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Date Fruits and Derivatives for Almond Beverage Fortification: Assessment of Beverages and Generated Residues

Running head: Dates Improved Almond Beverages and Residue Properties

Malek Ben Zid[1], Nesrine Rokbeni[1], Nouha M'hiri[1], Moncef Chouaibi[2], Nahla Zghonda[3] and Nourhene Boudhrioua[1*]

[1]Laboratory of Pathophysiology, Food, and Biomolecules, LR17ES03, Higher Institute of Biotechnology of Sidi Thabet, University of Manouba, Ariana 2020, Tunisia
[2]Laboratory of Innovation and Valorization for a Sustainable Food Industry, Higher School of Food Industries of Tunis, Tunisia
[3]Boudjebel VACPA, Km 2 Route de Menzel Bouzelfa, C42, Béni Khalled 8021, Nabeul, Tunisia

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SUMMARY

Research background. The shift towards plant-based beverages, in particular almond drinks, heightened the need for the development of innovative products using fruits and herbal extracts to improve their nutritional and sensory properties. In this study, date palm fruits, Deglet Nour (Tamr stage), Besser Helou (Khalal stage), and two Deglet Nour-derived products (date powder and syrup), were assessed as fortifying ingredients in almond drinks. The antioxidant and nutritional properties of recovered solid residues were also assessed.

*Corresponding author:
Phone: +21658958375
Fax: +21671537044
E-mail: nourhene.boudhrioua@isbst.uma.tn

Experimental approach. The beverage-making process involved grinding blanched almonds into flour (12 % *m*/*m*), mixing with date products (20 % *m*/*m*), water extraction, filtration, and pasteurization. The raw ingredients, beverages, and recovered residues were analyzed for proximate composition, physicochemical properties, phenolic profiles (LC-ES–MS), and antioxidant activity using DPPH and FRAP assays. In addition, beverages were evaluated for their physical stability, rheological behavior, and their sensory attributes were assessed using descriptive analysis and acceptability tests.

Results and conclusions. The addition of date-based ingredients to almonds significantly reduced the extraction yields of beverages, with the reduction being less significant in syrup, moderate in Deglet Nour and Besser Helou, and more significant in date powder. Combining almonds with any form of dates not only significantly increased carbohydrates, ash contents and energetic values of beverages, but also their antioxidant activity, as confirmed by both FRAP and DPPH assays. Phenolics previously present in almonds and dates have been found multiplying, while new ones appeared in both drinks and residues, such as caffeic acid. A distinctive rheological profile was observed in fortified beverages with Deglet Nour, date syrup and date powder, characterized by shear thickening at low shear rates and a transition to shear thinning at higher shear rates. Sensory evaluations of enriched drinks revealed that dates provided new color shades, increased sweetness and mouthfeel viscosity, and improved almond taste perception. Date powder-based drinks had the highest overall acceptability rating, while syrup-based drinks had the lowest. Combining date ingredients with almonds reduced fat and protein content of residues while increasing carbohydrates. Quinic acid and quercetin were prevalent phenolic acids and flavonoids in almond residue, while caffeic acid and luteolin were primary compounds in date-based ones.

Novelty and scientific contribution. This study provides the first comprehensive evaluation of the nutritional, rheological, antioxidant, and sensory properties of almond beverages fortified with date-based ingredients. The nutritional and antioxidant properties of raw ingredients and residues produced were also assessed. It suggested that additional phenolics may be generated in fortified almond drinks during processing and showed that the generated date residue which were as relevant as potent dietary supplements.

Keywords: beverages; residues; almonds; date fruits; phenolics; rheological behavior; sensory properties

INTRODUCTION

Research and innovation in food science and technology have witnessed a major shift towards plant-based diets, which are becoming increasingly recommended not only for their health benefits, but also for their sustainability and minimal environmental impact [*1*]. This change in dietary pattern has led to a rapid growth of the global market of plant-based foods, with alternative dairy beverages accounting for the largest share. This category is overshadowed by the segment of almond milk, which is expected to continue growing in the coming years due to the increasing consumer preference for soy and gluten-free products [*2*].

To keep pace with this expected growth, recent studies have focused on developing new enriched beverages based on combining almond milk with other natural functional ingredients. Some of these studies have looked at the effect of almond milk on the bioaccessibility of bioactive compounds that derive from added ingredients such as curcumin [*3*], cranberry bush juice [*4*] and rosehip infusion [*5*]. Other researches have rather considered the effect of the used ingredients on the nutritional and/or functional properties of final products. For instance, a multivitamin supplement for the elderly has been developed by enriching almond milk with a mixture of tempeh milk and vegetable extracts (moringa leaf, beetroot and broccoli). This beverage has been found to provide 100 and 95.25 % of the Recommended Daily Allowances for vitamin E (0.65 mg/100 mL) and B9 (381.60 mg/100 mL), respectively [*6*]. Otherwise, fortifying almond milk with one of the following mixtures (carrot juice, honey and stevia), (carrot juice, powder of quinoa seeds, honey and stevia) or (banana juice, oat powder, honey and stevia), appears to have beneficial effects for preventing metabolic syndrome and the associated hepatic and vascular complications in high-fat high-fructose diet rats [*7*]. Overall, there seems to be quite strong evidence that adding functional ingredients to almonds improved the nutritional and antioxidant properties of beverages. However, the effects of such ingredients on the sensory profile of final products, as well as the properties of residues that are generated after beverage making, have not been addressed.

This study will therefore focus on these aspects of evaluating date palm fruits (*Phoenix dactylifera*) as new ingredients for the production of innovative almond-based drinks. These fruits have been selected for their nutritional value and versatility. Indeed, dates, or nature's candies as they are called, are composed of digestible sugars, mainly glucose, fructose and sucrose, providing quick and high energy [*8*]. They are a rich source of dietary fiber (cellulose, hemicelluloses, pectin, hydrocolloids and lignin) and essential minerals (potassium, calcium, magnesium, phosphorus, sodium, iron, copper, fluorine, sulfur, boron, selenium and zinc) [*9*]. They also have a rich pool of bioactive compounds, including carotenoids, phytosterols and phytoestrogens, flavonoids and phenolic acids [*10*].

These compounds, together with dietary fiber, have been associated with a wide array of health-related properties such as antioxidant, prebiotic, antimicrobial, antimutagenic, anti-inflammatory, antitoxic, antihyperlipidemic, anticancer and gastro-, hepato- and nephron-protective activities [*9*]. Date chemical composition and sensory traits are influenced, among other factors, by variety, ripening stages and processing methods. Depending on the variety, dates can be consumed at three different stages of maturation: Khalal or Besser (50 % moisture, crisp texture, hard surface, bright or red color), Rutab (30–35 % moisture, partially brown color) and Tamr (10–30 % moisture, soft to hard texture, amber to dark brown color) [*11,12*]. Only varieties with a low tannin content are suitable for consumption at Besser stage [*13*]. Considering the above, two types of Tunisian dates, Deglet Nour and Besser Helou, commonly consumed at two different stages of maturity, Tamr and Besser respectively, as well as two processed forms, powder and syrup are evaluated in the present work. The selection of these varieties is justified by the fact that Deglet Nour is the main exported variety, known for its long-term conservation at cold temperature and year-round availability [*14*]. As for Besser Helou, it is a traditional variety known for its sweetness and astringency, is yet to be valued as processed fruit. Scanty information is available on its nutritional and antioxidant properties at the Besser stage (Khalal).

The main aims of this work are: (i) to use date palm fruit and its derivatives (Deglet Nour, Besser Helou, date powder and syrup) to develop innovative fortified almond-based beverages, (*ii*) to investigate the nutritional, physicochemical, physical stability, rheology profiles, functional and sensory attributes of the developed beverages, and (*iii*) to assess the main nutritional and antioxidants properties of recovered solid residues for further applications as dietary supplement.

MATERIALS AND METHODS

Production of almond beverages and residues

Sweet almonds (*Prunus amygdalus* var. *dulcis*) and Besser Helou dates at Khalal stage, were purchased from a local market in Tunis. Fresh Deglet Nour dates at the Tamr maturity stage, as well as their processed forms, powder and syrup, have been supplied by a date export company, Boudjebel S.A. VACPA (Nabeul, Tunisia).

Almonds were blanched in water at 100 °C for 2 min, peeled, and gently wiped with absorbent paper, then dried at room temperature for 30 min. For a 1 kg batch, 120 g of almonds (12 % *m*/*m*) were ground into a fine powder using a Thermomix TM 6 Vorwerk (Wuppertal, Germany) at 2000 rpm for 40 s. Subsequently, 100 mL of water was added, and the mixture was blended at 5800 rpm for 1 min. Date ingredients (200 g, 20 % *m*/*m*) were then incorporated along with an additional 100 mL of water, and the mixture was blended at 5800 rpm for 1 min. Water was added to reach the total batch weight, and the mixture was filtered through a 200 μm fine mesh filter bag. The filtrate (beverage) was pasteurized at 95 °C for 10 min, cooled to 5 °C, and stored under refrigeration until analysis. Residues remaining in the filter were collected immediately for moisture content and water activity determination, dried at 60 °C in a Memmert UN55 oven (Germany) until constant weight, and stored in airtight glass jars at 5 °C until further analyses.

Yield extraction and distribution of nutrients in beverages and residues

The extraction yield (%) is expressed as the ratio of the beverage mass (kg) to the mass (kg) of the ingredients (almonds, dates and water) [*15*] according to the following equation:

$$Y = \left(\frac{m_{beverage}}{m_{ingredients}}\right) \cdot 100 \qquad /1/$$

Proximate composition and energy value determination

The moisture content was determined by drying samples in oven at 105 °C to a constant mass [*16*]. Ash content was assessed by incineration in a muffle furnace (Nabertherm GmbH, Lilienthal/Bremen, Germany) at 550 °C for 8 h. Total protein content was determined using the Kjeldahl method (UDK 129, VELP Scientifica, Italy) described in ISO [*17*] for beverages and the Kjeldahl method described in JORF [*18*] for raw materials and residues. The fat content was quantified using the Soxhlet extraction method with hexane as the extraction solvent for 6 h in a Soxhlet apparatus (Eurothermal, Italy). Total carbohydrate was obtained by the difference between total sample weight and the sum of the percentages of moisture, ash, total fat and total protein. The energy value was calculated according to the equation below, and expressed in kJ /100 g of sample:

$$E = w(\text{carbohydrate}) \cdot 4 + w(\text{protein}) \cdot 4 + w(\text{fat}) \cdot 9 \qquad /2/$$

Physicochemical properties

Total soluble solids (TSS) of samples were determined by the refractometric method following the procedure described in [*19*] using a digital refractometer (PAL-3 ATAGO, Japan). The pH was measured as detailed in [*20*] using a digital pH-meter (PAL-pH ATAGO, Japan). The titratable acidity was assessed according to the method described in [*21*] and expressed in grams of malic acid per 100 g of product. Water activity was determined in triplicate at 20 ° C, using a water activity meter (LabMaster-aw neo, Switzerland). The color attributes of samples were evaluated by measuring the response color coordinates *L**, *a** and *b** with a colorimeter tester (PCE-TCR200, PCE Instruments, Spain). Whiteness (WI), yellow (YI) and browning (BI) indices were used to assess the characteristic colors of almonds (white), Besser Helou (yellow) and Deglet Nour dates as well as their processed forms (Yellow-Brown). They were calculated using the following equations [*22,23*]:

$$\mathrm{WI} = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad /3/$$

$$\mathrm{YI} = 142.86\ ({b^*}/{L^*}) \quad /4/$$

$$\mathrm{BI} = \frac{100\ (\frac{a^*+1.75L^*}{5.645L^*+a^*-3.012b^*}\ -0.31)}{0.172} \quad /5/$$

The density of beverages was determined following the method reported by Siddeeg, Salih [*24*] with modifications. A known volume flask (50 mL) was washed, dried, cooled in a desiccator and then weighed as (m_1). Afterwards, the flask was filled with the sample beverage and the obtained mass value was recorded as (m_2). The density was calculated as the ratio of the beverage mass (m_2-m_1) to the known volume (V), and expressed in kg/m^3.

Antioxidant properties

Phenolic extraction and liquid chromatography-high resolution electrospray ionization mass spectrometry (LC-ESI-MS) analysis

The phenolic compounds were extracted from almonds, dates, beverages, and by-products using methanol (min. 99, 8 %, HPLC grade) at a solvent-to-dry material ratio of 1:10 *m*/*m* in an ultrasonic cleaning bath at 30 °C for 40 min (EMAG AG Emmi-60 HC, Germany). The sonicated solutions were centrifuged for 5 min at 5000 rpm/min at 4 °C in a centrifuge (Mikro 220 R-Hettich, Germany), then filtered through 0.45 µm Acrodisc filters and stored at -20 °C. Sample analyses were carried out using a Shimadzu LCMS-2020 quadrupole mass spectrometer (Kyoto, Japan) equipped with an electrospray ionisation source (ESI) and set to negative ionization mode. The spectrometer was connected to an ultra-fast liquid chromatography system, which included an LC-20AD XR binary pump system, a SIL-20AC XR auto sampler, a CTO-20AC column oven, and a DGU-20A 3R degasser (Shimadzu, Kyoto, Japan). An Inertsustain C18 column (GL Sciences, Japan) (150 mm×3 mm, 3 µm) was used for analysis. The mobile phase included 0.02 % acetic acid in H2O/ACN, with a 10-minute acquisition time. The mobile phase flow rate was 0.4 mL/min, the column temperature was held at 40 °C, and the injection volume was 5 µL. Spectra were collected in SIM mode (selected ion monitoring) and analyzed with Shimadzu LabSolutions LC-MS. Phenolic substances were identified by comparing retention times and mass spectra to chemical standards of >98 % purity from Sigma-Aldrich (St Louis, MO, USA). The results were represented as mg of phenolic compound per 100 g of sample [*25,26*].

Antioxidant activity assays (DPPH and FRAP)

The antioxidant potential of the extracts was evaluated by two spectrophotometric methods: the DPPH radical scavenging assay and the ferric reducing antioxidant power (FRAP) assay. Absorbance was measured using a UV–Vis spectrophotometer (PEAKII UV, C7200S, Houston, TX, USA).

The DPPH radical scavenging activity was determined according to the method described by [*27*]. Briefly, 400 µL of the sample was mixed with 2.4 mL of methanolic DPPH solution (0.02 mg/mL). The mixture was vortexed and kept in the dark at room temperature for 20 min, after which the absorbance was measured at 517 nm.

The FRAP assay was conducted according to the method of Benzie and Strain [*28*] with slight modifications. The FRAP reagent was freshly prepared by mixing 0.2 M acetate buffer (pH=3.6), 10 mM 2,4,6-tripyridyl-s-triazine (TPTZ) solution in 40 mM HCl, and 20 mM $FeCl_3\cdot 6H_2O$ in a ratio of 10:1:1 (*V*/*V*/*V*). Then, 100 µL of the sample was added to 2 mL of FRAP reagent and incubated at 37 °C for 30 min in the dark. The increase in absorbance was measured at 593 nm.

Results for both assays were expressed as mg Trolox equivalents per 100 g of sample (mg TE/100 g).

Rheological characterization

The rheological properties of the beverages were measured using a rotary viscometer (Rheometric RM180, Rheomat, Caluire, France) equipped with a coaxial cylinder geometry. Steady shear tests were carried out over a shear rate range of 10–500 s^{-1} at a controlled temperature of 25 °C. Apparent viscosity (η_{app}) was recorded as a function of shear rate ($\dot{\gamma}$), and the flow behavior of each sample was modeled using the Ostwald–de Waele (power-law) equation [*29*]:

$$\eta_{\mathrm{app}} = K \cdot \dot{\gamma}^{n-1} \qquad /6/$$

where η_{app} is the apparent viscosity (Pa·s), $\dot{\gamma}$ the shear rate (s^{-1}), K the consistency index ($Pa\cdot s^n$), and *n* the flow behavior index (dimensionless). The goodness of fit of the model was evaluated using regression analysis, and the coefficient of determination (R^2) was used to assess model adequacy.

Physical stability

Physical stability of beverages was assessed by determining the sedimentation index under centrifugation, as described by [*30*] with minor modifications, and by monitoring phase separation at 4 °C. The sedimentation index was determined by centrifuging 30 g of beverage in 50 mL centrifuge tubes at 6000 rpm for 10 min using an OHAUS centrifuge (FRONTIER-FC5706, Germany). The supernatant was carefully discarded, and the mass of sediment was recorded. The sedimentation index was calculated as the ratio of the sediment mass (g) to the initial beverage mass (g), as shown in the following equation:

$$\text{Sedimentation index} = \left(\frac{m_{sediment}}{m_{beverage}}\right) \cdot 100 \qquad /7/$$

Stability at rest was also evaluated at 4 °C by transferring samples into 15 mL sealed centrifuge tubes, leaving them undisturbed, and measuring the heights (in mm) of the different phases (sediment, intermediate liquid, and top supernatant) after 0, 24, 96 and 240 h. The separation kinetics were expressed using a phase ratio calculated as a function of time, as shown in the following equation:

$$\text{Phase ratio}(t) = \left(\frac{h_{\text{phase}}(t)}{h_{\text{total}}}\right) \cdot 100 \qquad /8/$$

where $h_{\text{phase}}(t)$ is the height (in mm) of the considered phase at time t, and $h_{\text{total}}$is the total height of the sample (mm).

Sensory evaluation

The sensory profile of beverages was evaluated by internally recruited panelists (7 women and 3 men aged between 26 and 45 years) from the Higher Institute of Biotechnology of Sidi Thabet, Tunisia, and trained in accordance with the ISO 8586 [*31*] to ensure consistency and reliability in descriptive sensory analysis. Training focused on attribute definition, consensus building, and repeatability under the supervision of the panel leader. A total of nine descriptors were selected for the assessment of appearance (brown color and visual viscosity), odor (almond odor, date odor), flavor (almond flavor, date flavor), taste (sweetness and acidity), and mouthfeel (viscosity mouthfeel), using a 7-point intensity scale (1=not perceived, 7=extremely strong intensity). Beverages were evaluated after 1 day of processing and cold storage at 5 °C. Participants received all samples after homogenization simultaneously in 60 mL clear plastic drinking cups with lids, coded with 3-digit numbers in a random order at 20 °C.

The hedonic test was performed by 30 untrained panelists (21 women and 9 men aged between 22 and 53 years). They were asked to score their liking for color, odor, viscosity, taste, and overall attributes (*7*) using a 7-hedonic scale from "dislike extremely" to "like extremely". Panelists received mineral water and soft unsalted bread for palate cleansing between tastings in all sensory sessions .

Statistical analysis

Analysis of variance (ANOVA) and Tukey post-hoc test were used to compare the different attributes of raw materials, beverages, and residues. Significant levels were set at p-values less than 5 %. Principal component analysis (PCA) and Pearson correlation test were applied in interpreting sensory data and correlating with nutritional, antioxidant and physicochemical properties. All statistical tests were performed with XLSTAT software v. 2019 [*32*].

RESULTS AND DISCUSSION

Physicochemical and functional profile of almonds and date derivatives

Compositional and physicochemical attributes

The proximate composition of the different ingredients (Deglet Nour, Besser Helou, date powder and syrup, blanched almonds), given in Table 1 on a wet mass basis, indicated that blanched almonds contained (6.61±0.21) % moisture, (47.08±0.01) % fat, (26.66±0.05) % protein, (16.47±0.20) % carbohydrates, and (3.18±0.01) % ash. They provided 1.5–4-fold higher caloric values than date-based ingredients, which were characterized by a high carbohydrate content (37.76–88.78 %) and low levels of fat (0.02–0.28 %), protein (1.58–3.24 %), and ash (1.02–2.41 %). These ingredients differed from each other according to date variety, ripening stage and processing method. Indeed, moisture made up on average (59±0.28) % of Besser Helou's mass, followed by carbohydrates (37.76±0.25) %, protein (1.58±0.03) %, ash (1.02±0.01) % and fats (0.28±0.01) %. By contrast, three-fourths of Deglet Nour date total mass was carbohydrates (75.11±0.08) %, with moisture content accounting for only one-fifth (20.98±0.12) %. They contained less fat (0.07±0.01) % and more protein (2.16±0.05) %, and ash (1.68±0.02) % than Besser Helou. These findings were consistent with the already known fact that moisture content decreased from 50–60 % to about 10–25 % as sugars accumulated during the ripening of date fruits from khalal to Tamr stage. These changes in moisture and carbohydrate content prevented the fruits from fermentation, thereby enabling their long-term storage [*33*]. The powder contained less moisture (5.51±0.08) %, and consequently more protein (3.24±0.02) %, ash (2.41±0.01) %, carbohydrates (88.78±0.09) %, and energy value (1542.60±1.17) kJ/100 g than fresh dates. It was also richer in nutrients than the syrup, from which some of its insoluble compounds were partially eliminated during the manufacturing process based on a filtration operation. Almonds exhibited the highest pH (5.82±0.02) and the lowest titratable acidity (TA; (0.34±0.02) %) and total soluble solids (TSS; (26.00±0.35) g/100 g), compared with date-based ingredients, which showed a more acidic pH range (4.20±0.01–5.07±0.02) and higher TA ((0.36±0.02)–(0.71±0.03) %) and TSS values ((37.00±0.35)–(90.00±0.60) g/100 g). These results are due to the fact that date fruits contained much more organic acids and soluble sugars than almonds. Almonds contained small concentrations of soluble sugars, including 3.95 % sucrose, 0.17 % glucose, 0.11 % fructose, with negligible amounts of other monosaccharides (<0.1 %) and sugar alcohols [*34*].

Functional attributes

The identified phenolic compounds in the methanolic extracts of the different ingredients (Deglet Nour, Besser Helou, date powder and syrup, blanched almonds) are listed in Table 2. The extract of blanched almonds showed the presence of four cinnamic acid derivatives (quinic acid, 1,3-di-O-caffeoylquinic acid, chlorogenic acid, and rosmarinic acid) and five flavonoids, of which one flavonol (quercetin), three flavones (apigenin-7-O-glucoside, luteolin, and cirsiliol) and one flavanone (naringenin). Quinic acid and apigenin-7-O glucoside were the major compounds among the groups of phenolic acids and flavonoids. With the exception of chlorogenic acid, luteolin and naringenin, all the rest of the phenolics were newly identified compounds in almond kernels. Indeed, chlorogenic acid and luteolin have been detected in whole kernels of 20 Serbian varieties [*35*], with concentrations ranging from 0.098-2.103 mg/100 g and from 0.034-0.624 mg /100 g respectively, which is in agreement with our findings indicating (1.526±0.005) mg/100 g for chlorogenic acid and (0.498±0.001) mg/100 g for luteolin. Naringenin has been found in 8 varieties of blanched Californian almonds [*36*] and in the Serbian whole almonds mentioned earlier. Its concentrations ranged from 0.009 to 1.574 mg/100 g [*35*], which is in line with our finding (0.958±0.001) mg/100 g.

The date-based ingredients shared common phenolic compounds with almonds, with the notable exceptions of quinic acid and naringenin, which appeared to be specific to almonds, and luteolin which was not detected in syrup. They additionally contained other compounds, including trans-ferulic acid, *o*-coumaric acid, salvianolic acid, naringin and acacetin. Trans-ferulic acid was found only in the powder extract, while *o*-coumaric acid was detected in both fresh dates of Deglet Nour and Besser Helou. Salvianolic acid was present in all date-ingredient extracts except syrup. Naringin was found only in Besser Helou, while acacetin has been detected only in Deglet Nour. Similar findings have been reported for fresh Deglet Nour, indicating the presence of acacetin, in addition to luteolin, quercetin and cirsiliol [*37*]. From a quantitative point of view, the common phenolics between ingredients were higher in date-based products than in almonds, with the exception of 1,3-di-O-caffeoylquinic acid, which exhibited a lower level in Besser Helou than in almonds. The comparison of individual phenolic contents between date-based ingredients revealed significant differences according to variety and processing technique. Indeed, Besser Helou exhibited the highest levels of *o*-coumaric acid and luteolin, while Deglet Nour showed the highest content of salvianolic acid. The syrup was characterized by the highest levels of chlorogenic acid, 1,3-di-O-caffeoylquinic acid and apigenin 7-O glucoside. As for date powder, it was the richest ingredient in rosmarinic acid, quercetin and cirsiliol. Otherwise, it may be noted that in all ingredients, the contents of phenolic acids were higher than those of flavonoids. The highest content of phenolic acids corresponded to the powder extract (about 74.6 mg/100 g), while the lowest one was observed in Besser Helou extract (24.87 mg/100 g). Interestingly, all date-based products had around 3-4 times more flavonoids than blanched almonds. Accordingly, the lowest total flavonoid content was observed in almonds. Besser Helou showed the highest content in total flavonoids due to its high luteolin content, followed by Deglet Nour, date powder and syrup, respectively. However, considering the total contents of phenolics, it appeared that the date powder was the richest, followed by syrup, Deglet Nour, almonds and Besser Helou. This may be due to the high dry matter content of processed fruits (powder and syrup) compared to raw ones (Deglet Nour), as well as that of Deglet Nour at Tamr stage compared to that of Besser Helou at Khalal stage. Date powder exhibited the highest antioxidant activity in both DPPH and FRAP assays, with values significantly higher than all other samples, confirming its high concentration of redox-active compounds. In contrast, almonds and Besser Helou showed the lowest DPPH radical-scavenging activity, indicating a limited ability to neutralize free radicals through hydrogen or electron donation. The FRAP assay revealed a different pattern: almonds and date syrup presented the lowest reducing power, suggesting weaker Fe^{3+}-reducing capacity. Deglet Nour exhibited intermediate antioxidant activities between these extremes, although its relative position varied slightly between assays.

Color characteristics

The blanched almonds, off-white in color (Fig. S1), showed the highest values of WI and the lowest value of BI (Table 3). The yellow color of Besser Helou, indicated by the highest YI value (60.61±4.31), could be ascribed to the predominance of luteolin, while the brown color of Deglet Nour, indicating their full ripening, could be associated with the concentration of dactyliferic acid (5-O-caffeoylshikimic acid) [*38*]. The deep dark brown color of syrup, with a high browning index of (96.59±3.5), may be attributed to the formation of melanoidins through Maillard reactions [*39*]. The date powder had a sandy color, with corresponding WI, YI and BI mean values of (50.44), (49.01), and (56.13).

Physicochemical, functional and sensory attributes of formulated beverages

Compositional and physicochemical attributes

As indicated in Table 1, the extraction yields of beverages were considerably reduced when date-based ingredients were added to almonds. However, this reduction was less significant in the case of syrup (88.94±1.76) %, moderate in the case of Deglet Nour (80.84±0.43) % and Besser Helou (79.66±1.41) %, and more significant in the case of date powder (76.03±2.03) %. This may be explained by the fact that syrup dissolved more readily than the other ingredients did. In fact, the fresh dates were composed of hydrophobic substances, mainly insoluble fibers (lignin) and waxes [*40,41*] that could not be extracted with water while the dehydrated form of date powder favored water absorption simultaneously with the dissolution of soluble substances during the process. A mass of 1 g of Deglet Nour powder could hold (2.0±0.2) mL of water [*42*].

Based on the beverages' proximate composition given in Table 1, the almond drink is composed of 92.86 % moisture, 3.98 % fat, 2.17 % protein, 0.22 % ash, and 0.76 % carbohydrates. The energetic value was 47.58 kcal/100 g. Adding date products to almonds significantly decreased moisture and fat contents of the beverages while increasing the carbohydrate and ash contents. Besser Helou, the ingredient with the lowest dry matter produced the least changes, showing a drop of moisture, fat, and protein to about 87.40, 3.80 and 2.07 % respectively, and an increase of carbohydrates and ash to about 6.43 and 0.30 %, respectively. Due to its highest dry matter content, date powder caused the greatest drop in moisture content of the beverage, reaching (79.02±0.06) %. Along with syrup, it provided the largest enrichment in ash and carbohydrates, showing increases of 2.5 times for the former (0.30–0.58 %) and about 19–20 times for the latter (6.43–15.11 %). The protein content has been found to increase only with the incorporation of Deglet Nour (2.38±0.02) % and powder ((2.31±0.01) %). It decreased when Besser Helou were added ((2.07±0.03) %) and remained unchanged with syrup ((2.1± 0.03) %). Similar effects have been reported for palmyrah fruit pulp when mixed with coconut beverage, with a decrease of moisture (from 85.06 to 80.47 %) and fat (from 5.61 % to 1.50 %) contents with an increase of ash (from 0.26 to 3.77 %), protein (from 1.27 % to 2.80 %) and carbohydrates (from 22.19 % to 27.73 %) contents [*43*]. As carbohydrates increased the energetic density of beverages increased. Beverages based on powder had the greatest energy value (403.84 kJ/100 g), followed by those based on Deglet Nour and syrup (379.87 and 377.48 kJ/100 g, respectively). The beverage made with Besser Helou had a lower energy density of (285.18 kJ/100 g). Although these drinks are not designed to replace milk, their energy density values and protein contents have been found to be within the proposed nutrient standards for plant-based beverages intended as milk alternatives, with a maximum of 355.64–418.4 kJ/100 g and a minimum content of 2.2 % of protein [*44*]. The increase in the carbohydrate proportions of different samples (in dry matter) resulted in an increase in their TSS contents (from (8.90±0.44) to (18.53±0.21) g/100 g), with the lowest value for the beverage based on Besser Helou and the highest one for the beverage based on powder. Drinks made from Deglet Nour and syrup showed statistically similar values of (15.77±0.12) g/100 g and (16.83±1.36) g/100 g respectively. Additionally, it has been noted that the densities of the beverages increased, suggesting that the date ingredients may function as both thickeners and sweeteners. This effect was more pronounced in powder (1054.83±0.76) g/L with the greatest dry matter content than in fresh Deglet Nour (1034.28±0.62) g/L, syrup (1029.94±0.05) g/L, and Besser Helou (1009.58±0.39) g/L. The titratable acidity of produced drinks increased from (1.49±0.07) to (2.95±0.07) %, indicating that date ingredients enriched the beverages with organic acids. A fall in *pH* levels between (5.07±0.06) and (5.97±0.12) was also noticed, suggesting an acidifying effect of these products. However, the drinks remained in the low-acid food category (pH>4.5), needing refrigerated storage if pasteurized [*43*]. Water activity of different beverages did not change with syrup or powder supplementation, but dropped with Deglet Nour and rose with Besser Helou supplementation.

Functional attributes

According to the displayed data in Table 2, the phenolic composition of almond beverage was similar to that of blanched almonds, with the noticeable appearance of quercetin derivative, hyperoside (quercetin-3-O-galactoside), and the absence of naringenin, luteolin and cirsiliol. Caffeic acid, which has not been detected in raw ingredients, was found in the beverages obtained from the combination of almonds with Deglet Nour, Besser Helou, and syrup, and also in all residues.

The appearance of such phenolic acid might be ascribed to the decomposition of chlorogenic acids (CQAs) into caffeic acid and quinic acid under the influence of pasteurization. Indeed, CQAs are temperature-sensitive. Increasing the temperature led to intramolecular isomerization and transesterification of these compounds, as well as their degradation. The diCQAs degrade to the corresponding monoCQAs, and then to caffeic and quinic acid. The amount of each produced component varies with the heating duration and temperature [*45*]. It could be concluded, therefore, that the presence of quinic acid in all produced drinks may be attributed not only to almonds but also to the breakdown of CQAs that initially existed in each ingredient. The comparison of phenolic composition of each beverage with the corresponding raw materials (almonds, date-based ingredient) revealed the appearance of new compounds: hyperoside in Besser Helou and Deglet Nour beverages, naringenin in Besser Helou Beverage, naringin in Deglet Nour beverage, quercitrin (quercetin 3-O-glycoside derivative) in both Deglet Nour and syrup beverages, *o*-coumaric acid and, rutin (quercetin 3-O-glycoside derivative) in syrup-based beverage. These compounds are poorly soluble in water, so they could not be the result of the water extraction that occurred during the production of beverages. It was possible, however, that they already existed with low concentrations in the raw materials and that the large quantities of ingredients used for the drink's development were sufficient to allow their detection.

The quantitative profiles of phenolics were significantly different between beverages. For instance, the almond beverage showed the highest amounts of quinic acid and salvianolic acid. The Besser Helou-based beverage showed the greatest quantities of rosmarinic acid, hyperoside and naringin. The Deglet Nour-based beverage was the richest in caffeic acid, 1,3-di-O-caffeoylquinic acid, *o*-coumaric acid, luteolin and cirsiliol. The syrup-based beverage was rather richer in chlorogenic acid, quercitrin and apigenin-7-O-glucoside. The highest concentration of quercetin was detected in a powder-based beverage. Similar to the ingredients, the contents of total phenolic acids in beverages were higher than those of flavonoids. The combination of date-ingredients with almonds substantially increased the total flavonoid content in beverages, and consequently the total content of identified phenolics, with the exception of the powder-based drink (84.66±0.01) mg/100 g. This might be because it contained the least amount of quinic acid and no caffeic acid when compared to the other drinks. Deglet Nour was the ingredient that gave the highest content of total identified phenolics ((319.300±0.029) mg/100 g), followed by Besser Helou ((269.277±0.044) mg/100 g) and date syrup ((211.024±0.014) mg/100 g).

FRAP and DPPH assays revealed clear differences in the antioxidant capacity of the tested ingredients. Enriched beverage with date powder showed the strongest activity, with an exceptionally high FRAP value ((39.56±0.06) mg TE/100 g) and similarly elevated DPPH scavenging capacity ((47.53±2.47) mg TE/100 g), significantly surpassing all other samples. The beverage based on date syrup also exhibited high antioxidant activity, clustering with powder-based drink in the DPPH assay ((48.50±2.14) mg TE/100 g), but showing a more moderate reducing power in FRAP ((15.20±0.18 mg) TE/100 g). Beverages enriched with Deglet Nour and Besser Helou displayed intermediate antioxidant capacities. Almond beverage consistently presented the lowest antioxidant activity in both assays.

When DPPH results were compared with values reported in the literature, it appeared that the incorporation of date fruits enabled the development of beverages with markedly higher antioxidant capacities than those fortified with other fruit- or plant-based ingredients. For instance, previous studies reported DPPH activities of (8.508±0.059), (12.219±0.085) and (8.97±0.062) mg TE/100 g for almond beverages supplemented with: (*i*) blended boiled carrot, honey, and stevia; (*ii*) the same mixture with the addition of quinoa seeds; and (*iii*) banana juice, honey, stevia, and oat powder. Notably, the almond content in these formulations (11–12 % *m*/*m*) was comparable to that used in the present study [*7*].

Regardless of the quantitative aspect, almond and enriched beverages all contained potent phenolics recognized for their healing properties. The majority of these compounds were endowed with antioxidant, antidiabetic, anticancer, antibacterial, antiviral, anti-aging, anti-nociceptive, anti-inflammatory and analgesic effects.

Color characteristics

The color attributes of the beverages (Table 3) revealed an obvious color difference between samples (Fig. S2). The almond drink was distinguished by a white color, while that based on Besser was somewhat yellowish. They had the highest WI value and the lowest YI and BI values. The beverage based on Deglet Nour, brownish in color, showed statistically similar BI and YI values, but lower WI. Those made with date powder (brown) and syrup (deep brown) had the highest YI and BI values, but differed according to the WI. These findings indicated that certain pigments were removed from dates and their derivatives during processing and diffused into the aqueous phase, resulting in the formation of yellow and brown colors.

Rheological properties of beverages

Rheological profile characterization revealed distinct flow behaviors among the five beverage formulations. Both the almond beverage and the Besser Helou-enriched beverage exhibited pronounced non-Newtonian shear-thinning behavior, with apparent viscosity decreasing continuously as shear rate increased (Fig. 1a). This is typical of plant-based beverages, where suspended particles or polymeric structures are held together by weak forces that are progressively disrupted under stress [*46*]. While their flow behavior indices were similarly low (n≈0.025–0.027), indicating comparable shear-thinning responses, the consistency indices differed markedly, with the Besser Helou-enriched beverage (K=385.10 Pa·s^n) being much more viscous than the almond beverage (K=29.06 Pa·s^n), reflecting substantial differences in apparent viscosity at low shear rates (Table 4).

In contrast, the enriched beverages with Deglet Nour, date syrup and date powder showed shear-thickening behavior at low shear rates, which transitioned into shear-thinning as the shear rate was further increased (Fig. 1b). This may be explained by the high content of dietary fibers in Deglet Nour [*47*], which can form a gel-like network that resists deformation at low shear rates. This particular rheological pattern has been reported for polysaccharides such as lentinan and xanthan in water, curdlan in 0.01 M NaOH [*48*], as well as for apple and tomato pectins [*49*]. It was attributed to particle–particle collisions at low shear rates, which promote the formation of larger aggregates and result in increased viscosity as shear rate rises. At higher shear rates, however, the stronger shear forces disrupt these aggregates, causing the system to transition into shear-thinning, pseudoplastic behavior [*48*]. To characterize this specific rheological behavior, a coefficient—referred to as the extent of shear thickening—has been proposed to quantify the degree of shear thickening observed at low shear rates. In addition, the *n* and *K* parameters of the power-law model are determined within the shear-thinning region. This coefficient corresponds to the ratio of the peak viscosity to the viscosity at the onset of shear thickening (η_{top}/η_{onset}) [*49*]. These parameters presented in Table 4, showed that beverage based on date powder had the most shear thickening extent (η_{top}/η_{onset}=3.63), likely due to high particle concentration or stronger particle–particle interactions, as supported by its very high consistency index (*K*=430.74 Pa·s^n), followed by beverage enriched with Deglet Nour (η_{top}/η_{onset}=1.88), and syrup (η_{top}/η_{onset}=1.26). Overall, the contrasting behaviors highlight substantial differences in microstructure and particle interactions among the formulations. Shear-thinning beverages (based on almonds and Besser Helou) are expected to show easier flow under agitation, while the shear-thickening beverages may present higher resistance at low shear but structural destabilization at higher deformation rates, with implications for mouthfeel, processing, and stability.

Physical stability of almond and enriched beverages

Although all formulated beverages exhibited a similar phase separation pattern after centrifugation (accelerated phase separation), characterized by a bottom sediment layer composed of the densest insoluble particles, an intermediate liquid phase, and an upper cream layer, as illustrated in Fig. S3, the extent of this separation differed between formulations, as reflected by the sedimentation index (Fig. S4). Beverage based on date powder showed the highest sedimentation index (15.45), followed by beverage enriched with Deglet Nour (11.36), while beverages based on almonds, Besser Helou and date syrup exhibited lower values (9.43, 9.33 and 7.44, respectively), indicating a lower tendency to sediment under centrifugal force. However, this trend did not strictly match the stability behavior observed under storage at rest. Indeed, despite its high sedimentation index, beverage based on date powder showed good visual stability over time, with a delayed phase separation reaching a 50:50 ratio only after 240 h (Fig. S5a), while beverage based on Besser Helou remained fully homogeneous throughout the entire storage period (Fig. S5b) and only showed phase separation at the end of the test, similarly to the control almond beverage (Fig. S5c), with the formation of a sediment layer at the bottom, an intermediate liquid phase, and an upper creaming layer. This apparent discrepancy can be explained by the fact that centrifugation mainly emphasizes density differences and particle size effects, whereas stability at rest depends on prolonged interactions between sugars, fibers, proteins and lipids, as well as on the microstructural organization of the beverage. In the case of ABHB, the presence of Besser Helou, characterized by its white flesh, leads to the diffusion of particles with density, color and optical properties close to those of almond particles, promoting better dispersion in the continuous phase and enhancing product homogeneity. For APB, the soluble and insoluble fibers released from Deglet Nour powder during beverage processing likely contribute to water structuration and fat droplet entrapment, thereby improving resistance to phase migration and visual instability during storage. The beverages enriched with Deglet Nour (Fig. S5d) and date syrup (Fig. S5e) developed only two phases, namely a lower syrup-rich phase and an upper dense phase, while the appearance of a distinct sediment layer was minimal and only observed at the end of the storage period.

Sensory profile and overall acceptability of beverages

From the displayed results in Fig. 2, it could be seen that the produced beverages differed significantly according to their sensory profiles.

The incorporation of date fruit ingredients, with the exception of Besser, increased the brown color intensity of fortified beverages as well as their visual viscosity. The highest ratings for these attributes were associated to syrup-based beverage. All drinks showed the same low intensity of almond note. The note of dates was absent in the drinks based on almonds, Besser and Deglet Nour fruits and barely noticeable in the drinks based on powder and syrup. The flavor of almonds was predominant in beverages based on almonds, Besser and Deglet Nour fruits, while the flavor of dates was more pronounced in powder and syrup drinks. As expected, date ingredients increased the perception of sweet taste in all beverages, without exceeding the middle intensity range. The acidity was negligible in all products, except for the syrup-based beverage, which displayed the highest score. As for the mouthfeel viscosity, it showed the same tendency as visual viscosity, indicating minimum levels in almonds and Besser beverages and maximum levels in syrup beverages.

The PCA applied for sensory attributes and physicochemical properties (Fig. 3) explained 76.64 % of the variation in the data with the first two principal components (PC1=56.87 % and PC2=19.77 %). PC 1 accounted for 56.87 % and was associated positively with the attributes of brown color, odor and flavor of dates, visual viscosity and viscosity mouthfeel and acidity, but negatively with almond flavor. Strong Pearson correlations have been found between the attributes loaded positively on PC1, with the exception of acidity, with DPPH antioxidant activity (0.920<r<0.975), ash content (0.935<r<0.988), and color parameters; *a** (0.924<r<0.978), *b** (0.903<r<0.988), YI (0.948<r<0.998) and BI (0.947<r<0.991). These physicochemical properties were at higher levels in the beverages obtained from the mixture of almonds with processed dates (powder and syrup), which were also loaded positively on PC1. A strong positive correlation was also observed between FRAP and DPPH assays (r= 0.774), indicating good consistency between the two antioxidant evaluation methods. The attribute of almond flavor was relatively strongly correlated to fat content (r=0.817) and color parameters; *L** (r=0.836) and WI (0.823), which were associated with the beverages obtained from almonds and the combination of almond and Besser-Helou. PC 2 accounted for 19.77 % and was associated positively with almond odor and sweetness. The sweet taste was highly correlated to density (r=0.975), energetic value (r=0.950), TSS (0.917), carbohydrate content (r=0.908), and the extent of shear thickening (r=0.849) and was associated with the beverage based on date powder. The acidity was rather correlated to the contents of rutin (r=0.930) and chlorogenic acid (r=0.819), and was linked to the beverage based on date syrup. An intriguing correlation between almond odor and luteolin was noted (r=0.920). This flavonoid was renowned for its ability to improve olfactory memory and was found to enhance olfactory dysfunction and memory in individuals with extended COVID and chronic olfactory loss when coupled with palmitoylethanolamide [*50*].

The results obtained from hedonic ratings are displayed in Fig. 4. The almond-based beverage showed the highest mean liking scores for odor and color attributes, 5.69 and 6.23, respectively, while Deglet-Nour beverage displayed the lowest scores (3.77 and 4.77, respectively). The five beverages shared similarities according to the viscosity attribute. As for flavor attribute, the highest liking score was associated with powder-based drink (4.54), followed by almond and Deglet Nour drinks, 4.31 and 3.92, respectively. The beverages based on Besser and syrup received the lowest scores, being 2.50 and 2.62, respectively. Overall acceptance was highest for powder-based beverages (5.85) and lowest for syrup-based beverages (3.39).

Nutritional and functional characterization of beverage residues

Compositional and physicochemical attributes

Table 1 shows the compositions of the produced residues. From the displayed results, it could be noted that after direct extraction of beverages, they contained more than 50 % moisture and had high, comparable water activity values ranging from 0.9504 to 0.9701. Fairly similar moisture content values have been reported for by-products derived from the preparation of almond ((62.2±0.2) %), coconut ((55.0±0.2) %) and oat ((60.6±0.1) %) drinks [*51*]. It was noted, however, that the most water-rich residue ((71.93±0.19) %) has been derived from Besser Helou, the wettest ingredient. As these co-products were generally preserved and valued in dried form, they were dried until reaching a water activity of 0.6. The almond residue had the lowest carbohydrate content ((10.65±0.04) %), but the highest percentages of ash ((2.74±0.03) %), fat ((58.39±0.01) %), and protein ((22.47±0.03) %), making it the most calorie-dense by-product. Combining date ingredients to almonds decreased the residue contents in fat (24.86-41.93) %, protein (8.45-14.40) %, while increasing significantly carbohydrates content (36.52-53.04) %. This increase in carbohydrates could mostly due to insoluble fiber retention. Indeed, the *TSS* contents of the used by-products (7.20-13.20) g/100 g were low even they were larger than that of almond-based one (2.40±1.59) g/100 g. All investigated by-products had comparable ash contents (2.26±0.13-2.74±0.03) %, except for date powder, which had the lowest value (1.85±0.44) %.

Since date-almond residues had lower fat and protein contents than almond residues, they showed lower but considerable calories, ranging between 1991.3 (Deglet Nour) and 2347.48 kJ/100 g (syrup). The residues based on almonds, Deglet Nour and syrup had higher pH values compared to those based on Besser Helou and date powder. All samples showed comparable TA values, except for date powder residue, which had the highest value, indicating that it retained more organic acids than the others. Some studies have attempted to investigate the incorporation of such co-products in bakery as replacements of wheat or almond flours. It has been reported that the partial substitution of wheat flour with dried almond residue improve the nutritional value of biscuits due to its richness in fiber, protein and fat, with a limited impact on the sensory properties of final products [*52*]. On the other side, the total substitution of almond flour with dried almond residues increased the total dietary fiber in macaroons, with no significant effect on taste and overall preference [*53*]. Applied innovative residue processing, such as fermentation and ultrasonication, before replacing wheat flour with almon by-product in white breads, showed that including 20% of fermented almond residue resulted in the highest overall acceptance of final products, whereas ultrasonicated one significantly decreased the acrylamide level of breads [*51*].

Functional attributes

All residues retained considerable quantities of bioactive compounds and showed an interesting antioxidant activity (Table 2). As in beverages, some phenolics that had not been found in raw materials emerged in by-products. These phenolics are trans-ferulic acid, which was detected only in date powder residue, and hyperoside. Caffeic acid, which was lacking from almond and powder beverages, was detected in the corresponding by-products in addition to Besser Helou, Deglet Nour and syrup residues. This confirmed the previously proposed hypothesis that it was formed as a result of chlorogenic acid breakdown caused by heat treatment. Each by-product was characterized by the predominance of one or more phenolic compounds. For instance, the almond-based residue showed the highest concentrations of quinic acid, chlorogenic acid and salvianolic acid. The Besser-Helou based-residue was the richest in 3-di-O caffeoylquinic acid, trans-ferulic acid, *o*-coumaric acid, hyperoside, naringin, naringenin and cirsiliol. Deglet Nour-based by-product showed the highest content of luteolin. The residue based on syrup was characterized by the abundance of rosmarinic acid and apigenin-7-O- glucoside while that based on powder was the richest in caffeic acid, quercetin and quercitrin.

Generally, it could be noted that almond-based residue was distinguished by the predominance of quinic acid from the phenolic acids group and quercetin from the flavonoids group, whereas the date-based residues were characterized by the prevalence of caffeic acid ((53.439±0.001)–(67.899±0.001) mg/100 g) and luteolin ((5.517±0.001)–(45.836±0.002) mg/100 g), respectively. The by-product derived from almonds contained less flavonoids ((6.814±0.031) mg/100 g) and more phenolic acids ((294.705±0.571) mg/100 g) than those derived from date fruits, and consequently more phenolics than the other samples ((301.519±0.586) mg/100 g). Of the by-products based on date ingredients, those derived from Deglet Nour exhibited the highest concentrations of total phenolics ((228.194±0.003) mg/100 g) and total flavonoids ((59.810±0.003) mg/100 g). Although almond-based residue had the most phenolics, it had the lowest antioxidant capacity. The DPPH value was (27.65±3.03) mg TE/100 g, consistent with Duarte, Betoret [*54*] values of 0.20–0.23 mg TE/g dm for almond by-products dried at 60 and 70 °C, respectively. The by-products based on Deglet Nour, syrup and date powder had comparable DPPH values of (52.92±0.64), (50.61±0.48) and (53.26±0.31) mg TE/100 g, respectively, whereas the one based on Besser Helou showed a lower value of (45.98±2.54) mg TE/100 g. A significant variation in FRAP values was observed, with date powder residue showing the highest value ((52.61±4.98) mg TE/100 g) and Besser Helou the lowest ((12.31±0.13) mg TE/100 g), suggesting that bioactive compounds responsible for high DPPH and FRAP values were largely preserved in the date powder.

Color characteristics

Fig. S6 presents a view of the colors of the produced residues. The almond-based residue was white with the highest WI and the lowest YI and BI values (Table 3). The residues obtained from dates and their derived products showed different shades of brown color. The Besser-based residue was light yellowish brown, showing the highest WI and the lowest BI and YI among date-based residues. The residue obtained from date powder was deeper brown than that obtained from Deglet Nour and the syrup, displaying therefore the lowest WI and the highest BI.

CONCLUSIONS

This study highlights the strong potential of date fruits as natural ingredients for the fortification of almond-based beverages. The incorporation of date-derived products significantly enhanced the antioxidant properties of the formulations, as evidenced by increased FRAP and DPPH values. The positive correlation observed between these two assays further confirmed the consistency and reliability of the antioxidant improvement attributed to date constituents, which are known to be rich in phenolics, flavonoids, and other bioactive compounds. Rheological characterization revealed that all fortified beverages exhibited non-Newtonian behavior, with certain date-enriched formulations displaying a distinctive shear-thickening behavior at low shear rates followed by shear-thinning at higher shear rates. This particular flow profile, likely related to the presence of date polysaccharides and pectic substances, may contribute positively to mouthfeel and texture, offering sensory and processing advantages in beverage applications. In terms of physical stability, date fortification influenced sedimentation and phase separation behavior. While some formulations exhibited a clear separation into syrup and serum phases during storage, others maintained a more homogeneous structure for extended periods, demonstrating improved colloidal stability. This suggests that date ingredients not only contribute nutritionally but also act as natural stabilizing agents by modifying the continuous phase and particle interactions within the beverage matrix. Importantly, this work provides the first comprehensive evaluation of the combined effects of date fruit ingredients on the nutritional, rheological and stability attributes of fortified almond beverages. The findings open new perspectives for the development of clean-label, plant-based functional drinks with enhanced health benefits and tailored physicochemical properties, using locally available agro-resources such as date fruits.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in this research.

SUPPLEMENTARY MATERIALS

All supplementary materials are available at: www.ftb.com.hr.

ETHICS APPROVAL

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki and COPE recommendations. The sensory evaluation involved healthy adult volunteers, with no invasive procedures, no vulnerable populations, and no collection of sensitive or identifiable personal data. Participation was voluntary, oral informed consent was obtained prior to inclusion, and confidentiality was ensured through anonymous data collection. Ethical risks were therefore considered minimal.

AUTHORS' CONTRIBUTION

M. Ben Zid performed the experiments, analyzed the data, and wrote the manuscript. N. Rokbeni, N. M'hiri, and M. Chouaibi contributed to the optimization of experimental methods. N. Zghonda assisted in procuring samples and reviewing the manuscript. N. Boudhrioua designed, supervised and administered the project, and reviewed the manuscript.

ORCID ID

M.Ben Zid https://orcid.org/0000-0002-9447-2425

M. Chouaibi https://orcid.org/0000-0002-9548-6773

N.Boudhrioua https://orcid.org/0000-0001-9862-9744

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Table 1. Nutritional and physicochemical properties of raw ingredients, beverages, and their corresponding residues

Ingredient	Blanched almonds	Besser Helou	Deglet Nour	Syrup	Powder
w(moisture)/%	(6.61±0.21)[b]	(59.36±0.28)[e]	(20.98±0.12)[c]	(29.58±0.04)[d]	(5.51±0.08)[a]
w(ash)/%	(3.18±0.01)[e]	(1.02±0.01)[a]	(1.68±0.02)[b]	(1.75±0.001)[c]	(2.41±0.01)[d]
w(fat)/%	(47.08±0.01)[d]	(0.28±0.01)[c]	(0.07±0.01)[b]	(0.02±0.01)[c]	(0.07±0.01)[b]
w(protein)/%	(26.66±0.05)[d]	(1.58±0.03)[a]	(2.16±0.05)[b]	(1.61±0.01)[a]	(3.24±0.02)[c]
w(carbohydrate)/%	(16.47±0.20)[a]	(37.76±0.25)[b]	(75.11±0.08)[d]	(67.04±0.04)[c]	(88.78±0.09)[e]
E/(kJ/100 g)	(2494.50±3.64)[e]	(669.06±4.56)[a]	(1295.95±2.18)[c]	(1149.55±0.63)[b]	(1542.60±1.17)[d]
w(TSS)/(g/100 g)	(26.00±0.35)[a]	(37.00±0.35)[b]	(74.40±0.001)[c]	(73.80±1.04)[c]	(90.00±0.60)[d]
pH	(5.82±0.02)[e]	(4.86±0,02)[c]	(5.07±0,02)[d]	(4.20±0,01)[a]	(4.67±0,01)[b]
TA/%	(0.34±0.02)[a]	(0.36±0.02)[a]	(0.71±0.03)[c]	(0.60±0.03)[b]	(0.57±0.02)[b]
a_w	(0.7423±0.0025)[c]	(0.9336±0.0005)[e]	(0.6521±0.0003)[b]	(0.7322±0.0005)[d]	(0.2820±0.0017)[a]
Beverage	**A**	**ABH**	**ADN**	**AS**	**AP**
$Y_{extraction}$/%	(89.68±1.05)[e]	(79.66±1.41)[bc]	(80.84±0.43)[c]	(88.94±1.76)[d]	(76.03±2.03)[a]
w(moisture)/%	(92.86±0.04)[d]	(87.40± 0.02)[c]	(81.31±0.03)[b]	(80.56±1.05)[b]	(79.02±0.06)[a]
w(ash)/%	(0.22±0.02)[a]	(0.30±0.01)[b]	(0.42±0.01)[c]	(0.57±0.04)[d]	(0.58±0.01)[d]
w(fat)/%	(3.98±0.08)[e]	(3.80±0.01)[d]	(3.54±0.04)[c]	(2.68±0.04)[a]	(2.98±0.03)[b]
w(protein)/%	(2.17±0.03)[b]	(2.07±0.03)[a]	(2.38±0.02)[d]	(2.17±0.03)[b]	(2.31±0.01)[c]
w(carbohydrate)/%	(0.76±0.03)[a]	(6.43±0.04)[b]	(12.35±0.06)[c]	(14.36±0.37)[d]	(15.11±0.09)[d]
E/(kJ/100 g)	(199,07±1,84)[a]	(285,18±0,42)[b]	(379,87±0,96)[c]	(377,48±8,20)[c]	(403,84±0,71)[d]
w(TSS)/(g/100 g)	(4.57±0.23)[a]	(8.90±0.44)[b]	(15.77±0.12)[c]	(16.83±1.36)[c]	(18.53±0.21)[d]
pH	(6.30±0.17)[d]	(5.97±0.12)[c]	(5.50±0.001)[b]	(5.07±0.06)[a]	(5.30±0.10)[ab]
TA/%	(0.42±0.07)[a]	(2.32±0.07)[c]	(1.49±0.07)[b]	(2.95±0.07)[d]	(2.88±0.08)[d]
a_w	(0.9662±0.0041)[ab]	(0.9701±0.0006)[b]	(0.9592±0.0014)[a]	(0.9623±0.0014)[ab]	(0.9650±0.0051)[ab]
ρ/(g/L)	(978.07±0.89)[a]	(1009.58±0.39)[b]	(1034.28±0.62)[d]	(1029.94±0.05)[c]	(1054.83±0.76)[e]
Residue	**A**	**ABH**	**ADN**	**AS**	**AP**
w(moisture before drying)/%	(58.60±0.06)[b]	(71.93±0.19)[e]	(66.61±0.24)[d]	(56.44±0.19)[a]	(63.08±0.14)[c]
a_w before drying	(0.9678±0.0148)[a]	(0.9572±0.0107)[a]	(0.9701±0.0007)[a]	(0.9645±0.0009)[a]	(0.9504±0.0116)[a]

w(moisture after drying/%	(5.76±0.036)[a]	(9.09±0.08)[b]	(9.83±0.03)[d]	(9.61±0.01)[c]	(9.81±0.01)[d]
w(ash)/%	(2.74±0.03)[b]	(2.66±0.01)[b]	(2.26±0.13)[ab]	(2.54±0.06)[b]	(1.85±0.44)[a]
w(fat)/%	(58.39±0.01)[e]	(30.13±0.01)[c]	(24.86±0.01)[b]	(41.93±0.01)[d]	(25.21±0.01)[a]
w(protein)/%	(22.47±0.03)[e]	(8.45±0.02)[a]	(8.74±0.06)[b]	(14.40±0.08)[d]	(10.08±0.05)[c]
w(carbohydrate)/%	(10.65±0.04)[a]	(49.67±0.09)[c]	(54.31±0.10)[d]	(36.52±0.07)[b]	(53.04±0.41)[d]
E/(kJ/100 g)	(2752.82±1.13)[e]	(2107.31±1.26)[c]	(1991.29±2.47)[a]	(2347.48±1.00)[d]	(2005.77±7.07)[b]
w(TSS)/(g/100 g)	(2.40±1.59)[a]	(10.00±0.35)[c]	(7.20±0.60)[b]	(9.80±0.35)[c]	(13.20±0.60)[d]
pH	(5.77±0.20)[b]	(5.10±0.32)[a]	(5.33±0.12)[ab]	(5.43±0.27)[ab]	(4.89±0.27)[a]
TA/%	(0.27±0.02)[ab]	(0.28±0.02)[a]	(0.24±0.02)[a]	(0.23±0.03)[a]	(0.36±0.02)[b]
a_w	(0.5988±0.0004)[a]	(0.5990±0.0001)[a]	(0.6000±0.0001)[a]	(0.5996±0.0001)[a]	(0.6001±0.0002)[a]

Data are expressed on a fresh mass basis as mean value±standard deviation, *N*=3. Mean values followed by different letters in superscript within columns indicate significant differences at p≤0.05 according to Tukey's test. TSS=total soluble solutes, TA=titratable acidity, a_w=water activity, A=blanched almonds, BH=Besser Helou, DN=Deglet Nour, S=date syrup, P=date powder

Table 2. Identified phenolic compounds and antioxidant properties of raw ingredients, beverages, and their corresponding residues

Ingredient	Blanched almonds	Besser Helou	Deglet Nour	Syrup	Powder
w(phenolic acid)/mg/100 g					
Quinic acid	(40.448±0.048)	ND	ND	ND	ND
Chlorogenic acid	(1.526±0.005)[a]	(1.596±0.002)[b]	(5.002±0.002)[c]	(8.981±0.001)[e]	(5.926±0.006)[d]
1,3-di-O-Caffeoylquinic acid	(19.857±0.003)[b]	(13.620±0.001)[a]	(44.850±0.002)[c]	(51.582±0.001)[e]	(47.923±0.002)[d]
trans-Ferulic acid	ND	ND	ND	ND	(1.592±0.002)
o-Coumaric acid	ND	(1.701±0.001)[c]	(1.560±0.002)[b]	ND	ND
Rosmarinic acid	(0.701±0.001)[a]	(7.320±0.001)[b]	(3.939±0.001)[c]	(10.594±0.002)[d]	(17.897±0.007)[e]
Salvianolic acid	ND	(0.663±0.001)[a]	(1.341±0.002)[c]	ND	(1.257±0.002)[b]
w(flavonoid)/mg/100 g					
Naringin	ND	(1.777±0.001)	ND	ND	ND
Apigenin-7-O-glucoside	(2.676±0.001)[a]	(3.472±0.002)[b]	(7.435±0.001)[d]	(11.330±0.001)[e]	(5.631±0.001)[c]
Quercetin	(0.233±0.032)[a]	(0.363±0.001)[b]	(0.356±0.001)[b]	(0.368±0.002)[b]	(0.576±0.001)[c]

Naringenin	(0.958±0.001)[b]	ND	ND	ND	ND
Luteolin	(0.498±0.001)[b]	(13.972±0.001)[c]	(5.786±0.002)[b]	ND	(3.656±0.003)[a]
Cirsiliol	(0.157±0.002)[a]	(0.497±0.001)[b]	(4.176±0.002)[d]	(3.368±0.002)[c]	(7.871±0.002)[e]
Acacetin	ND	ND	(0.192±0.002)	ND	ND
Total phenolic acid/(mg/100 g)	(62.532±0.048)[c]	(24.874±0.001)[a]	(61.692±0.003)[b]	(71.157±0.002)[d]	(74.595±0.008)[e]
Total flavonoid/(mg/100 g)	(4.523±0.032)[a]	(19.480±0.002)[e]	(17.945±0.004)[d]	(15.068±0.003)[b]	(17.733±0.002)[c]
Total/(mg/100 g)	(67.055±0.059)[b]	(44.354±0.002)[a]	(79.637±0.007)[c]	(86.225±0.002)[d]	(92.328±0.010)[e]
DPPH/(mg TE/100 g)	(23.80±1.30)[a]	(23.47±0.08)[a]	(45.27±0.09)[b]	(49.36±0.13)[c]	(53.50 ±0.13)[d]
FRAP/(mg TE/100 g)	(33.601±1.67)[a]	(65.295±1.54)[c]	(52.025±2.86)[b]	(39.713±4.31)[a]	(171.024±0.43)[d]

Beverage	A	ABH	ADN	AS	AP
w(phenolic acid)/mg/100 g					
Quinic acid	(149.965±0.056)[e]	(143.019±0.019)[d]	(46.610±0.011)[b]	(59.687±0.006)[c]	(35.508±0.007)[a]
Chlorogenic acid	(2.659±0.008)[c]	(2.559±0.001)[b]	(3.079±0.001)[d]	(7.107±0.001)[e]	(0.184±0.006)[a]
Caffeic acid	ND	(80.326±0.024)[b]	(171.420±0.018)[c]	(69.310±0.001)[a]	ND
1,3-di-O-caffeoylquinic acid	(9.010±0.010)[a]	(9.864±0.003)[b]	(62.537±0.001)[e]	(43.927±0.001)[d]	(35.943±0.002)[c]
o-Coumaric acid	ND	(0.222±0.001)[a]	(1.967±0.001)[c]	(1.079±0.001)[b]	ND
Rosmarinic acid	(1.126±0.001)[a]	(25.244±0.001)[e]	(18.317±0.001)[c]	(18.679±0.001)[d]	(7.628±0.001)[b]
Salvianolic acid	(4.065±0.001)[b]	(1.106±0.001)[a]	ND	ND	ND
w(flavonoid)/mg/100 g					
Rutin	ND	ND	ND	(0.136±0.001)	ND
Hyperoside	(0.435±0.001)[a]	(1.145±0.001) [c]	(1.012±0.001)[b]	ND	ND
Naringin	ND	(2.107±0.001) [b]	(1.382±0.001)[a]	ND	ND

Quercitrin	ND	ND	(0.982±0.001)[a]	(2.084±0.001)[b]	ND
Apeginin-7-O-glucoside	(0.683±0.001)[b]	(0.345±0.002)[a]	(5.762±0.001)[d]	(7.942±0.001)[e]	(4.579±0.001)[c]
Quercetin	(0.268±0.001)[a]	(0.281±0.001)[b]	(0.487±0.001)[d]	(0.335±0.001)[c]	(0.612±0.001)[e]
Naringenin	ND	(0.382±0.001)	ND	ND	ND
Luteolin	ND	(2.462±0.001)[a]	(4.468±0.001)[c]	ND	(4.200±0.002)[b]
Cirsiliol	ND	(0.216±0.001)[a]	(1.277±0.002)[d]	(0.745±0.002)[b]	(1.006±0.002)[c]
Total phenolic acid/(mg/100 g)	(166.825±0.055)[b]	(262.339±0.043)[d]	(303.930±0.029)[e]	(199.781±0.014)[c]	(74.263±0.010)[a]
Total flavonoid/(mg/100 g)	(1.386±0.001)[a]	(6.938±0.004)[b]	(15.370±0.001)[e]	(11.242±0.001)[d]	(10.397±0.002)[c]
Total/(mg/100 g)	(168.210±0.055)[b]	(269.277±0.044)[d]	(319.300±0.029)[e]	(211.024±0.014)[c]	(84.660±0.009)[a]
DPPH/(mg TE/100 g)	(11.63±2.01)[a]	(26.77±2.30)[b]	(31.16±0.43) [b]	(48.50±2.14)[c]	(47.53±2.47)[c]
FRAP/(mg TE/100 g)	(1.54± 0.24)[a]	(11.41±1.69) [b]	(12.88±0.69) [bc]	(15.20± 0.18)[c]	(39.56±0.06)[d]
Residue	A	ABH	ADN	AS	AP
w(phenolic acid)/mg/100 g					
Quinic acid	(201.451±0.002)[e]	(44.115±0.001)[d]	(40.014±0.002)[c]	(19.000±0.001)[a]	(21.078±0.001)[b]
Chlorogenic acid	(12.611±0.001)[e]	(7.679±0.002)[c]	(7.891±0.001)[d]	(6.058±0.001)[a]	(7.273±0.002)[b]
Caffeic acid	(47.841±0.001)[a]	(53.439±0.001)[b]	(57.057±0.002)[d]	(54.138±0.001)[c]	(67.899±0.001)[e]
1,3-di-O-caffeoylquinic acid	(14.833±0.002)[a]	(42.334±0.001)[d]	(30.742±0.001)[b]	(33.034±0.001)[c]	(33.279±0.001)[c]
trans-Ferulic acid	(0.343±0.001)[a]	(0.898±0.001)[e]	(0.530±0.001)[d]	(0.392±0.001)[c]	(0.359±0.001)[b]
o-Coumaric acid	ND	(4.982±0.001)[d]	(1.834±0.001)[a]	(4.965±0.005)[c]	(4.084±0.001)[b]
Rosmarinic acid	(8.046±0.002)[a]	(21.451±0.001)[b]	(25.756±0.002)[d]	(28.543±0.002)[e]	(22.776±0.002)[c]

Salvianolic acid	(9.540±0.001)[e]	(6.695±0.001)[d]	(4.558±0.001)[c]	(2.946±0.001)[b]	(2.243±0.001)[a]
w(flavonoid)/mg/100 g					
Hyperoside	(0.510±0.001)[a]	(2.234±0.002)[e]	(1.007±0.001)[b]	(1.819±0.001)[d]	(1.641±0.001)[c]
Naringin	(1.466±0.003)[a]	(4.215±0.002)[b]	ND	ND	ND
Quercitrin	ND	ND	ND	(1.984±0.001)[a]	(2.100±0.001)[b]
Apeginin-7-O-glucoside	(0.967±0.001)[b]	(0.859±0.001)[a]	(0.997±0.001)[c]	(3.273±0.002)[e]	(2.318±0.001)[d]
Quercetin	(1.994±0.001)[b]	(3.599±0.001)[d]	(2.954±0.001)[c]	(1.753±0.002)[a]	(4.666±0.001)[e]
Naringenin	(1.235±0.001)[d]	(1.826±0.001)[e]	(0.982±0.001)[b]	(0.763±0.001)[a]	(1.154±0.001)[c]
Luteolin	ND	(11.417±0.001)[b]	(45.836±0.002)[d]	(5.517±0.001)[a]	(27.719±0.002)[c]
Cirsiliol	(0.642±0.001)[a]	(9.025±0.001)[e]	(8.036±0.002)[c]	(2.893±0.006)[b]	(8.419±0.001)[d]
Total phenolic acid/(mg/100 g)	(294.705±0.571)[e]	(181.593±0.008)[d]	(168.382±0.003)[c]	(149.076±0.006)[a]	(158.992±0.002)[b]
Total flavonoid/(mg/100 g)	(6.814±0.031)[a]	(33.175±0.003)[c]	(59.810±0.003)[e]	(17.997±0.006)[b]	(48.817±0.002)[d]
Total/(mg/100 g)	(301.519±0.586)[e]	(214.768±0.006)[c]	(228.194±0.003)[d]	(167.074±0.009)[a]	(207.009±0.001)[b]
DPPH/(mg TE/100 g)	(27.65±3.03)[a]	(45.98±2.54)[b]	(52.92±0.64)[c]	(50.61±0.48)[bc]	(53.26±0.31)[c]
FRAP	(13.97±2.80)[b]	(12.31 ±0.13)[a]	(36.10 ±5.99) [c]	(25.40 ±1.52)[bc]	(52.61 ±4.98)[d]

Data are expressed on a fresh mass basis as mean value±standard deviation, *N*=3. Mean values followed by different letters in superscript within columns indicate significant differences at $p \leq 0.05$ according to Tukey's test. ND=not detected, A=blanched almonds, BH=Besser Helou, DN=Deglet Nour, S=date syrup, P=date powder

Table 3. Color properties of raw ingredients, beverages, and their corresponding residues

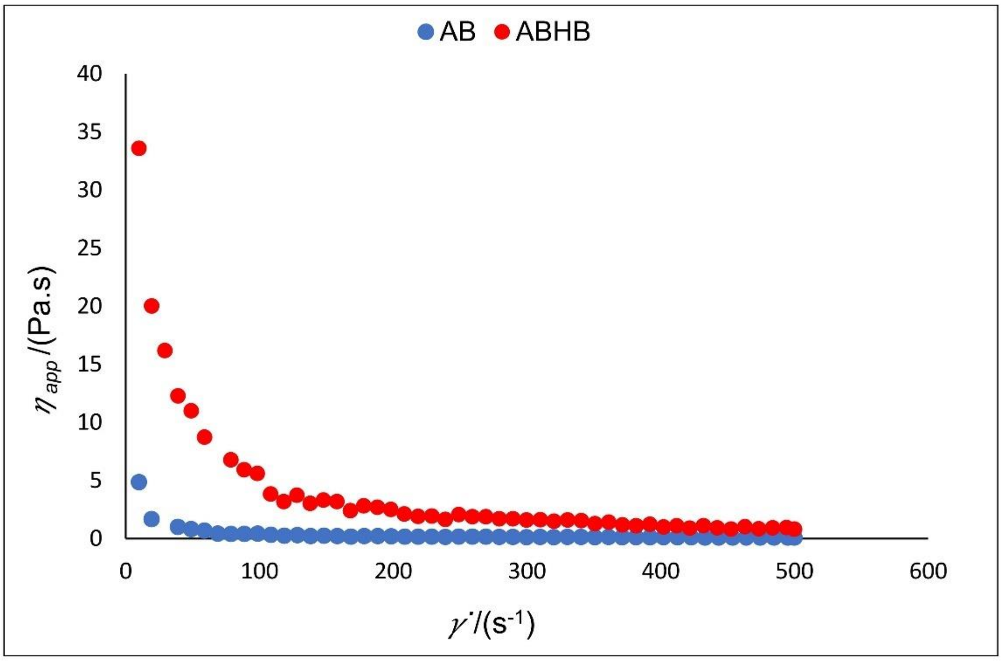
Ingredient	Blanched almonds	Besser Helou	Deglet Nour	Syrup	Powder
*L**	(75.94± 0.43)[e]	(62.27± 1.92)[d]	(46.07± 0.09)[b]	(4.23± 0.25)[a]	(55.83± 0.26)[c]
*a**	(2.59± 0.55)[a]	(4.25± 0.11)[a]	(8.08± 0.39)[c]	(8.04± 0.17)[c]	(11.75± 0.38)[d]
*b**	(15.01± 0.56)[c]	(26.38± 1.10)[e]	(12.62± 0.34)[b]	(-0.17± 0.04)[a]	(19.15± 0.34)[c]
WI	(71,52±0,71)[e]	(53.76±2.20)[d]	(44.03±0.12)[b]	(3.90±0.52)[a]	(50.44±0.23)[c]
YI	(28.24±1.20)[b]	(60.61±4.31)[e]	(39.12±1.11)[c]	(-5.10±1.58)[a]	(49.01±0.73)[d]
BI	(23.81±1.57)[a]	(58.18±5.11)[d]	(43.84±1.11)[b]	(96.59±3.59)[e]	(56.13±0.47)[c]
Beverage	**A**	**ABH**	**ADN**	**AS**	**AP**
*L**	(95.95±1.76)[d]	(75.36± 2.79)[c]	(66.70±1.53)[b]	(65.10±1.16)[b]	(50.50±1.93)[a]
*a**	(2.34±0.15)[a]	(4.40±0.99)[ab]	(9.29±2.00)[c]	(6.93±0.48)[bc]	(15.48±0.24)[d]
*b**	(8.55±0.56)[a]	(12.36±0.50)[b]	(13.12±0.99)[b]	(20.92±1.21)[d]	(16.20±0.20)[c]
WI	(90.15 ±0.59)[e]	(72.05±2.50)[d]	(62.96±0.60)[c]	(58.71±0.71)[b]	(46.99±3.01)[a]
YI	(12.73±0.76)[a]	(23.44±1.16)[b]	(28.08±1.58)[c]	(45.90±2.24)[d]	(45.87±1.64)[d]
BI	(10.78±0.50)[a]	(21.62±1.19)[b]	(31.29±2.98)[c]	(45.41±1.69)[d]	(59.67±2.70)[e]
Residue	**A**	**ABH**	**ADN**	**AS**	**AP**
*L**	(81.47±4.98)[d]	(80.28±1.94)[d]	(70.60±2.26)[c]	(46.09±1.53)[a]	(56.31±1.14)[b]
*a**	(1.37±0.60)[a]	(2.63±1.77)[ab]	(2.27±1.51)[ab]	(9.81±3.71)[c]	(7.55±1.73) [bc]
*b**	(2.37±0.68)[a]	(4.10±1.97)[a]	(5.95±2.27)[a]	(14.93±0.35)[b]	(18.73±0.80)[b]
WI	(81.25±4.91)[d]	(79.57±1.85)[d]	(69.84±2.42)[c]	(43.11±1.14)[a]	(51.84±1.12)[b]
YI	(4.15±1.17)[a]	(7.25±3.42)[a]	(12.07±4.66)[a]	(46.33±2.32)[b]	(47.52±1.93)[b]
BI	(4.05±0.29)[a]	(7.40±0.82)[a]	(10.91±4.95)[a]	(53.43±3.46)[b]	(49.09±1.84)[b]

Data are expressed as mean value±standard deviation, *N*=3. Mean values followed by different letters in superscript within columns indicate significant differences at $p \leq 0.05$ according to Tukey's test. *L**=lightness, *a**=redness, *b**=yellowness, WI=whiteness index, YI=yellowness index, BI=browning index, A=blanched almonds, BH=Besser Helou, DN=Deglet Nour, S=date syrup, P=date powder

Table 4. Power law constants describing the steady-shear rheological behavior of beverages based on almonds (AB), Besser Helou (ABHB), Deglet Nour (ADNB), date syrup (ASB), and date powder (APB), evaluated only within the shear-thinning regions, along with the extent of shear thickening (η_{top}/η_{onset})

Beverage	K/(Pa.s^n)	n	R^2	η_{top}/η_{onset}
AB	(29.06±2.00)[b]	(0.025±0.001)[b]	0.9986	-
ABHB	(385.10±2.00)[c]	(0.027±0.001)[b]	0.9764	-
ADNB	(22.09±1.00)[a]	(0.162±0.002)[d]	0.9676	(1.88±0.01)[b]
ASB	(28.95±1.00)[b]	(0.068±0.001)[c]	0.8879	(1.26±0.01)[a]
APB	(430.74±2.00)[d]	(0.001±0.001)[a]	0.9239	(3.63±0.01)[c]

a)



b)

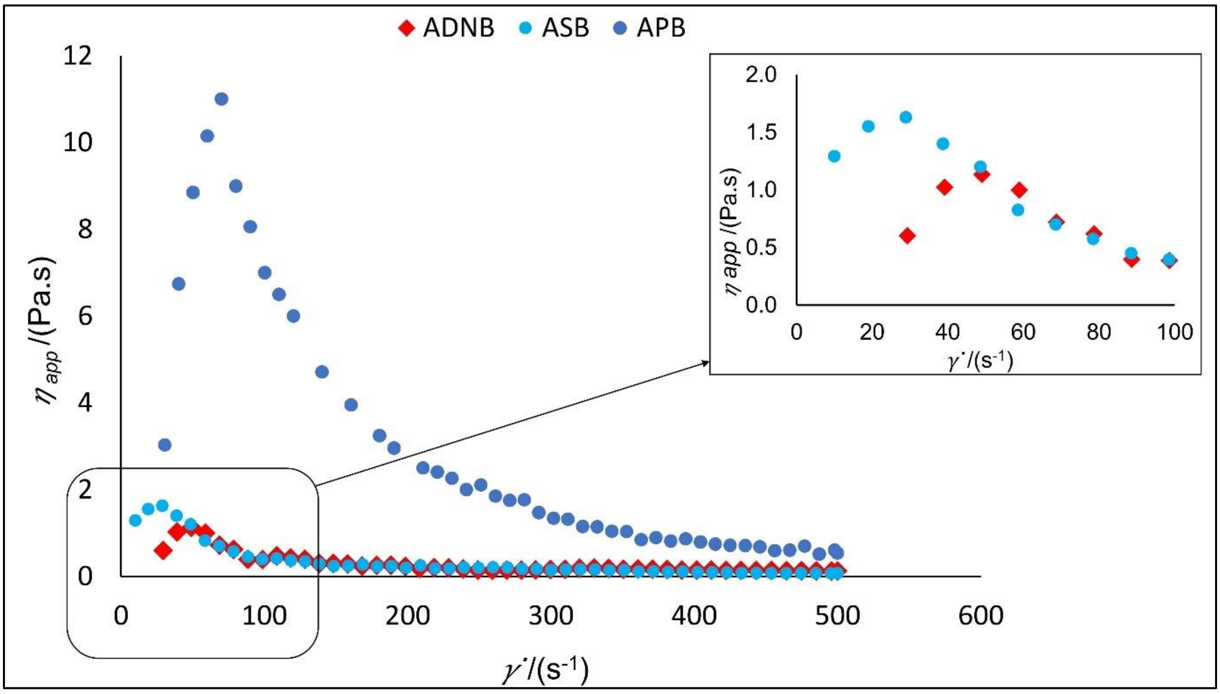


Fig. 1. Flow curves of beverages based on: a) almonds (AB) and Besser Helou (ABHB), Deglet Nour (ADNB), date syrup (ASB), and date powder (APB) showing apparent viscosity ($\eta_{\mathrm{app}}/(\mathrm{Pa}\cdot\mathrm{s})$) as a function of shear rate ($\dot{\gamma}/\mathrm{s}^{-1}$). A magnified view of the low-shear-rate region (upper right panel) highlights the shear-thickening behavior observed below approximately 80 s^{-1}, followed by the onset of shear-thinning at higher shear rates

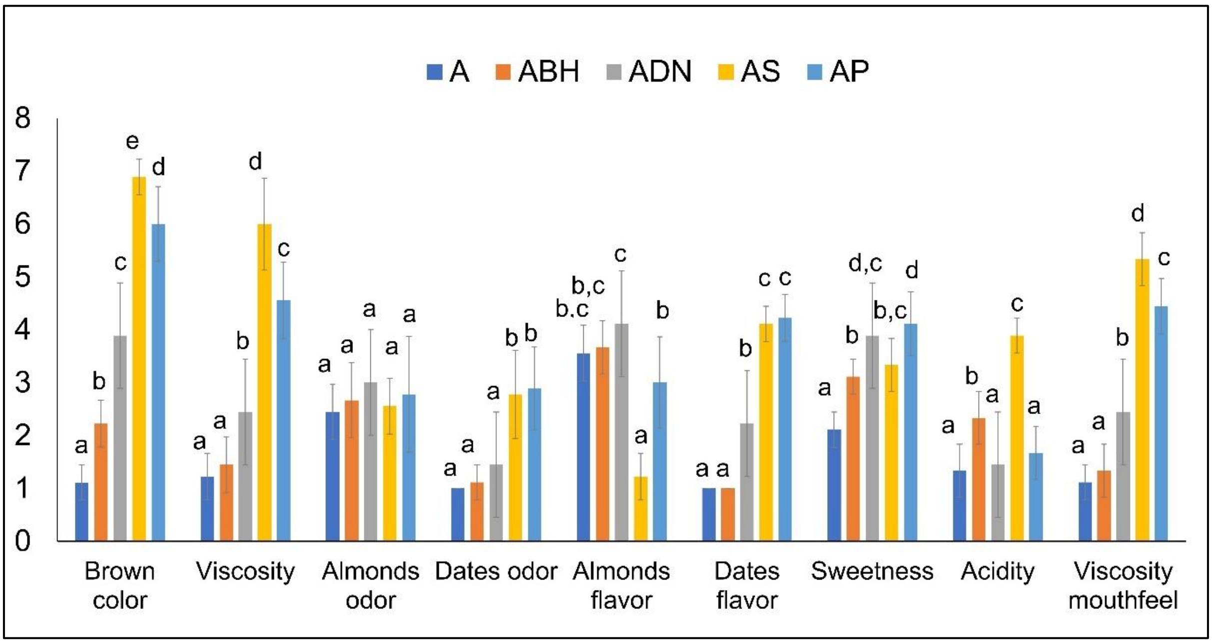


Fig. 2. Descriptive sensory profiles of beverages based on almonds (A), Besser Helou (ABH), Deglet Nour (ADN), date syrup (AS) and date powder (AP)

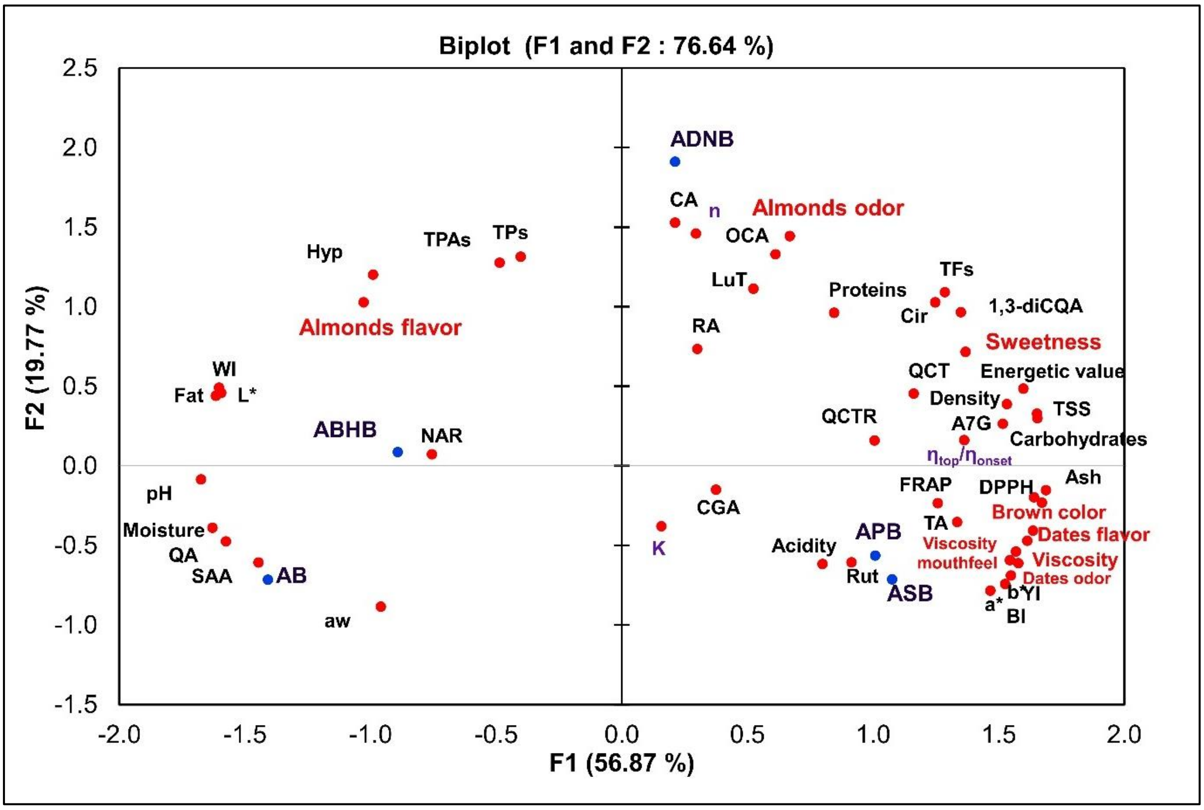


Fig. 3. Principal component analysis of sensory attributes (red color) and nutritional, physicochemical and antioxidant properties of beverages based on almonds (AB) and beverages

fortified with Besser Helou (ABHB), Deglet Nour (ADNB), date syrup (ASB), and date powder (APB). QA=quinic acid, CGA=chlorogenic acid, CA=caffeic acid, 1,3-diCQA=1,3-di-O-caffeoylquinic acid, OCA=*o*-coumaric acid, RA=rosmarinic acid, SAA=salvianolic acid, Rut=rutin, Hyp=hyperoside, NAR=naringin, QCTR=quercitrin, A7G=apigenin-7-O-glucoside, QCT=quercetin, NRG=naringenin, LuT=luteolin, Cir=cirsiliol, TPAs=total phenolic acids, TFs=total flavonoids, TPs=total phenolics, TSS=total soluble solids, TA=titratable acidity, a_w=water activity, L^*=lightness, a^*=redness, b^*=yellowness, WI=whiteness index, YI=yellowness index, BI=browning index, K=consistency index, n=flow index, η_{top}/η_{onset}=extent of shear thickening, DPPH and FRAP=antioxidant activities

Fig. 4. Hedonic evaluation of beverages based on almonds (A), Besser Helou (ABH), Deglet Nour (ADN), date syrup (AS) and date powder (AP)

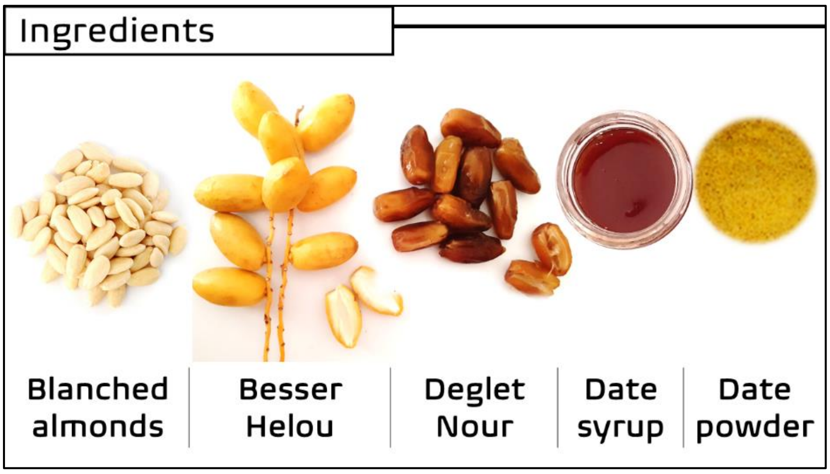


Fig. S1. Visual aspects of ingredients

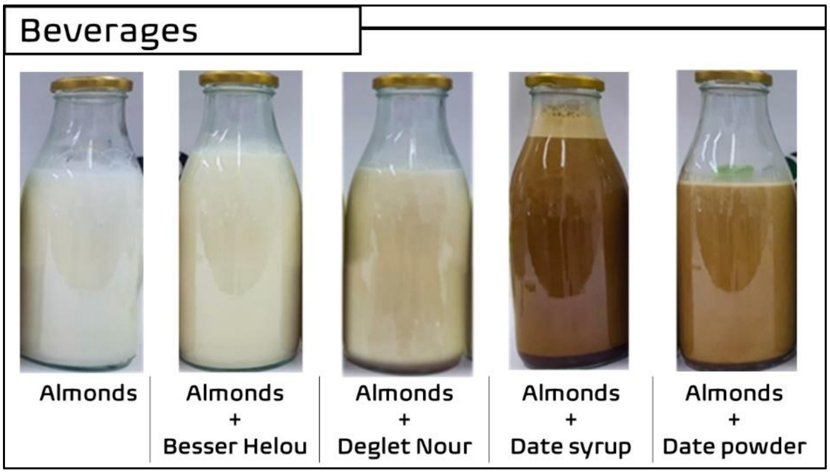


Fig. S2. Visual aspects of beverages

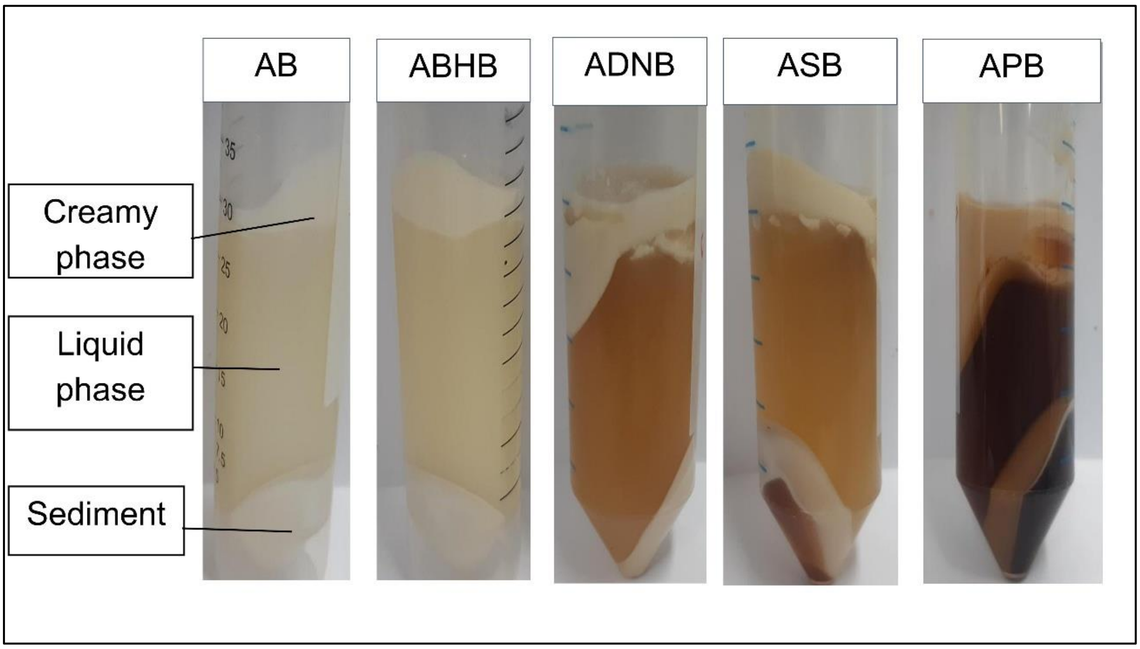


Fig. S3. Different phases obtained after centrifugation of beverages based on almonds (AB), Besser Helou (ABHB), Deglet Nour (ADNB), date syrup (ASB), and date powder (APB)

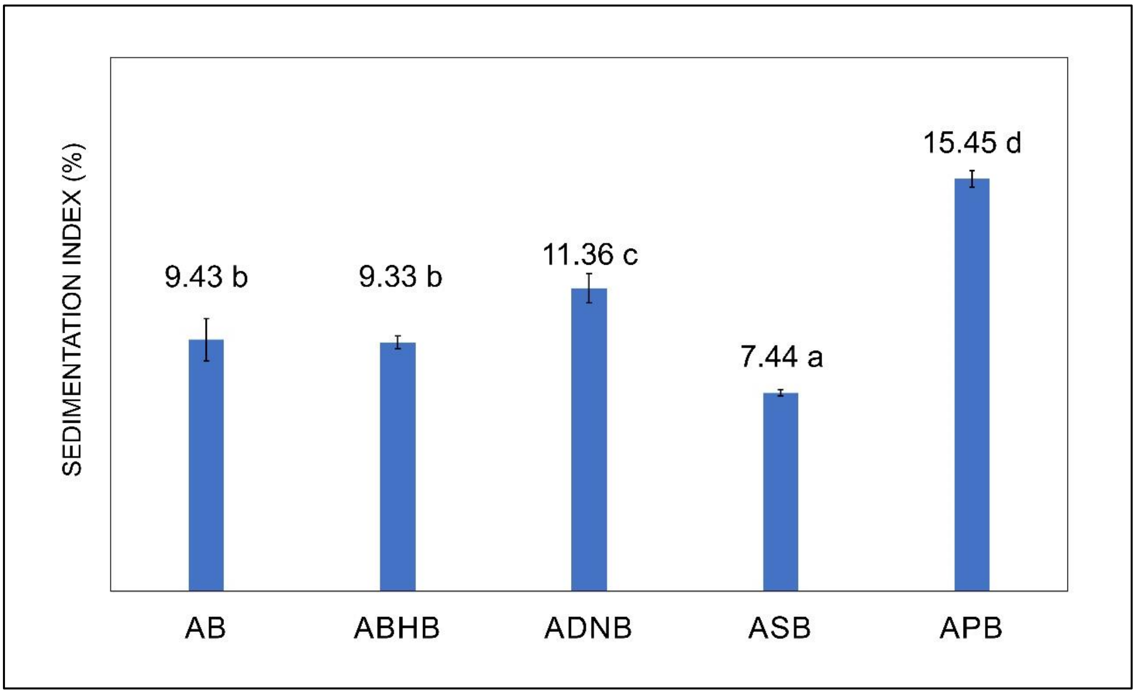
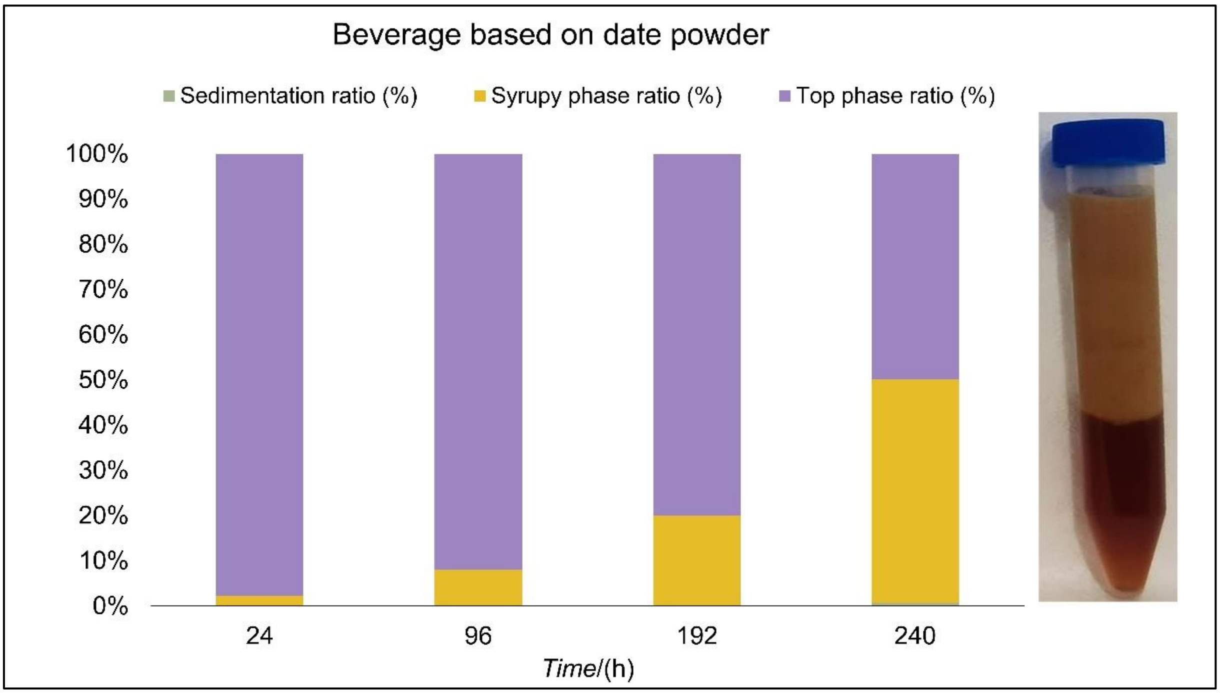
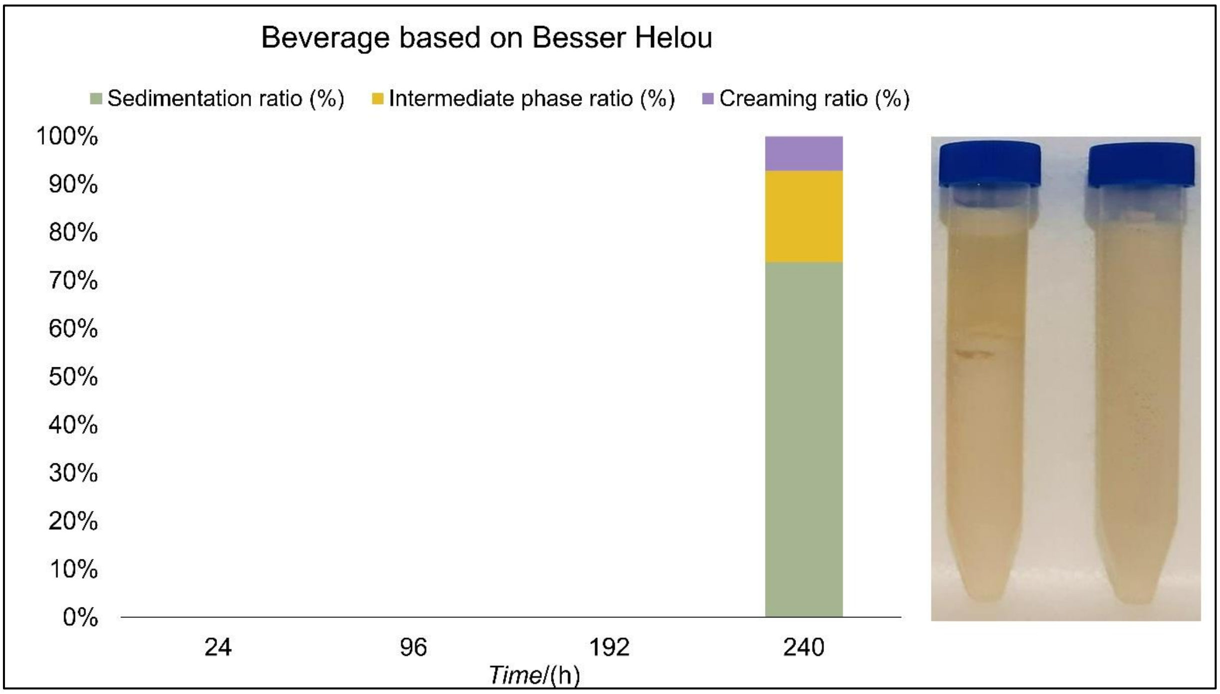


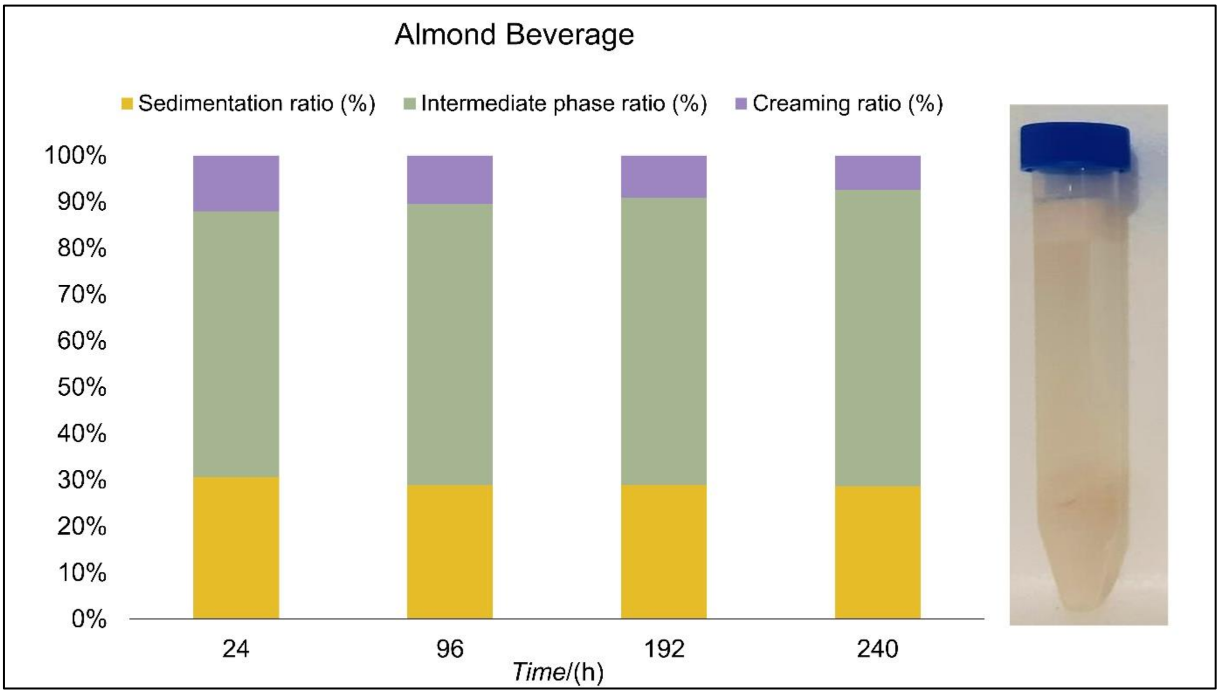
Fig. S4. Sedimentation index of beverages based on almonds (AB), Besser Helou (ABHB), Deglet Nour (ADNB), date syrup (ASB), and date powder (APB) a)


Beverage based on date powder
Sedimentation ratio (%)
Syrupy phase ratio (%)
Top phase ratio (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
24
96
192
240
Time/(h)

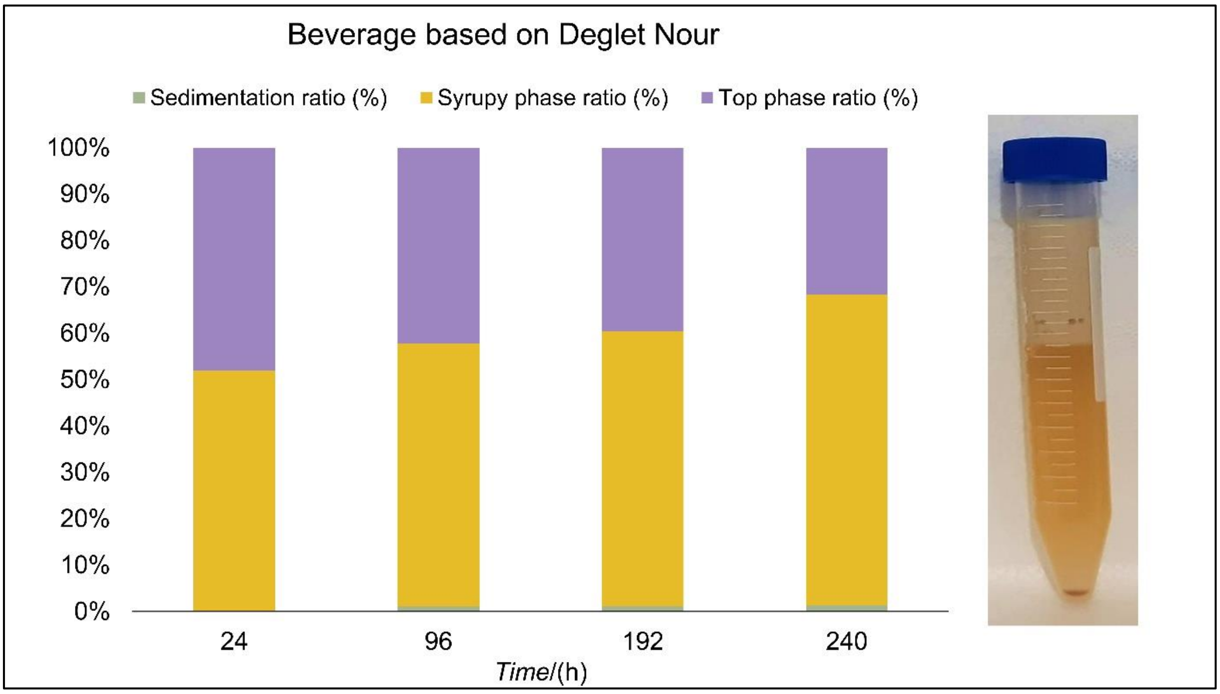
b)


Beverage based on Besser Helou
Sedimentation ratio (%)
Intermediate phase ratio (%)
Creaming ratio (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
24
96
192
240
Time/(h)

c)


Almond Beverage
Sedimentation ratio (%)
Intermediate phase ratio (%)
Creaming ratio (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
24
96
192
240
Time/(h)

d)


Beverage based on Deglet Nour
Sedimentation ratio (%)
Syrupy phase ratio (%)
Top phase ratio (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
24
96
192
240
Time/(h)

e)

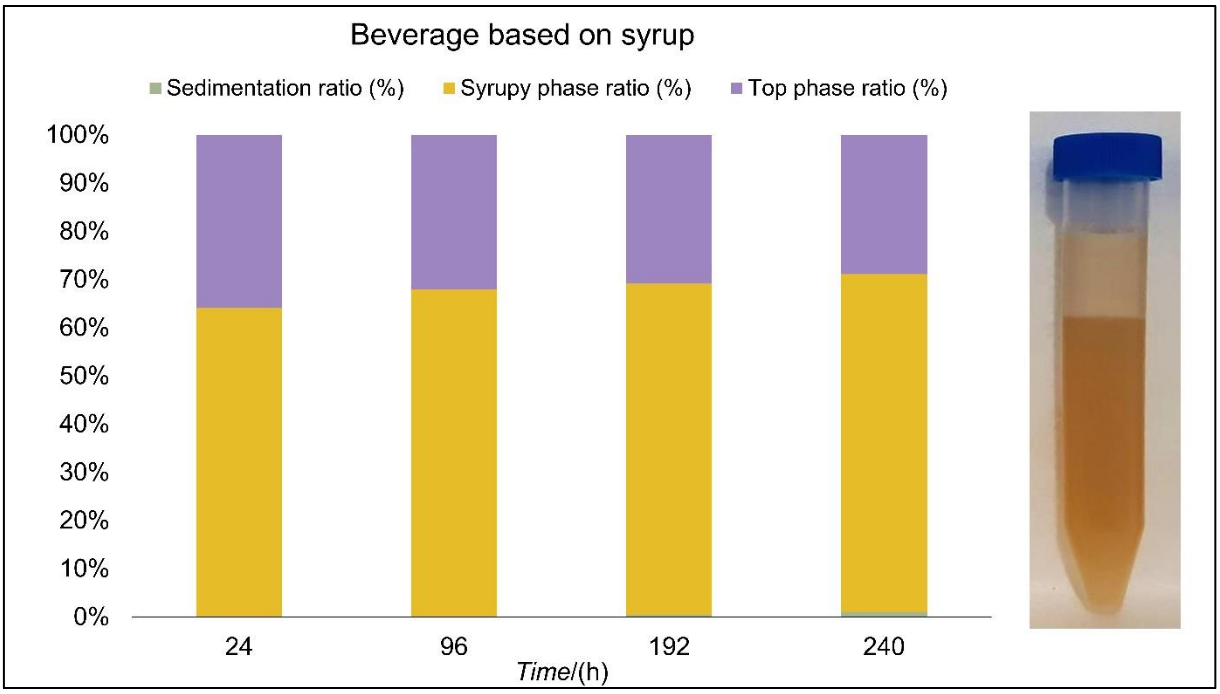


Fig. S5. Stability of beverages based on: a) date powder, b) Besser Helou, c) almonds, d) Deglet Nour, and e) date syrup at 4 °C during 240 h

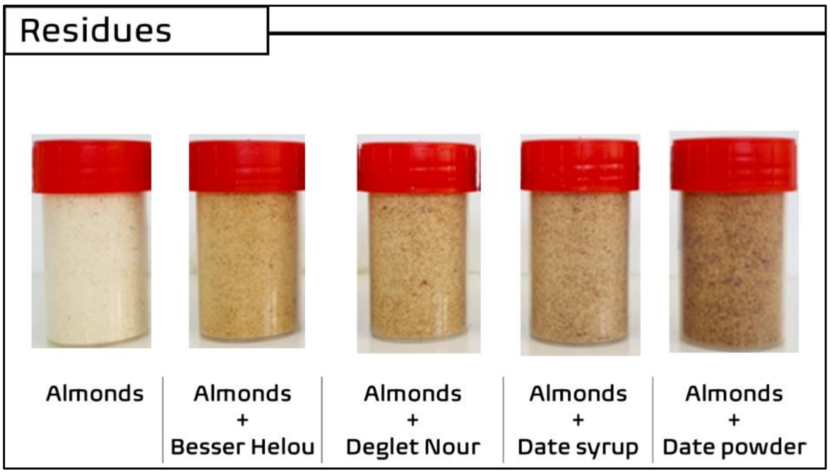


Fig. S6. Visual aspects of residues