AIMS Agriculture and Food

AIMS Agriculture and Food, 9(3): 822–841.
DOI: 10.3934/agrfood.2024044
Received: 16 May 2024
Revised: 05 July 2024
Accepted: 12 July 2024
Published: 29 July 2024

http://www.aimspress.com/journal/agriculture

Research article

Enhancing yogurt overall quality with enzymatically hydrolyzed cantaloupe rind powder: Effects of the supplement ratio on texture, rheology, stability, phenolic content, and antioxidant activity

Thi Quynh Ngoc Nguyen[1,2,*], Thi Thuy Le[1,2] and Thi Ho Thanh Dong[1,2]

[1] Department of Food Technology, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

[2] Vietnam National University - Ho Chi Minh City (VNU-HCM), Linh Trung Ward, Thu Duc City, Ho Chi Minh City, Vietnam

Correspondence: Email address: qngocnguyen@hcmut.edu.vn; Tel: +84(028)38650484.

Abstract: Recently, there has been growing interest in incorporating dietary fiber into yogurt products, driven by its potential to improve the texture, rheology, and stability of yogurt, as well as the associated health benefits. This study specifically focused on the utilization of enzymatically hydrolyzed cantaloupe rind powder, which was the product of the enzymatic hydrolysis of the raw cantaloupe rind powder using cellulase and xylanase enzymes to increase its soluble dietary fiber content. The resulting hydrolyzed cantaloupe rind powder (referred to as HCRP) was added to a probiotic yogurt recipe at varying ratios of 0.5%, 1.0%, and 1.5% (w/w). Physicochemical, textural, and rheological properties, and syneresis of the control yogurt (without HCRP addition) and the HCRP-fortified yogurts at different addition ratios, were evaluated during a 15-day storage period at 4°C. Additionally, the color, total phenolic content (TPC), and antioxidant property of the yogurts were assessed at the end of the storage period. The results demonstrated that the addition of HCRP increased the hardness, viscosity, elasticity, and stability of the yogurt compared to the control yogurt. Specifically, the addition of 1.5% HCRP to yogurt resulted in a 1.6, 6.0, 1.9, 1.7, and 1.5 times increase in hardness, adhesiveness, apparent viscosity, storage modulus, and loss modulus compared to the control yogurt on day 15 of the storage period, respectively. Meanwhile, the syneresis was reduced by approximately 3 times in the 1.5% HCRP-added yogurt (5.60%) compared to the control yogurt (17.41%). The TPC of the yogurt also increased with higher levels of HCRP addition, reaching approximately 1.5 times that of the control yogurt at a 1.5% addition level. Furthermore, the antioxidant activity, as determined by the

DPPH assay, was not detected in the control yogurt but exhibited a significant increase with higher concentrations of HCRP. This study highlights the potential of enzymatically hydrolyzed cantaloupe rind powder as a functional ingredient to enhance the quality attributes of yogurt, including its textural, rheological properties, stability, phenolic content, and antioxidant activity.

Keywords: dietary fiber; fortified yogurt; cantaloupe rind; enzyme treatment; texture, rheology; stability; antioxidant; phenolic content

1. Introduction

Yogurt, a globally consumed food product, is produced by the fermentation of milk using bacterial cultures (starter culture), typically containing *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus* [1]. The production of lactic acid during fermentation lowers the pH of the milk, resulting in a coagulation of casein to form a gel network [1]. Yogurt is valued for its nutritional values and sensory properties including a refreshing aroma and a subtly tangy taste resulting from the process of lactic acid fermentation. Moreover, yogurt is easier to digest compared to milk, making it suitable for people suffering from lactose intolerance [2]. The consumption of yogurt was reported to associate with a range of health benefits, including an enhancing immune system, reducing the risk of type 2 diabetes, improving gut health and bone health, and reducing serum cholesterol and the risk of cardiovascular diseases [3].

Recently, food by-products, particularly the fruit by-products, have been recognized as a promising dietary fiber source to enhance the functionality and structural properties of yogurt [4]. The utilization of food by-products in yogurt production not only has positive environmental implications but also improves the functionality of yogurt [4]. Food by-products often contain significant amounts of phenolic compounds such as flavonoid, tannin, and anthocyanin which possess antioxidant properties [4]. The consumption of antioxidant-rich foods can help protect against oxidative damage and lower the chances of developing a range of chronic illnesses such as diabetes, cardiovascular diseases, and inflammatory conditions [5]. Notably, the prebiotic activity of food by-products from various sources, such as mango [6], orange [7], and guava [8] by-product, has been demonstrated. Prebiotics primarily consist of non-digestible dietary fibers that can be fermented by the gut bacteria and selectively stimulate the growth of probiotics and beneficial gut bacteria, thereby promoting human health improvements [9]. The addition of food by-products to yogurt has been explored as a means to enhance the prebiotic activities and probiotic viability of the final product [4]. Supplementing yogurt with fruit and vegetable by-products, including mango, banana, and pineapple peel [10,11], cranberry pomace [12], apple, banana, and passion fruit processing by-products [13], and rice bran [14], has been reported to enhance probiotic viability, prebiotic activities, dietary fiber content, and antioxidant capacity, while also influencing post-acidification, textural properties, rheological properties, and the stability of the yogurt products.

Cantaloupe is widely consumed worldwide because of its delightful aroma and nutritional value [15]. Consumption of cantaloupe fruit and its processed products such as juices, nectars, and jams generates significant quantities of the peel as a by-product [15]. Cantaloupe rind is rich in dietary fiber, minerals, vitamin C, phenolic compounds, carotenoids, and flavonoids, and it exhibits high antioxidant activity which could provide important human health benefits [15,16]. Therefore, incorporating cantaloupe rind into food products is highly desirable as an approach to reduce food waste, and simultaneously enhance the dietary fiber content, phenolic content, and antioxidant activity of the fortified food products.

The effects of dietary fiber addition on texture, rheology, and stability of yogurts vary depending on the fiber sources, fiber particle size [17], and fiber concentration [18,19]. Furthermore, the soluble and insoluble dietary fibers in fruit and vegetable by-products can impact the stability, texture, and rheology of yogurt in different ways [20,21]. Soluble fibers have the ability to increase yogurt viscosity, interacting with casein protein to form a stronger gel network, thereby reducing the syneresis of yogurt [18,22,23]. On the other hand, insoluble fiber may destabilize the yogurt gel due to steric hindrance to protein coagulation, resulting in higher syneresis [17,19,21,24,25]. Additionally, the solubility of dietary fibers can influence their fermentability by gut microbiota, with soluble fibers demonstrating superior fermentability compared to insoluble fibers [26]. While many current carbohydrate-based prebiotics are soluble fibers such as inulin, fructose oligosaccharides, and xylo-oligosaccharides [27], the majority of fibers from food by-products are composed of insoluble cellulose polysaccharides [28,29]. To enhance the solubility and prebiotic activity of dietary fibers from food by-products, various studies have employed enzymatic hydrolysis, resulting in increased solubility and improved prebiotic effects [30,31,32,33,34].

The objective of this study was to evaluate the impacts of incorporating enzymatically hydrolyzed cantaloupe rind powder (HCRP) of varying ratios into yogurt on the physicochemical properties, textural properties, rheological properties, and stability of the yogurt product during a 15-day storage period. The findings of this study provide valuable insights into the characteristics of yogurt fortified with HCRP. Moreover, these results contribute to the development of novel functional probiotic yogurt using enzymatically hydrolyzed fruit by-products.

2. Materials and methods

2.1. Materials

Sterilized milk was purchased from a local supermarket. Commercial, freeze-dried, mixed-strain probiotic yogurt starter cultures consisting of *Bifidobacterium longum, Streptococcus thermophilus, Lactobacillus casei, Lactobacillus bulgaricus, Lactobacillus helveticus, Lactobacillus rhamnosus, and Lactobacillus acidophilus* were purchased from Yógourment, France. Unless otherwise specified, chemicals were acquired from either Sigma (USA) or Merck Co. (Germany). The Ultraflo Max enzyme, which contains endo-1,3(4)-β-glucanase (700 U/g) and endo-1,4-β-xylanase (250 U/g), was purchased from Novozymes, Denmark. Absolute ethanol was purchased from Chemsol Vina, Vietnam.

2.2. Method

2.2.1. Preparation of enzymatically hydrolyzed cantaloupe rind powder

The cantaloupe rinds were collected from melons grown at a local farm in Binh Duong Province, Vietnam. The cantaloupe peels were washed with tap water, and the outermost tough skin was peeled off. The green rinds were then sliced into 2-mm-thick pieces and blanched at 90 °C for 30 seconds. Subsequently, they were dried at 60 °C until a moisture content of 10–13% was reached. After drying, the cantaloupe rinds were ground into powder using a hammer mill and sieved through a 0.210 mm (70 mesh) sieve.

Cantaloupe rind powder was hydrolyzed using Ultraflo Max enzyme which contains endo-1,3(4)-β-glucanase and endo-1,4-β-xylanase to hydrolyze cellulose and xylan, respectively, which are the two major components of plant cell walls [35]. To prepare the enzymatically hydrolyzed cantaloupe rind powder (HCRP), the raw cantaloupe rind powder was mixed with deionized water at a ratio of 15:1 (v:w). The mixture was then microwaved in a household microwave at 1100 W for 120 s then allowed to cool down to room temperature before the enzyme mixture was added at a ratio of 3:1000 (w:w). After adding the enzyme, the mixture was incubated at 55 °C for 8 h before being inactivated at 95 °C for 15 min. This enzyme treatment condition was selected based on our preliminary investigation on the pretreatment condition (microwave or not) and enzyme concentration to obtain the optimal soluble fiber content. After inactivation, ethanol was added at a ratio of 4:1 (v:v) to precipitate the soluble fiber. The supernatant was then removed by vacuum filtration and the solid residue was collected and dried at 60 °C until reaching a moisture content of 10–13%. After drying, the enzyme-treated cantaloupe rind was ground into powder using a hammer mill and sieved through a 0.210 mm (70 mesh) sieve. The powder that passed through the sieve was collected and stored at 4 °C until use.

2.2.2. Dietary fiber content quantification

Insoluble dietary fiber (IDF) and soluble dietary fiber (SDF) were determined using AOAC 991.42 and 993.19 methods, respectively. 1 g of the sample was utilized for each quantification. The sample was successively subjected to incubation with α-amylase, protease, and glucoamylase enzymes to break down proteins and starches. After that, the quantification of soluble and insoluble fiber contents was carried out using the gravimetric method.

2.2.3. Yogurt preparation

For the preparation of the HCRP-fortified yogurts, hydrolyzed cantaloupe rind powder was added to milk at 0.5%, 1.0 %, and 1.5% (w/w). The resulting mixtures were homogenized using a high-pressure homogenizer at 240 Kpa. After that, the mixture was heated at 75 °C for 30 min and then cooled in a water bath. Next, the freeze-dried, mixed-strain probiotic starter cultures were added to the milk at the ratio of 0.3% (w/w). Subsequently, the mixture was fermented at 43 °C for 2 h then poured aseptically into pots. After pouring, the mixture continued fermenting at 43 °C until pH reached 4.6 ± 0.1 to produce yogurt. The yogurts prepared with the addition of 0.5%, 1.0%, and 1.5% HCRP were denoted as 0.5% HCRP, 1.0% HCRP, and 1.5% HCRP yogurt, respectively. The control yogurt, without HCRP addition, was prepared following the same procedure, with the exception that no homogenization step was done. All yogurts were stored at 4 °C before being analyzed.

2.2.4. Measurement of syneresis

The syneresis of yogurt was determined after being stored for 1, 8, and 15 days at 4 °C using a centrifugation method as described previously with a slight modification [36]. To measure syneresis, the yogurt samples were centrifuged at 500 g for 10 minutes at 4 °C. The supernatant obtained after centrifugation was separated and weighed. Syneresis was calculated using the following formula.

$$Syneresis = \frac{weight\ of\ supernatant\ (g)}{total\ weight\ of\ yogurt\ (g)} \times 100\% \quad (1)$$

2.2.5. Measurement of pH and titratable acidity (TA)

The pH of yogurt was determined using a pH meter (HI2210, Hanna instruments, UK) after being stored at 4 °C for 1, 8, and 15 days. Total titratable acidity was quantified using the previously described method [20]. To determine total titratable acidity, 4 g of yogurt was mixed with 16 g of deionized water and the resulting mixture was titrated with NaOH 0.1 M until the pH reached 8.1. The titratable acidity (TA) was determined as follows.

$$TA\ (\%\ Lactic\ acid) = \frac{V_{NaOH}\ (L) \times 0.1 \times 90}{weight\ of\ yogurt\ (g)} \times 100 \quad (2)$$

2.2.6. Textural analysis

The hardness and adhesiveness of the yogurt were determined using the TA.XTPlus texture analyzer (Stable Co., UK) equipped with a 25-mm-diameter cylindrical probe. Yogurt in each pot was delicately stirred for 10 s using a flat spatula, and then 85 g of yogurt was gently transferred into a sample container for texture analysis. The texture analyzer was set to a test speed of 0.5 mm/s, a test distance of 16 mm, and a trigger force of 5 g. The test was carried out at 25 °C, immediately after removing the sample from the refrigerator, ensuring that the temperature of the sample was nearly 4 °C. The hardness and adhesiveness were the maximum force and the negative area obtained from the force-time curve, respectively [37].

2.2.7. Rheological analysis

The rheological properties of yogurt were characterized using a MCR302 rheometer (Anton Paar, Germany) equipped with a cone-plate CP50-2 (diameter: 50 mm, angle: 2°) at 4 °C. The shear stress was performed with shear rate range of 0.1 to 250 s^{-1} to determine the flow behavior of the yogurt samples. The flow curves were fitted to the power law model: $\sigma = K\dot{\gamma}^n$, where σ is the shear stress (Pa), K is the consistency index ($Pa \cdot s^n$), n is the flow index (dimensionless), and $\dot{\gamma}$ is the shear rate (s^{-1}). The apparent viscosity of yogurt during 15 days of storage was recorded at a constant shear rate of 50 s^{-1} [38]. The frequency sweep analysis was performed from 0.1 to 10 rad/s at a fixed strain of 0.5% (predetermined within the linear viscoelastic region) [39]. The storage modulus (G′), loss modulus (G″), and loss tangent (tanδ = G′/G″) were recorded during the test.

2.2.8. Color analysis

The color of the yogurt samples was analyzed using L*, a*, and b* color values derived from the CIE-Lab color system. Yogurt was transferred to a quartz cuvette and the L*, a*, and b* were recorded on a Model CR-300 colorimeter (Konica Minolta, Japan). The color difference ΔE between the fortified yogurts and the control yogurt was calculated by the formula [40]:

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (3)$$

where L_0^*, a_0^*, and b_0^* are the color values of the control yogurt without HCRP addition, and L^*, a^*, and b^* are the color values of the HCRP-fortified yogurts.

2.2.9. Total phenolic content (TPC) and antioxidant activity

For determination of TPC and DPPH, 1 mL ethanol was added to 1 g of the yogurt sample and the mixture was vortexed and placed at room temperature for 30 min before being centrifuged at 4500 rpm for 30 min. The supernatant was collected and made up to 2 mL. The TPC was quantified using the Folin–Ciocalteu reagent spectrophotometric method [41] with a slight modification. 0.3 mL of sample extract was mixed with 1.45 mL deionized water and 0.25 mL Folin–Ciocalteu reagent. The mixture was placed at room temperature for 6 min. Next, 0.5 mL Na_2CO_3 20% (w/v) was added and the resulting mixture was placed at room temperature in the dark for 30 min before the absorbance at 760 nm was recorded. The TPC was expressed as µg gallic acid equivalent (GAE)/ g yogurt. The antioxidant activity was determined using the DPPH (di(phenyl)-(2,4,6-trinitrophenyl) iminoazanium) assay [42]. The result was expressed as µmol Trolox equivalent (TE)/100 g yogurt.

2.2.10. Statistical analysis

All experiments were done in triplicate. The experiment results were displayed as the mean value with standard division (mean ± SD). One-way analysis of variance (ANOVA) and Tukey's post hoc test were done using Statgraphics Centurion 18.1.12 (Statgraphics Technologies, Inc., VA, USA). A p-value less than 0.05 ($p < 0.05$) was considered statistically significant. Principal component analysis (PCA) was done using Statistica software. The data set for the PCA analysis consisted of yogurt attributes including pH, TA, hardness, adhesiveness, viscosity, K value, n value, G′, G″, tanδ, syneresis, TPC, and DPPH activity.

3. Results and discussion

3.1. The dietary fiber content of HCRP

The content of soluble and insoluble dietary fiber in the raw cantaloupe rind powder was 4.99 ± 0.05 and 32.16 ± 0.15 g/100 g dw, respectively. After enzyme hydrolysis, the soluble fiber content of the HCRP increased by approximately 2 folds to 9.39 ± 0.06 g/100 g dw, while the insoluble fiber content decreased by approximately 20% to 25.92 ± 0.07 g/100 g dw. These results demonstrate that the hydrolysis of cantaloupe rind powder using cellulase and xylanase significantly enhanced the soluble dietary fiber content in the HCRP compared to the raw cantaloupe rind powder.

3.2. Effect of HCRP fortification on the pH and titratable acidity of yogurt

A decrease in pH and an increase in acidity was observed for all types of yogurt during the storage period (see Table 1) due to the continuing lactic acidification. Generally, within the first 8 days of storage, the pH of 1.5% HCRP yogurt was the highest, while its titratable acidity was the lowest among all yogurt types. However, after 15 days of storage, there were no significant differences in pH among the yogurt samples. On day 1 of the storage period, the titratable acidity values of all HCRP-fortified yogurts were not statically significantly different. Additionally, the yogurts fortified with HCRP tended to have lower titratable acidity than that of the control yogurt. By day 15 of storage, the titratable acidity of the control yogurt was not statically significantly different from those of the 0.5% and 1.0% HCRP yogurts, but slightly higher than that of the 1.5% HCRP yogurt. Collectively, these observations indicate that the addition of HCRP at 1.5% may result in a reduction of the post-acidity during cold storage of yogurt. The decrease in acidity of yogurt resulting from dietary fiber addition was observed in a previous study where rice bran was added to yogurt [14]. This observation could be explained by the inhibitory effect of polyphenols present in dietary fiber sources, which can inhibit the bacteria activity, and thus reduce lactic acid production [14,43]. In addition, the increased viscosity of HCRP-fortified yogurt (as discussed in the later section) can impede the diffusion of metabolites necessary for bacteria to produce lactic acid, leading to a reduction in lactic acid production. It should be noted that small variations in temperature among yogurt samples during storage are not excluded as a factor that can affect the activity of bacteria, resulting in changes in the production of lactic acid.

Table 1. The pH and titratable acidity of the control yogurt and HCRP-fortified yogurts at different addition ratios measured on day 1, day 8, and day 15 of the storage period.

	pH			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
Day 1	4.14 ± 0.05^{aB}	4.18 ± 0.02^{a}C	4.17 ± 0.05^{aB}	4.34 ± 0.02^{b}C
Day 8	4.05 ± 0.02^{aA}	4.10 ± 0.02^{abB}	4.11 ± 0.02^{abB}	4.15 ± 0.06^{bB}
Day 15	4.02 ± 0.01^{aA}	4.02 ± 0.01^{aA}	4.02 ± 0.02^{aA}	4.02 ± 0.02^{aA}
	TA			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
Day 1	0.79 ± 0.02^{bA}	0.73 ± 0.02^{aA}	0.75 ± 0.00^{abA}	0.71 ± 0.00^{aA}
Day 8	0.85 ± 0.01^{bB}	0.83 ± 0.02^{bB}	0.83 ± 0.00^{bB}	0.79 ± 0.00^{aB}
Day 15	0.95 ± 0.02^{b}C	0.91 ± 0.02^{ab}C	0.94 ± 0.01^{b}C	0.89 ± 0.01^{a}C

Results are shown as mean ± standard deviation (n = 3). Values that do not share the same lowercase superscript letters (a–b) in the same row are significantly different (Tukey's comparison test, $p < 0.05$). Values that do not share the same uppercase superscript letters (A–C) in the same column are significantly different (Tukey's comparison test, $p < 0.05$).

Hardness, which refers to the force required to attain yogurt deformation, is commonly used to assess yogurt texture [19,23]. Different impacts of dietary fiber addition on the yogurt hardness were reported. For instance, the addition of rice bran [14], pineapple peel [24], and orange fiber [21] powder were reported to reduce the hardness of yogurt. In these cases, it was explained by the weakened yogurt gel caused by the steric hindrance effect of fiber particles and the incompatibility between milk proteins and polysaccharides [21,24]. Conversely, the addition of apple pomace powder [19] and Lour fruit powder [43] were found to increase the hardness of yogurt. In these cases, the increase in hardness was explained by the increased total solid content and the increased density and rigidity of the yogurt gel network by the interactions between dietary fibers and polyphenols in the fiber sources with the yogurt protein matrix. In this study, a progressive increase in yogurt hardness was observed as the addition level of HCRP increased from 0.5 to 1.5% (see Table 2). Throughout the storage period, the HCRP-fortified yogurt generally exhibited higher hardness compared to the control yogurt, except for the 0.5% HCRP yogurt, which showed similar hardness to the control yogurt on day 8 and day 15. The storage time had minimal impact on the hardness of the yogurt, except for the control and 0.5% HCRP yogurt, which experienced a slight increase from day 1 to day 15 of storage (Table 2). The rise in the yogurt hardness observed with the increase of the HCRP fortification level could indicate the formation of a stronger gel structure facilitated by the addition of HCRP. Previous studies have reported that dietary fibers can strengthen the gel structure of yogurt through various mechanisms such as increasing the viscosity of the continuous phase, immobilizing water due to their high water-holding capacity, the bridging effect, and acting as filler [18,44,45].

3.3. Effect of HCRP fortification on the texture of yogurt

Table 2. Hardness and adhesiveness of the control and HCRP-fortified yogurt at different addition ratios measured on day 1, day 8, and day 15 of the storage period.

	Hardness (g)			
	Control	0.5% HCRP	1% HCRP	1.5% HCRP
Day 1	25.70 ± 0.96^{aA}	28.83 ± 0.42^{bA}	37.77 ± 0.67^{cA}	41.23 ± 1.76^{dA}
Day 8	28.37 ± 1.33^{aA}	32.80 ± 2.56^{aB}	38.57 ± 1.97^{bA}	46.63 ± 2.51^{cA}
Day 15	29.50 ± 2.62^{aA}	34.90 ± 0.36^{abB}	39.83 ± 1.37^{bA}	47.33 ± 3.40^{cA}
	Adhesiveness (g.s)			
	Control	0.5% HCRP	1% HCRP	1.5% HCRP
Day 1	22.14 ± 11.09^{aA}	48.40 ± 5.91^{aA}	135.28 ± 10.83^{bA}	186.70 ± 20.41^{cA}
Day 8	30.88 ± 12.83^{aA}	86.29 ± 23.52^{abB}	139.36 ± 17.26^{bAB}	246.67 ± 52.77^{cA}
Day 15	47.07 ± 13.89^{aA}	93.62 ± 2.16^{aB}	169.87 ± 6.79^{bB}	283.99 ± 50.36^{cA}

Results are shown as mean ± standard deviation (n = 3). Different lowercase superscript letters (a–d) within the same row are significantly different (Tukey's comparison test, $p < 0.05$). Different uppercase superscript letters (A–B) within the same column are significantly different (Tukey's comparison test, $p < 0.05$).

The yogurt adhesiveness positively influenced the yogurt thickness and the stability of the yogurt gel [40]. High adhesiveness is often associated with a pleasant mouth-feel, improved texture properties, and enhanced yogurt stability [40]. During the 15-day storage period, the adhesiveness gradually increased as the HCRP addition level increased (see Table 2). Storage time slightly affected the adhesiveness. The 0.5% and 1% HCRP yogurts displayed higher adhesiveness values on day 15 compared to day 1, while adhesiveness of the control and 1.5% HCRP yogurt remained largely unchanged throughout the entire storage period. Overall, the textural analysis indicated that the addition of HCRP resulted in an increase in the hardness and adhesiveness of the yogurt compared to the control yogurt during the 15-day storage period.

3.4. Effect of HCRP fortification on the rheology of yogurt

Figure 1 illustrates the change of the shear stress and the apparent viscosity of all of the yogurt samples as the shear rate increases. The steady-state flow test constants obtained from the power law model, including the consistency index (K) and flow behavior index (n), for each yogurt sample during storage are presented in Table 3. All yogurt samples displayed a flow behavior index (n) of less than 1, featuring the shear thinning pseudoplastic behavior of the yogurts [46]. Generally, the flow behavior index of fortified yogurts increased as the fortification level increased from 0.5% to 1.5% and the flow behavior index values of HCRP-fortified yogurts tended to be lower than that of the control yogurt.

The addition of HCRP resulted in a higher consistency index (K), with the higher addition level tending to be associated with a higher K value. The apparent viscosity values at 50 s^{-1} shear rate, which were suggested to have a strong correlation with sensory attributes such as thickness, stickiness, and sliminess for a wide range of viscous foods, are provided in Table 3 [38]. The addition of HCRP led to a substantial increase in the apparent viscosity throughout the entire storage period. Specifically, the apparent viscosity of 1.5% HCRP yogurt was generally 2 times higher compared to the control yogurt at the same storage time. There was a slight increase in the apparent viscosity of all yogurt types from day 1 to day 15 of storage. The increase in the consistency index and apparent viscosity of the yogurt with an increasing HCRP fortification level indicated that the addition of HCRP resulted in stronger gel structures. Previous studies have reported similar findings, where the incorporation of various fiber sources including passion fruit fiber [47], carrot soluble fiber [22], apple pomace [20], and jujube mucilage [39] resulted in a higher consistency index and apparent viscosity. Whereas the opposite effect on the viscosity was observed when rice bran [14] and pineapple peel powder [24] were added to yogurt. These variations in the viscosity could be attributed to the distinct characteristics of the fiber sources, especially the soluble and insoluble fiber content. The soluble fibers in HCRP can significantly contribute to increase the viscosity of the continuous phase. Meanwhile, they also can interact with the casein protein to strengthen the gel network [44], thereby increasing the consistency index and viscosity of the yogurt.

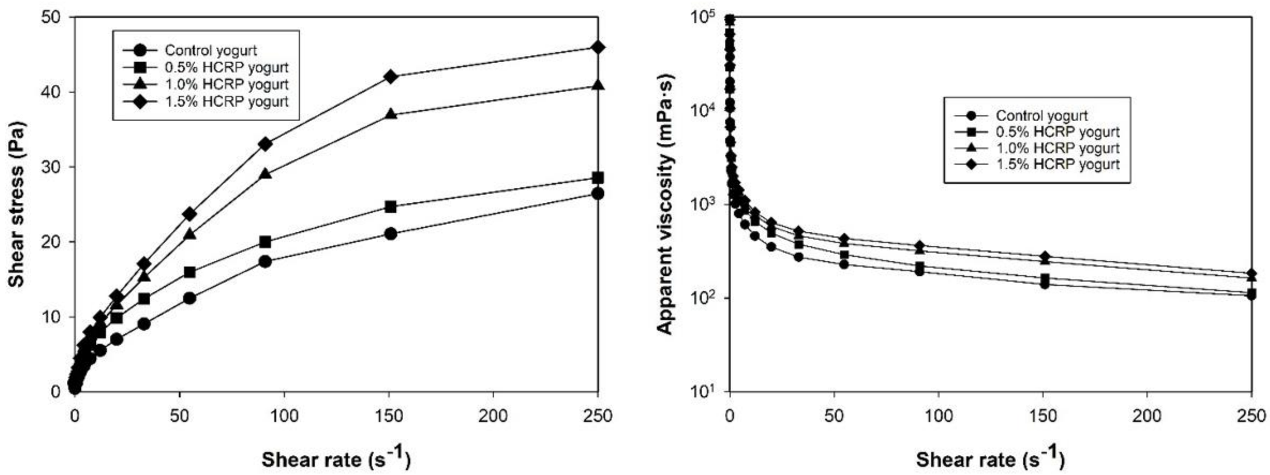

Figure 1. Representative plots of shear stress-shear rate (left) and the viscosity curve (right) for the control and HCRP-fortified yogurt at different addition ratios analyzed on day 1 of the storage period.

The storage modulus (G′) represents the elasticity of yogurt while the loss modulus (G″) reflects the viscous property of yogurt. Figure 2 shows the dependence of the storage modulus (G′), loss modulus (G″), and tanδ (ratio of G″/ G′) on angular frequency (ω) for different yogurt samples on day 1 of the storage period, as determined by the frequency sweep test. Consistent with previous studies [19,22,39], all yogurt samples displayed higher values of G′ than G″ across all tested frequencies, and tanδ was consistently smaller than 1. These findings indicate the notable elasticity of the yogurt gel and predominantly solid-like property of the yogurt.

Table 3. Consistency index (K), flow behavior index (n), and apparent viscosity at 50 s^{-1} of the control and HCRP-fortified yogurt at different addition ratios measured on day 1, day 8, and day 15 of the storage period.

	Consistency index, K (Pa·s^n)			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
Day 1	2.27 ± 0.1^{aA}	3.52 ± 0.36^{bA}	3.98 ± 0.21^{bA}	3.96 ± 0.16^{bA}
Day 8	2.34 ± 0.1^{aA}	4.01 ± 0.14^{bAB}	4.60 ± 0.07^{cB}	5.06 ± 0.17^{dB}
Day 15	2.81 ± 0.05^{aB}	4.46 ± 0.02^{bB}	4.91 ± 0.11^{bB}	6.17 ± 0.40^{cC}
	Flow behavior index, n			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
Day 1	0.39 ± 0.01^{bcB}	0.34 ± 0.01^{aB}	0.37 ± 0.00^{bB}	0.40 ± 0.01^{cC}
Day 8	0.39 ± 0.01^{cB}	0.32 ± 0.01^{aAB}	0.34 ± 0.01^{abA}	0.35 ± 0.01^{bB}
Day 15	0.36 ± 0.01^{bA}	0.31 ± 0.01^{aA}	0.33 ± 0.00^{aA}	0.32 ± 0.00^{aA}
	Apparent viscosity at 50 s^{-1} (mPa·s)			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
Day 1	235.35 ± 5.37^{aA}	313.82 ± 8.82^{bA}	405.96 ± 19.91^{cA}	441.39 ± 4.84^{dA}
Day 8	236.23 ± 6.04^{aA}	330.54 ± 9.45^{bA}	424.08 ± 11.45^{cA}	475.60 ± 7.44^{dA}
Day 15	268.39 ± 4.77^{aB}	355.47 ± 3.47^{bB}	410.57 ± 11.45^{cA}	514.49 ± 24.08^{dB}

Results are shown as mean ± standard deviation (n = 3). Values that do not share the same lowercase superscript letters (a–d) in the same row are significantly different (Tukey's comparison test, $p < 0.05$). Values that do not share the same uppercase superscript letters (A–C) in the same column are significantly different (Tukey's comparison test, $p < 0.05$).

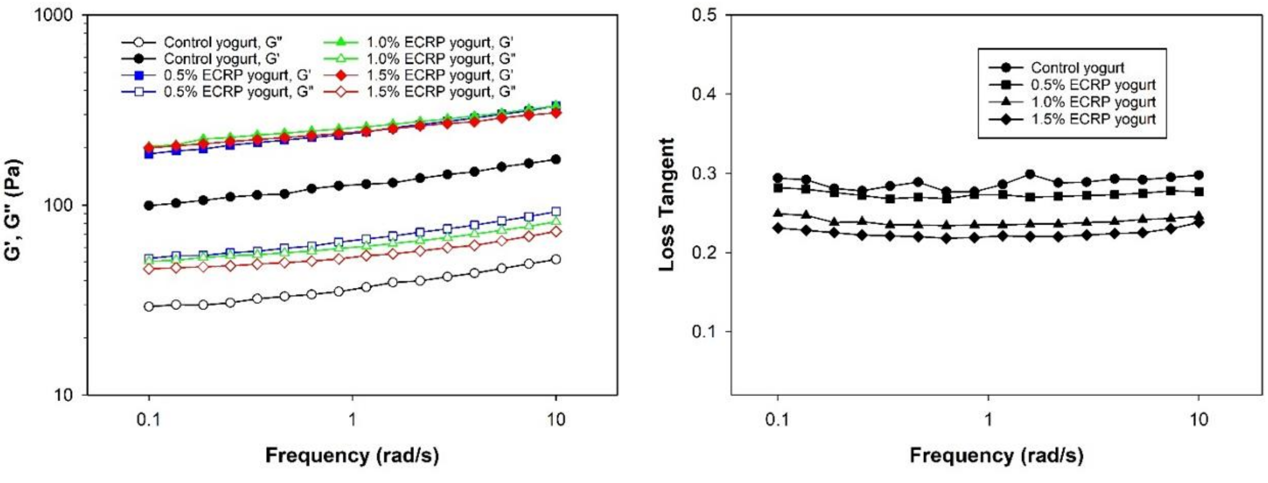

Figure 2. Representative plots showing the dependence of the storage modulus (G′), loss modulus (G″), and tanδ (ratio of G″/ G′) on the frequency (rad/s) of the control and HCRP-fortified yogurt at different addition ratios, characterized on day 1 of the storage period.

To facilitate the comparison, G′, G″, and tanδ values recorded at 10 rad/s during storage were extracted and presented in Table 4. The addition of HCRP tended to increase both storage modulus and loss modulus of the fortified-yogurts during the storage period. These moduli at a 1.5% addition ratio were significantly higher than those of the control yogurt. The loss tangent tended to decrease as the HCRP ratio increased from 0 (control) to 1.5%. This indicates that the elastic property of the yogurt became more dominant with the increased HCRP fortification and the addition of HCRP enhanced the solid-like property of fortified yogurt compared to the control yogurt.

Previous studies have shown that the addition of jujube mucilage [39], guar gum [18], carrot soluble fiber [22], and apple pomace [19] to yogurt led to an increase in the value of G′ and G″. In contrast, the supplementation of rice bran and pineapple peel powder [24] resulted in a decrease in the G′ and G″ value. The results of this study suggest that the addition of HCRP may reinforce the casein network in yogurt, leading to the higher apparent viscosity, consistency index, storage and loss modulus, and lower loss tangent compared to the control yogurt. The reinforcement ability on the casein network was observed previously for dietary fiber materials such as okara fiber [45], apple pectin [23], and konjac glucomannan [23]. The soluble fibers in HCRP could strengthen the casein network through the electrostatic interactions, hydrogen-bonding interactions with casein proteins, and aggregation promoting effect, leading to smaller voids and larger protein clusters in the gel network [23,45]. Meanwhile, the insoluble fibers in HCRP can contribute to enhance the viscosity and solid-like property by contributing to increase the solid and insoluble fraction of the gel structure and to reduce the mobile fraction within the gel due to the high water absorption capacity [17]. However, it should be noted that insoluble fibers may also have a disruptive effect on the gel structure of yogurt due to their steric hindrance, which hinders the formation of the gel network [17,19,21]. The disruptive effect of soluble fibers that have strong electrostatic interaction with milk proteins such as carrageenan has also been reported [48]. The results of this study indicate that the yogurt gel was strengthened by the insoluble and soluble fibers present in the hydrolyzed cantaloupe rind powder and this strengthening effect overcame any potential disruptive effects caused by the dietary fiber.

Table 4. Storage modulus (G′), loss modulus (G″), and loss tangent of the control and HCRP-fortified yogurt at different addition ratios measured on day 1, day 8, and day 15 of the storage period.

	G′ at 10 rad/s (Pa)			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
Day 1	173.91 ± 13.49^{aA}	362.26 ± 62.41^{bA}	282.16 ± 56.87^{abA}	270.04 ± 31.8^{abA}
Day 8	155.28 ± 10.59^{aA}	277.41 ± 43.38^{abA}	305.11 ± 16.4^{bA}	400.54 ± 91.29^{bA}
Day 15	241.66 ± 16.92^{aB}	328.58 ± 44.38^{bA}	288.30 ± 19.58^{abA}	415.55 ± 38.35^{cA}
	G″ at 10 rad/s (Pa)			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
Day 1	50.34 ± 3.40^{aA}	96.04 ± 12.22^{bA}	68.21 ± 14.08^{aA}	65.80 ± 6.48^{aA}
Day 8	40.95 ± 3.60^{aA}	70.36 ± 10.44^{abA}	74.13 ± 4.75^{abA}	92.89 ± 22.40^{bA}
Day 15	60.26 ± 4.52^{aB}	84.12 ± 11.67^{abA}	63.21 ± 5.27^{aA}	92.40 ± 13.84^{bA}
	Loss tangent (tanδ) at 10 rad/s			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
Day 1	0.29 ± 0.01^{bA}	0.27 ± 0.01^{bB}	0.24 ± 0.01^{aB}	0.24 ± 0.01^{aA}
Day 8	0.28 ± 0.02^{bA}	0.26 ± 0.01^{abAB}	0.24 ± 0.01^{aB}	0.23 ± 0.01^{aA}
Day 15	0.25 ± 0.01^{bA}	0.26 ± 0.00^{bA}	0.22 ± 0.00^{aA}	0.22 ± 0.01^{aA}

Results are shown as mean ± standard deviation (n = 3). Values that do not share the same lowercase superscript letters (a–c) in the same row are significantly different (Tukey's comparison test, $p < 0.05$). Values that do not share the same uppercase superscript letters (A–B) in the same column are significantly different (Tukey's comparison test, $p < 0.05$).

3.5. The effect of HCRP fortification on the stability of yogurt

The syneresis of the yogurt after 1, 8, and 15 days of storage is shown in Figure 3. Syneresis refers to the undesired phenomenon of yogurt where the gels spontaneously shrink, leading to the accumulation of the expelled liquid on the surface of yogurt. In this study, the syneresis of yogurt gradually decreased with the increase of the HCRP fortification level. On day 1, the control yogurt exhibited a syneresis value of 16.21% while the syneresis values for the 0.5%, 1.0%, and 1.5% HCRP yogurt were 10.77%, 9.78%, and 9.25%, respectively. The syneresis of the control and 0.5% HCRP yogurt was increased on day 8, while that of the 1.0% and 1.5% HCRP yogurt decreased compared to day 1. By day 15, the syneresis of all of the yogurt samples was lower than that on day 8 of storage. Collectively, these findings indicate that the addition of HCRP significantly improved yogurt stability. The improvement effect of HCRP in this study was concentration-dependent, with the lowest syneresis observed in the 1.5% HCRP yogurt, followed by the 1.0% and 0.5% HCRP yogurt, respectively. On day 1, the syneresis of the 1.5% HCRP yogurt was approximately half of the control. The improvement effect on syneresis was even more pronounced on day 15 of storage, with approximately 3 times less syneresis in the 1.5% HCRP yogurt compared to the control yogurt.

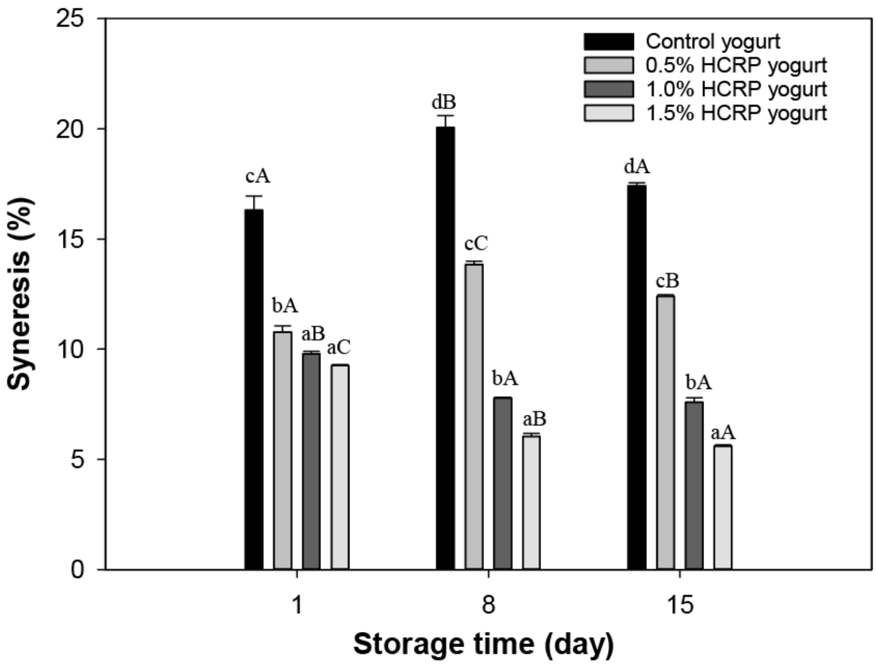

Figure 3. Syneresis of the control and HCRP-fortified yogurt at different addition ratios measured on day 1, day 8, and day 15 of the storage period. Different lowercase letters (a–d) indicate significant differences in values for the same storage period (Tukey's comparison test, $p < 0.05$). Different capital letters (A–C) indicate significant differences in values for the same type of yogurt across different storage periods (Tukey's comparison test, $p < 0.05$).

The reduction in syneresis in the HCRP yogurt with an increasing HCRP addition level could be attributed to the higher viscosity and stronger gel, as indicated by higher values of G' and G". These properties could inhibit the shrinkage of the gel network and help to retain more water in the HCRP-fortified yogurt compared to the control yogurt. Additionally, the high water-holding capacity of

HCRP can also contribute to preventing water expulsion from the yogurt structure. Similar results regarding the reduction of syneresis were observed when 0.25% partial hydrolyzed guar gum [18], 0.5–1.5% orange fiber [25], 10% red beetroot [49], and 2.0–3.0% of rice bran [14] were added to the yogurt recipe before fermentation. However, the increase in syneresis was also observed when 0.5% partially hydrolyzed guar gum and 0.1% orange pectin fiber [18] or 1% pineapple peel [24] were added to the yogurt recipe, which was explained by the weakening effect of these materials on the gel structure. The difference in the effect of dietary fiber addition of different sources on the syneresis could arise from the variations in the nature of fiber sources, soluble and insoluble fiber contents, and yogurt preparation methods, which should be further investigated. It should be noted that the insoluble fiber fraction has mixed effects on the yogurt stability. On one side, it can immobilize the whey within the casein network due to their high water-holding capacity, thereby reducing the syneresis [18]. On the other side, it can pose steric hindrance to the formation of the yogurt gel network [21], thereby weakening the gel and enhancing syneresis. Depending on which effect is dominated, the insoluble fiber can contribute to either an increase or decrease of syneresis [17,18]. In this study, the stabilization effect of insoluble and soluble fibers in HCRP dominated the destabilization effect of insoluble fiber, resulting in reduced syneresis of the HCRP-fortified yogurt compared to the control yogurt.

3.6. The effect of HCRP fortification on the color of yogurt

The color parameters (L*, a*, b*) showed significant differences ($p < 0.05$) among the various yogurt types, as presented in Table 5. The lightness (L*) value decreased as the level of HCRP addition increased. The green/red (a*) indicator was negative in the control and 0.5% HCRP yogurt, while it was positive in the 1.0% and 1.5% HCRP yogurt. This indicates that the addition of HCRP resulted in a shift toward a reddish hue in the yogurt. The blue/yellow (b*) indicator increased with higher levels of HCRP addition, indicating that the fortification of HCRP enhanced the yellowish color of the yogurt. The color difference value (ΔE) of the 0.5% HCRP and control yogurt was less than 5 (see Table 5), implying that the naked eye may not perceive the color difference between the 0.5% HCRP yogurt and the control yogurt. Meanwhile, the color difference values of 1.0% and 1.5% HCRP yogurt were higher than 5 (see Table 5), indicating that the color difference between these two yogurts and the control yogurt can be visually perceived [50]. Previous studies reported that the alternation in color can impact the sensory assessment of yogurt [21,51,52]. Therefore, the color change resulting from the addition of HCRP to yogurt could affect the sensory perception of the HCRP-added yogurt, which should be further investigated.

Table 5. L*, a*, and b* values of the control and HCRP-fortified yogurt at different addition ratios measured at day 15 of storage.

	Color parameters			
	Control	0.5% HCRP	1.0% HCRP	1.5% HCRP
L*	93.61 ± 0.23^d	89.85 ± 0.52^c	86.11 ± 0.41^b	82.45 ± 0.14^a
a*	-0.78 ± 0.01^a	-0.31 ± 0.05^b	0.16 ± 0.02^c	0.39 ± 0.02^d
b*	8.41 ± 0.17^a	10.81 ± 0.23^b	13.05 ± 0.44^c	15.58 ± 0.24^d
ΔE	0 ± 0^a	4.49 ± 0.77^b	8.87 ± 0.83^c	13.32 ± 0.49^d

Results are shown as mean ± standard deviation (n = 3). Values that do not share the same lowercase superscript letters (a–d) in the same row are significantly different (Tukey's comparison test, $p < 0.05$).

3.7. The effect of HCRP fortification on the total phenolic content and antioxidant property of yogurt

The total phenolic content (TPC) and antioxidant activity of the yogurt were quantified on day 15 of storage and presented in Figure 4. The addition of HCRP resulted in a gradual increase in the TPC and antioxidant activity of the yogurt. It should be noted that the detection of TPC in the control yogurt could be attributed to the limitations of the Folin–Ciocalteu assay, which relies on a redox reaction with the Folin reagent. Reducing sugar and other reducing agents, such as reducing amino acid side chains, present in the control yogurt may also react with the Folin reagent, leading to interference with the result. The detection of TPC in the control yogurt was observed previously [43]. The TPC of 1.5% HCRP yogurt was approximately 1.6 times higher compared to the control yogurt. The antioxidant activity determined by the DPPH assay was not detected in the control yogurt, while it was 5.13, 8.48, and 10.62 μmole TE/g yogurt in the 0.5%, 1.0%, and 1.5% HCRP yogurt, respectively. Increasement in TPC and antioxidant activity was generally reported with the addition of fruit by-product such as apple pomace powder [51], orange fiber [25], and grape pomace [53].

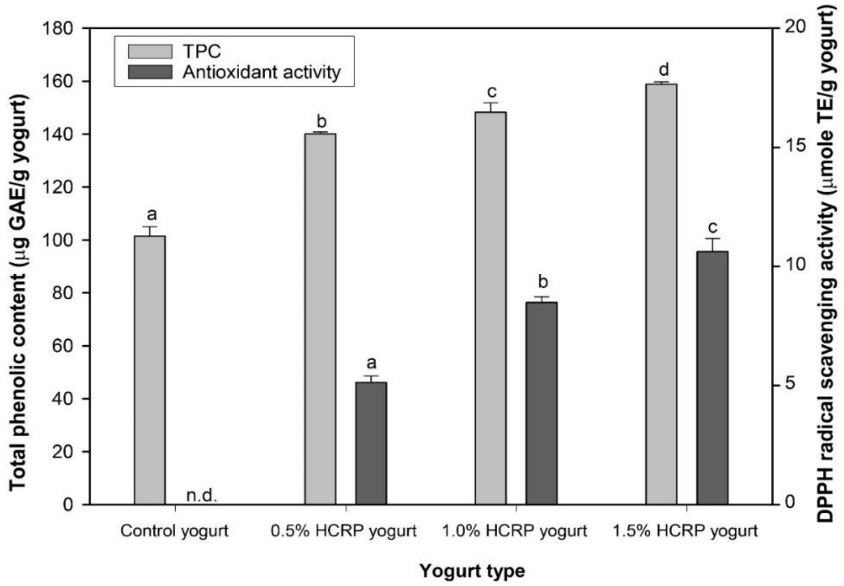

Figure 4. Total phenolic content (TPC) and antioxidant activity quantified by DPPH assay of the control and HCRP-fortified yogurt at different addition ratios measured on day 15 of the storage period. Different lowercase letters (a–d) indicate significant differences in values within the same quantification (Tukey's comparison test, $p < 0.05$). n.d. = not detected.

3.8. Principal component analysis (PCA)

Principal component analysis was carried out to investigate the relationships among physiochemical, textural properties, rheological properties, syneresis, color, and antioxidant properties of the HCRP-fortified yogurt. The results of the PCA are shown in Figure 5 and Table S1. The first component (PC1) and second component (PC2) explained for a total 86.31% of the total variance in which PC1 accounted for 74.93% and PC2 accounted for 11.38%, suggesting that the PC1-PC2 plot could reflect the majority of the contribution of the variables. Based on Figure 5A, it can be observed that yogurt samples from each group of the control, 0.5% HCRP, 1.0% HCRP, and 1.5% HCRP form distinct and separated clusters, indicating the significant difference in the properties of these four yogurt groups. In Figure 5B, the adjacent dots indicate that the corresponding variables are positively correlated while the opposite dots indicate that the corresponding variables are negatively correlated. The correlation coefficients of variables are shown in Table S1. There are strong positive correlations between hardness, adhesiveness, viscosity, K value, G′, G″, TPC, DPPH, a*, and b* while these variables are negatively correlated to syneresis, n value, tanδ, TA, and L*. Collectively, the principal component analysis pointed out that the addition of HCRP to yogurt at different ratios significantly influenced the yogurt properties. Additionally, the syneresis of yogurt was shown to have strong negative correlations with hardness, adhesiveness, viscosity, K value, G′, and G″ while being positively correlated with the n value, TA, and tanδ (see Table S1).

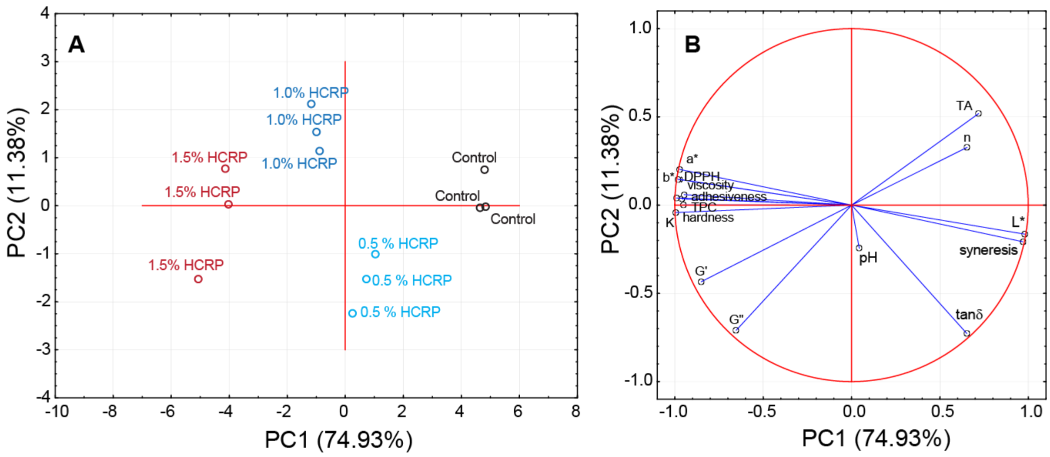

Figure 5. Principal component analysis of yogurt with different HCRP addition levels. (A) PCA scores plot of samples belonging to the control, 0.5% HCRP, 1.0% HCRP, and 1.5% HCRP yogurt. (B) Variable correlation plot showing the relationship between yogurt attributes.

4. Conclusions

This study highlights the potential utilization of enzymatically hydrolyzed cantaloupe rind powder for producing functional yogurt with enhanced structure. The addition of 0.5–1.5% of HCRP to yogurt resulted in significant improvements in stability, hardness, viscosity, and gel strength of the yogurt. The effectiveness of HCRP in improving these properties was observed to be concentration-dependent, with higher HCRP concentrations exhibiting greater efficacy. The syneresis of the 1.5% HCRP yogurt decreased by approximately three times compared to the control yogurt by the end of the storage period. Furthermore, the addition of HCRP significantly enhanced the antioxidant property and total phenolic content of the yogurt. To gain further insights into the effects of HCRP supplementation on yogurt quality and microstructure, microbial and sensory analysis using different methods such as hedonic testing and check-all-that-apply (CATA) of the HCRP-fortified yogurt should be conducted. Additionally, evaluation of prebiotic activities of HCRP can be carried out to access the health benefits of HCRP. The knowledge obtained from these studies would contribute to the development of functional yogurts with improved quality using fruit by-products, thereby reducing waste in the food industry, generating additional economic value for food producers, and contributing to the achievement of sustainable development goals.

Supplementary

Table S1. Correlation coefficients for the relationship among yogurt attributes.

	pH	TA	hardness	adhesiveness	viscosity	K	n	G'	G"	tanδ	TPC	DPPH	syneresis	L*	a*	b*
pH	1.0000															
TA	0.0224	1.0000														
hardness	−0.0025	−0.6992	1.0000													
adhesiveness	−0.0185	−0.6474	0.9545	1.0000												
viscosity	−0.0473	−0.7062	0.9804	0.9698	1.0000											
K	−0.0346	−0.7237	0.9581	0.9379	0.9873	1.0000										
n	0.0196	0.5269	−0.4901	−0.4415	−0.5696	−0.6906	1.0000									
G'	−0.0157	−0.8158	0.8007	0.8300	0.8359	0.8534	−0.5912	1.0000								
G"	0.0441	−0.7961	0.6010	0.6172	0.6246	0.6722	−0.5863	0.9375	1.0000							
tan	0.2076	0.1092	−0.6296	−0.6718	−0.6740	−0.6086	0.1560	−0.2770	0.0698	1.0000						
TPC	0.0065	−0.6590	0.8748	0.8244	0.9170	0.9538	−0.7813	0.7437	0.5712	−0.5929	1.0000					
DPPH	−0.0175	−0.5995	0.9115	0.8955	0.9528	0.9607	−0.6633	0.7426	0.5145	−0.7368	0.9729	1.0000				
syneresis	0.0330	0.5617	−0.9282	−0.9100	−0.9569	−0.9558	0.6159	−0.7117	−0.4704	0.7702	−0.9555	−0.9944	1.0000			
L*	0.0491	0.6353	−0.9520	−0.9503	−0.9818	−0.9662	0.5617	−0.7631	−0.5184	0.7607	−0.9280	−0.9790	0.9830	1.0000		
a*	−0.0536	−0.5679	0.9348	0.9177	0.9644	0.9604	−0.6047	0.7311	0.4879	−0.7759	0.9499	0.9929	−0.9983	−0.9848	1.0000	
b*	−0.0869	−0.6501	0.9503	0.9491	0.9822	0.9658	−0.5570	0.7850	0.5440	−0.7521	0.9249	0.9759	−0.9774	−0.9976	0.9817	1.00000

Acknowledgments

This research is funded by the Murata Science Foundation under grant number 23VH05. The authors acknowledge Ho Chi Minh City University of Technology (HCMUT), VNU-HCM, for supporting this study.

Conflict of interest

The authors declare no conflicts of interest.

Authors contributions

Thi Quynh Ngoc Nguyen: Conceptualization, formal analysis, data curation, funding acquisition, investigation, methodology, supervision, validation, visualization, writing—original draft, Writing—review & editing; Thi Thuy Le: Investigation, methodology; Thi Ho Thanh Dong: Investigation, methodology, formal analysis, data curation, validation.

References

1. Nagaoka S (2019) Yogurt Production. In: Kanauchi M (Ed.), *Lactic Acid Bacteria: Methods and Protocols*. New York, NY: Springer New York, 45–54. https://doi.org/10.1007/978-1-4939-8907-2_5
2. Ugidos-Rodríguez S, Matallana-González MC, Sánchez-Mata MC (2018) Lactose malabsorption and intolerance: A review. *Food Funct* 9: 4056–4068. https://doi.org/10.1039/C8FO00555A
3. Hadjimbei E, Botsaris G, Chrysostomou S (2022) Beneficial effects of yoghurts and probiotic fermented milks and their functional food potential. *Foods* 11: 2691. http://doi.org/10.3390/foods11172691
4. Oliveira FLd, Arruda TYP, Morzelle MC, et al. (2022) Fruit by-products as potential prebiotics and promising functional ingredients to produce fermented milk. *Food Res Int* 161: 111841. https://doi.org/10.1016/j.foodres.2022.111841
5. Rudrapal M, Khairnar SJ, Khan J, et al. (2022) Dietary polyphenols and their role in oxidative stress-induced human diseases: Insights into protective effects, antioxidant potentials and mechanism(s) of action. *Front Pharmacol* 13: 806470. https://doi.org/10.3389/fphar.2022.806470
6. Wongkaew M, Tangjaidee P, Leksawasdi N, et al. (2022) Mango pectic oligosaccharides: A novel prebiotic for functional food. *Front Nutr* 9: 798543. https://doi.org/10.3389/fnut.2022.798543
7. Vieira ADS, Bedani R, Albuquerque MAC, et al. (2017) The impact of fruit and soybean by-products and amaranth on the growth of probiotic and starter microorganisms. *Food Res Int* 97: 356–363. https://doi.org/10.1016/j.foodres.2017.04.026
8. Hui CY, Lee KC, Chang YP (2022) Cellulase-xylanase-treated guava purée by-products as prebiotics ingredients in yogurt. *Plant Foods Hum Nutr* 77: 299–306. https://doi.org/10.1007/s11130-022-00981-4
9. Sanders ME, Merenstein DJ, Reid G, et al. (2019) Probiotics and prebiotics in intestinal health and disease: From biology to the clinic. *Nat Rev Gastroenterol Hepatol* 16: 605–616. http://doi.org/10.1038/s41575-019-0173-3
10. Zahid HF, Ranadheera CS, Fang Z, et al. (2022) Functional and healthy yogurts fortified with probiotics and fruit peel powders. *Fermentation* 8: 469. https://doi.org/10.3390/fermentation8090469

11. Sah BNP, Vasiljevic T, McKechnie S, et al. (2015) Effect of refrigerated storage on probiotic viability and the production and stability of antimutagenic and antioxidant peptides in yogurt supplemented with pineapple peel. *J Dairy Sci* 98: 5905–5916. https://doi.org/10.3168/jds.2015-9450
12. Varnaitė L, Keršienė M, Šipailienė A, et al. (2022) Fiber-rich cranberry pomace as food ingredient with functional activity for yogurt production. *Foods* 11: 758. https://doi.org/10.3390/foods11050758
13. do Espírito Santo AP, Cartolano NS, Silva TF, et al. (2012) Fibers from fruit by-products enhance probiotic viability and fatty acid profile and increase CLA content in yoghurts. *Int J Food Microbiol* 154: 135–144. https://doi.org/10.1016/j.ijfoodmicro.2011.12.025
14. Wu T, Deng C, Luo S, et al. (2023) Effect of rice bran on properties of yogurt: Comparison between addition of bran before fermentation and after fermentation. *Food Hydrocolloids* 135: 108122. https://doi.org/10.1016/j.foodhyd.2022.108122
15. Fundo JF, Miller FA, Garcia E, et al. (2018) Physicochemical characteristics, bioactive compounds and antioxidant activity in juice, pulp, peel and seeds of cantaloupe melon. *J Food Meas Character* 12: 292–300. http://doi.org/10.1007/s11694-017-9640-0
16. Silva MA, Albuquerque TG, Alves RC, et al. (2020) Melon (Cucumis melo L.) by-products: Potential food ingredients for novel functional foods? *Trends Food Sci Technol* 98: 181–189. https://doi.org/10.1016/j.tifs.2018.07.005
17. Sendra E, Kuri V, Fernández-López J, et al. (2010) Viscoelastic properties of orange fiber enriched yogurt as a function of fiber dose, size and thermal treatment. *LWT-Food Sci Technol* 43: 708–714. https://doi.org/10.1016/j.lwt.2009.12.005
18. Mary PR, Mutturi S, Kapoor M (2022) Non-enzymatically hydrolyzed guar gum and orange peel fibre together stabilize the low-fat, set-type yogurt: A techno-functional study. *Food Hydrocolloids* 122: 107100. https://doi.org/10.1016/j.foodhyd.2021.107100
19. Wang X, Kristo E, LaPointe G (2019) The effect of apple pomace on the texture, rheology and microstructure of set type yogurt. *Food Hydrocolloids* 91: 83–91. https://doi.org/10.1016/j.foodhyd.2019.01.004
20. Wang X, Kristo E, LaPointe G (2020) Adding apple pomace as a functional ingredient in stirred-type yogurt and yogurt drinks. *Food Hydrocolloids* 100: 105453. https://doi.org/10.1016/j.foodhyd.2019.105453
21. Kieserling K, Vu TM, Drusch S, et al. (2019) Impact of pectin-rich orange fibre on gel characteristics and sensory properties in lactic acid fermented yoghurt. *Food Hydrocolloids* 94: 152–163. https://doi.org/10.1016/j.foodhyd.2019.02.051
22. Dong R, Liao W, Xie J, et al. (2022) Enrichment of yogurt with carrot soluble dietary fiber prepared by three physical modified treatments: Microstructure, rheology and storage stability. *Innovative Food Sci Emerging Technol* 75: 102901. https://doi.org/10.1016/j.ifset.2021.102901
23. Xu K, Guo M, Du J, et al. (2019) Okra polysaccharide: Effect on the texture and microstructure of set yoghurt as a new natural stabilizer. *Int J Biol Macromol* 133: 117–126. https://doi.org/10.1016/j.ijbiomac.2019.04.035
24. Sah BNP, Vasiljevic T, McKechnie S, et al. (2016) Physicochemical, textural and rheological properties of probiotic yogurt fortified with fibre-rich pineapple peel powder during refrigerated storage. *LWT-Food Sci Technol* 65: 978–986. https://doi.org/10.1016/j.lwt.2015.09.027
25. Erkaya-Kotan T (2020) In vitro angiotensin converting enzyme (ACE)-inhibitory and antioxidant activity of probiotic yogurt incorporated with orange fibre during storage. *J Food Sci Technol* 57: 2343–2353. http://doi.org/10.1007/s13197-020-04272-1

26. Gill SK, Rossi M, Bajka B, et al. (2021) Dietary fibre in gastrointestinal health and disease. *Nat Rev Gastroenterol Hepatol* 18: 101–116. https://doi.org/10.1038/s41575-020-00375-4
27. You S, Ma Y, Yan B, et al. (2022) The promotion mechanism of prebiotics for probiotics: A review. *Front Nutr* 9: 1000517. https://doi.org/10.3389/fnut.2022.1000517
28. Garcia-Amezquita LE, Tejada-Ortigoza V, Serna-Saldivar SO, et al. (2018) Dietary fiber concentrates from fruit and vegetable by-products: Processing, modification, and application as functional ingredients. *Food Bioprocess Technol* 11: 1439-1463. https://doi.org/10.1007/s11947-018-2117-2
29. Chawla R, Patil GR (2010) Soluble dietary fiber. *Compr Rev Food Sci Food Saf* 9: 178–196. https://doi.org/10.1111/j.1541-4337.2009.00099.x
30. Phirom-on K, Apiraksakorn J (2021) Development of cellulose-based prebiotic fiber from banana peel by enzymatic hydrolysis. *Food Biosci* 41: 101083. https://doi.org/10.1016/j.fbio.2021.101083
31. Chang YP, Wee WY, Wan KW, et al. (2022) Improvement of prebiotic activity of guava purée by-products through cellulase treatment. *Food Biotechnol* 36: 38–57. https://doi.org/10.1080/08905436.2021.2006063
32. Song H, Zhang Z, Li Y, et al. (2022) Effects of different enzyme extraction methods on the properties and prebiotic activity of soybean hull polysaccharides. *Heliyon* 8: e11053. https://doi.org/10.1016/j.heliyon.2022.e11053
33. Montemurro M, Casertano M, Vilas-Franquesa A, et al. (2024) Exploitation of spent coffee ground (SCG) as a source of functional compounds and growth substrate for probiotic lactic acid bacteria. *LWT* 198: 115974. https://doi.org/10.1016/j.lwt.2024.115974
34. Liu X, Hu KKY, Haritos VS (2024) Enzymatic production of cello-oligosaccharides with potential human prebiotic activity and release of polyphenols from grape marc. *Food Chem* 435: 137562. https://doi.org/10.1016/j.foodchem.2023.137562
35. Hood EE, Requesens DV (2012) Production of Industrial Proteins in Plants. In: Wang A, Ma S (Eds.), *Molecular Farming in Plants: Recent Advances and Future Prospects*. Dordrecht: Springer Netherlands, 161–181. https://doi.org/10.1007/978-94-007-2217-0_8
36. Robitaille G, Tremblay A, Moineau S, et al. (2009) Fat-free yogurt made using a galactose-positive exopolysaccharide-producing recombinant strain of Streptococcus thermophilus. *J Dairy Sci* 92: 477–482. https://doi.org/10.3168/jds.2008-1312
37. Najgebauer-Lejko D, Witek M, Żmudziński D, et al. (2020) Changes in the viscosity, textural properties, and water status in yogurt gel upon supplementation with green and Pu-erh teas. *J Dairy Sci* 103: 11039–11049. https://doi.org/10.3168/jds.2020-19032
38. Nguyen PTM, Kravchuk O, Bhandari B, et al. (2017) Effect of different hydrocolloids on texture, rheology, tribology and sensory perception of texture and mouthfeel of low-fat pot-set yoghurt. *Food Hydrocolloids* 72: 90–104. https://doi.org/10.1016/j.foodhyd.2017.05.035
39. Yekta M, Ansari S (2019) Jujube mucilage as a potential stabilizer in stirred yogurt: Improvements in the physiochemical, rheological, and sensorial properties. *Food Sci Nutr* 7: 3709–3721. https://doi.org/10.1002/fsn3.1230
40. Delikanli B, Ozcan T (2017) Improving the textural properties of yogurt fortified with milk proteins. *J Food Proc Preserv* 41: e13101. https://doi.org/10.1111/jfpp.13101
41. Kupina S, Fields C, Roman MC, et al. (2019) Determination of total phenolic content using the Folin-C Assay: Single-Laboratory Validation, first action 2017.13. *J AOAC Int* 102: 320–321. https://doi.org/10.1093/jaoac/102.1.320

42. Brand-Williams W, Cuvelier ME, Berset C (1995) Use of a free radical method to evaluate antioxidant activity. *LWT-Food Sci Technol* 28: 25–30. https://doi.org/10.1016/S0023-6438(95)80008-5
43. Rashwan AK, Karim N, Xu Y, et al. (2022) Chemical composition, quality attributes and antioxidant activity of stirred-type yogurt enriched with Melastoma dodecandrum Lour fruit powder. *Food Funct* 13: 1579–1592. https://doi.org/10.1039/D1FO03448K
44. Everett DW, McLeod RE (2005) Interactions of polysaccharide stabilisers with casein aggregates in stirred skim-milk yoghurt. *Int Dairy J* 15: 1175–1183. https://doi.org/10.1016/j.idairyj.2004.12.004
45. Chen B, Zhao X, Cai Y, et al. (2023) Incorporation of modified okara-derived insoluble soybean fiber into set-type yogurt: Structural architecture, rheological properties and moisture stability. *Food Hydrocolloids* 137: 108413. https://doi.org/10.1016/j.foodhyd.2022.108413.
46. Zhong Q, Daubert CR (2013) Chapter 15—Food Rheology. In: Kutz M (Ed.), *Handbook of Farm, Dairy and Food Machinery Engineering (Second Edition)*. San Diego: Academic Press, 403–426.
47. Espírito-Santo AP, Lagazzo A, Sousa ALOP, et al. (2013) Rheology, spontaneous whey separation, microstructure and sensorial characteristics of probiotic yoghurts enriched with passion fruit fiber. *Food Res Int* 50: 224–231. https://doi.org/10.1016/j.foodres.2012.09.012
48. Pang Z, Deeth H, Bansal N (2015) Effect of polysaccharides with different ionic charge on the rheological, microstructural and textural properties of acid milk gels. *Food Res Int* 72: 62–73. https://doi.org/10.1016/j.foodres.2015.02.009
49. Ozdemir T, Ozcan T (2020) Effect of steviol glycosides as sugar substitute on the probiotic fermentation in milk gels enriched with red beetroot (Beta vulgaris L.) bioactive compounds. *LWT* 134: 109851. https://doi.org/10.1016/j.lwt.2020.109851
50. Obón JM, Castellar MR, Alacid M, et al. (2009) Production of a red-purple food colorant from Opuntia stricta fruits by spray drying and its application in food model systems. *J Food Eng* 90: 471–479. https://doi.org/10.1016/j.jfoodeng.2008.07.013
51. Jovanović M, Petrović M, Miočinović J, et al. (2020) Bioactivity and sensory properties of probiotic yogurt fortified with apple pomace flour. *Foods* 9: 763. https://doi.org/10.3390/foods9060763
52. Çalişkanlar S, Saygili D, Karagözlü N, et al. (2024) Utilization of pomegranate and black grape seed by-products in yogurt production: Effects on phenolic compounds and antioxidant activity. *Food Sci Nutr* 12: 1170–1179. https://doi.org/10.1002/fsn3.3832
53. Demirkol M, Tarakci Z (2018) Effect of grape (Vitis labrusca L.) pomace dried by different methods on physicochemical, microbiological and bioactive properties of yoghurt. *LWT* 97: 770–777. https://doi.org/10.1016/j.lwt.2018.07.058