential for the development of value-added ingredients from date processing waste, and contributing to the economic and environmental sustainability of the date industry.

1. Introduction

Date palm (*Phoenix dactylifera* L.) is one of the important subsistent crops in many countries. The plant originated from warm dessert areas of the Middle East region and North Africa (Alu'datt et al., 2025). Algeria possesses considerable potential in date palm cultivation, featuring a diverse array of a thousand inventoried cultivars. The production of Algerian date palms is noteworthy, reaching annual yields of hundreds of thousands of tons, being the most abundant fruits in Algeria. They are distinguished by their extensive variety of cultivars, showcasing distinctions in taste, shape, colour, preservation methods, and applications within the food industry (Yamina et al., 2023). The nutritional composition of date fruit mainly consists of carbohydrates and dietary fiber, low amounts of proteins and fat, and notable amounts of micronutrients, including thiamine, riboflavin, vitamins C and E, potassium and magnesium, and different phytochemicals (Obayomi et al., 2025).

Due to their composition, dates are commonly used for the preparation of syrup and are considered as a natural alternative liquid sugar. Typically, syrup production from fruits consists of extraction and concentration of fruit juice or sap. An efficient extraction process is very important to the yield and quality of the obtained juice. Microwave,

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ultrasound, and enzyme-assisted extractions represent alternative methods aimed at enhancing the efficiency of date fruit juice extraction when compared to traditional methods involving solely conventional heating or mechanical pressing (Djaoud, Daglia, et al., 2020; Lynda et al., 2024; Touati et al., 2021).

Date syrup (also called dibs) is extracted from the fruits, leaving behind two types of industrial waste: the seeds and the fibrous material of the fruit pulp, named date fruit pomace or date press cake (Alqahtani et al., 2025). According to M. Al-Farsi et al. (2007), date syrup production yields approximately 52–64 g/100 g syrup, 17–24 g/100 g date fruit pomace, and 8–15 g/100 g seeds, on a dry matter basis. Currently, the large amount of date fruit pomace waste is either fed to animals or dumped into landfills, where its fermentation causes serious waste management issues (Oladzad, Fallah, Mahboubi, Afsham, & Taherzadeh, 2021).

Ultraviolet-C (UV-C) light is a promising non-thermal preservation technology for industries due to its ease and low-cost regarding installation and maintenance. Moreover, this technology can ensure food safety and extend the shelf life without adverse effects of physicochemical and sensory characteristics when adequate doses are applied (Molina-Hernandez et al., 2025). However, there is limited data on how UV-C treatment affects food composition through the photochemical reactions it induces, and how these alterations may affect nutritional and bioactive compounds, as well as antioxidant capacity (J Csapó, Prokisch, et al., 2019).

To address the challenges of waste management in the date processing industry and to promote sustainable valorization approaches, this study collects the dietary fiber characterization and the physicochemical and functional properties of residues (pomace) after date syrup extractions through three processes: microwave-assisted, ultrasound-assisted, and water bath extractions. Beyond the mentioned characterization, the study focuses on the effects of UV-C irradiation on these residues, specifically examining its impact on soluble carbohydrates, polyphenol content, and antioxidant capacity. The rationale behind UV-C application lies in its potential as a non-thermal, low-cost, and environmentally friendly technology capable of enhancing the bioactive profile of plant by-products. By inducing photochemical reactions, UV-C treatment may stimulate the release or synthesis of phenolic compounds and improve antioxidant capacity, offering a promising approach for upgrading date pomace into value-added ingredients for functional foods or nutraceutical applications. This work therefore seeks to evaluate UV-C irradiation as a viable strategy to enhance the nutritional and functional value of date fruit pomace within the framework of circular economy and sustainable food processing.

2. Material and methods

2.1. Chemicals and reagents

Analytical-grade chemicals were used in this study. The mobile phase and standard solution preparations employed Ultrapure water (Milli-Q® Advantage A10 Water Purification System from Millipore, Merck KGaA, Darmstadt, Germany). Pullulan samples, including Pullulan 100 (100 kDa), Pullulan 50 (50 kDa), Pullulan 20 (20 kDa) and Pullulan 10 (10 kDa) were procured from Waters (Madrid, Spain) as part of the Shodex pullulan standard P-82 kit. Additionally, Inulin (5.94 kDa), Verbascose (0.83 kDa), Stachyose (0.67 kDa), Cellotriose (0.50 kDa), Rhamnose (0.50 kDa), Glucose (0.18 kDa) and Fructose (0.18 kDa) were obtained from Sigma (Alcobendas, Madrid, Spain). Cellobiose (0.34 kDa) and Sucrose (0.34 kDa) were acquired from Merck (Darmstadt, Germany).

2.2. Plant material

Second-grade date fruits, exhibiting a relatively hard texture, belonging to an Algerian variety, namely "Degla-Beida", were sourced from the oasis of Biskra in the southern region of Algeria at the "Tamr stage", which signifies full ripeness. Subsequently, the dates underwent a series of preparatory steps: cleaning, pitting, drying at 40 °C until constant weight, was achieved, and finally, grounding into a fine powder and storing (Djaoud, Boulekbache-Makhlouf, et al., 2020) before syrup extraction.

Three methods of date syrup extraction were employed in this study as outlined by Djaoud, Boulekbache-Makhlouf, et al. (2020), (1) microwave-assisted extraction, (2) ultrasound-assisted extraction and (3) water bath extraction. After the extraction process, the generated residues (MWR: microwave residue, USR: ultrasound residue, and WBR: water bath residue) were collected, dried in an oven at 40 °C, grinded and sieved to obtain a homogeneous powder, and transported to the laboratory located in the Department of Nutrition and Food Science at Complutense University of Madrid in Spain, for further analysis.

2.3. Techno-functional properties

The techno-functional properties of date residues (MWR, USR, WSR) was assessed using the methodology outlined by Mateos-Aparicio et al. (2010). The calculations for WRC were carried out as follows:

$$\mathrm{WRC}(g/g) = (M_1\text{-}M_2)/M_1 \tag{1}$$

Similarly, the oil holding capacity (OHC) and swelling capacity (SWC) were determined according to the procedure described by Mateos-Aparicio et al. (2010). The calculations for OHC and SWC were then performed as follows:

2.3.1. Water holding capacity (WHC)

An amount of 250 mg of the dry sample (denoted as M_1) was accurately weighed and placed in a 50 mL centrifuge tube. Then, 15 mL of distilled water was added. The mixture was thoroughly shaken and left to stand at room temperature for 24 h. Following this, the sample was centrifuged at 3000 ×g for 20 min. After centrifugation, the supernatant was carefully discarded, and the hydrated residue was weighed (denoted as M_2). The water holding capacity was calculated using the following formula:

$$WHC\ (g/g) = (M_2 - M_1)/M_1 \tag{1}$$

2.3.2. Oil holding capacity (OHC)

The oil holding capacity (OHC) was determined using the same procedure as described for WHC, except that distilled water was replaced with virgin olive oil. The oil holding capacity was calculated using the following equation:

$$OHC\ (g/g) = (m_2 - m_1)/m_1 \tag{2}$$

2.3.3. Bulk density (BD)

Bulk density (BD) was determined according to the method described by Benítez et al. (2011). A 5 mL portion of the sample was placed in a graduated cylinder and tapped gently and repeatedly until a constant volume (V, in mL) was obtained. The weight of the sample (W_1, in g) was then measured, and bulk density was calculated using the following equation:

$$BD\ (mL/g) = W_1/V \tag{3}$$

2.3.4. Swelling capacity (SWC)

To determine the swelling capacity (SWC), 250 mg of the dry sample (denoted as m_1) was placed into a 10 mL graduated measuring cylinder (with 0.1 mL graduations). Then, 5 mL of distilled water was added. The mixture was gently stirred to remove any trapped air bubbles and left undisturbed at room temperature overnight to allow for complete swelling. After 24 h of hydration, the final volume occupied by the swollen sample (V, in mL) was recorded. The SWC was calculated as follows:

$$SWC\ (mL/g) = V/m_1 \quad (4)$$

2.4. Content and monomeric composition of dietary fiber fractions

Date fruit residues (MWR, WBR and USR) were analysed to determine their various dietary fiber fractions (TDF: total dietary fiber and IDF: insoluble dietary fiber) using the enzymatic-gravimetric procedure (AOAC 991.43). Briefly, 1 g of samples were incubated with heat-stable alpha amylase (100 °C, pH 6, 30 min), and then enzymatically digested with protease (60 °C, pH 7.5, 30 min), followed by incubation with amyloglucosidase (60 °C, pH 4.5, 30 min) to remove protein and starch. Then, the samples were filtered, washed (with water, 95 % ethanol and acetone), dried and weighed to determine insoluble fiber fraction (IDF). Four volumes of 95 % ethanol (preheated to 60 °C) were added to the Erlenmeyer flasks. Then, the precipitates were filtered and washed with 78 % ethanol, 95 % ethanol and acetone. After that, the residues (total dietary fiber TDF) were dried and weighed. The obtained values were corrected for ash and protein. Soluble dietary fiber (SDF) content was calculated as the difference between TDF and IDF. The gravimetric residues were hydrolysed, and the released neutral sugars transform into alditol acetates to quantify by gas liquid chromatography (GLC-FID) in a Perkin-Elmer Autosystem Chromatograph equipped with a hydrogen flame ionization detector. The column used was a SP-2330 (30 m long, 0.25 mm i.d., and 0.25 μm film thickness) and nitrogen served as carrier gas. Temperatures of injector and detector were 275 °C and oven temperature was 235 °C.

Additionally, uronic acid content in the hydrolysates was determined according to the colorimetric method of 3,5-dimethylphenol with Synergy™ HTX Multi-Mode Microplate Reader, using galacturonic acid (Merck) as standard. Dietary fiber content was calculated as the sum of both, neutral sugars and uronic acids. The results were expressed as g/100 g of dry weight (Mateos-Aparicio et al., 2010).

2.5. Treatment with UV-C light

To assess the impact of the UV-C irradiation on soluble carbohydrates, total polyphenol content (TPC) and antioxidant capacity, experiments were conducted with date residues exposed to UV-C light at a dosage of 0,18 J/cm^2. Before the UV-C exposition, the samples were placed in zip plastic bags and divided into four batches. Each batch underwent irradiation for 5, 10, 20 and 40 min at a Dosimetry Unit from Environment Department (CIEMAT). Following the treatment, the samples were stored at 4 °C for 24 h before the extraction of soluble carbohydrates and polyphenols. Subsequently, these extracts were analysed using HPLC-RID to determine soluble carbohydrate composition, HPLC-QTOFF for polyphenol profiling, and assessment of multifunctional antioxidant capacity.

2.6. Soluble carbohydrates profile

Two hundred and fifty milligrams (250 mg) of both control and UV-C light-treated samples were precisely weighed in a falcon tube and then combined with 10 mL of distilled water. The samples were dissolved through agitation for 60 min, followed by centrifugation and filtration using 0.22 mm syringe filters. Subsequently, date carbohydrates were subjected to analysis with an HPLC system (Agilent 1200 series autosampler, Agilent quaternary pump system 1100 series with online degasser, Agilent 1100 series chromatography thermostatic oven, Agilent HPLC control unit 1100 series fitted with an Agilent 1100 series Refractive Index Detector (RID), using ionic exchange column Rezex™ RSO-Oligosaccharide Ag 4 %, LC Column (200 × 10 mm), preceded by a Rezex™ RSO-Oligosaccharide Ag 4 %, LC Guard Column (60 × 10 mm) (Phenomenex®, Torrance, California, CA, USA), with an isocratic mobile phase of HPLC grade water, retained at a flow rate 1.0 mL/min. The injection volume was 0.3 μL at room temperature. All the samples were analysed in triplicate and data acquisition and analysis were performed with Agilent ChemStation from Agilent Technologies (Santa Clara, USA), including identification by RT coincidence and quantification according to peak area. The obtained results were expressed in grams per 100 g of dry weight (g/100 g DW).

2.7. Phenolic compounds profile

The high-performance liquid chromatography (Agilent Technologies, Waldbroon, Germany) combined an integrated degasser with a quaternary pump, an autosampler, and a thermostatized column compartment. This system was coupled to a diode array detector and a hybrid mass spectrometer quadrupole-time of flight *via* an electrospray ionization source (ESI) with JetStream technology (Agilent Accurate Mass QTOF LC-MS, Waldbronn, Germany). The chromatographic column used was a Zorbax Eclipse XDB C18 Agilent 150 mm × 5 μm × 4.6 mm. Gradient elution was executed using a binary system consisting of 0.1 % formic acid in water (solvent A) and 0.1 % acetonitrile in aqueous formic acid (solvent B). The following gradient was applied at a flow rate of 1 mL/min: 0 min, 95 % (A) 5 % (B); 20 min, 85 % (A) 15 % (B); 30 min, 70 % (A) 30 % (B); 35 min, 50 % (A) 50 % (B); 37 min, 95 % (A) 5 % (B). The injection volume was 10 μL, and the column temperature was 40 °C. The quantification of the phenolic compounds was performed using the calibration curve of commercial standards (Sigma, St. Louis, MO, USA), namely, chelodonic acid, vanillic acid (two different isomers), luteolin, syringic acid, trans cinamic acid, isorhamnetin hexoside, isorhamnetin hexoside rhamnoside, quercetin hexoside, luteolin rutenoside, kaempferol rutinoside, luteolin hexoside, kaempferol hexoside, quercetin derivative, catechin-epicatechin dimer, hydroxybenzoic acid, protocatechuic acid, trans p-coumaric acid, gallic acid, caffeic acid, rutin, quercetin, ferulic acid, trans ferulic acid, chlorogenic acid, catechin and cyanidin-glucoside.

2.8. Phenolic content and multifunctional antioxidant capacity

2.8.1. Extraction of polyphenols

Polyphenols were extracted using a two-step procedure adapted from Saura-Calixto (1998). A 250 mg of each sample were first treated with 2.5 mL of acidified methanol–distilled water (50:50, *v*/v, pH 2), followed by 2.5 mL of acetone–distilled water (70:30, *v*/v). The mixture was shaken at room temperature for 1 h. The resulting extracts were combined, filtered through 0.45 μm syringe filters, and stored at −20 °C until analysis.

The obtained extracts, both pre and post UV-C treatment, underwent comprehensive analysis using Folin-Ciocalteu and Fast Blue, both for TPC, and Ferric Reducing Antioxidant Power (FRAP), as well as Oxygen Radical Absorbance Capacity (ORAC) and DPPH-free radical scavenging activity for the antioxidant capacity determination. All measurements were performed, in triplicate, using a Synergy™ HTX Multi-Mode microplate reader (BioTek Instruments, Winooski, VT, USA).

2.8.2. Total phenolic content (TPC)

The Folin-Ciocalteu assay was executed following the methodology outlined by Singleton et al. (1999). Briefly, 15 μL of Folin–Ciocalteu reagent (Scharlab, S.L., Sentmenat, Barcelona, Spain) was added to 15 μL of the sample. Then, 120 μL of distilled water and 30 μL of sodium carbonate (Na_2CO_3) were added, followed by an additional 120 μL of distilled water. After incubation, absorbance was measured at 750 nm.

The Fast-Blue method was conducted in accordance with the protocol established by Medina (2011). A volume of 150 μL of the sample was mixed with 15 μL of Fast-Blue diazonium salt solution (0.1 g/100 mL) (Sigma-Aldrich Química S.A, Madrid, Spain), followed by 15 μL of NaOH solution (5 g/100 mL). After 90 min of reaction at room temperature, absorbance was measured at 420 nm. Results were expressed as milligrams of gallic acid equivalents (mg GAE) per gram of dry weight (dw).

2.8.3. Multifunctional antioxidant capacity

The FRAP assay was conducted following the method of Chen et al. (2013). A volume of 9 μL of each sample was mixed with 265 μL of freshly prepared FRAP reagent and 26 μL of distilled water. The FRAP reagent was prepared by combining 2.5 mL of 10 mmol/L TPTZ solution (Sigma-Aldrich Química S.A, Madrid, Spain), 25 mL of 0.3 mol/L acetate buffer (Scharlab, S.L., Sentmenat, Barcelona, Spain) (pH 3.6), and 2.5 mL of 0.03 mol/L ferric chloride solution (Sigma-Aldrich Química S.A, Madrid, Spain), and incubated at 37 °C. After 30 min of reaction, absorbance was measured at 595 nm. Results were expressed as millimoles of Trolox equivalents per gram of dry weight (mmol TE/g dw).

The determination of Oxygen Radical Absorbance Capacity (ORAC) followed the methodology proposed by Serra et al. (2011). Samples (12.5 μL) were added to the wells of a 96-well microplate, followed by 75 μL of disodium fluorescein. Peroxyl radicals were generated using AAPH (Sigma-Aldrich Química S.A, Madrid, Spain) as the radical initiator. Antioxidant activity was assessed based on the fluorescence decay over time. Results were expressed as micromoles of Trolox equivalents per gram of dry weight (μmol TE/g dw).

Lastly, the DPPH assessment was carried out in accordance with the procedure outlined by Karadag et al. (2009). Briefly, 20 μL of each sample was added to 280 μL of 100 μmol/L DPPH solution (Sigma-Aldrich Química S.A, Madrid, Spain). After incubation in the dark for 30 min, absorbance was measured at 517 nm. The antioxidant capacity was expressed as EC_{50}, defined as the concentration of the sample required to scavenge 50 % of DPPH radicals.

2.9. Statistical analysis

All experiments were conducted in triplicate, and results are expressed as mean ± standard deviation. Statistical analysis was performed using XLSTAT Release 10 (Addinsoft, Paris, France). One-way analysis of variance (ANOVA) was used to assess significant differences among treatments, followed by Tukey's Honest Significant Difference (HSD) post-hoc test at a confidence level of 95 % ($p < 0.05$). This approach ensured robust comparison of the means and accurate identification of statistically significant variations in the studied parameters.

3. Results and discussion

3.1. Techno-functional properties

3.1.1. Water holding capacity (WHC)

Water holding capacity (WHC) reflects the abilities of gel-forming, and thickening, relying on two mechanisms. Firstly, water binds to the hydrophilic groups of dietary fiber, including hydroxyl, carbonyl, and carboxyl groups, through polar interactions and hydrogen bonding. Secondly, the polymer strands of dietary fiber can combine in ordered assemblies (junction zones), forming a three-dimensional network wherein large amounts of water (Karim et al., 2024). Soluble dietary fibers are composed of a large number of hydrophilic groups and has a high molecular weight and branched structure, which impart this fraction high hydration capacity and viscosity (Karim et al., 2024). The WHC of date MWR was measured at 11.03 g/g, while that of WBR and USR were 10.51 and 11.46 g/g, respectively (Table 1). The observed increase in WHC after ultrasonication is likely attributed to the development of spongy structure generated by peptide chains and due to the ionized polarity groups formed after ultrasound treatment. These newly formed groups, lead to the creation of looser structures providing more space for water storage and consequently resulting in higher WHC (Knorr et al., 2004).

Table 1
Techno-functional properties of date fruit residues recovered after syrup production.

Sample	MWR	WBR	USR
Oil holding capacity (g/g)	7.31 ± 0.36^{a}	6.53 ± 0.03^{b}	6.35 ± 0.09^{b}
Water holding capacity (g/g)	11.03 ± 0.38^{a}	10.51 ± 0.36^{a}	11.46 ± 0.49^{a}
Bulk density (g/mL)	2.96 ± 0.11^{a}	2.29 ± 0.17^{b}	2.58 ± 0.12^{ab}
Swelling capacity (mL/g)	6.45 ± 0.01^{b}	6.95 ± 0.01^{b}	7.98 ± 0.01^{a}

Data are mean values ± standard deviation. Values with letters (a-b-c) were significantly different (Tukey, $p < 0.05$); MWR: microwave extraction residue; USR: ultrasound extraction residue and WBR: water bath extraction residue.

3.1.2. Oil holding capacity (OHC)

The oil holding capability (OHC) values in this investigation ranged from 6.35 to 7.31 g/g of the sample. The results revealed that MWR significantly ($p < 0.05$) had the highest OHC compared to other residues. Meanwhile, WBR demonstrated a similar OHC level to that observed in USR. MWR contained more lipophilic fraction compared to that in other treatments. Therefore, a lower level of OHC showed a higher hydrophilic fraction, potentially leading to increased water solubility. A higher OHC was indicative to enhance performance in terms of food stabilization, mouthfeel and reduced losses during food processing (Benitez et al., 2019). Therefore, a higher OHC level may contribute to improved functionality in food processing applications.

3.1.3. Bulk density (BD)

The bulk density of foods is closely related to their moisture content, as well as the structure and size of its particles. Elevated moisture levels contribute to particles stickiness, resulting in increased interspaces between particles and ultimately yielding a larger bulk volume. Bulk density reflects the 'heaviness' of a material and is often used to assess its physical stability (Jakubczyka et al., 2011). The bulk density values of date fruit residues varied significantly among samples. The highest bulk density was observed in MWR (2.96 g/mL) and the lowest in USR and WBR (2.58 and 2.29 g/mL). Low density, is particularly advantageous for the preparation of infant and complementary food as highlighted by Moriconi et al. (2024).

3.1.4. Swelling capacity (SWC)

Water absorption leads to swelling of the fiber. Natural fibers are prone to water absorption due to their chemical composition rich in cellulose, hydrophilic in nature. Water absorption of natural fiber is more likely to increase with the increase in cellulose content of the fiber due to the increase in the number of free hydroxyl groups existing in the fiber (Begum et al., 2021). In the current investigation, the swelling capacity ranged from 6.45 mL/g (lowest in MWR) to 7.98 mL/g (highest in USR). The swelling capacity allows the establishment of an enlargement rate of the particles as a result of water absorption and accumulation (Pellegrini et al., 2018). Research has affirmed a correlation between moisture content and swelling power, indicating that lower swelling power leads to increased water absorption in particles (Li et al., 2019).

3.2. Composition of dietary fiber

The processes designed for syrup extraction (microwave, ultrasound or water-bath), with the main objective of sugar recovery, also co-extract other components, such as polyphenols and dietary fiber (DF), altering the composition of the resulting residues depending on the processes used. Thus, it is clear that once the syrup is extracted, independently of the processes used, DF is concentrated in the residue, turning this residue in a source of DF (Table 2), as well the date fruit (2–17 %) is considered too (Aljutaily et al., 2022; Djaoud et al., 2024).

On the other hand, despite this overall increase in DF content, the extent and nature of the changes differ across the extraction methods. So in USR, the DF content remains relatively close to that of the whole date, both in terms of total content (date fruit: 17.1 g/100 g) and the insoluble (69.8 %) to soluble (30.2 %) fiber ratio (IDF:SDF) (Djaoud et al., 2024). It could indicate a DF extraction to the syrup remaining lesser DF cotent

Table 2
Insoluble dietary fiber (IDF), soluble dietary fiber (SDF) and total dietary fiber (TDF) of date fruit residues recovered after syrup production.

Sample	IDF (g/100 g)		
	MWR	WBR	USR
Rhamnose	0.32 ± 0.18[a]	0.18 ± 0.04[b]	0.33 ± 0.06[a]
Fucose	0.81 ± 0.03[a]	0.31 ± 0.12[b]	0.67 ± 0.11[ab]
Arabinose	7.64 ± 0.10[a]	5.02 ± 0.61[c]	6.10 ± 0.27[b]
Xylose	8.88 ± 0.10[a]	7.24 ± 0.01[b]	3.99 ± 0.19[c]
Mannose	0.62 ± 0.01[a]	0.42 ± 0.07[b]	0.35 ± 0.03[b]
Galactose	3.16 ± 0.04[a]	2.74 ± 0.03[b]	0.82 ± 0.12[c]
Glucose	1.13 ± 0.02[a]	0.56 ± 0.04[b]	0.41 ± 0.10[b]
Uronic acids	1.77 ± 0.03[a]	1.76 ± 0.08[a]	1.61 ± 0.08[a]
Total	24.31 ± 0.39[a]	18.23 ± 0.78[b]	14.28 ± 0.53[c]
Sample	SDF (g/100 g)		
	MWR	WBR	USR
Rhamnose	0.14 ± 0.03[b]	0.11 ± 0.02[b]	0.30 ± 0.11[a]
Fucose	0.23 ± 0.00[a]	0.21 ± 0.02[a]	0.25 ± 0.00[a]
Arabinose	0.73 ± 0.14[c]	1.73 ± 0.09[a]	1.17 ± 0.22[b]
Xylose	0.30 ± 0.12[c]	0.92 ± 0.45[b]	1.23 ± 0.02[a]
Mannose	0.49 ± 0.02[a]	0.31 ± 0.10[a]	0.32 ± 0.09[a]
Galactose	0.22 ± 0.09[b]	0.49 ± 0.04[a]	0.46 ± 0.13[ab]
Glucose	0.64 ± 0.06[a]	0.51 ± 0.03[a]	0.33 ± 0.13[b]
Uronic acids	2.15 ± 0.07[a]	2.10 ± 0.09[a]	0.77 ± 0.09[b]
Total	4.91 ± 0.27[b]	6.39 ± 0.80[a]	4.82 ± 0.40[b]
Sample	TDF (g/100 g)		
	MWR	WBR	USR
Rhamnose	0.49 ± 0.01[ab]	0.29 ± 0.02[b]	0.63 ± 0.09[a]
Fucose	1.04 ± 0.04[a]	0.61 ± 0.02[b]	0.91 ± 0.07[a]
Arabinose	8.37 ± 0.06[a]	6.32 ± 0.21[b]	6.95 ± 0.37[b]
Xylose	9.17 ± 0.11[a]	8.16 ± 0.45[b]	5.05 ± 0.18[c]
Mannose	1.11 ± 0.03[a]	0.71 ± 0.04[b]	0.67 ± 0.26[b]
Galactose	3.38 ± 0.08[a]	3.24 ± 0.02[a]	1.28 ± 0.02[b]
Glucose	1.76 ± 0.05[a]	1.05 ± 0.04[b]	0.74 ± 0.04[c]
Uronic acids	3.91 ± 0.19[a]	3.87 ± 0.13[a]	2.38 ± 0.11[b]
Total	29.23 ± 0.15[a]	24.26 ± 0.68[b]	18.62 ± 0.42[c]
IDF/SDF	4.95	2.85	2.96

Data are mean values ± standard deviation; Values with letters (a-b-c-d) were significantly different (Tukey, $p < 0.05$); MWR: microwave extraction residue; USR: ultrasound extraction residue and WBR: water bath extraction residue.

in the USR compared with the residues from the other extraction methods. Thus, US extracted more DF than the others methods to the syrup but maintain similar DF proportions in USR as date fruit. Moreover, US extraction achieved an IDF/SDF ratio of 2.96, the closest to the nutritionally recommended ratio 3:1. Regarding WBR, the proportion IDF:SDF is quite similar to USR and in extension to the whole date (Djaoud et al., 2024). However, the DF content of WBR is higher than USR and date fruit meaning few DF extraction to syrup. Last, microwave extraction is the technique less efficient extracting DF, and thus, MWR presented the greatest DF content, richer in insoluble (83.3 %) than soluble (16.7 %) fiber, and diferent to the composition of the other residues and date fruit. Consequently, this process modifies the DF composition of the remaining residue by extracting SDF into the syrup, thereby concentrating IDF in the residue, and yielded a higher IDF/SDF ratio of 4.95. While the USR method appears optimal for maintaining a balanced fiber profile in the residue, the date syrup yield and phenolic compound recovery were lower than the other extraction methods as described in previous research (Djaoud, Arkoub-Djermoune, et al., 2020; Djaoud, Daglia, et al., 2020).

The analysis of sugar monomers across the fiber fractions (SDF, IDF, TDF) reveals that the extraction processes selectively affect specific polysaccharide components. Microwave-assisted extraction retained the highest amounts of most sugars in both IDF and TDF, particularly for arabinose, xylose, galactose, and glucose. Water-bath extraction showed intermediate retention, while ultrasound-assisted extraction had the lowest retention, except for rhamnose. In SDF, WBR retained more arabinose and galactose, USR retained more xylose, and MWR retained more glucose and mannose. These differences in sugar retention among extraction methods suggest varying impacts on the polysaccharide structures and potential functional properties of the resulting dietary fiber residues. Indeed, in the original date fruit, the SDF fraction consist of rhamnogalacturonan backbone substituted by arabinans and IDF is rich in arabinoxylans and other hemicelluloses (Djaoud et al., 2024). These polysaccharides are partially extracted into the syrup, with a notable transfer of rhamnose-rich pectins found in both IDF and SDF. It is also remarkable the increased content of arabinose and xylose in the reidues, mainly in MWR, indicating that the processes used for syrup extraction, especially microwave, cannot extract arabinoxylans to the syrup remaining in the residues. Therefore, the extraction processes and their conditions not only influence the total amount of DF retained in residues but also its monomer composition. Indeed, the higher SDF content observed in WBR can be attributed to the milder thermal conditions of this technique, which may promote partial solubilization and mild hydrolysis of pectic substances and hemicelluloses without extensive degradation. As a result, a greater portion of these soluble fibers remains unextracted in the solid residue (Vilcapoma et al., 2023). In contrast, microwave-assisted extraction, characterized by rapid and localized heating, can enhance the solubilization and breakdown of soluble fiber components (Wang et al., 2025), thereby increasing their transfer into the syrup and decreasing their concentration in the residue. These differences underline the importance of selecting appropriate extraction parameters to design the dietary fiber profile of date fruit residues and to optimize their functional and nutritional applications.

3.3. Carbohydrate content

The effect of UV-C treatment on soluble carbohydrate content of date fruit residues (MWR, USR and WBR) for various exposure durations (5, 10, 20 and 40 min) was determined, using high performance liquid chromatography (HPLC) by means of a refractive index detector (RID). Data in Tables 3 reflect triplicate analysis of sugar profiles. Additionally, Fig. 1 shows the graphical representation of typical chromatographic profiles of sugars in each sample. The total carbohydrate contents of date residues mainly consisted of the amounts derived from peaks 6, 7 and 8 detected between 34 and 46 min of retention time identified as saccharose, glucose and fructose, respectively. The UV-C treatment maintained the concentrations of the peaks for each residue type. The mean comparison of the data showed that UV-C irradiation does not have a significant effect on total carbohydrate content. The highest carbohydrate content was obtained in WBR (50.23 g/100 g) followed by MWR (44.43 g/100 g), respectively, and the lowest concentration was obtained in USR (34.32 g/100 g). The impact of UV-C irradiation on the soluble carbohydrate profile was mainly observed as a decrease in the content of medium molecular weight carbohydrates (peak 4) and a corresponding increase in the trisaccharide's content (peak 5), suggesting partial depolymerization of larger saccharide chains.

UV-C irradiation generates direct photochemical reactions, which depend on the wavelength of the adopted light for that will determine the photon's energy and the wavelength of light that the molecule in question will be able to absorb. Once the photon has been absorbed, the molecule enters an excited state and undergoes a photochemical change during, which it may dissociate into radicals, may isomerize, dimerize, or form ions. Carbohydrates are not particularly sensitive to light, but some carbohydrate derivatives, such as sugar alcohols or acids, can be sensitive to light, and upon its absorption the fragmentation of polysaccharides could take place, thus changing, for instance, the properties of fruits and vegetables (János Csapó, Albert, et al., 2019). In any case, limited research has been carried out on the effect of UV-C treatment on plant carbohydrates.

These findings align with studies on UV-C treated "Hongyu" apples (Onik et al., 2019) and apple juice (Xiang et al., 2020), where carbohydrate levels remained largely unchanged after irradiation. Indeed, Djaoud et al. (2024), showed that UV-C technology changes minimally the total water-soluble carbohydrate content in Degla-Beida date fruit, although slightly increased high molecular weight polysaccharides with

Table 3
HPLC-RID analysis of water-soluble carbohydrates from untreated and treated date fruit residues recovered after syrup production during 5, 20, 30, and 40 min of irradiation with UV-C light.

Microwave extraction residue (MWR)												
Peak	Standards		Untreated		5 min		10 min		20 min		40 min	
N°	Mw (kDa)	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)
Peak 1	100	11.90–12.30	0.57 ± 0.07^{b}	12.27	0.59 ± 0.08^{b}	12.03	0.84 ± 0.10^{a}	12.18	0.96 ± 0.09^{a}	12.16	0.88 ± 0.06^{a}	12.11
Peak 2	100	14.50–14.60	2.13 ± 0.00^{a}	14.54	2.14 ± 0.10^{a}	14.48	2.15 ± 0.09^{a}	14.47	2.12 ± 0.03^{a}	14.45	2.13 ± 0.06^{a}	14.44
Peak 3	20	15.10–15.30	0.52 ± 0.04^{a}	15.20	0.55 ± 0.02^{a}	15.20	0.63 ± 0.10^{a}	15.21	0.61 ± 0.05^{a}	15.15	0.67 ± 0.07^{a}	15.14
Peak 4	20	15.80–15.90	1.12 ± 0.04^{a}	15.83	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd
Peak 5	0.50	28.90–29.10	0.30 ± 0.02^{b}	29.12	0.66 ± 0.05^{a}	29.08	0.59 ± 0.12^{a}	29.08	0.47 ± 0.05^{ab}	29.06	0.44 ± 0.04^{ab}	29.09
Peak 6	0.34	34.30	16.87 ± 0.08^{c}	34.33	18.48 ± 0.09^{a}	34.29	18.23 ± 0.23^{a}	34.25	18.36 ± 0.12^{a}	34.23	17.86 ± 0.07^{b}	34.28
Peak 7	0.18	41.90	11.17 ± 0.07^{a}	41.96	9.95 ± 0.04^{b}	41.94	9.82 ± 0.21^{b}	41.92	10.53 ± 0.09^{ab}	41.90	9.74 ± 0.01^{b}	41.95
Peak 8	0.18	45.20–45.40	11.98 ± 0.06^{a}	45.48	11.54 ± 0.22^{ab}	45.45	11.34 ± 0.28^{ab}	45.43	11.38 ± 0.12^{ab}	45.40	11.04 ± 0.02^{b}	45.45
Total			42.66 ± 0.13^{c}		43.59 ± 0.35^{ab}		43.78 ± 0.07^{ab}		44.43 ± 0.00^{a}		42.76 ± 0.11^{c}	
Water bath extraction residue (WBR)												
Peak	Standards		Untreated		5 min		10 min		20 min		40 min	
N°	Mw (kDa)	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)
Peak 1	100	11.90–12.30	0.68 ± 0.08^{a}	12.35	0.74 ± 0.09^{a}	12.07	0.80 ± 0.10^{a}	12.06	0.67 ± 0.11^{a}	12.07	0.89 ± 0.05^{a}	12.09
Peak 2	100	14.50–14.60	2.35 ± 0.06^{a}	14.60	2.42 ± 0.02^{a}	14.49	2.33 ± 0.11^{a}	14.50	2.30 ± 0.09^{a}	14.51	2.55 ± 0.07^{a}	14.53
Peak 3	20	15.10–15.30	0.52 ± 0.05^{a}	15.26	0.68 ± 0.03^{a}	15.24	0.63 ± 0.04^{a}	15.20	0.56 ± 0.06^{a}	15.21	0.72 ± 0.07^{a}	15.25
Peak 4	20	15.80–15.90	1.08 ± 0.07^{a}	15.82	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd
Peak 5	0.50	28.90–29.10	0.38 ± 0.02^{b}	29.12	0.75 ± 0.02^{a}	29.06	0.65 ± 0.09^{ab}	29.09	0.57 ± 0.07^{ab}	29.10	0.58 ± 0.07^{ab}	29.10
Peak 6	0.34	34.30	17.53 ± 0.07^{b}	34.31	19.06 ± 0.12^{a}	34.22	18.79 ± 0.01^{a}	34.27	19.78 ± 0.49^{a}	34.24	18.84 ± 0.16^{a}	34.29
Peak 7	0.18	41.90	11.48 ± 0.07^{b}	41.94	11.97 ± 0.15^{ab}	41.88	11.97 ± 0.21^{ab}	41.94	12.54 ± 0.26^{a}	41.91	11.91 ± 0.18^{ab}	41.96
Peak 8	0.18	45.20–45.40	13.55 ± 0.08^{a}	45.46	13.85 ± 0.22^{a}	45.37	13.60 ± 0.25^{a}	45.44	13.61 ± 0.30^{a}	45.41	13.58 ± 0.27^{a}	45.47
Total			47.57 ± 0.24^{c}		49.09 ± 0.07^{b}		49.33 ± 0.12^{b}		50.23 ± 0.19^{a}		48.78 ± 0.16^{c}	
Ultrasound extraction residue (USR)												
Peak	Standards		Untreated		5 min		10 min		20 min		40 min	
N°	Mw (kDa)	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)	g/100 g	RT (min)
Peak 1	100	11.90–12.30	0.27 ± 0.06^{b}	11.96	0.33 ± 0.05^{ab}	12.09	0.45 ± 0.03^{ab}	12.00	0.58 ± 0.18^{a}	12.04	0.41 ± 0.03^{ab}	12.09
Peak 2	100	14.50–14.60	2.45 ± 0.05^{a}	14.63	2.33 ± 0.02^{a}	14.49	2.41 ± 0.05^{a}	14.53	2.56 ± 0.13^{a}	14.51	2.24 ± 0.03^{a}	14.53
Peak 3	20	15.10–15.30	0.51 ± 0.04^{a}	15.11	0.59 ± 0.03^{a}	14.99	0.58 ± 0.02^{a}	14.97	0.69 ± 0.14^{a}	14.93	0.48 ± 0.01^{a}	15.25
Peak 4	20	15.80–15.90	0.05 ± 0.04^{a}	15.82	Nd	Nd	Nd	Nd	Nd	Nd	Nd	Nd
Peak 5	0.50	28.90–30.00	0.11 ± 0.03^{b}	29.12	0.32 ± 0.02^{a}	29.68–30.01	0.29 ± 0.01^{a}	29.05–29.56	0.11 ± 0.03^{b}	29.13	0.13 ± 0.02^{b}	29.12
Peak 6	0.34	34.30	Nd	Nd	0.15 ± 0.01^{a}	34.24	0.12 ± 0.02^{c}	34.29	Nd	Nd	Nd	34.30
Peak 7	0.18	41.90	13.48 ± 0.08^{a}	41.96	13.01 ± 0.05^{ab}	41.86	13.07 ± 0.04^{ab}	41.90	13.35 ± 0.02^{a}	41.92	12.76 ± 0.07^{b}	41.97
Peak 8	0.18	45.20–45.40	16.61 ± 0.07^{ab}	45.49	16.94 ± 0.20^{a}	45.38	16.83 ± 0.20^{a}	45.41	17.03 ± 0.10^{a}	45.43	16.29 ± 0.07^{b}	45.48
Total			**33.43 ± 0.25^{ab}**		**33.61 ± 0.20^{ab}**		**33.63 ± 0.18^{ab}**		**34.32 ± 0.30^{a}**		**32.32 ± 0.18^{c}**	

Data are mean values ± standard deviation; Values with letters (a-b-c-d) were significantly different (Tukey, $p < 0.05$); RT: Retention time; Nd: Not detected; Peaks 1–8 were estimated as polysaccharides or high molecular weight carbohydrates (HMWC). Peaks 9–13 were estimated as oligosaccharides and simple sugars or low molecular weight carbohydrates (LMWC).

irradiation time (IT) up to 20 min, and some oligosaccharides with irradiation time up to 5 min. However, these results differ from research on UV-C treated sweet oranges (Hu et al., 2019), and *Aloe Vera* gel (Rodríguez-Rodríguez et al., 2019), which reported significant increases in total carbohydrates. Conversely, studies on waste grape berries (K. Zhang et al., 2021) and Egyptian Henbane (*Hyoscyamus muticus* L.) (Aboseidah et al., 2019) observed decreases in total carbohydrate content following UV-C treatment compared to control.

3.4. *Phenolic compounds profile*

We aimed to assess how UV-C irradiation time affects phenolic

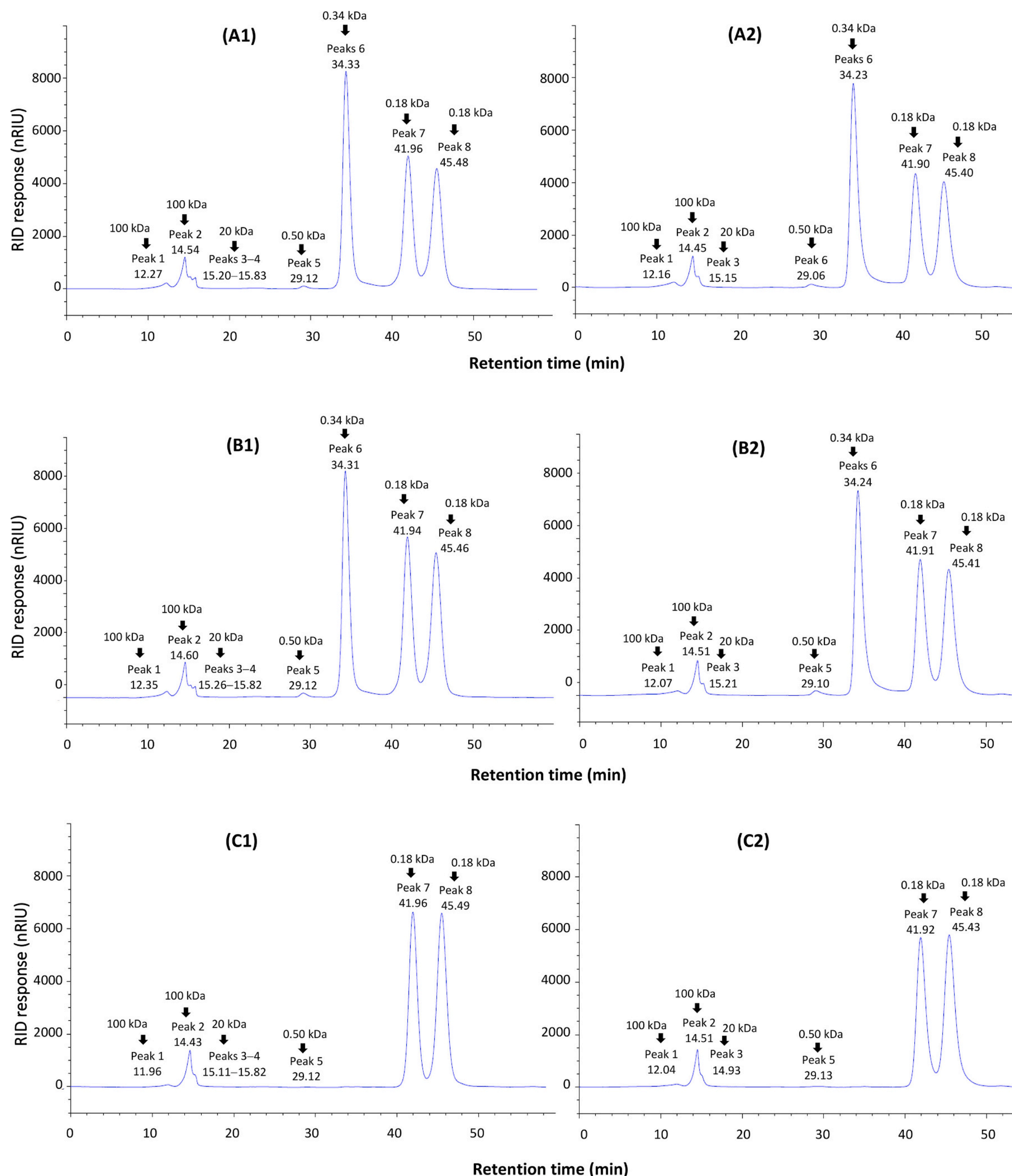

Fig. 1. HPLC-RID analysis of water-soluble carbohydrates from untreated and treated date fruit residues from syrup production with UV-C irradiation (A1: untreated MWR, A2: treated WBR, B1: untreated WBR, B2: treated WBR, and C1: untreated USR, C2: treated US) during 20 min of irradiation with UV-C light.

content of date residues, by conducting the HPLC-QTOF analysis (Fig. 2). The UV-C treatment was applied directly to the solid residues prior to phenolic extraction, aiming to evaluate how different exposure times influence the retention and formation of phenolic compounds within the matrix. The identified compounds were chelidonic acid, vanillic acid, vanillic acid isomer, p-coumaric acid, rutine, catechin, epicatechin, hydroxybenzoic acid, quercetin hexoside, derived quercetin and dimer catequin-epicatequin, respectively. Notably, significant variations emerged among the different irradiation times in all the samples. Specifically, the residues treated for 20 min exhibited the highest amount of phenolic compounds (MWR, followed by WBR, then USR) compared to the other exposure times. These findings suggest that a correlation exists between the identified polyphenols and irradiation time from 5 to 20 min. At 40 min, a substantial reduction in main polyphenols content was observed. The efficiency of UV-C light treatment in the enhancement of phenolic compounds profile of common Degla-Beida date variety was elucidated in our previous work (Djaoud et al., 2024) in the same sense, reaching the maximum polyphenolic content at 20 min and to decrease in those submitted to 40 min. Interestingly, the profile of polyphenols detected in UV-C treated residues shows both similarities and differences compared to the untreated date fruit, as reported in previous studies. Untreated date fruits, especially the Degla-Beida variety, are typically rich in phenolic acids such as gallic, ferulic, p-coumaric, and caffeic acids, and flavonoids including quercetin hexoside, rutin, isoquercetin hexoside, quercetin, and luteolin (Benmeddour et al., 2013). Other studies also commonly report 3,4-dihydroxybenzoic acid, vanillic acid, catechin, syringic acid, and chlorogenic acid (Airouyuwa et al., 2023; Bouhlali et al., 2020). In

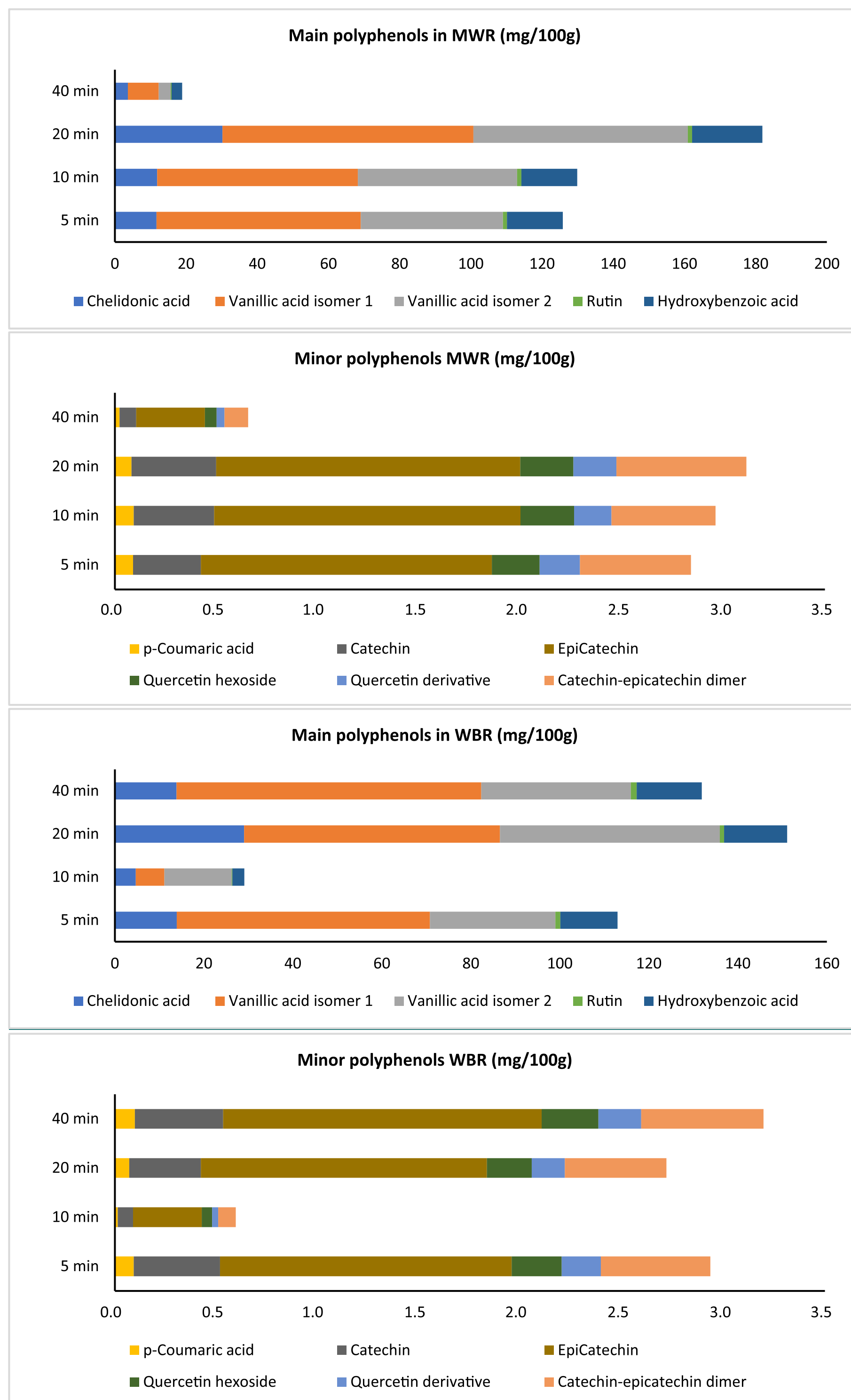

Fig. 2. Main and minor polyphenols from date fruit residues (MWR, WBR and USR), treated with UV-C irradiation for 5, 10, 20, and 40 min.

contrast, our analysis of UV-C treated pomace residues revealed the presence of compounds such as chelidonic acid and catechin-epicatechin dimers, which are less commonly reported in the fruit matrix itself, suggesting either the formation of novel compounds or a differential retention in the fibrous matrix of the residues. These differences highlight the potential of UV-C treatment to induce not only the degradation but also the transformation or synthesis of new phenolic derivatives.

Sonntag et al. (2023) affirms that UV radiation has an enhancing effect on the phenolic compounds, especially UV-C leads to the accumulation of various phenolics. Some authors suggest that the production of flavonoids under the stress of UV light is mainly carried out by plants to counteract the generation of reactive oxygen species (ROS) (Agati et al., 2011; Fini et al., 2011). A review by Urban et al. (2016), summarized that UV-C light induces phenylalanine ammonia lyase activity at the post-transcriptional level, along with various enzymes of the phenolic biosynthetic pathway, depending on the species and variety.

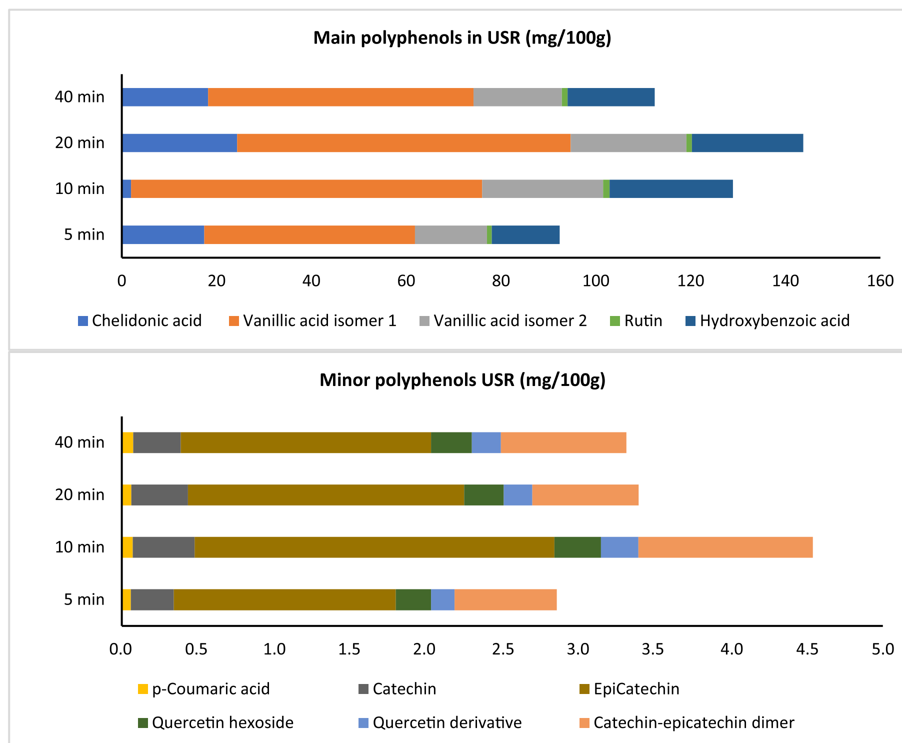

Fig. 2. (*continued*).

3.5. Phenolic content and multifunctional antioxidant capacity

Ultraviolet-C (UV-C), a short-wave ultraviolet light, has been extensively proved to regulate reactive oxygen species (ROS) homeostasis and increase antioxidant capacity in fruit and vegetables (Zhang et al., 2023). However, whether UV-C may regulate ROS homeostasis and antioxidant capacity at residues from date syrup production has not been reported. The total phenolic content measured by both, Folin-Ciocalteu and Fast Blue increased for all samples after UV-C radiation as compared to the untreated residues (Table 4). Furthermore, it was possible to observe that the phenolic content, measured by both methodologies, was greater in the UV-C radiated residues as compared to UV-C date fruit treated samples previously reported (Djaoud et al., 2024). The highest data for phenolic content was determined in USR samples and the raise was greater for date fruit residues after 40 min of treatment. Similar patterns (longer exposure to UV-C radiation- higher phenolic content) was observed for all treated samples. This phenomenon is in accordance with Bravo et al. (2012) for UV-C radiation in breaker tomatoes, were greater times of exposure to the treatment resulted in higher phenolic content. Results may be related to the activation of the phenolic biosynthesis pathway caused by stress induction and the accumulation of phenolic compounds in the fruit.

Regarding the antioxidant capacity of the samples measured by FRAP and ORAC, UV-C treatment initially led to a decrease, followed by an increase after 40 min of exposure. Specifically, FRAP values showed a significant ($p < 0.05$) at the longest treatment duration, indicating the highest antioxidant capacity. While for ORAC values remained relatively stable throughout the treatment, reflecting a preservation of antioxidant potential. Different studies showed that the antioxidant capacity may decrease depending on the dose of UV-C radiation applied, as observed in grape juices (Pinto et al., 2022), pitaya (Ochoa-Velasco & Guerrero-Beltrán, 2012), apple juices (Caminiti et al., 2012) and date fruit ((Djaoud et al., 2024)) after UV-C exposure. The reduction in antioxidant capacity could be due to the reaction of the antioxidant compounds with the reactive oxygen species (ROS) produced by the UV stress (Maharaj et al., 2014) and similarly, Gonzalez-Aguilar et al. (2010) described that UV-C interacts with atoms and molecules producing ROS and then activating the mechanism of antioxidant enzymes. The increase in the antioxidant capacity could be attributed to the synthesis of some compounds, such as phenols, flavonoids, or other non-phenolic compounds, such as enzymes, since previous studies have found that antioxidant enzymes are still active in dried plant tissues (Muflihah et al., 2021). Indeed, UV irradiation results in the formation of reactive oxygen species, since it is an abiotic stress for plant tissues.

EC50 from DPPH antioxidant capacity resulted higher in MWR, WBR and USR residues after the application of UV-C as compared to untreated ones. These results are in accordance with previously reported for the UV-C-treated date samples, in which it was possible to observe a decrease of the scavenging activity after the application of UV-C light on date fruit (Djaoud et al., 2024). On the other hand, the EC50 is lower in the UVC-treated residues compared to the UVC-treated date (Djaoud et al., 2024).

The relationship between the polyphenol profile and the antioxidant activity in date syrup residues reveals a complex interaction, particularly regarding the unexpected increase in antioxidant capacity at 40 min of UV-C treatment compared to 5, 10 and 20 min of exposure, despite a reduction in polyphenol content during this period. This apparent discrepancy could be explained by several factors. Prolonged UV-C exposure might trigger the synthesis of non-phenolic antioxidant compounds or induce structural modifications in existing polyphenols, enhancing their antioxidant capacity without increasing their quantity. Additionally, the remaining polyphenols and newly formed compounds could interact synergistically, leading to a higher overall antioxidant capacity. The enhancement in antioxidant capacity observed at 40 min could potentially be attributed to a hormetic effect induced by UV-C irradiation, where initial stress leads to adaptive mechanisms that enhance overall antioxidant capacity through non-phenolic pathways. Similar observations have been made in previous studies on dates, where antioxidant capacity did not always; directly correlate with polyphenol content, underscoring the complex nature of antioxidant systems in plant tissues (Djaoud et al., 2024; Majid et al., 2023; Ouamnina et al., 2024;).

Table 4
Total polyphenol content and multi-antioxidant capacity of date fruit residues recovered after syrup production untreated and after 5, 10, 20 and 40 min of irradiation with UV-C light.

Sample	Fast-Blue (mg GA/g DW)	Folin (mg GA/g DW)	FRAP (mg TE/g DW)	ORAC (μmol TE/g DW)	DPPH EC_{50} (mg/mL)
Microwave extraction residue (MWR)					
Untreated	96.91 ± 1.23^{bc}	17.25 ± 0.39^{d}	173.98 ± 0.77^{b}	69.43 ± 12.77^{a}	17.14 ± 0.09^{d}
5 min	115.06 ± 0.70^{ab}	21.23 ± 1.95^{b}	156.82 ± 0.36^{c}	68.72 ± 13.31^{a}	34.25 ± 0.60^{c}
10 min	103.58 ± 2.27^{b}	19.53 ± 1.38^{c}	146.90 ± 1.85^{d}	66.80 ± 5.23^{ab}	36.99 ± 0.55^{b}
20 min	92.84 ± 1.75^{c}	19.72 ± 2.87^{c}	136.25 ± 2.19^{e}	64.25 ± 1.48^{b}	38.67 ± 0.05^{a}
40 min	118.52 ± 3.14^{a}	24.97 ± 0.27^{a}	178.05 ± 1.11^{a}	69.62 ± 14.15^{a}	34.22 ± 0.02^{c}
Water bath extraction residue (WBR)					
Untreated	114.50 ± 1.38^{d}	20.70 ± 0.19^{d}	200.76 ± 2.73^{a}	78.89 ± 12.90^{a}	14.00 ± 0.27^{c}
5 min	141.11 ± 2.27^{a}	25.94 ± 0.04^{b}	184.12 ± 0.61^{b}	75.39 ± 15.57^{a}	30.74 ± 0.26^{b}
10 min	133.21 ± 0.52^{b}	24.48 ± 0.04^{c}	158.17 ± 2.19^{c}	74.50 ± 7.48^{ab}	35.00 ± 0.04^{a}
20 min	125.19 ± 2.44^{c}	23.23 ± 0.04^{c}	152.22 ± 2.50^{d}	71.02 ± 7.50^{b}	35.50 ± 1.71^{a}
40 min	142.47 ± 1.67^{a}	28.48 ± 0.34^{a}	197.34 ± 2.15^{a}	78.59 ± 14.25^{a}	30.88 ± 0.13^{b}
Ultrasound extraction residue (USR)					
Untreated	116.91 ± 1.33^{e}	21.81 ± 0.20^{c}	204.35 ± 2.08^{a}	82.72 ± 12.78^{a}	13.66 ± 0.12^{c}
5 min	157.04 ± 1.40^{b}	26.05 ± 1.57^{b}	193.02 ± 0.73^{b}	78.72 ± 16.00^{a}	29.72 ± 0.07^{b}
10 min	148.77 ± 1.22^{c}	25.56 ± 0.04^{b}	162.58 ± 2.19^{c}	76.15 ± 8.23^{ab}	34.49 ± 0.11^{a}
20 min	145.06 ± 3.32^{d}	25.48 ± 0.54^{b}	158.63 ± 1.21^{d}	73.69 ± 7.54^{b}	34.58 ± 0.32^{a}
40 min	161.07 ± 2.31^{a}	29.56 ± 0.57^{a}	203.80 ± 2.82^{a}	80.91 ± 15.09^{a}	29.70 ± 0.44^{b}

Data are mean values ± standard deviation. Values with letters (a-b-c-d) were significantly different (Tukey, $p < 0.05$).

4. Conclusion

This study offers novel insights into the valorisation of date fruit pomace—a traditionally underutilized by-product of syrup production—by demonstrating how green extraction methods for date syrup, combined with UV-C irradiation of the resulting pomace, can significantly enhance its nutritional and functional properties.

Three extraction methods—microwave (MW), water-bath (WB), and ultrasound (US)—produced residues (MWR, WBR, and USR, respectively) with comparable techno-functional characteristics. Notably, MWR exhibited the highest oil-holding capacity, while USR showed superior swelling capacity. However, the dietary fiber composition varied among the residues, with microwave-assisted extraction yielding the highest total dietary fiber content, particularly in the insoluble fraction, and being the water bath extraction residue the richest in soluble fiber.

Subsequent UV-C irradiation of the MWR, WBR, and USR affected the profile of soluble carbohydrates, decreasing medium molecular weight carbohydrates while increasing trisaccharide content. This suggests that UV-C treatment may induce partial depolymerization of higher molecular weight carbohydrate chains, possibly through the disruption of glycosidic bonds induced by photochemical reactions. Remarkably, a 40-min UV-C treatment enhanced total phenolic content and ferric reducing antioxidant power (FRAP), while preserving oxygen radical absorbance capacity (ORAC), despite a reduction in both major and minor polyphenols, in certain residues, as determined by HPLC-QTOF analysis. This suggests that UV-C irradiation may either induce the formation of non-phenolic antioxidant compounds or trigger structural modifications in existing polyphenols, thereby increasing their antioxidant capacity without elevating their concentration. Moreover, residual polyphenols and newly formed compounds may act synergistically, further enhancing the overall antioxidant potential.

In summary, these findings underscore the potential of date pomace as a valuable source of dietary fiber and support the use of UV-C treatment as an effective strategy for upgrading plant-based residues. The novelty of this work lies in its integrated approach, combining a comparative analysis of residues from different green extraction methods with the application of UV-C irradiation to enhance their value. Future research will focus on incorporating UV-C-treated date pomace into food formulations, contributing to sustainable, commercial-scale applications in line with circular economy principles.

CRediT authorship contribution statement

Kahina Djaoud: Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Rocío De la Peña-Armada:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Alejandra García-Alonso:** Writing – review & editing, Validation, Data curation. **Virgilio Correcher:** Writing – review & editing, Validation, Methodology, Investigation. **María Luisa Pérez-Rodríguez:** Visualization, Validation, Methodology. **Lila Boulekbache-Makhlouf:** Visualization, Validation, Supervision. **Inmaculada Mateos-Aparicio:** Writing – review & editing, Validation, Supervision, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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