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AFBC
Agriculture and Food Bioactive Compounds

Quality attributes and antioxidants of yogurt supplemented with lemon peel powder

Nesrine Ghanem[1,2], Nouha M'hiri[2], Wafa Mkadem[2], Khaoula Belguith[2] and Nourhène Boudhrioua[2*],

[1]Laboratory of Applied Fluid Mechanics, Process Engineering and Environment, National School of Engineers of Sfax, Route Soukra Km 3.5 BP 1173 3038, Sfax, Tunisia; [2]LR Physiopathology, Food and Biomolecules, LR17ES03, Higher Institute of Biotechnology of Sidi Thabet, University of Manouba, BP-66, 2020 Ariana-Tunis, Tunisia.

***Corresponding author:** Nourhène Boudhrioua, LR Physiopathology, Food and Biomolecules, LR17ES03, Higher Institute of Biotechnology of Sidi Thabet, University of Manouba, BP-66, 2020 Ariana-Tunis, Tunisia.

Submission Date: January 2nd, 2025; **Acceptance Date:** February 17th, 2025; **Publication Date:** February 24th, 2025

Please cite this article as: Ghanem N., M'hiri N., Mkadem W., Belguith K., Boudhrioua N. Quality attributes and antioxidants of yogurt supplemented with lemon peel powder. *Agriculture and Food Bioactive Compounds* 2025; 1(2): 32-46. DOI: https://doi.org/10.31989/afbc.v1i2.1537

ABSTRACT

Background: Yogurt is one of the most consumed fermented dairy products. Despite its high nutritional value and specific sensory properties, it cannot be considered a significant source of antioxidants or prebiotics. Lemon peel powder, a natural source of fiber and antioxidants, could be used for supplementation of fermented dairy products.

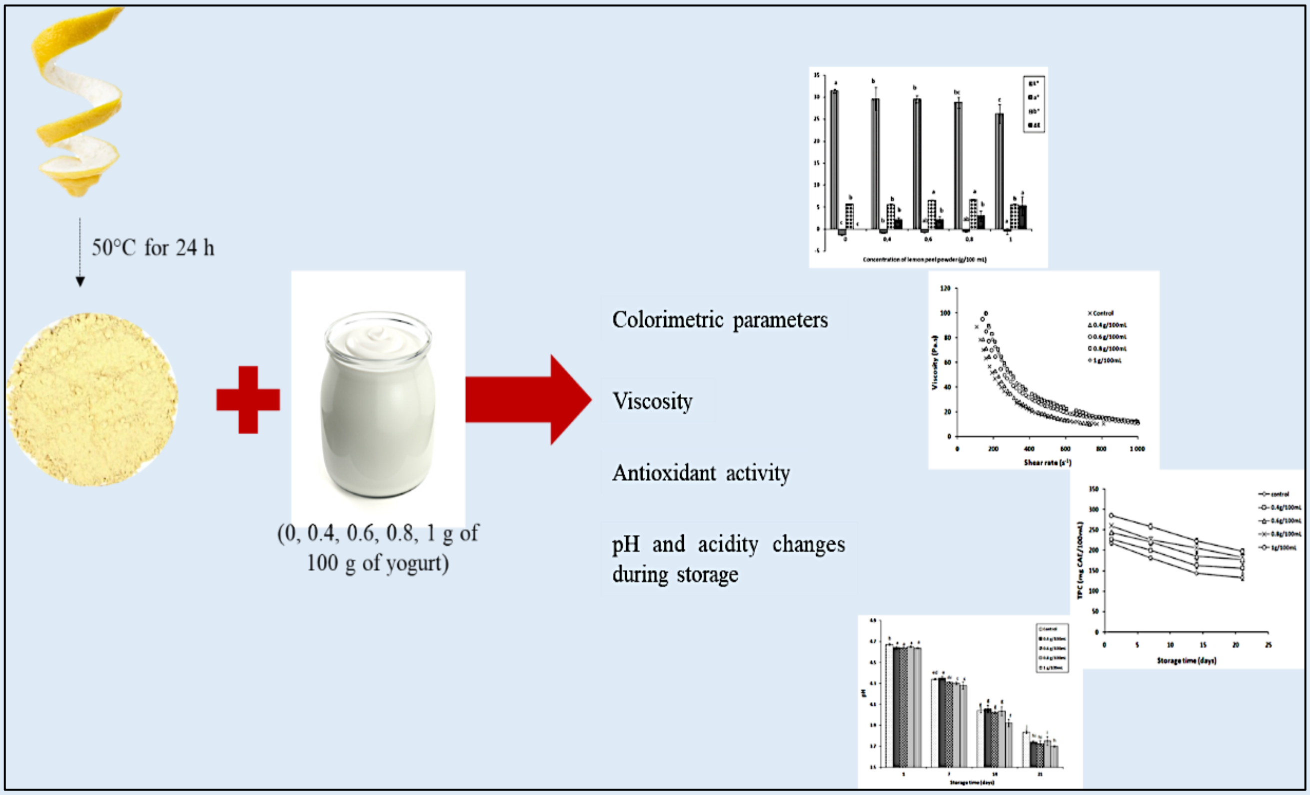
Objective: This work aims to investigate the effect of fortifying stirred yogurt with lemon peel powder (0-1%) on its main quality attributes: physiochemical (acidity pH, viscosity, color), antioxidant, textural, and sensory properties.

Methods: The lemon peels were oven-dried at 50°C for 24 h and ground to a particle size of 0.70-0.99 mm. The phytochemical composition (moisture, ashes, fat, protein, total sugar, fiber, mineral, total phenolic and flavonoid content) of lemon peel powder was determined. The lemon peel powder (0, 0.4, 0.6, 0.8, 1 g of 100 g of yogurt) was added. Color, textural properties, and sensory analysis of yogurt supplements with and without different ratios of lemon peel powder were determined. The antioxidants (total phenols and radical scavenging activity) of stirred yogurt and its stability during 21 days of cold storage were evaluated.

Results: Supplementation of stirred yogurt with 1% lemon peel powder allows for the improvement of its antioxidant and textural properties without any significant deterioration of its overall acceptability ($p>0.05$). The supplemented yogurt samples presented higher titratable acidity and lower pH values during cold storage than those unfortified yogurt. The total phenolic content and radical scavenging activity of the fortified stirred yogurt increased with increasing lemon peel powder content (+32% for total phenols and +34% for radical scavenging activity for 1% fortified yogurt) and decreased with storage time (-31% for total phenols and -20% for radical scavenging activity for 1% fortified yogurt after 21 days of cold storage).

Conclusion: Fortifying yogurt with lemon peel powder improved its rheological properties, particularly its viscosity, firmness, and cohesiveness. Fortifying stirred yogurts with 1% lemon peel powder maintained the highest levels of total phenols and, importantly, radical-scavenging antioxidant activity.

Keywords: yogurt, lemon peel, antioxidants, texture, sensory attributes.



INTRODUCTION

Yogurt remains among the most consumed fermented dairy products made by the bacterial fermentation of milk [1]. Yogurt has been considered a healthy fermented milk product with an excellent source of protein, calcium, vitamins, fat, and minerals [2]. Additionally, yogurt provides lactic acid and metabolites (mainly organic acids and exopolysaccharides) produced by the lactic bacteria [2], which improves its functional and sensory properties and prevents the growth of pathogenic bacteria [2-3]. Yogurt provides added health benefits by enhancing nutrient absorption and digestion [1-2]. It allows the control of intestinal infections, stimulation or modulation of the immune system, improvement of lactose utilization, and control of serum cholesterol levels [2].

Yogurt is poor in antioxidants and fiber [2]. Its fortification with new bioactive natural ingredients, allowing the development of beneficial health functions and the improvement of its technological properties, has gained great interest for industrial applications [4-10].

Many studies have been done on fortifying and expanding the nutritional quality of yogurt including the addition of selenium [11], phenolic compounds from grape and callus extract [3,12], fiber-rich cranberry pomace [13], wine grape pomace [14], Pleurotusostreatus aqueous extract [15], hazelnut skins [16], mango peel [17], wild pomegranate peel [18], vitamin-A from pumpkin [19], calcium [20], pineapple peel [21], dietary fiber from orange [22- 26], lemon juice byproduct [27], and citrus peels [28-29]. These studies demonstrated that fortifying with natural ingredients increases the health benefits and sensory attributes of yogurt [2].

Citrus peel, a fruit-processing co-product, is a substantial source of naturally rich health-promoting compounds, including phenols, and has great potential as a dietary supplement [29]. Lemon peel is rich in nutritional ingredients such as sugars (14.892 ± 0.610 g/100g dry matter), proteins (5.872 ± 1.170 g/100g dry matter), fat (0.489 ± 0.157 g/100g dry matter), minerals (4.683 ± 0.278 g/100g dry matter), and in bioactive compounds like dietary fibers (39.135 ± 1.250 g/100g dry matter), and phenols (2.451 ± 0.022 g caffeic acid/100 g dry matter) [30]. Subsequently, lemon peels containing flavonoids and fibers could be used as functional ingredients for supplementation of dairy products [28-30]. Dietary fibers are interesting for industrial valorization because of their desirable nutritional properties like decreasing constipation risk, hypercholesterolemia, and diabetes [17, 19-20, 28], their technological properties such as water and oil holding capacities, thickening, texturizing, flavoring functionalities [27, 31-33] and their availability as food industry co-products [34- 35].

The objective of this work was to fortify yogurt with lemon peel powder and to determine the effect of its incorporation on the main physicochemical properties (rheological, color, and sensory attributes) and on the antioxidants (total phenols and radical scavenging activity) of stirred yogurt and its stability during 21 days of cold storage.

MATERIALS AND METHODS

Materials: Fresh *Citrus limon v. lunari* fruits were collected from Beni Khalled (Nabeul, Tunisia). A coffee grinder (Moulinex®, France) was used to grind the dried lemon peels. The lemon peel powder (LPP) was stored in vacuum packaging bags at 4 °C before experimentation. Stirred yogurt was prepared at a semi-pilot scale at the Sectoral Center for Training in Agro-Food Industries (El Khadra City, Tunis, Tunisia).

Stirred yogurt ingredients (sucrose, starch, and milk powder) were purchased from MAFI Dairy company (Tunis, Tunisia), and the pasteurized whole milk (80 °C, 3 min) was provided by the Sectoral Center for Training in Agro-Food Industries (El Khadra city, Tunis, Tunisia). A Lactoscan MCCW (Milkotronic Ltd, Bulgaria) was used to analyze the proximate composition of pasteurized milk. The yogurt starter culture used was YO-MIXTM Yogurt cultures, DANISCO, France. A colorimeter type (CPCE, TCR200, Spain) was used to determine the colorimetric parameters. A rheometer (RM 180 Rheomat, Rheometric Scientific, Julabo F25) was used for the viscosity determination.

The Texture Analyzer used was Analysis LLOYD instruments, France, and equipped with a 25 mm diameter acrylic cylinder probe. Plastic polyethylene-coated pots of 200 mL each were used to contain yogurt. A pH meter (Mettler Toledo, MP 220) was used for pH measurement. Acetone solution (70%), HCl (0.1%) (v/v), and Whatman No.1 paper were used for the extraction of phenolic compounds. Folin-Ciocalteu reagent, $CaCO_3$ solution, caffeic acid, and spectrophotometer (Halo RB-10, France) were used in the determination of total phenolic and flavonoid contents. DPPH solution was used for the determination of antioxidant activities.

Preparation of lemon peel powder: The fresh lemon peels were separated from the endocarp and scalded in a water bath (90°C, 5 min). The peels were oven-dried at 50°C for 24 h. To achieve a standard particle size of 0.70-0.99 mm. The peels were ground. The LPP was stored in vacuum packaging bags at 4°C before experiments.

The moisture content and the total dietary fiber content of LPP were about 0.113 ± 0.007 g water/g DM and 39.1355 ± 0.051 g/100 g DM, respectively.

Phytochemical characterization of LPP: Moisture, ashes, fat, protein, total sugar, fiber, and mineral contents of lemon peel powder were determined according to [30]. The total phenolic content, total flavonoid content, and radical scavenging activity of lemon peel powder were determined according to [34].

Yogurt manufacturing: Stirred yogurt was prepared, and two trials were performed using 20 L of milk for each trial. Sirred yogurt was made using ingredients (sucrose, starch, and milk powder) and pasteurized whole milk (80 °C, 3 min). The approximate composition of pasteurized milk analyzed was 3.43% fat, 3.43% protein, 4.50% lactose, and 0.65% ash. Sucrose (11.50%), milk powder (3.00%), and starch (2.50%) were dissolved in the milk.

The mixture was homogenized and dissolved at 72 °C for 3 min and then cooled at 45 °C. Next, it was inoculated with yogurt starter culture, which is a combination of *Streptococcus thermophilus* and *Lactobacillus Bulgaricus*. Incubation was accomplished at 45 °C until the acidity of 80-85 °D was achieved. The LPP (0, 0.4, 0.6, 0.8, 1 g of 100 g of yogurt) was added and the yogurt was stirred then placed at 4 °C under dark. The fortified and unfortified yogurt samples were analyzed on days 1, 7, 14, and 21 of cold storage. All analyses were triplicate, and the results were represented as mean values ± standard deviation.

Color, textural, and sensory properties of yogurt: Color, textural properties, and sensory analysis of yogurt supplements with or without different ratios of lemon peel powder were determined.

The colorimetric parameters (L*, a*, b*) were determined. The total color difference (ΔE) was calculated by using the equation (Eq. 1). The subscript "0" indicates the color of unfortified yogurt:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad \text{Eq. (1)}$$

Where L* represented the brightness and ranged from 0 (black) to 100 (white); a* ranged from -100 (green) to 100 (redness), and b* varied from -100 (blue) to +100 (yellow).

The yogurt samples were submitted to shear rate variations from 100 to 1000 s-1, which enabled measurements of apparent viscosity values and the determination of the flow curves. The measurements were conducted in a constant-temperature environment (20 °C) for a 2-minute period.

The textural properties of the yogurt were evaluated. The penetration speed of the probe was 5 mm/s to 50 mm height from the yogurt surface. The following parameters were measured: firmness, cohesiveness, and extensibility.

The prepared stirred yogurt samples supplemented or not with lemon peel powder (LPP: 0.4, 0.6, 0.8, and 1%) were placed in plastic polyethylene-coated pots of 200 mL each. They were randomly presented and tasted by 12 trained panelists (aged between 25 and 45 years) from the Sectoral Center for Training in Agro-Food Industries (El Khadra city, Tunis, Tunisia). Hedonic evaluation, including color, taste, flavor, firmness, and overall acceptance, was performed. Evaluation was based on a nine-point scale ranging from 1 (lowest score) to 09 (highest score) [36].

Evolutions of pH, acidity, and antioxidants of yogurt during cold storage: The pH measurement was carried out during 21 days of cold storage. The titratable acidity was determined according to the reference method and expressed as a Dornic degree [37].

Total phenols and radical scavenging activity (RSA) of yogurt were evaluated during 21 days of cold storage.

Yogurt extracts were obtained according to [14] with some modifications. Each yogurt, supplemented or not with LPP (10g), was added to 15 mL of acetone solution (70%) HCl (0.1%) (v/v) and incubated for 24 h at 4 °C. The solutions obtained were filtered through the Whatman No.1 paper.

The total phenol content (TPC) of yogurt was measured using the Folin-Ciocalteu method [14]. The samples were mixed with Folin-Ciocalteu reagent and $CaCO_3$ solution and placed in a water bath at 40 °C for 30 min before spectrophotometric analysis at 765 nm. TPC was expressed as g of caffeic acid equivalent (CAE) per 100 mL of sample ± standard deviation for three triplicates.

The radical scavenging activity of yogurt was determined by the DPPH assay described by [38], with minor modifications. 40 µL of samples were added to 2.9 mL of DPPH solution (0.1 mM in methanol) and incubated in the dark for 30 min. The reduction of the DPPH radical was determined by measuring the absorption at 517 nm. The RSA was calculated between A_0 and A_t, with A_0 as the initial optical density and A_t as the final optical density. The results were expressed as mg Ascorbic Acid Equivalent/100 mL of sample, and the percentage of inhibition was calculated according to the following equation (Eq. (2).

$$Percentage of inhibition = \frac{(A_{0-}A_t)}{A_0} 100 \quad \text{(Eq. 2)}$$

Statistical analysis: Statistical analyses were carried out using the software package IBM. SPSS 20.0 [39]. The mean values were compared by the analysis of variance (ANOVA) at a significant level of 5%. Values having the same letter are not statistically significant according to Duncan's test at a significance level of $p < 0.05$.

RESULTS

Physicochemical properties of lemon peel powder: The results of proximate composition and mineral content of lemon peel powder are presented in **Table 1.** The obtained results indicated low moisture content, high dietary fiber, moderate levels of soluble sugars, low protein, and fat content. A considerable ash content (4.683 ±0.278 g/100 g DM) was also observed in lemon peel powder. Particularly, the powder was rich in calcium (747.359 mg/100 g DM), potassium (527.925 mg/100 g DM), sodium (188.004 mg/100 g DM), and magnesium (182.081 mg/100 g DM). The obtained results revealed the substantial nutritional value of lemon peel, justifying its potential use in functional food formulation.

Table 1. Proximate composition and minerals content of lemon peel powder

Component	Content
Moisture (g /100 g DM)	3.010 ± 0.143
Total Dietary fiber (g /100 g DM)	39.135 ± 1.250
Soluble sugars (g /100 g DM)	14.892 ± 0.610
Protein (g /100 g DM)	5.872 ± 1.17
Fat (g /100 g DM)	1.959 ± 0.632
Ash (g /100 g DM)	4.683 ± 0.278
Minerals	
K (mg/100 g DM)	527.925 ± 67.615
Ca (mg/100 g DM)	747.359 ± 97.005
Na (mg/100 g DM)	188.004 ± 4.006
Mg (mg/100 g DM)	182.081 ± 23.061
Fe (mg/100 g DM)	7.865 ± 0.644
Zn (mg/100 g DM)	8.612 ± 0.020
Cu (mg/100 g DM)	1.19 ± 0.087

Table 2 presents the antioxidant properties of lemon peel powder. The results indicated that the powder possessed a considerable antioxidant capacity (1.02 ±0.610 mg TE/100 g DM) and an inhibition percentage of 68%. The results suggested that lemon peel powder is a promising source of natural antioxidants for applications in food formulation.

Table 2. Total phenolic, total flavonoid contents, and antioxidant activity of lemon peel powder.

	Average value
Total phenolic content (g QE/100 g DM)	2.10 ± 0.080
Total flavonoid content (mg TE/100 g DM)	1.50 ± 0.014
DPPH-RSA (mg TE/100 g DM)	1.02 ± 0.610
Inhibition percentage (%)	68 ± 1

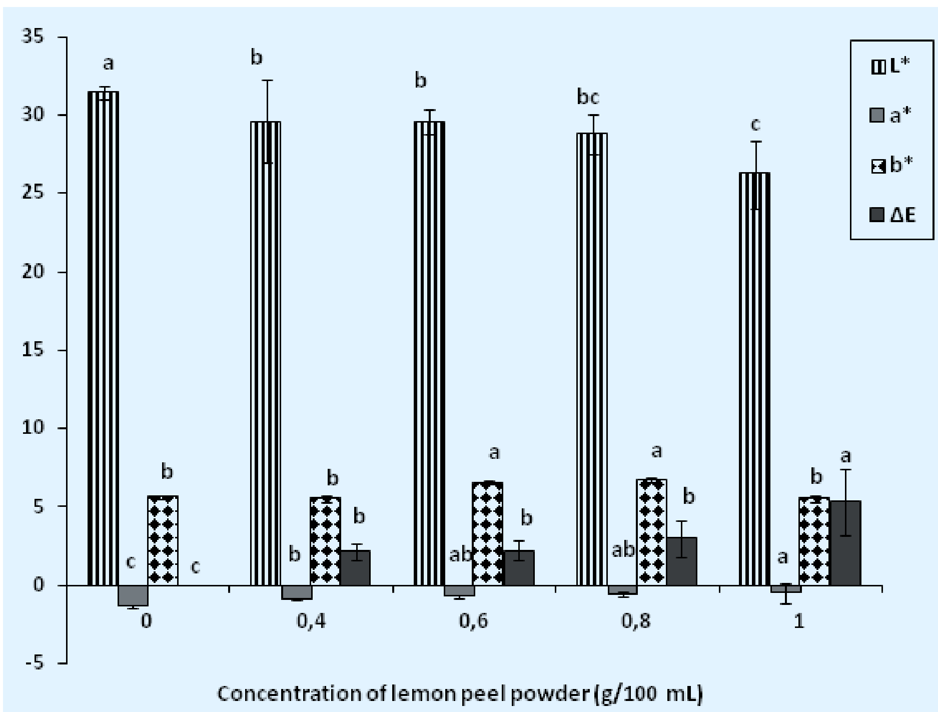


Figure 1. Effect of lemon peel powder supplementation on yogurt at different concentrations on color parameters: L* (lightness), a* (redness), b* yellowness, and ΔE.

Effect of lemon peel powder on colorimetric parameters of yogurt: Colorimetric parameters (L*, a*, b*) of yogurt supplemented or not with LPP were presented in Figure 1.

Figure 1 shows that the unfortified yogurt presents the highest lightness parameter (L* = 31.435 ± 0.445) compared to the supplemented LPP samples. The increase of LPP level from 0 to 1% leads to the decrease of the lightness parameter, without a significant difference ($p < 0.05$) between yogurt supplemented with 0.4% and 0.6% of LPP. The color parameter a* raised significantly ($p < 0.05$) from −1.29 ± 0.11 (control sample) to -0.45 ± 0.62 (1% LPP enriched yogurt). The maximum value of a* (-0.450 ± 0.621) was recorded for supplemented yogurt at 1% of LPP. All reported b* values of fortified or unfortified yogurts were positive, indicating the yellow color of the samples. Yogurt supplemented with 0.6 and 0.8% of LPP shows the highest b* value, indicating the predominance of yellowish tint, but the increase of b* value is not positively correlated to the increase of LPP level.

The total color difference, ΔE, expressing the variation of the L*, a*, and b* parameters compared to the control samples, is generally used to assess global color variation during processing. Our results show the highest ΔE value for yogurt supplemented with 1% LPP (5.319 ± 2.107). All ΔE values are superior to 3, indicating a well-visible (3.0–6.0) variation of yogurt color.

Effect on rheological properties of yogurt: The viscosity (Pa.s) of stirred yogurts supplemented or not with LPP was presented in Figure 2.

All yogurt samples exhibited pseudo-plastic behavior in which the effect of time was not considered. The control yogurt showed a low value of viscosity (88.94 ± 0.02 Pa.s). However, the increase of LPP incorporated dose in yogurts (0.4-1%) induced a significant increase ($p < 0.05$) of viscosity (6.81-12.21%) compared to the unfortified samples. Indeed, for a shear rate of 210 s-1, the viscosity of yogurt supplemented with 1% LPP was ~ 1.54 times higher compared to the control sample. The increase of LPP level from 0.8 to 1% has no significant effect ($p > 0.05$) on the yogurt viscosity. Consequently, an addition of 0.8% is sufficient to obtain an optimal viscosity.

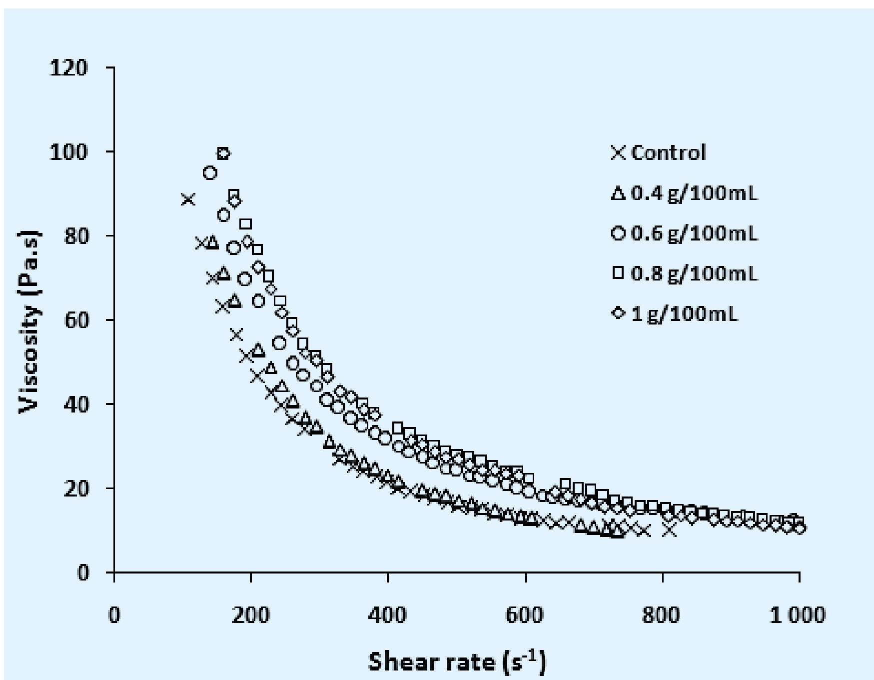


Figure 2. Representative Plot of viscosity (Pa.s) versus shear rate (s^{-1}) of yogurts supplemented with lemon peel powder (0, 0.4, 0.6, 0.8, and 1 %).

Table 3. Mean values for the instrumental parameters of yogurt supplemented with lemon peel powder.

LPP (%)	Firmness	Cohesiveness	Extensibility
0	0.181 ± 0.024^{c}	0.537 ± 0.017^{b}	17.606 ± 0.881^{a}
0.4	0.211 ± 0.023^{c}	0.613 ± 0.081^{ab}	16.552 ± 0.937^{ab}
0.6	0.227 ± 0.036^{bc}	0.617 ± 0.047^{ab}	15.661 ± 0.621^{bc}
0.8	0.271 ± 0.027^{ab}	0.680 ± 0.134^{a}	15.035 ± 0.191^{b}
1	0.309 ± 0.024^{a}	0.695 ± 0.083^{a}	14.922 ± 0.315^{b}

The values for the instrumental texture parameters of yogurt supplemented without and with LPP are shown in Table 3.

The values of firmness and cohesiveness present a significant difference ($p < 0.05$) for the yogurt supplemented with LPP compared to the control sample. Furthermore, as expected, the addition of LPP (0.4, 0.6, 0.8, and 1 %) significantly increased the firmness (16.57, 25.41, 49.72, and 70.71%, respectively) and cohesiveness (14.15, 14.90; 26.63; and 29.42%; respectively) but decreased the extensibility of yogurt.

Effect on sensory attributes of yogurt

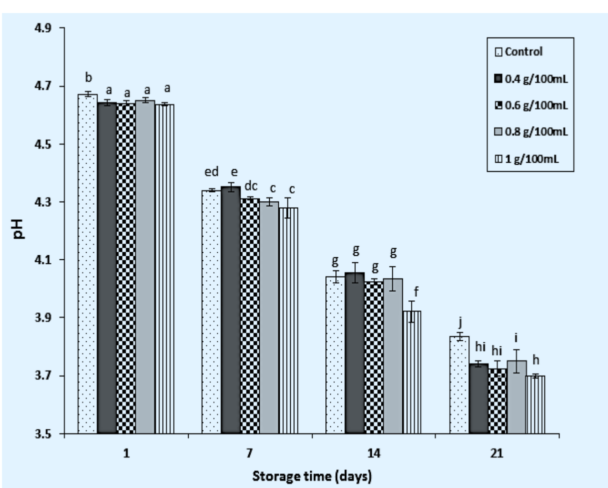
The results of the sensorial analysis are presented in Table 4. The control yogurt obtained the highest sensory score (7.26 ± 1.82 on a nine-point scale, Table 2). However, all stirred yogurts supplemented with LPP received average scores between 6.16 - 6.63 on a 09-point scale.

Table 4. Effect of yogurt supplemented with lemon peel powder on sensory properties.

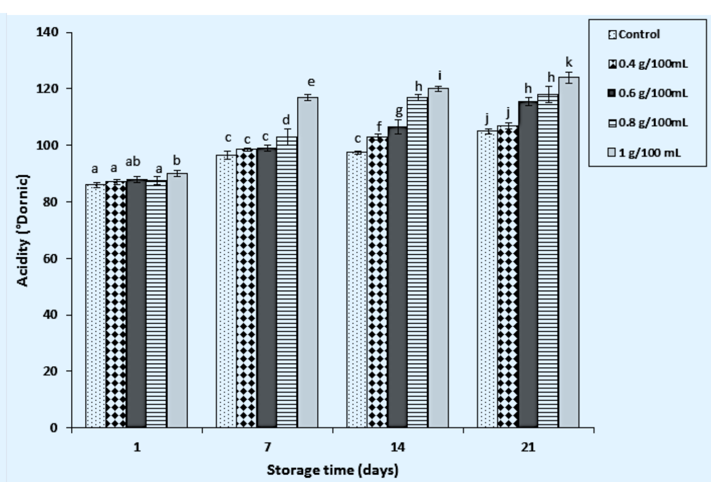
LPP (%)	Color	Taste	Flavor	Firmness	Acceptance
0	6.84 ± 1.34^a	7.21 ± 1.61^a	6.31 ± 1.85^a	7.26 ± 1.52^a	7.26 ± 1.82^a
0.4	6.73 ± 1.69^a	6.21 ± 1.93^a	6.26 ± 1.62^a	6.63 ± 1.46^a	6.63 ± 1.77^a
0.6	5.94 ± 1.84^a	6.36 ± 1.64^a	6.21 ± 1.43^a	6.94 ± 1.10^a	6.44 ± 1.50^a
0.8	6.52 ± 1.90^a	6.53 ± 1.88^a	5.78 ± 1.84^a	6.47 ± 1.64^a	6.56 ± 1.75^a
1	6.60 ± 1.45^a	6.11 ± 1.72^a	6.00 ± 1.69^a	6.42 ± 1.46^a	6.16 ± 1.75^a

The hedonic evaluation revealed no significant difference ($p > 0.05$) between the different samples for the overall acceptance, color, taste, flavor, and firmness among the yogurt samples. Thus, supplementing stirred yogurt with 1% lemon peel powder didn't show any significant deterioration of its sensory properties ($p > 0.05$).

Effect on pH and acidity changes during storage: The results of the acidity and pH of yogurt supplemented with LPP during storage at 4 °C for 21 days are presented in Figure 3.



(a)

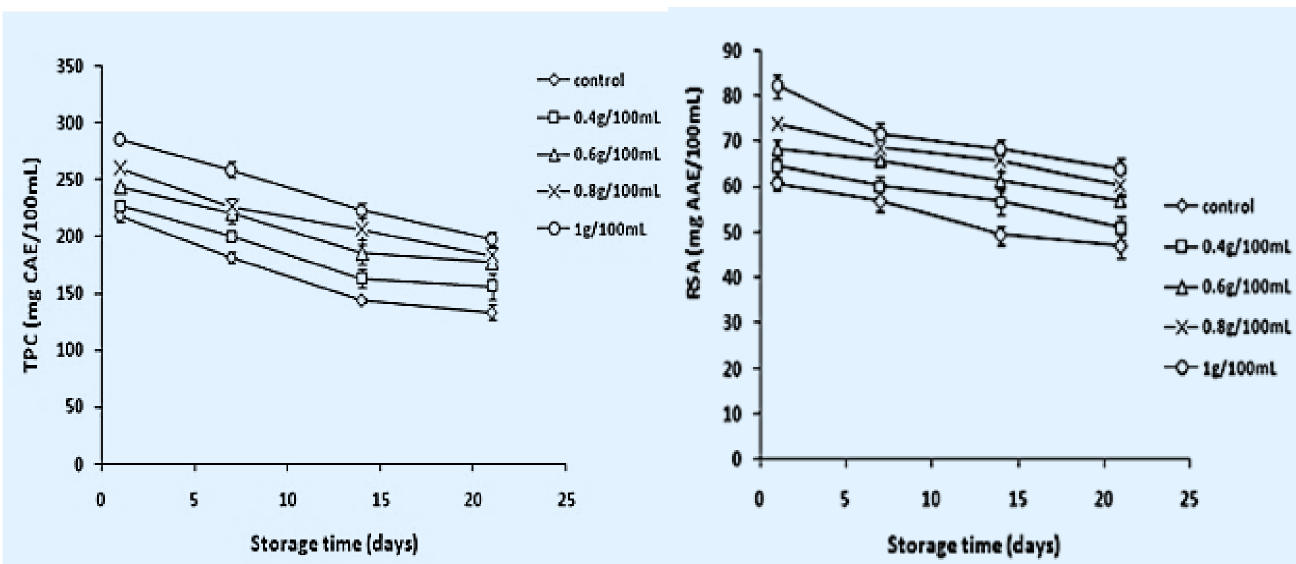


(b)

Figure 3. Effect of yogurt supplemented with lemon peel powder on pH (a) and acidity (b) during 21 days of cold storage at 4°C.

Figure 3 showed that the pH of all samples of yogurt supplemented or not with LPP decreased by 19.92-20.25% during the storage at 4 °C to reach the minimum value at 21 days. Furthermore, the evaluation of acidity during the same period was marked by a significant increase ($p < 0.05$) on the average of 18.69-37.38% for all yogurt samples. These results can be explained by the fact that lactic strains used to produce yogurt (*Streptococcus thermophilus* and *Lactobacillus bulgaricus*) ferment lactose into lactic acid, resulting in a lowering of pH and an increase in the acidity of yogurt [26]. Moreover, the addition of LPP to yogurt has a significant effect ($p < 0.05$) and leads to a decrease in pH and a progressive increase in acidity. Yogurt supplemented with 1% LPP showed the highest value of acidity and the lowest value of pH compared to the other samples.

Effect on antioxidant properties of yogurt during storage: The results of total phenol contents TPC of yogurt supplemented with LPP during storage at 4 °C for 21 days are shown in Figure 4. a.



(a) (b)

Figure 4. Total phenols content (a) and radical scavenging activity (b) of yogurt supplemented with lemon peel powder during 21 days at 4°C. Abbreviation: CAE=Caffeic Acid Equivalent, AAE=Ascorbic Acid Equivalent.

Figure 4. a. shows that control yogurt presents a low TPC (217.810 ± 4.703 mg CAE/100 mL). The TPC of yogurt increased in percentage with the increasing of LPP levels (0.4, 0.6, 0.8, and 1%) about 4.45%, 12.07%, 19.33 and 31.33%, respectively. The same trend was observed for the DPPH-RSA of the different yogurt samples (Figure 4b). Supplementation of stirred yogurt with 1% LPP allows the improvement of its total phenol contents and antioxidant activity. As expected, and in agreement with the results of total phenols in yogurt, 1% LPP yogurt had the highest RSA of 82.098 mg AAE/100 mL compared to the other yogurt samples. Figure 5 shows the established correlation between TPC and RSA of yogurt samples (0; 0.4, 0.6, 0.8, and 1% LPP) during storage at 4 °C. It can be noted that regardless of the storage time and the added LPP, the RSA of yogurt is positively correlated to its TPC. This relationship can be expressed by the following equation with R2 > 0.90.

$$RSA_{(0-1\%)} = 0.1788 \times [TPC]_{(0-1\%)} + 26.682$$

Eq. (3)

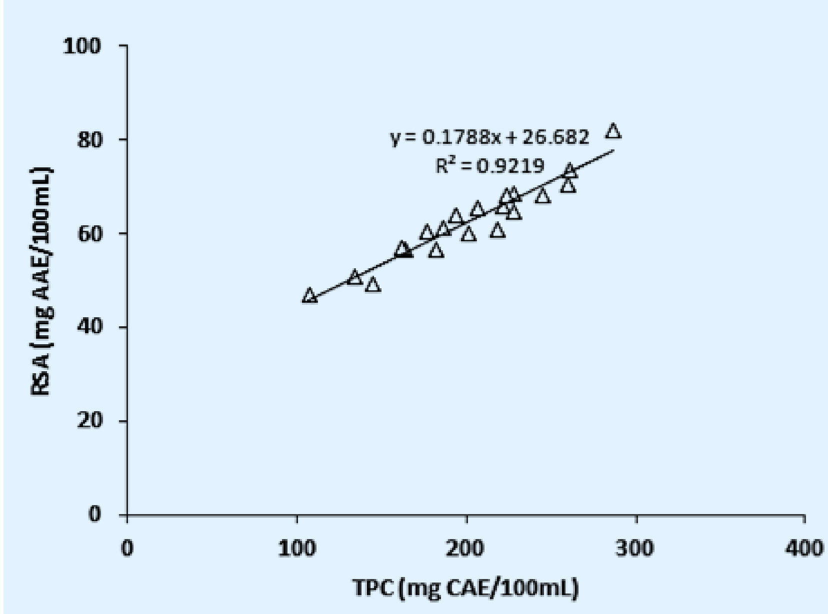


Figure 5. Correlation between the radical scavenging capacities (mg AAE/100mL) versus total phenols content (TPC) (mg CAE/100mL) of yogurts supplemented with lemon peel powder. Abbreviation: CAE= Caffeic Acid Equivalent, AAE=Ascorbic Acid Equivalent.

DISCUSSION

The results obtained for the approximate composition of lemon peel powder were lower than those obtained in similar studies on dried Citrus limon by-products, particularly for protein and fiber contents [33]. In addition, lemon peel extract exhibited comparable total phenolic content and antioxidant capacity to those reported in the literature for dried lemon peel positioning it as a potential ingredient for functional food applications [30- 33].

The lowest value of L^* (26.238 ± 2.171) was obtained for yogurt with 1% LPP. The luminosity of unfortified yogurt is due to the presence of colloidal particles, such as milk fat globules and casein micelles, which are capable of scattering light in the visible spectrum [2- 3- 7]. The addition of LPP induces a decrease in the luminosity of yogurt due to the interaction between the milk-gelling matrix and LPP pigments [2]. Indeed, carotenoids are the main pigment responsible for the yellowish color and are naturally present in milk [8]. Bakirci et al. [44] showed similar trends after the incorporation of pumpkin fiber in yogurts.

The difference in color among supplemented and control yogurts could be attributed to the interaction of caseins and phenolic compounds with vegetable pigments [41]. These results are also concordant with those reported by [41-43] for yogurts supplemented with *Rosa spinosissima* fruit extracts, strawberry fruits, and banana and mango peel powders, respectively. Color remains an important quality parameter that affects consumer attractiveness [40-44]. Thus, it is important to check if this significant instrumental measured color change was perceived by the consumers.

Our viscosity analysis was in accordance with other studies [2- 25- 46- 47]. Sendra et al. [25] showed that supplementing yogurt with orange fiber by-product at an orange fiber level over 0.6 g/100 mL strengthens the yogurt gel structure. It can be concluded that the addition of LPP had a positive effect on yogurt by enhancing its viscosity due to its richness in fibers, especially pectin. Indeed, pectin may create a three-dimensional network able to absorb maximum water inducing an increase in viscosity of the enriched yogurts [45]. Furthermore, increasing the concentration of the fibers decreased the free space of motion during shear and enhanced links among water molecules, which strengthens the formed matrix [2- 46]. This significant increase in viscosity in fortified yogurt should be positively correlated to an increase in textural parameters such as firmness.

The values of firmness and cohesiveness presented a significant difference ($p < 0.05$) for the yogurt supplemented with LPP. Rashwan et al. [2] reported that the viscosity and water retention capacity of yogurt samples were enhanced after their enrichment with natural fibers, which retain more water and reduce syneresis. Dried vegetable powder is reported to act as a natural gelling and thickener agent in fermented yogurt [2- 45- 48]. In our study, yogurt supplemented with 1% LPP showed the highest values of firmness and cohesiveness (0.309 ± 0.024 and 0.695 ± 0.083, respectively), and the lowest value of extensibility (14.922 ± 0.315). These results agree with previous research showing the positive effect of dietary fiber on yogurt textural parameters. Indeed, the enrichment of yogurt with apple pomace powder improved its cohesiveness, firmness, and viscosity index [47]. Indeed, dietary fibers increase the total solid content of the supplemented products, interact with caseins, and positively affect the formed gel of dairy products [2, 47-48]. Rashwan et al. [2] and Rashwan et al. [48] proved that enriched stirred yogurt with M. dodecandrum Lour fruit powder presented higher firmness if compared to the non-enriched samples. In addition, the density and rigidity of enriched yogurt samples were increased.

The results of sensory evaluation are in concordance with those of Fathy et al. [29]. The authors reported that enriching yogurt with 0.5% citrus peel did not affect the overall acceptance of acidophilus-bifidus-thermophilus synbiotic yogurt. According to Rashwan et al. [2], fortifying yogurt with natural functional ingredients can improve the acceptability of consumers due to the presence of organic acids, natural gelling agents such as pectin, and flavoring bioactive compounds like phenols.

The lower value of pH and higher value of acidity shown in stirred yogurt could be explained by the presence of organic acids such as citric acid, malic acid, and oxalic acid in lemon peels [2]. This agrees with previous studies reporting that natural functional ingredients from fruit and vegetables can increase the acidity of fermented dairy products: orange [25-26]; pineapple peel [21]; water extract from Siraitia grosvenorii fruit extract [50], argel leaf extract powder-fortified yogurts [51] and hydrolyzed potato powder [52]. According to Prasanna et al. [49], some fibers may stimulate the metabolism of starter culture by providing an additional source of carbohydrates in fermented dairy products. Besides, several studies showed that the incorporation of fruit peels into fermented dairy products enhanced the biological efficiency of lactic acid bacteria thanks to product fortification with fibers and flavonoids [2, 29].

Supplementation of stirred yogurt with LPP allows the improvement of its total phenol contents and antioxidant activity. Similar trends were observed for other applications using fruit powder or extracts for yogurt fortification [2-3, 29]. Milk contains some phenolic compounds such as equol and simple phenol (O-cresol, acid protocatechuic), which contribute with vitamins to its radical scavenging activity [2]. Supplementing yogurts with natural functional compounds such as LPP increases their TPC and antioxidant activity due to the presence of other antioxidant compounds like phenols, flavonoids, vitamins... [2- 52- 56]. TPC of supplemented yogurt dropped during storage, with a reduction rate of 38.65% and 31.03% for control yogurt and supplemented with 1% LPP: respectively. Our results are concordant with the literature [2- 3- 57]. Indeed, it was reported that enriched yogurt samples with Hibiscus sabdariffa L. flowers marmalade presented higher antioxidant activity compared to control yogurt [57].

Furthermore, supplementing stirred yogurt samples with *M. dodecandrum Lour* fruit powder induced an increase in their antioxidant activity [48]. RSA of yogurt supplemented or not with LPP significantly ($p < 0.05$) dropped during storage, with a reduction rate of about 10-20% LPP. A similar result was reported in previous studies [14]. The authors reported that TPC and RSA of yogurt fortified with wine grape pomace 1, 2, and 3% decreased by 4.37-39.08% and 29.52%, respectively, during 4 weeks of cold storage, compared to the day of manufacturing. Karaaslan et al. [12] concluded that the TPC and RSA of yogurt fortified with red grape extract (Merlot variety) declined 17.57% and 1.86 times, respectively, after 14 days of storage. Many reasons can explain the drop in TPC and RSA during the storage period. For example, phenolic compounds can be degraded during storage due to several factors: pH, microbial activity, and enzymatic activity of phenol oxidase [34- 35]. Other authors explained the drop of TPC and RSA in supplemented yogurt after the first week of storage to the formation of a complex between polyphenols and milk proteins, which reduces phenols extractability [58]. In fact, caseins are proline-rich proteins, which in turn have a strong affinity for the hydroxyl (-OH) group of phenolic compounds. This protein-phenol interaction is maximal at the isoelectric point of the protein [45- 58].

CONCLUSION

This work shows the potential of valorization of dried lemon peel powder in the supplementation of stirred yogurt. Fortification of yogurt with lemon peel powder improved the rheological properties of yogurt, in particular viscosity, firmness, and cohesiveness. The total phenols content and radical scavenging activity of fortified stirred yogurt increased with increasing lemon peel powder concentration from 0 to 1% and decreased during cold storage for 21 days at 4 °C. The increase in antioxidant activity of stirred yoghurts is strongly correlated with the lemon peel powders content. No significant differences ($p > 0.05$) between sensory indicators of control and fortified yogurts were detected. The fortified stirred yogurt presented higher titratable acidity and lower pH during cold storage than those unfortified yogurts. Fortification of stirred yogurts with 1% lemon peel powder seems to be very suitable because it keeps the highest levels of total phenols and, subsequently, the most important radical scavenging antioxidant activity.

List of Abbreviations: LPP, lemon peel powder; ΔE, the total color difference; TPC, total phenol contents; RSA, Radical Scavenging Activity CAE, Caffeic Acid Equivalent; 0% LPP, yogurt without lemon peel powder, control

Competing interests: The authors declare that they have no competing interests

Authors' contributions: Nesrine G: Formal analysis, Methodology, Writing – original draft. M'hiri N: W: Writing – review and Editing. Mkadem, W: Writing – review & Editing, Belguith, K: Writing – review & Editing. Boudhrioua, N: Conceptualization, Funding acquisition, Supervision, Writing – review & Editing.

REFERENCES

1. Deshwal GK, Tiwari S, Kumar A, Raman RK, Kadyan S: Review on factors affecting and control of post-acidification in yoghurt and related products. *Trends in Food Science & Technology*. 2021; 109:499-512. DOI: https://doi.org/10.1016/j.tifs.2021.01.057
2. Rashwan AK, Osman AI, Chen W: Natural nutraceuticals for enhancing yogurt properties: a review. *Environmental Chemistry Letters*. Published online March 13, 2023. DOI: https://doi.org/10.1007/s10311-023-01588-0
3. Silva AF, de Cássia Ramos do Egypto Queiroga R, de Souza EL, et al.: Incorporation of phenolic-rich ingredients from integral valorization of Isabel grape improves the nutritional, functional and sensory characteristics of probiotic goat milk yogurt. *Food Chemistry*. 2022; 369:130957-130957. DOI: https://doi.org/10.1016/j.foodchem.2021.130957

4. Jaagura M, Part N, Adamberg K, Kazantseva J, Viiard E: Consumption of multi-fiber enriched yogurt is associated with increase of Bifidobacterium animalis and butyrate producing bacteria in human fecal microbiota. *Journal of Functional Foods*. 2022; 88:104899.
DOI: https://doi.org/10.1016/j.jff.2021.104899
5. Santillán-Urquiza E, Méndez-Rojas MÁ, Vélez-Ruiz JF: Fortification of yogurt with nano and micro sized calcium, iron and zinc, effect on the physicochemical and rheological properties. *LWT*. 2017; 80:462-469. DOI: https://doi.org/10.1016/j.lwt.2017.03.025
6. Fernandez MA, Marette A: Potential Health Benefits of Combining Yogurt and Fruits Based on Their Probiotic and Prebiotic Properties. *Advances in Nutrition: An International Review Journal*. 2017;8(1):155S164S.
DOI: https://doi.org/10.3945/an.115.011114
7. Salehi F: Quality, physicochemical, and textural properties of dairy products containing fruits and vegetables: A review. *Food Science & Nutrition*. Published online June 24, 2021.
DOI: https://doi.org/10.1002/fsn3.2430
8. Gilbert A, Turgeon SL: Studying stirred yogurt microstructure and its correlation to physical properties: A review. *Food Hydrocolloids*. 2021; 121:106970.
DOI: https://doi.org/10.1016/j.foodhyd.2021.106970
9. Rubio F, Windson C, Albino P, et al.: Development of natural pigments microencapsulated in waste yeast *Saccharomyces cerevisiae* using spray drying technology and their application in yogurt. 2021;12(19):8946-8959.
DOI: https://doi.org/10.1039/d1fo00708d
10. Luo H, Bao Y, Zhu P: Development of a novel functional yogurt rich in lycopene by Bacillus subtilis. *Food Chemistry*. 2023;407:135142.
DOI: https://doi.org/10.1016/j.foodchem.2022.135142
11. Palomo M, Gutiérrez AM, Pérez-Conde MC, Cámara C, Madrid Y: Se metallomics during lactic fermentation of Se-enriched yogurt. *Food Chemistry*. 2014; 164:371-379.
DOI: https://doi.org/10.1016/j.foodchem.2014.05.007
12. Karaaslan M, Ozden M, Vardin H, Turkoglu H: Phenolic fortification of yogurt using grape and callus extracts. *LWT - Food Science and Technology*. 2011;44(4):1065-1072.
DOI: https://doi.org/10.1016/j.lwt.2010.12.009
13. Varnaitė L, Keršienė M, Šipailienė A, Kazernavičiūtė R, Venskutonis PR, Leskauskaitė D: Fiber-Rich Cranberry Pomace as Food Ingredient with Functional Activity for Yogurt Production. *Foods*. 2022;11(5):758.
DOI: https://doi.org/10.3390/foods11050758
14. Tseng A, Zhao Y: Wine grape pomace as antioxidant dietary fibre for enhancing nutritional value and improving storability of yogurt and salad dressing. *Food Chemistry*. 2013;138(1):356-365.
DOI: https://doi.org/10.1016/j.foodchem.2012.09.148
15. Pelaes Vital AC, Goto PA, Hanai LN, et al.: Microbiological, functional and rheological properties of low fat yogurt supplemented with Pleurotus ostreatus aqueous extract. *LWT - Food Science and Technology*. 2015;64(2):1028-1035.
DOI: https://doi.org/10.1016/j.lwt.2015.07.003
16. Bertolino M, Belviso S, Dal Bello B, et al.: Influence of the addition of different hazelnut skins on the physicochemical, antioxidant, polyphenol and sensory properties of yogurt. *LWT - Food Science and Technology*. 2015;63(2):1145-1154.
DOI: https://doi.org/10.1016/j.lwt.2015.03.113
17. Zahid HF, Ali A, Ranadheera CS, Fang Z, Dunshea FR, Ajlouni S: In vitro bioaccessibility of phenolic compounds and alpha-glucosidase inhibition activity in yoghurts enriched with mango peel powder. *Food Bioscience*. 2022; 50:102011.
DOI: https://doi.org/10.1016/j.fbio.2022.102011
18. Hamid, Thakur NS, Sharma R, Thakur A: Optimization of lyophilized microencapsulated phenolic extract concentration for enrichment of yoghurt and effect on chemical parameters, bioactive compounds, antioxidant activity and sensory quality under storage. *South African Journal of Botany*. Published online April 2022. DOI: https://doi.org/10.1016/j.sajb.2022.04.015
19. Ahmed MW, Khan MSI, Parven A, Rashid MH, Md Meftaul I: Vitamin-A enriched yogurt through fortification of pumpkin (Cucurbita maxima): A potential alternative for preventing blindness in children. *Heliyon*. 2023;9(4):e15039.
DOI: https://doi.org/10.1016/j.heliyon.2023.e15039
20. Draz A, Jaffar HM, Rizwan B, et al.: Comparison and effect of plain and calcium fortified yogurt on glycemic responses, anthropometrics and metabolic biomarkers. *Immunological medicine*. 2023;47(1):30-36.
DOI: https://doi.org/10.1080/25785826.2023.2228074

21. Sah BNP, Vasiljevic T, McKechnie S, Donkor ON: Physicochemical, textural and rheological properties of probiotic yogurt fortified with fibre-rich pineapple peel powder during refrigerated storage. *LWT - Food Science and Technology*. 2016; 65:978-986. DOI: https://doi.org/10.1016/j.lwt.2015.09.027
22. García-Pérez FJ, Lario Y, Fernández-López J, Sayas E, Pérez-Alvarez JA, Sendra E: Effect of orange fiber addition on yogurt color during fermentation and cold storage. *Color Research & Application*. 2005;30(6):457-463. DOI: https://doi.org/10.1002/col.20158
23. García-Pérez FJ, Sendra E, Lario Y, Fernández-López J, Pérez-Alvarez JA: Rheology of orange fiber enriched yogurt. *Milchwissenschaft*. 2006;61(1):55-59.
24. Sendra E, Fayos P, Lario Y, Fernández-López J, Sayas-Barberá E, Pérez-Alvarez JA: Incorporation of citrus fibers in fermented milk containing probiotic bacteria. *Food Microbiology*. 2008;25(1):13-21. DOI: https://doi.org/10.1016/j.fm.2007.09.003
25. Sendra E, Kuri V, Fernández-López J, Sayas-Barberá E, Navarro C, Pérez-Álvarez JÁ : Viscoelastic properties of orange fiber enriched yogurt as a function of fiber dose, size and thermal treatment. *Lebensmittel-Wissenschaft & Technologie*. 2010;43(4):708-714. DOI: https://doi.org/10.1016/j.lwt.2009.12.005
26. Arioui F, Ait Saada D, Cheriguene A: Physicochemical and sensory quality of yogurt incorporated with pectin from peel ofCitrus sinensis. *Food Science & Nutrition*. 2016;5(2):358-364. DOI: https://doi.org/10.1002/fsn3.400
27. Lario Y, Sendra E, García-Pérez FJ, Fernández-López J, Pérez-Alvarez JA : Evolution of microbial populations of fiber enriched yogurt during commercial shelf-life. *Milchwissenschaft*. 2004;59(11):646-649.
28. Zaki N, Mai N: Antioxidant, Antimicrobial and Anticancer Activities of Citrus Peels to Improve the Shelf Life of Yoghurt Drink. *Egyptian Journal of Food Science*. 2021;0(0). DOI: https://doi.org/10.21608/ejfs.2021.58310.1092
29. Fathy HM, Abd El-Maksoud AA, Cheng W, Elshaghabee FMF: Value-Added Utilization of Citrus Peels in Improving Functional Properties and Probiotic Viability of Acidophilus-bifidus-thermophilus (ABT)-Type Synbiotic Yoghurt during Cold Storage. *Foods*. 2022;11(17):2677. DOI: https://doi.org/10.3390/foods11172677
30. Ghanem N, Mihoubi D, Kechaou N, Mihoubi NB: Microwave dehydration of three citrus peel cultivars: Effect on water and oil retention capacities, color, shrinkage and total phenols content. *Industrial Crops and Products*. 2012; 40:167-177. DOI: https://doi.org/10.1016/j.indcrop.2012.03.009
31. Ozturkoglu-Budak S, Akal C, Yetisemiyen A: Effect of dried nut fortification on functional, physicochemical, textural, and microbiological properties of yogurt. *Journal of Dairy Science*. 2016;99(11):8511-8523. DOI: https://doi.org/10.3168/jds.2016-11217
32. Gómez B, Gullón B, Yáñez R, Parajó JC, Alonso JL: Pectic Oligosacharides from Lemon Peel Wastes: Production, Purification, and Chemical Characterization. *Journal of Agricultural and Food Chemistry*. 2013;61(42):10043-10053. DOI: https://doi.org/10.1021/jf402559p
33. Gargouri B, Ammar S, Verardo V, Besbes S, Segura-Carretero A, Bouaziz M: RP-HPLC–DAD-ESI-TOF–MS based strategy for new insights into the qualitative and quantitative phenolic profile in Tunisian industrial Citrus Limon by-product and their antioxidant activity. *European Food Research and Technology*. 2017;243(11):2011-2024. DOI: https://doi.org/10.1007/s00217-017-2904-4
34. Mhiri N, Ioannou I, Paris C, Ghoul M, Boudhrioua N: Antioxidants of Maltease orange peel: comparative investigation of the efficiency of four extraction methods. *Journal of Applied Pharmaceutical Science*. Published online 2017. DOI: https://doi.org/10.7324/japs.2017.71119
35. ISO 22935-2, 2009 ISO 22935-2:2009 | IDF 99-2:2009. Lait et produits laitiers — Analyse sensorielle — Partie 2: Méthodes recommandées pour l'évaluation sensorielle. 1-23. ISO.
36. AOAC (1984) Association of Official Analytical Chemists. Official Methods of Analysis, 14th ed. AOAC, Washington, DC.
37. Gad AS, Kholif AM, Sayed AF: Evaluation of the Nutritional Value of Functional Yogurt Resulting from Combination of Date Palm Syrup and Skim Milk. *American Journal of Food Technology*. 2010;5(4):250-259. DOI: https://doi.org/10.3923/ajft.2010.250.259
38. Package IBM. SPSS 20.0 Statistical Package for Social Science, 2011.
39. Jouki M, Khazaei N, Rezaei F, Taghavian-Saeid R: Production of synbiotic freeze-dried yoghurt powder using microencapsulation and cryopreservation of L. plantarum in alginate-skim milk microcapsules. *International Dairy Journal*. 2021; 122:105133-105133. DOI: https://doi.org/10.1016/j.idairyj.2021.105133

40. Ścibisz I, Ziarno M, Mitek M: Color stability of fruit yogurt during storage. *Journal of Food Science and Technology*. 2019;56(4):1997-2009. DOI: https://doi.org/10.1007/s13197-019-03668-y
41. Szołtysik M, Kucharska AZ, Sokół-Łętowska A, Dąbrowska A, Bobak Ł, Chrzanowska J: The Effect of Rosa spinosissima Fruits Extract on Lactic Acid Bacteria Growth and Other Yoghurt Parameters. *Foods*. 2020;9(9):1167. DOI: https://doi.org/10.3390/foods9091167
42. Zahid HF, Ranadheera CS, Fang Z, Ajlouni S. Functional and Healthy Yogurts Fortified with Probiotics and Fruit Peel Powders. *Fermentation*. 2022;8(9):469. DOI: https://doi.org/10.3390/fermentation8090469
43. Bakirci S, Dagdemir E, Boran OS, Hayaloglu AA: The effect of pumpkin fibre on quality and storage stability of reduced-fat set-type yogurt. *International Journal of Food Science & Technology*. 2016;52(1):180-187. DOI: https://doi.org/10.1111/ijfs.13264
44. Dickinson E, Semenova MG, Antipova AS, Pelan EG: Effect of high-methoxy pectin on properties of casein-stabilized emulsions. *Food Hydrocolloids*. 1998;12(4):425-432. DOI: https://doi.org/10.1016/s0268-005x(98)00057-5
45. Chen B, Zhao X, Cai Y, et al: Incorporation of modified okara-derived insoluble soybean fiber into set-type yogurt: Structural architecture, rheological properties and moisture stability. *Food Hydrocolloids*. Published online December 2022:108413. DOI: https://doi.org/10.1016/j.foodhyd.2022.108413
46. Wang X, Kristo E, LaPointe G: Adding apple pomace as a functional ingredient in stirred-type yogurt and yogurt drinks. *Food Hydrocolloids*. 2020; 100:105453. DOI: https://doi.org/10.1016/j.foodhyd.2019.105453
47. Rashwan AK, Karim N, Xu Y, et al. Chemical composition, quality attributes and antioxidant activity of stirred-type yogurt enriched with *Melastoma dodecandrum* Lour fruit powder. *Food & Function*. 2022;13(3):1579-1592. DOI: https://doi.org/10.1039/d1fo03448k
48. Prasanna PHP, Grandison AS, Charalampopoulos D: Microbiological, chemical and rheological properties of low fat set yoghurt produced with exopolysaccharide (EPS) producing Bifidobacterium strains. *Food Research International*. 2013;51(1):15-22. DOI: https://doi.org/10.1016/j.foodres.2012.11.016
49. Abdel-Hamid M, Romeih E, Huang Z, Enomoto T, Huang L, Li L: Bioactive properties of probiotic set-yogurt supplemented with Siraitia grosvenorii fruit extract. *Food Chemistry*. 2020; 303:125400. DOI: https://doi.org/10.1016/j.foodchem.2019.125400
50. Mohamed Ahmed IA, Alqah HAS, Saleh A, et al.: Physicochemical quality attributes and antioxidant properties of set-type yogurt fortified with argel (Solenostemma argel Hayne) leaf extract. *LWT*. 2021; 137:110389. DOI: https://doi.org/10.1016/j.lwt.2020.110389
51. Ahmad I, Xiong Z, Xiong H, et al.: Physicochemical, rheological and antioxidant profiling of yogurt prepared from non-enzymatically and enzymatically hydrolyzed potato powder under refrigeration. *Food Science and Human Wellness*. 2023;12(1):69-78. DOI: https://doi.org/10.1016/j.fshw.2022.07.024
52. Du H, Wang X, Yang H, et al.: Changes of phenolic profile and antioxidant activity during cold storage of functional flavored yogurt supplemented with mulberry pomace. *Food Control*. 2022; 132:108554. DOI: https://doi.org/10.1016/j.foodcont.2021.108554
53. Lee JA, Kim HY, Park CY, Seo ID, Lee KW, Seol KH: Antioxidant Activity and Quality Characteristics of Yogurt Added with Blueberry Powder. *Resources Science Research*. 2020;2(2):76-85. DOI: https://doi.org/10.52346/rsr.2020.2.2.76
54. Shori AB: Storage quality and antioxidant properties of yogurt fortified with polyphenol extract from nutmeg, black pepper, and white pepper. *Electronic Journal of Biotechnology*. 2022; 57:24-30. DOI: https://doi.org/10.1016/j.ejbt.2022.03.003
55. AL Zahrani AJ, Shori AB: Viability of probiotics and antioxidant activity of soy and almond milk fermented with selected strains of probiotic Lactobacillus spp. *LWT*. 2023; 176:114531. DOI: https://doi.org/10.1016/j.lwt.2023.114531
56. Arslaner A, Salik MA, Bakirci İ: The effects of adding Hibiscus sabdariffa L. flowers marmalade on some quality properties, mineral content and antioxidant activities of yogurt. *Journal of Food Science and Technology*. 2020;58(1):223-233. DOI: https://doi.org/10.1007/s13197-020-04533-z
57. Scalbert A, Manach C, Morand C, Rémésy C, Jiménez L: Dietary Polyphenols and the Prevention of Diseases. *Critical Reviews in Food Science and Nutrition*. 2005;45(4):287-306. DOI: https://doi.org/10.1080/1040869059096
58. Lamothe S, Azimy N, Bazinet L, Couillard C, Britten M: Interaction of green tea polyphenols with dairy matrices in a simulated gastrointestinal environment. *Food Funct*. 2014;5(10):2621-2631. DOI: https://doi.org/10.1039/c4fo00203b