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A comparative study on utilization of different plant-derived nano-mucilage as a fat replacer in yogurt: Product optimization, physicochemical attributes, shelf-life evaluation, and consumer perception with market orientation

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ABSTRACT

This study aimed to utilize different plant-derived mucilage as a fat substitute in yogurt production. *Colocasia esculenta* rhizome mucilage (CEM), *Cordia dichotoma* fruit mucilage (CDM), and *Psyllium* husk mucilage (PHM) were extracted using different extraction process, and spray dried to acquire nano-scaled mucilage particles (100–300 nm). Seven different types of yogurts were prepared with the addition of varied mucilage concentrations (1–10 % *w/v*). Results showed that the yogurt with 4.5 % PHM exhibited suitable viscosity, higher water holding capacity, and reduced syneresis over the 16 days of storage. Furthermore, selected yogurt sample revealed similar physicochemical, textural, and color attributes as compared to control (full-fat and skimmed-milk yogurt). Moreover, this study showed that consumers highly accepted mucilage-formulated yogurt, with a mean score of 97.16 ± 1.58 %. Overall, nano-mucilage holds potential as a sustainable biomaterial for producing low-fat yogurt.

1. Introduction

Growing consumer demand for healthier food options has sparked significant research and innovation in the food industry, especially in the development of low-fat dairy products. Yogurt, a widely consumed fermented dairy product, has been valued for its nutritional properties, including probiotics, high protein content, and essential vitamins and minerals (El-Aidie & Khalifa, 2024; Li et al., 2023). However, the production of low-fat yogurt presents significant challenges, primarily due to the reduction of fat, which plays a crucial role in determining the texture, mouthfeel, and overall sensory attributes of the final product (Zhao et., 2023). The creamy texture, flavor, and stability of yogurt are primarily influenced by its fat content. Reducing fat typically leads to a less desirable product, characterized by lower viscosity, increased syneresis (whey separation), and an undesirable mouthfeel (Gantumur et al., 2024). To address these challenges, researchers have explored various strategies, including the incorporation of texturizing agents, stabilizers, and fat replacers (Gharibzahedi & Altintas, 2024). Among these alternatives, plant-derived mucilage has emerged as a promising natural substitute, owing to its unique rheological properties and associated well-being health benefits.

Plant-derived mucilage, extracted from various botanical sources, serves as a natural hydrocolloid known for its exceptional water-oil holding capacity, emulsifying ability, and strong gelling properties, making it an ideal candidate for use as a fat replacer and texture modifier in a wide range of food products (Goksen et al., 2023). Mucilage, is a hydrophilic polysaccharide complex, exhibits unique functional properties that reduce it promising for fat replacement in dairy, meat, and bakery products (Amiri et al., 2020). Mucilage sourced from plants such as *Colocasia esculenta* (Taro) rhizome, *Cordia dichotoma* (Indian

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cherry) fruit, and *Psyllium* husk has the ability to absorb water, form robust gels when exposed to water and heat, and stabilize emulsions. These raw materials are cost-effective, easily available, non-toxic and possess excellent health benefits. Moreover, unique properties enable mucilage to replicate the textural and sensory attributes of fats while providing notable health benefits (de Oliveira Filho et al., 2020; Tosif et al., 2021; Mijinyawa et al., 2018). The capacity of mucilage to trap and retain substantial amounts of water creates a gel-like consistency that mimics the mouthfeel and moisture retention properties of fats. This characteristic is particularly crucial in food formulations where fat contributes to the product's juiciness and softness, such as in baked goods and dairy products (Ahmadinia et al., 2023). Additionally, the high viscosity of mucilage solutions accurately mimics the thickness contributed by fats in numerous food products, which is especially beneficial in applications like dressings, sauces, and dairy alternatives, where preserving the desired consistency is necessary for customer acceptance (Câmara et al., 2020). Mucilage also stabilizes oil-in-water emulsions, similar to the role of fats in numerous food systems. By reducing surface tension between immiscible phases, mucilage aids in maintaining stable emulsions, thereby preventing the separation of oil and water. This stabilization is essential in products like mayonnaise, salad dressings, and ice creams (Tosif et al., 2021). Moreover, the gel-forming capability of mucilage is comparable to that of fats, providing the necessary structure and stability in food products. This property is vital in confections, jellies, and other gelled desserts where a firm yet smooth texture is desired (Nazir & Wani, 2021). Due to these exceptional techno-functional properties, mucilage holds significant potential as a fat replacer in food formulations.

Recent advancements in nano-technology have further enhanced the functional properties of mucilage, leading to the development of nano-mucilage (Aswathy et al., 2024). This nanoformulation exhibits improved solubility, stability, and bioavailability, making it a highly effective ingredient in modern food applications. Taro rhizome (*Colocasia esculenta*) is a vegetable rich in mucilage, which is famous due to its remarkable functional properties, contributes to improved viscosity and texture in yogurt formulations (Tosif et al., 2023). Similarly, *Cordia dichotoma*, known for its mucilaginous fruits, offers comparable texturizing effects (Tak et al., 2024). Moreover, *Psyllium* husk, recognized for its high fiber content, boosts texture and offers health advantages, including enhanced gastrointestinal wellness (Azam et al., 2023).

Thus, the study aims to compare the utilization of various plant-derived nano-mucilage as fat replacers in yogurt formulations. The research focuses on optimizing the yogurt product by evaluating the physicochemical attributes such as viscosity, syneresis, water-holding capacity, and texture. Furthermore, the shelf-life of the formulated yogurt was assessed over 16 days of storage period. Consumer perception and acceptance of these nano-mucilage-based yogurts were also analyzed.

2. Materials and methods

2.1. Materials

2.1.1. Chemicals and raw material

For yogurt preparation, different types of milk including skimmed milk, double-toned milk, toned milk, standardized milk, and full-fat milk were purchased from the Amul parlor (Punjab, India). Yogurt cultures are rich in *Streptococcus thermophilus*, *Lactobacillus bulgaricus*, *Lactococcus lactis* were obtained from Alla's posh (New Delhi, India). Different analytical chemicals and reagents such as petroleum ether, sodium hydroxide, sodium carbonate, and quercetin were procured from Loba Chemie Pvt. Ltd. (Mumbai, India). Sodium nitrate, aluminum chloride, ammonium hydroxide, and phenolphthalein indicator were procured from the Central Drug House (New Delhi, India). All the class "A" certified glassware and analytical-grade reagents were used throughout the study.

2.1.2. Sample preparation

The specific variety of *Colocasia esculenta* (CE) (Punjab Arvi-1) was used in the study. The rhizomes were harvested after seven months of planting, sourced from the Punjab Agricultural University, Ludhiana, Punjab, India. Freshly harvested CE rhizomes were graded based on size, with medium-sized, thick, and long corms selected for the experiments. The rhizomes had a brown exterior and creamy inner flesh. Dust and debris were removed using running tap water, and the rhizomes were peeled with a laboratory peeler. Subsequently, the rhizomes were dried using a tray drier (NSW 86, Narang Scientific Works, Mumbai, India) at 45 °C and stored at room temperature (27 °C) for further analysis. Additionally, freshly ripened *Cordia dichotoma* (CD) fruits were collected from a local agricultural farm in Bhatinda, Punjab, India. Medium-sized, green-colored fruits were selected and cleaned with running tap water to remove debris and dust from the surface. Due to their climacteric nature and susceptibility to environmental conditions, CD fruits were stored in a deep freezer at −18 °C until further processing. *Psyllium* husk (PH) was obtained from the Sarvoday Sat Isabgol factory in Sidhpur, Gujarat, India.

2.2. Extraction of CEM, CDM and PHM

The *Colocasia esculenta* rhizome mucilage (CEM) was extracted by using cold-water extraction (CWE) based on the method described by Andrade et al. (2015) with certain modifications. Initially, 20 g of rhizomes were thoroughly washed, peeled, and sliced into small pieces. Subsequently, 100 mL of cold refrigerated water (4–7 °C) was added. The mixture was then homogenized at 7000 rpm using a high-speed homogenizer (IKA L004510, Acme Instruments, New York, USA) and filtered through muslin cloth. The filtrate was subjected to centrifugation at 10,000 ×*g* for 15 min, and the resultant mucilage was dried using a spray dryer.

The *Cordia dichotoma* mucilage (CDM) fruits was extracted using microwave-assisted water extraction (MWE) by using our previous method Tosif et al. (2024). During the mucilage extraction, 30 g of CD fruits were manually crushed and combined with 200 mL of a 10 mM citric acid solution. The mixture was then subjected to microwave treatment (MC28A5013AK, Samsung, Mumbai, India) at 720 W for 5 min. Afterward, the samples were filtered through muslin cloth to remove water-insoluble fractions, and the filtrate was centrifuged at 10,000 ×*g* for 15 min. The supernatant was collected, and its pH was adjusted to 4.2 using 0.1 N HCl. Centrifugation was repeated at 10,000 ×*g* for 10 min to obtain the precipitated mucilage, which was subsequently resolubilized in 0.1 N NaOH and spray dried.

The *Psyllium* husk mucilage (PHM) was extracted using microwave-assisted water extraction (MWE) following the method described by Shiehnezhad et al. (2022) with specific modifications. In this process, 2 g of *Psyllium* husk was dispersed in 100 mL of distilled water and exposed to microwave treatment (MC28A5013AK, Samsung, Mumbai, India) at 520 W for 6 min. The upper layer of purified liquid mucilage was then carefully separated using a glass pipette (50 mL) and subjected to centrifugation at 10,000 ×*g* for 10 min. The resulting supernatant was collected and spray dried. The mucilage yield was calculated on a dry weight basis.

2.3. Spray-drying of mucilage

Appropriate conditions for the following spray drying procedure were selected based on the aforementioned methods. A pilot-scale spray dryer (model MW-SD01, Japan) equipped with a rotary atomizer was employed to produce uniform spray-dried nano-mucilage powder (SDMP). The spray drying parameters were determined in accordance with Sharma et al. (2023). During the spray drying process, the inlet temperature was maintained at 160 °C, the outlet temperature at 70 °C, the atomizer speed was set to 2400 rpm, and a feed flow rate of 7 mL/min was employed. The nano-mucilage yield was calculated on a dry weight basis using Eq. (1).

$$\textbf{\textit{Yieldofmucilage}}\ (\%) = \left[\left(\frac{Weightofdriedmucilagepowder\ (g)}{Totalweightof\ CD\ fruits\ (g)} \times 100\right)\right] \tag{1}$$

2.4. Proximate analysis of nano-mucilage

Spray-dried CEM, CDM, and PHM powders were subjected to the evaluation of the nutritional composition in terms of moisture, fat, fiber, protein, ash, and total carbohydrate contents by following the AOAC (2010) standard methods.

2.5. Particle size analysis

The spray-dried CEM, CDM, and PHM were assessed for their particle size based on a method proposed by Ma et al. (2021) and (Karabulut, Nemzer, & Feng, 2024) using a zeta sizer Nano ZS analyzer at ambient conditions. Briefly, 100 mg of all the samples were dispersed into the 20 mL of deionized water separately in 50 mL of glass vials and then exposed to the ultrasonication process using a bath sonicator (Malvern-Aimil instruments, India) for 3 min. The acquired sample was subjected to particle size and zeta potential analysis. All the analyses were performed in triplicates using the clean cuvettes for each sample respectively.

2.6. Formulation of yogurt

Yogurt was prepared by using a method of Ribes et al. (2021) with slight modification. Seven types of yogurts were prepared including skimmed yogurt (SKYC), toned yogurt (TYC), double-toned yogurt (DTYC), standardized yogurt (STYC), full-fat yogurt (FFYC), market full-fat yogurt control (MFFYC), and different concentrations of skimmed yogurt with addition of CEM, CDM, and PHM (1–10 %) as shown in Table 1. Briefly, the milk was prepared by adding 100 g of skimmed milk powder in 1 L of distilled water and 100 g of commercial full-fat cream was added as per the need of standard percentage for different milk. All the samples were heated in a water bath at 72 °C for 30 min and cooled at 37 °C. After the cooling, SKYC, TYC, DTYC, and STYC, FFYC, and MFFYC were kept as a control sample while different concentration of the mucilage was added to the SKYC. Yogurt culture (10^7 CFU/mL) was added to each sample followed by incubation at 42 °C until the final pH was achieved to 4.4–4.6. Prepared yogurts were stored in pre-sterilized glass bottles and stored at 4–7 °C for 16 days.

2.7. Viscosity of yogurt

The viscosity of the control yogurt samples and mucilage-added yogurt samples was determined using a rotational viscometer (Anton Paar ViscoQC 300) in accordance with the method described by Lin et al. (2022a) using Brookfield Spindle No. RH6. The viscosity readings were recorded at 200 rev/min on the prepared yogurt samples in a 250 mL cup. Samples were subjected to a constant shear rate throughout all viscosity analyses, which were carried out at room temperature. The unit of measurement for apparent viscosity was centipoises (cP).

2.8. Syneresis

The method suggested by Basiri et al. (2018) was used to analyze the syneresis of all the prepared yogurt with minor modifications. The yogurt sample (25 g) was placed in a glass funnel that was lined with Whatman filter paper number 1. The samples were then allowed to filter for the 0th, 4th, 8th, 12th, and 16th day at 4 °C. The proportion of whey separated from the initial sample weight, which was determined using the following Eq. (2), was used to quantify syneresis.

Table 1
Different formulations of yogurt samples containing varied amount of CEM, CDM and PHM.

Sample code	Fat (%)	CEM (%)	CDM (%)	PHM (%)
SKYC	0.1–0.3	0	0	0
DTYC	1.5	0	0	0
TYC	3	0	0	0
STYC	4.5	0	0	0
FFYC	6	0	0	0
MFFYC	6	0	0	0
SKYCEM1	0	0.5	0	0
SKYCEM2	0	1.5	0	0
SKYCEM3	0	3	0	0
SKYCEM4	0	4	0	0
SKYCEM5	0	4.5	0	0
SKYCEM6	0	6	0	0
SKYCEM7	0	8	0	0
SKYCEM8	0	10	0	0
SKYCDM1	0	0	0.5	0
SKYCDM2	0	0	1.5	0
SKYCDM3	0	0	3	0
SKYCDM4	0	0	4	0
SKYCDM5	0	0	4.5	0
SKYCDM6	0	0	6	0
SKYCDM7	0	0	8	0
SKYCDM8	0	0	10	0
SKYPHM1	0	0	0	0.5
SKYPHM2	0	0	0	1.5
SKYPHM3	0	0	0	3
SKYPHM4	0	0	0	4
SKYPHM5	0	0	0	4.5
SKYPHM6	0	0	0	6
SKYPHM7	0	0	0	8
SKYPHM8	0	0	0	10

(Skimmed yogurt control (SKYC), Toned yogurt control (TYC), Double-toned yogurt control (DTYC), Standardized yogurt control (STYC), Full-fat yogurt control (FFYC), Market full-fat yogurt control (MFFYC), (CEM: *Colocasia esculenta* mucilage); (CDM: *Cordia dichotoma* mucilage); (PHM: *Psyllium* husk mucilage).

$$\textbf{\textit{Syneresis}}\ (\%) = \left[\left(\frac{Separatedwhey\ (g)}{Initialsampleweight\ (g)} \times 100\right)\right] \tag{2}$$

2.9. Water holding capacity

The water-holding capacity (WHC) of each prepared yogurt was studied according to Lin et al. (2022b). Briefly, samples (10 g) were centrifuged at 6000 ×g for 20 min at 4 °C using a cold centrifuge (Hettich, Tuttlingen, Germany). For every sample, three triplicates were made and stored for 16 days. The following Eq. (3) was used to determine WHC:

$$\textbf{\textit{WHC}}\ (\%) = \left[\left(\frac{Initial\ sample\ weight\ (g) - Seperated\ material\ (g)}{Initial\ sample\ weight\ (g)} \times 100\right)\right] \tag{3}$$

2.10. Physicochemical properties of yogurt

2.10.1. Proximate analysis

The proximate analysis of yogurt, including moisture, ash, protein, fiber, fat, and total carbohydrates was estimated according to the standard procedures of the AOAC (2010). Briefly, moisture content was determined by drying 5 g of the selected yogurt samples at 105 °C in a hot air oven until a constant weight was achieved. Ash content was measured by charring the samples and then subjecting to a muffle furnace at 550 °C for 5 h. Protein content was determined using the Kjeldahl method, following the steps of digestion, distillation, and titration. Fat content was measured through Soxhlet extraction using petroleum ether. Carbohydrate content was calculated by subtracting the moisture, fat, protein, and ash contents from the total sample composition.

2.10.2. pH and titrable acidity

The selected yogurt samples (control and mucilage added) (10 g) were combined with 90 mL of distilled water in a 250 mL beaker and homogenized at 3000 rpm for 2 min in order to determine the pH of the yogurt. After 15 min, the pH of the resultant solution was determined based on the method proposed by Li et al. (2021). The Total Titratable Acidity (TTA) was evaluated using the AOAC (1990) method. Briefly, distilled water (90 mL) was used to dilute 10 g of yogurt samples. Following that, 20 mL of this diluted mixture was titrated with 0.1 N NaOH and few drops of phenolphthalein was added. Eq. (4) was used to calculate the TTA.

$$\boldsymbol{TTA}\ (\%) = \left[\left(\frac{Volume\ of\ 0.1\ N\ NaOH\ (mL) \times Factor\ of\ 0.1\ N\ NaOH \times 0.009)}{Weight\ of\ the\ sample\ (g)} \times 100\right)\right] \tag{4}$$

Where:

0.009 is a lactic acid amount equivalent to 1 mL of 0.1 N NaOH.

2.10.3. Total soluble solids (TSS)

The total soluble solids (TSS) of the yogurt samples were determined as per the protocol of Li et al. (2021). The TSS was analyzed using a Boeco Digital Abbe Refractometer. In brief, two or three drops of thoroughly yogurt samples were placed on a standardized refractometer at 18 °C. After swiftly closing the prism, the reading was recorded.

2.11. Texture analysis

All of the selected yogurt samples were analyzed using a Brookfield texture analyzer, with minor adjustments (Akhtar et al., 2022). The texture analysis was performed equipped with a TA11/1000 cylindrical probe (25.4 mm diameter, 35 mm length). The penetration speed was set at 1 mm/s, with a distance target of 10 mm and a trigger force of 6.8 g. The Texture Pro CTV1.3 software was used for data acquisition. Samples were removed from the refrigerator just before testing, and 100 mL of yogurt was analyzed for each group.

2.12. Color value

The color values of all the selected yogurt samples were studied based on the method followed by Wang et al. (2022) with slightly modifications. A colorimeter (PSC-30, EVERFINE; China) was calibrated using a blackboard and a whiteboard was used to study the color attributes of yogurts. The metrics L^* (brightness, where white = 100 and black = 0), a^* (positive values indicate red and negative values show green), and b^* (positive values suggest yellow and negative values show blue) were used to characterize the color features of the yogurts.

2.13. Microbial analysis

The spread plate method was used to evaluate the total viable counts in the sample by following the method of Turgut and Cakmakci (2018) with specific modification. On selective *Lactobacillus de Man Rogosa* Sharpe agar (pH 5.7), the probiotic concentration per mL of yogurt was analyzed after performing serial dilutions, followed by a 12 h incubation at 37 °C. Microbial counts were recorded at 0th, 4th, 8th, 12th and 16th day after inoculation. In addition, the viable cell counts in yogurt samples were also assessed. The dilutions were prepared using a 0.1 % *w/v* sterile peptone solution.

2.14. Consumer's acceptance

The consumer acceptance survey for mucilage-added yogurt (SKYPHM5) was conducted among 200 individuals aged 18 to 40 years in Phagwara, Punjab, India, through a face-to-face approach. The survey aimed to evaluate consumer perceptions regarding various attributes of the yogurt, including health benefits, texture, flavor, and overall acceptability. Participants, who were regular yogurt consumers, rated the yogurt using a structured questionnaire consisting of 10 questions as shown in supplementary material, which employed a 5-point Likert scale ranging from "very low" or "not at all" to "very high" or "extremely," depending on the specific context of the question. The key attributes evaluated included health benefits compared to other yogurts, contribution to overall health, texture and mouthfeel, taste and flavor expectations, natural and clean-label perception, price-value perception, and overall acceptability. Participants tasted the yogurt samples before responding to the questionnaire. The data collected were analyzed using various statistical methods. Descriptive statistics, including mean and standard deviation, were calculated for each attribute to summarize the central tendencies and variability in the responses. Multiple regression analysis was carried out to assess how individual attributes, such as health benefits, texture, flavor, and price-value perception, contributed to overall acceptability. The internal consistency of the questionnaire was evaluated using Cronbach's Alpha to ensure that the scale was reliable and provided consistent results. All analyses were conducted using SPSS (version 26), and statistical significance was set at $p < 0.05$.

2.15. Descriptive sensory analysis

A sensory evaluation of formulated yogurt was performed utilizing a panel of 30 semi-trained evaluators, comprising both male and female participants aged 25 to 45 years. To eliminate bias, the samples were presented on serving dishes with specific sample codes, effectively cover any brand identification or visual cues. Panelists were instructed to cleanse their palates with water between samples to ensure independent assessment and prevent carryover effects from previous tastings. A nine-point hedonic scale was employed to systematically rate sensory attributes, including flavor, mouthfeel, color, texture, and overall acceptability. This scale provided a standardized framework for evaluation. The study was approved by the Institutional Review Board of Lovely Professional University, India, and verbal informed consent was obtained from all participants prior to their voluntary participation.

2.16. In-vitro digestibility

In vitro digestion of selected yogurt was analyzed by INFOGEST static digestion model at simulating the oral, gastric, and intestinal phases Ye et al. (2022). Briefly, yogurt samples (5 g) were mixed with simulated salivary fluid (SSF) containing α-amylase (75 U/mL) and incubated at 37 °C for 2 min. The resulting mixture was then treated with simulated gastric fluid (SGF) containing pepsin (2000 U/mL) and incubated at 37 °C for 2 h, maintaining the pH at 3.0. The gastric chyme was then mixed with simulated intestinal fluid (SIF) containing pancreatin (100 U/mL lipase, 25 U/mL trypsin) and bile salts (10 mM), and incubated at 37 °C for 2 h, with the pH adjusted to 7.0. After digestion, samples were centrifuged at 4000 ×g for 20 min at 4 °C. The supernatant was collected for further analysis of protein hydrolysis using the OPA (o-phthaldialdehyde) assay and reducing sugar content by the DNS (3,5-dinitrosalicylic acid) method.

2.17. Statistical analysis

The experiments were conducted in triplicate. Experimental data were analyzed using Excel 2021 and IBM SPSS statistical software. Statistically significant differences ($p < 0.05$) among all the selected yogurt samples were determined through analysis of variance (ANOVA) followed by Tukey's test. Graphical data interpretation was performed using OriginPro 2023.

3. Results and discussion

3.1. Mucilage yield, proximate analysis and particle size of nano-mucilage

Mucilage was extracted from three different sources including *Colocasia esculanta* rhizomes (CEM) using the cold-water extraction method, and microwave-assisted water extraction was used to extract mucilage from *Cordia dichotoma* fruits (CDM), and from *Psyllium* husk (PHM). The spray-dried yield of PHM was found to be 30.26 ± 1.68 %, which was higher than the yields of CEM (2.38 ± 0.96 %) and CDM (7.89 ± 0.42 %). The variation in yield is due to the varied carbohydrate content in all the raw materials and also depends upon the extraction condition and geographical location. Several reports indicated that, CEM is rich in starch which is considered a major impurity existing in mucilage that interferes with the functional characteristics of mucilage (Tosif et al., 2023). Similarly, Andrade et al. (2020) extracted CEM using five different methods, including cold and hot water extraction. Their results revealed that cold water extraction yielded starch-free mucilage, as confirmed by the iodine test. Starch is considered a major impurity in mucilage, interfering with its techno-functional attributes and viscosity. Likewise, the particle size of the CEM, CDM and PHM was found to be 101.68 ± 4.68 nm, 157.12 ± 5.12 nm and 384.19 ± 6.48 nm respectively (Fig. 1). The zeta potential of value of CEM (−24.05 ± 0.04 mV), CDM (−11.68 ± 0.09 mV) and PHM (−8.06 ± 0.11 mV) was observed. Similarly, Sharma et al. (2023) optimized the different spray-drying conditions to acquire nano-mucilage from the Bael fruit. The extracted nano-mucilage with inherent techno-functional and anti-microbial properties can be potentially used in various food applications. The proximate composition analysis of CEM, CDM, and PHM demonstrated significant differences across various parameters. The moisture content was highest in CDM (7.28 ± 0.07 %), followed by CEM (5.12 ± 0.04 %) and PHM (2.35 ± 0.09 %). PHM exhibited the highest fiber content (21.91 ± 0.19 %), showed its potential for enhancing the dietary fiber content in food formulations, while CEM and CDM showed relatively lower fiber levels at 6.84 ± 0.15 % and 4.02 ± 0.21 %, respectively as displayed in Table 2A. Protein content was highest in CDM (4.20 ± 0.08 %), followed by CEM (3.32 ± 0.05 %), and was the lowest in PHM (1.08 ± 0.10 %). Ash content, indicative of mineral presence, was highest in CDM (3.37 ± 0.05 %), with CEM at 2.76 ± 0.02 % and PHM at 1.24 ± 0.07 %. The total carbohydrate content was the highest in PHM (95.33 ± 0.21 %), followed by CEM (88.80 ± 0.13 %) and CDM (85.15 ± 0.18 %). These findings highlight the distinct nutritional profiles of each mucilage, suggesting their varied applications as functional ingredients in low-fat and fiber-enriched food products.

Table 2A
Proximate composition of spray-dried CEM, CDM, and PHM.

Parameter	CEM	CDM	PHM
Moisture (%)	5.12 ± 0.04[c]	7.28 ± 0.07[b]	2.35 ± 0.09[a]
Fat (%)	–	–	–
Fiber (%)	6.84 ± 0.15[b]	4.02 ± 0.21[a]	21.91 ± 0.19[c]
Protein (%)	3.32 ± 0.05[b]	4.20 ± 0.08[c]	1.08 ± 0.10[a]
Ash (%)	2.76 ± 0.02[b]	3.37 ± 0.05[c]	1.24 ± 0.07[a]
Total carbohydrates (%)	88.80 ± 0.13[b]	85.15 ± 0.18[a]	95.33 ± 0.21[c]

Data are presented as mean ± SD (n = 3). Mean values with different lowercase (a-c) letters on same column significantly different values within a sample. (CEM: *Colocasia esculenta* mucilage); (CDM: *Cordia dichotoma* mucilage); (PHM: *Psyllium* husk mucilage).

3.2. Viscosity of yogurt

The viscosity of yogurt samples with different fat content and incorporating mucilage from CEM, CDM, and PHM was studied over 16 days of storage period and results are represented in Table 2B. Skimmed milk yogurt without the addition of mucilage (SKYC) exhibited a gradual

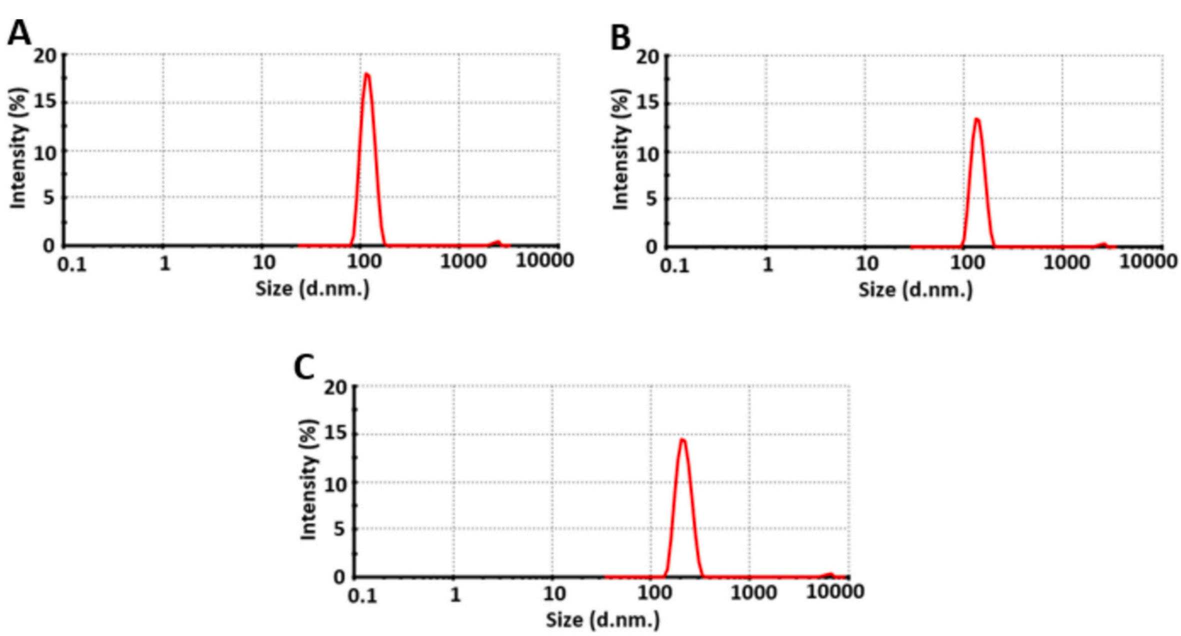

Fig. 1. Particle size of spray-dried mucilage (A) CEM, (B) CDM, (C), PHM. (*Colocasia esculenta* rhizome mucilage (CEM), *Cordia dichotoma* fruit mucilage (CDM), and *Psyllium* husk mucilage (PHM).

Table 2B
Apparent viscosity of formulated yogurt samples during the storage period.

Samples	Viscosity (cP)				
	Day-0	Day-4	Day-8	Day-12	Day-16
SKYC	1429.67 ± 0.68^{aC}	1405.52 ± 0.64^{aB}	1388.43 ± 0.29^{aB}	1305.99 ± 0.36^{aB}	1168.43 ± 0.08^{aA}
DTYC	1681.25 ± 0.12^{cC}	1673.99 ± 0.49^{cC}	1665.05 ± 0.82^{cdC}	1594.76 ± 0.25^{bB}	1344.15 ± 0.92^{cA}
TYC	1735.19 ± 0.19^{dC}	1724.31 ± 0.27^{dC}	1710.09 ± 0.19^{dBC}	1688.34 ± 0.61^{cB}	1543.68 ± 0.66^{eA}
STYC	1965.11 ± 0.88^{fC}	1955.03 ± 0.84^{fBC}	1911.72 ± 0.73^{fBC}	1824.09 ± 0.55^{eB}	1609.13 ± 0.12^{fA}
FFYC	2094.09 ± 0.91^{gD}	1978.22 ± 0.61^{fC}	1906.37 ± 0.42^{fC}	1883.94 ± 0.94^{eB}	1858.73 ± 0.06^{hA}
MFFYC	2035.49 ± 0.34^{gE}	1961.55 ± 0.57^{fD}	1861.77 ± 0.19^{eBC}	1843.08 ± 0.38^{eB}	1803.77 ± 0.29^{hA}
SKYCEM1	1495.12 ± 0.38^{aC}	1482.68 ± 0.20^{abC}	1475.19 ± 0.31^{bC}	1319.81 ± 0.29^{aB}	1268.16 ± 0.22^{bA}
SKYCEM2	1581.44 ± 0.15^{bC}	1570.09 ± 0.37^{bC}	1553.34 ± 0.19^{cC}	1487.66 ± 0.76^{bB}	1395.77 ± 0.33^{cA}
SKYCEM3	1632.25 ± 0.98^{cC}	1619.08 ± 0.81^{cC}	1597.84 ± 0.97^{cfB}	1526.37 ± 0.51^{bB}	1367.13 ± 0.68^{cA}
SKYCEM4	1694.19 ± 0.88^{cC}	1672.19 ± 0.95^{cC}	1661.27 ± 0.34^{cdC}	1519.33 ± 0.16^{bB}	1464.05 ± 0.05^{dA}
SKYCEM5	1773.66 ± 0.35^{cdC}	1769.05 ± 0.25^{deC}	1731.38 ± 0.39^{dC}	1683.94 ± 0.85^{cB}	1573.19 ± 0.68^{eA}
SKYCEM6	2308.39 ± 0.73^{jB}	2284.34 ± 0.61^{gA}	2265.18 ± 0.87^{gA}	2209.37 ± 0.72^{gA}	2284.37 ± 0.34^{kA}
SKYCEM7	2497.43 ± 0.11^{kB}	2379.35 ± 0.43^{hB}	2355.01 ± 0.97^{ghB}	2336.84 ± 0.34^{hB}	2167.13 ± 0.46^{lA}
SKYCEM8	2688.76 ± 0.94^{lC}	2519.08 ± 0.31^{iB}	2498.27 ± 0.19^{hiB}	2478.37 ± 0.49^{iB}	2322.19 ± 0.23^{nA}
SKYCDM1	1455.13 ± 0.13^{aC}	1423.84 ± 0.97^{aC}	1308.62 ± 0.77^{aC}	1255.19 ± 0.64^{aB}	1197.16 ± 0.19^{aA}
SKYCDM2	1491.45 ± 0.89^{aC}	1462.05 ± 0.35^{aC}	1385.16 ± 0.49^{aB}	1284.19 ± 0.76^{aA}	1243.06 ± 0.11^{bA}
SKYCDM3	1527.33 ± 0.08^{bC}	1498.72 ± 0.19^{abC}	1476.05 ± 0.28^{bC}	1388.19 ± 0.59^{abB}	1287.12 ± 0.09^{bA}
SKYCDM4	1587.16 ± 0.13^{bC}	1568.05 ± 0.28^{bC}	1543.27 ± 0.14^{cC}	1478.35 ± 0.34^{bB}	1309.11 ± 0.91^{cA}
SKYCDM5	1699.54 ± 0.66^{cC}	1643.12 ± 0.15^{cC}	1627.08 ± 0.35^{cdC}	1519.68 ± 0.95^{bcB}	1321.67 ± 0.15^{cA}
SKYCDM6	2097.13 ± 0.15^{gD}	1948.67 ± 0.37^{fD}	1856.17 ± 0.29^{eC}	1798.13 ± 0.43^{dB}	1464.43 ± 0.43^{dA}
SKYCDM7	2049.73 ± 0.33^{gD}	1808.34 ± 0.43^{eC}	1709.73 ± 0.66^{dC}	1519.43 ± 0.39^{bcB}	1489.01 ± 0.06^{dA}
SKYCDM8	2297.18 ± 0.16^{iD}	2168.10 ± 0.11^{fgD}	1978.16 ± 0.34^{fC}	1759.08 ± 0.43^{dB}	1507.34 ± 0.66^{eA}
SKYPHM1	1868.22 ± 0.09^{eB}	1818.15 ± 0.64^{eB}	1789.85 ± 0.19^{dA}	1752.37 ± 0.28^{dA}	1714.98 ± 0.76^{gA}
SKYPHM2	1905.13 ± 0.73^{fB}	1898.08 ± 0.93^{eA}	1887.19 ± 0.43^{eA}	1841.12 ± 0.73^{eA}	1864.05 ± 0.13^{hA}
SKYPHM3	1967.37 ± 0.37^{fA}	1958.13 ± 0.41^{fA}	1948.05 ± 0.91^{fA}	1911.94 ± 0.34^{fA}	1933.66 ± 0.98^{iA}
SKYPHM4	2262.03 ± 0.94^{iB}	2237.16 ± 0.22^{gB}	2227.38 ± 0.43^{gB}	2219.77 ± 0.43^{gB}	2108.15 ± 0.16^{jA}
SKYPHM5	2297.46 ± 0.43^{iB}	2275.19 ± 0.09^{gB}	2268.47 ± 0.38^{gB}	2259.73 ± 0.29^{gB}	2149.59 ± 0.99^{jA}
SKYPHM6	2598.76 ± 0.99^{kB}	2576.08 ± 0.76^{iC}	2434.19 ± 0.28^{hB}	2412.68 ± 0.37^{hiB}	2368.13 ± 0.25^{lA}
SKYPHM7	2608.12 ± 0.53^{lC}	2582.37 ± 0.69^{iB}	2573.09 ± 0.15^{iB}	2568.19 ± 0.19^{iB}	2494.22 ± 0.13^{mA}
SKYPHM8	2694.73 ± 0.87^{lB}	2679.05 ± 0.43^{jB}	2613.34 ± 0.44^{jB}	2576.13 ± 0.67^{iA}	2509.43 ± 0.58^{nA}

Data are presented as mean ± SD (n = 3). Mean values with different lowercase (a-l) letters within a column and uppercase (A-E) letters within a row represent significantly different values within the samples and days, respectively. (Skimmed yogurt control (SKYC), Toned yogurt control (TYC), Double-toned yogurt control (DTYC), Standardized yogurt control (STYC), Full-fat yogurt control (FFYC) Market full-fat yogurt control (MFFYC), CEM: *Colocasia esculenta* mucilage; CDM: *Cordia dichotoma* mucilage; PHM: *Psyllium* husk mucilage).

decrease in viscosity from 1429.67 cP on Day 0 to 1168.43 cP on Day 16, showing a consistent decline in viscosity over time. Full-fat yogurt without mucilage (FFYC) maintained the highest viscosity among controls started at 2094.09 cP on Day 0 and slightly decreased to 1858.73 cP by Day 16, indicating better viscosity stability compared to skimmed milk yogurt. Among the mucilage-added samples, those with PHM (SKYPHM) demonstrated a notable increase in viscosity. SKYPHM5, in particular, started with a viscosity of 2297.46 cP on Day 0 and exhibited only a slight decrease to 2149.59 cP by Day 16, maintaining higher viscosity throughout the storage period compared to other mucilage-added formulations. The viscosity of MFFYC was determined to be 2035.49 ± 0.34 cP on 0 days which was decreased up to 1803.77 ± 0.29 cP on 16 days. Similar values were observed in FFYC due to its similar fat content. However, during the storage, the viscosity was decreased due to the production of syneresis over the 16 days of storage period. This trend suggested that higher concentrations of PHM contribute to increased viscosity and better textural stability, likely due to water retention of mucilage and thickening properties. Conversely, the mucilage with CEM and CDM types also found increased viscosity, but not to the same extent as PHM, indicating that the type and concentration of mucilage significantly influence the yogurt's rheological properties. The results imply that PHM, particularly at higher concentrations, enhanced the viscosity and texture of yogurt, making it more stable over time compared to both skimmed milk and full-fat yogurt controls. However, higher concentrations (SKYCEM6, SKYCDM6) resulted in very high viscosities. Similarly, Leon et al. (2019) demonstrated that hydrocolloids like gums, mucilage, and inulin can effectively increase the viscosity in dairy products by forming a gel-like network. The gel formation at higher mucilage concentrations aligns with Medina-López et al. (2022), who emphasized the need for a critical balance in hydrocolloid concentration to maintain desirable textural properties and maximize viscosity. Consequently, the results demonstrated that appropriate mucilage concentrations (4.5%) can effectively substitute fat in yogurt formulations, thereby improving viscosity and product stability.

3.3. Syneresis of yogurt

The syneresis of yogurt samples was significantly increased over the 16-day storage period. The control samples, SKYC, exhibited the highest syneresis among the prepared formulations, started at 3.19 ± 0.18 % on Day 0 and increased to 15.08 ± 0.43 % by Day 16 (Fig. 2). This increase is expected as the gel matrix weakens over time, leading to more water release. FFYC and MFFYC, the full-fat yogurt formulations, showed significantly lower syneresis values compared to SKYC. FFYC exhibited an initial syneresis of 1.02 ± 0.15 % on Day 0, increased to 11.11 ± 0.37 % on Day 16, while MFFYC followed a similar trend, started from 1.04 ± 0.09 % to 11.32 ± 0.55 % on Day 16. The lower syneresis in full-fat samples is likely due to the stabilizing effect of fat, which helps maintain a stronger gel structure and retain water. Yogurts formulated with CEM (SKYCEM1-SKYCEM5) showed a progressive reduction in syneresis with increasing mucilage concentrations. SKYCEM1 had syneresis values comparable to SKYC, while SKYCEM5, with the highest mucilage concentration, exhibited the lowest syneresis (1.59 ± 0.43 % on Day 0, increased to 9.09 ± 0.71 % on Day 16). SKYPHM5 showed the least syneresis across all samples (1.65 ± 0.11 % on Day 0 to 7.59 ± 0.24 % on Day 16), and showed the superior water-binding capacity of PHM. The reduced syneresis in these samples can be attributed to the hydrocolloid properties of the mucilage, which enhance water-holding capacity and stabilize the protein network in yogurt (Tiwari et al., 2021). These findings are supported by literature, such as studies by Yousefi & Jafari (2019), which demonstrated that hydrocolloids like pectin and inulin reduce syneresis in dairy products by forming a gel-like

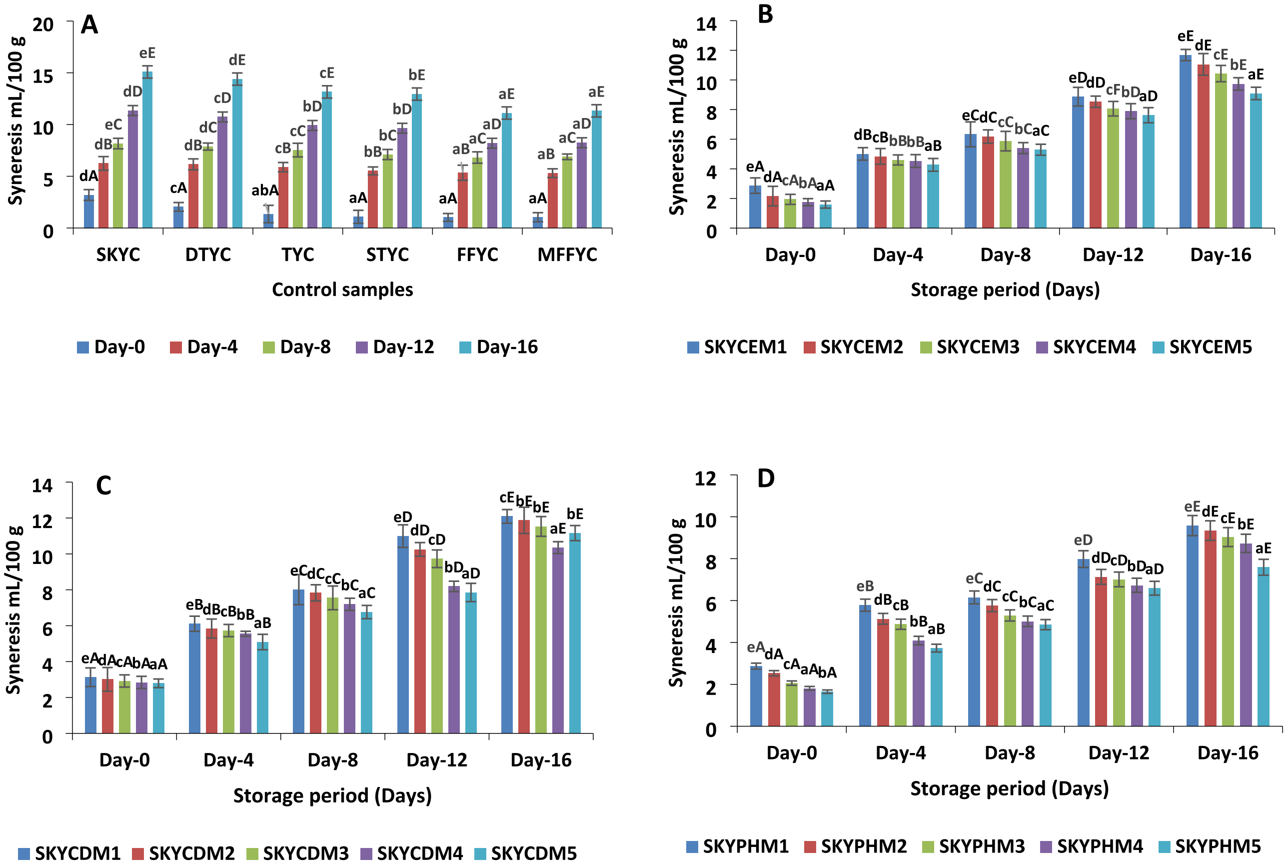

Fig. 2. Syneresis and water holding capacity of formulated yogurt. (A) Syneresis of control samples without addition of mucilage, (B) Syneresis of CEM based yogurt, (C) Syneresis of CDM based yogurt, (D) Syneresis of PHM based yogurt, (E) Water holding capacity of control samples without addition of mucilage, (F) Water holding capacity of CEM based yogurt, (G) Water holding capacity of CDM based yogurt, (H) Water holding capacity of PHM based yogurt. Different error bars represent the standard deviation from the mean values ($n = 3$) and lower case (a-d) represent the significantly different among the samples (SKYC, FFYC, SKYPHM5, and MFFYC), Uppercase (A-D) shows the significant difference within the days. (Skimmed yogurt control (SKYC), Full-fat yogurt control (FFYC), Market full-fat yogurt control (MFFYC), PHM: *Psyllium* husk mucilage.

network that traps water. The gel formation observed at higher mucilage concentrations aligns with the observations of Krstonošić et al. (2021), who noted the critical balance required in hydrocolloid concentration to maintain desirable textural properties and minimize syneresis. Thus, the results suggested that appropriate concentrations of mucilage can effectively replace fat in yogurt formulations, enhancing water retention and product stability.

3.4. Water holding capacity

The water holding capacity (WHC) of yogurt samples decreased over the 16-day storage period across all formulations. WHC of SKYC was observed at 22.38 ± 0.08 % on Day 0 and reduced to 14.83 ± 0.24 % on Day 16. This trend is typical as the gel structure weakens over time, leading to increased water expulsion (Tiwari et al., 2021). Full-fat formulations such as FFYC and MFFYC exhibited significantly higher WHC than SKYC as exhibited in Fig. 2. MFFYC followed a similar trend, starting at 35.72 ± 0.66 % and reduced to 17.58 ± 0.72 %. The higher fat content in these samples likely contributed to better water retention due to fat's stabilizing effect on the gel matrix. Furthermore, the unique properties of nano-mucilage, such as particle size and zeta potential, play a crucial role in its effectiveness as a fat replacer in yogurt. The nanoscale size (100–300 nm) increased the surface area of the mucilage particles, allowing them to interact more efficiently with the yogurt matrix. This enhanced water-binding capacity leads to better gel formation, which contributes to improved texture, such as firmness and springiness. Additionally, the small particle size enables better dispersion throughout the yogurt, ensuring a more uniform structure, which helps maintain stability and reduces syneresis during storage. Yogurts formulated with CEM (SKYCEM1-SKYCEM5) demonstrated a progressive improvement in WHC with increasing mucilage concentrations. SKYCEM5, which had the highest mucilage content, showed the highest WHC (35.28 ± 0.55 % on Day 0, decreasing to 26.31 ± 0.31 % on Day 16). This improvement can be attributed to the water-binding properties of CEM, which helped maintain a stable gel structure. Similarly, yogurts containing CDM (SKYCDM1-SKYCDM5) exhibited a gradual decline in WHC, with SKYCDM5 showing a WHC of 28.37 ± 0.73 % on Day 0 and 22.43 ± 0.28 % on Day 16. The mucilage from CDM also enhanced water retention, albeit to a lesser extent than CEM. The most significant improvement in WHC was observed in the samples containing PHM (SKYPHM1-SKYPHM5). SKYPHM5, which had the highest concentration of PHM, maintained a WHC of 42.00 ± 0.18 % on Day 0, decreased to 33.98 ± 0.34 % on Day 16. PHM, known for its strong water retention and gel-forming abilities, contributed to the superior WHC of these

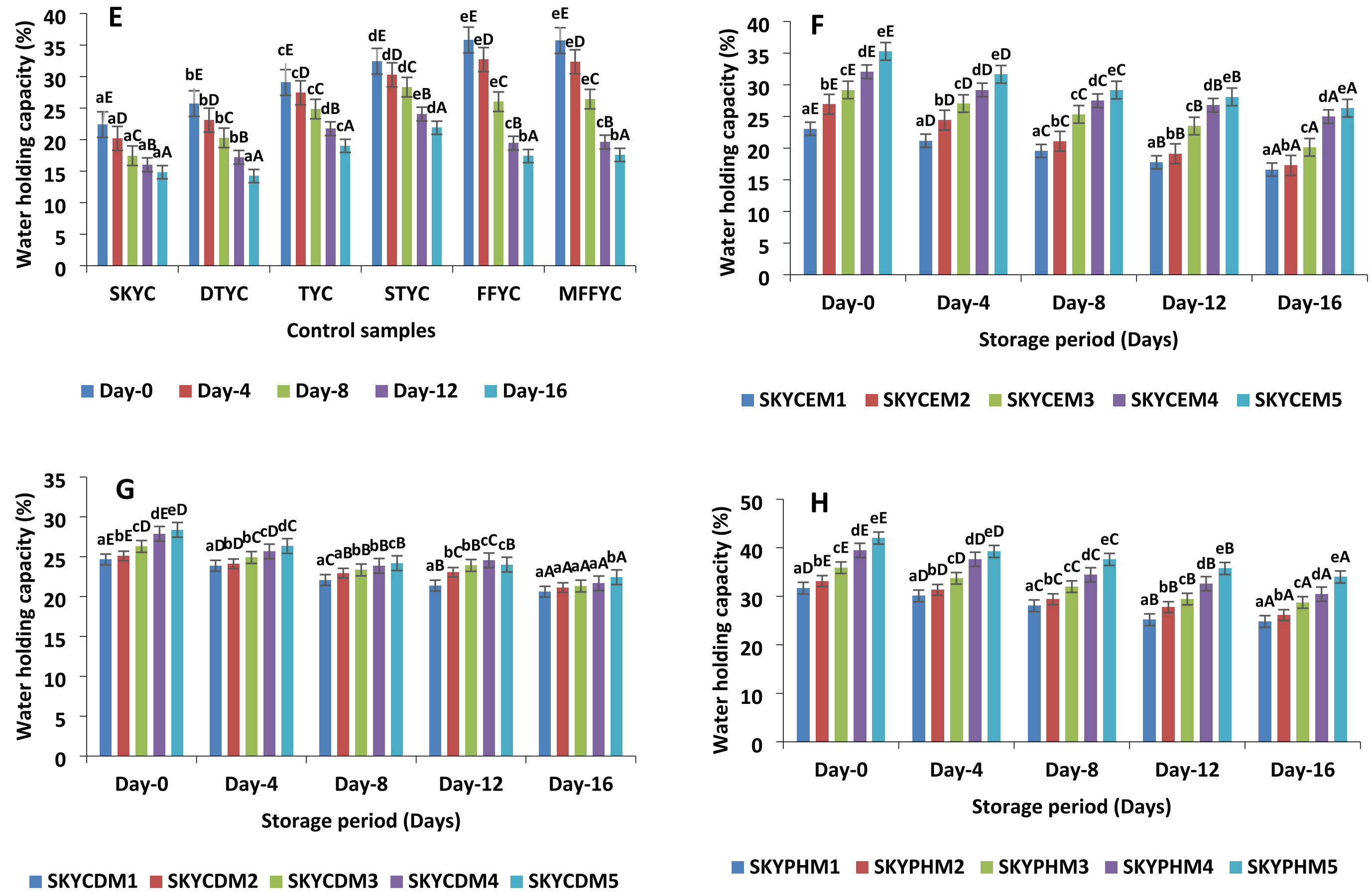

Fig. 2. (*continued*).

samples. Higher concentrations (SKYCEM6, SKYCDM6) were not evaluated due to stronger gel formation, suggested an optimal concentration range for effective WHC improvement without over-gelation (Ribes et al., 2021). Thus, based on viscosity, syneresis, and water-holding capacity data, SKYPHM5 showed excellent characteristics compared to other samples.

3.5. Physicochemical properties

3.5.1. Proximate analysis

The compositional analysis of the yogurt samples revealed significant variations in moisture content, ash, protein, fiber, fat, and total carbohydrates over the 16-day storage period. Moisture content increased in skimmed milk yogurt (SKYC) from 88.68 ± 0.72 % to 91.65 ± 0.34 %, indicating better moisture retention compared to full-fat yogurt (FFYC), which showed lower moisture content (84.46 ± 0.34 % to 86.34 ± 0.12 %) as shown in Table 2C. PHM-based yogurt (SKYPHM5) also demonstrated higher moisture retention, ranging from 84.07 ± 0.52 % to 85.12 ± 0.26 %. Whereas, the moisture content of MFFYC was found to be 84.73 ± 0.26 % on the 0th day which was increased up to 86.49 ± 0.73 % on the 16th day. The ash content was highest in SKYPHM5 (1.93 ± 0.98 %) compared to SKYC (1.65 ± 0.66 %) and FFYC (1.27 ± 0.42 %), reflecting the higher mineral content of the mucilage. Protein levels were highest in FFYC, ranging from 4.02 ± 0.55 % to 3.98 ± 0.39 %, while SKYPHM5 and SKYC had lower and stable protein levels. The fiber was only measured in SKYPHM5 and the value was calculated to be 4.68 ± 0.37 % and 4.82 ± 0.46 % 0th and 16th day, respectively. Fat content remained relatively constant across samples, with FFYC having the highest fat content (5.83 ± 0.22 %), while SKYC and SKYPHM5 exhibited lower fat content. Total carbohydrates decreased over time in all samples, with SKYC and FFYC showing a more substantial decline compared to SKYPHM5, which remained higher (10.34 ± 0.73 % to 9.69 ± 0.11 %). MFFYC showed almost similar physicochemical properties compared to FFYC. These results underscore the impact of formulation on the nutritional profile of yogurt, with PHM contributing to higher moisture retention, fiber content, and carbohydrate levels, while full-fat yogurt maintained higher protein and fat content. The control sample SKYC showed more variability in ash content and a significant decrease in total carbohydrates, reflecting less stability compared to the mucilage-enhanced and high-fat samples. These results align with literature suggesting that hydrocolloids like mucilage can improve the textural and nutritional stability of low-fat yogurt formulations, offering a healthier alternative without compromising quality (Pasha et al., 2022).

3.5.2. pH of selected yogurts

The pH levels of the yogurt samples was affected over the 16-day storage period. The pH value of SKYC was significantly decreased from 4.65 ± 0.09 to 4.18 ± 0.12 over the storage period. Similarly, full-fat yogurt (FFYC) showed a decline from 4.76 ± 0.12 to 4.11 ± 0.10 on the 0th and 16th day respectively as shown in Table 2C. PHM-based yogurt (SKYPHM5) also demonstrated a decreasing pH value from 4.43 ± 0.09 to 4.09 ± 0.19, though the changes were less pronounced compared to the other formulations. This decreased in pH across all samples can be attributed to the continued fermentation and acid production by lactic acid bacteria, which is common in yogurt (Leon et al., 2019). The results suggested that all yogurt types become more acidic over time, SKYPHM5 maintained a relatively higher pH compared to SKYC and FFYC, likely due to the buffering capacity of the added mucilage. In contrast, the control sample SKYC, with the lowest fat content, experienced a more significant pH drop, reflecting less buffering capacity and greater acidification. SKYPHM5, with added PHM

Table 2C
Physiochemical properties of selected yogurts.

Parameter	Samples	Storage period (Days)				
		Day-0	Day-4	Day-8	Day-12	Day-16
Moisture (%)	SKYC	88.68 ± 0.72^{bA}	89.16 ± 0.34^{bA}	91.17 ± 0.17^{bB}	91.58 ± 0.49^{bB}	91.65 ± 0.34^{bB}
	FFYC	84.46 ± 0.34^{aA}	84.95 ± 0.19^{aA}	85.16 ± 0.30^{aA}	85.63 ± 0.34^{aA}	86.34 ± 0.12^{aAB}
	MFFYC	84.73 ± 0.26^{aA}	84.12 ± 0.43^{aA}	85.34 ± 0.52^{aA}	85.06 ± 0.39^{aA}	86.49 ± 0.73^{aAB}
	SKYPHM5	84.07 ± 0.52^{aA}	84.32 ± 0.46^{aA}	84.74 ± 0.43^{aA}	84.99 ± 0.24^{aA}	85.12 ± 0.26^{aAB}
Ash (%)	SKYC	1.65 ± 0.04^{bB}	1.61 ± 0.05^{bA}	1.63 ± 0.08^{bB}	1.59 ± 0.14^{bA}	1.66 ± 0.03^{bB}
	FFYC	1.27 ± 0.02^{aA}	1.26 ± 0.10^{aA}	1.28 ± 0.12^{aB}	1.28 ± 0.07^{aB}	1.28 ± 0.05^{aB}
	MFFYC	1.25 ± 0.09^{aA}	1.24 ± 0.11^{aA}	1.26 ± 0.10^{aAB}	1.27 ± 0.15^{aB}	1.28 ± 0.17^{aB}
	SKYPHM5	1.93 ± 0.02^{cBC}	1.89 ± 0.14^{cB}	1.86 ± 0.18^{cA}	1.85 ± 0.03^{cA}	1.86 ± 0.09^{cA}
Protein (%)	SKYC	3.15 ± 0.43^{aD}	3.13 ± 0.34^{aC}	3.11 ± 0.43^{aC}	3.05 ± 0.39^{aB}	3.00 ± 0.19^{aA}
	FFYC	4.02 ± 0.55^{bA}	3.98 ± 0.44^{cA}	4.09 ± 0.37^{bA}	4.11 ± 0.74^{bA}	3.98 ± 0.39^{bA}
	MFFYC	4.13 ± 0.61^{bB}	3.95 ± 0.59^{cA}	4.06 ± 0.32^{bB}	4.08 ± 0.25^{bB}	3.95 ± 0.14^{bA}
	SKYPHM5	3.34 ± 0.34^{aB}	3.28 ± 0.56^{bB}	3.17 ± 0.56^{aA}	3.10 ± 0.43^{aA}	3.03 ± 0.73^{aA}
Fiber (%)	SKYC	–	–	–	–	–
	FFYC	–	–	–	–	–
	MFFYC	–	–	–	–	–
	SKYPHM5	4.68 ± 0.37^{aA}	4.72 ± 0.15^{aA}	4.74 ± 0.09^{aA}	4.78 ± 0.73^{aA}	4.82 ± 0.46^{aA}
Fat (%)	SKYC	0.28 ± 0.42^{aA}	0.26 ± 0.34^{aA}	0.21 ± 0.76^{aA}	0.23 ± 0.42^{aA}	0.25 ± 0.37^{aA}
	FFYC	5.83 ± 0.22^{bA}	5.78 ± 0.43^{bA}	5.80 ± 0.30^{bA}	5.83 ± 0.34^{bA}	5.87 ± 0.92^{bA}
	MFFYC	5.62 ± 0.35^{bAB}	5.52 ± 0.13^{bA}	5.47 ± 0.24^{bA}	5.41 ± 0.32^{bA}	5.38 ± 0.16^{bA}
	SKYPHM5	0.32 ± 0.98^{aA}	0.34 ± 0.38^{aA}	0.35 ± 0.49^{aA}	0.32 ± 0.16^{aA}	0.30 ± 0.73^{aA}
Total carbohydrates (%)	SKYC	6.24 ± 0.13^{bBC}	5.84 ± 0.05^{cB}	3.88 ± 0.07^{bA}	3.55 ± 0.15^{bA}	3.44 ± 0.18^{cA}
	FFYC	4.42 ± 0.05^{aD}	4.03 ± 0.03^{aD}	3.67 ± 0.08^{aBC}	3.15 ± 0.09^{aB}	2.53 ± 0.10^{aA}
	MFFYC	4.27 ± 0.19^{aC}	5.17 ± 0.21^{bD}	3.87 ± 0.10^{bB}	4.18 ± 0.13^{cB}	2.90 ± 0.24^{bA}
	SKYPHM5	10.34 ± 0.73^{cB}	10.17 ± 0.19^{dB}	9.88 ± 0.18^{cA}	9.74 ± 0.17^{dA}	9.69 ± 0.11^{dA}
pH	SKYC	4.65 ± 0.09^{aB}	4.42 ± 0.08^{aAB}	4.38 ± 0.10^{aAB}	4.27 ± 0.07^{aA}	4.18 ± 0.12^{aA}
	FFYC	4.76 ± 0.12^{aB}	4.69 ± 0.05^{bB}	4.42 ± 0.15^{aB}	4.37 ± 0.11^{bB}	4.11 ± 0.10^{aA}
	MFFYC	4.81 ± 0.02^{bC}	4.75 ± 0.09^{bB}	4.68 ± 0.08^{bA}	4.61 ± 0.11^{cA}	4.54 ± 0.06^{bA}
	SKYPHM5	4.43 ± 0.09^{bC}	4.36 ± 0.09^{aBC}	4.31 ± 0.12^{aB}	4.25 ± 0.04^{aB}	4.09 ± 0.19^{aA}
Total viable count (log CFU/mL)	SKYC	6.08 ± 0.09^{aA}	7.99 ± 0.08^{aC}	8.25 ± 0.10^{aD}	7.31 ± 0.07^{aC}	6.94 ± 0.12^{aB}
	FFYC	7.35 ± 0.12^{bA}	8.12 ± 0.05^{bB}	9.36 ± 0.15^{bC}	8.88 ± 0.11^{bB}	7.12 ± 0.10^{bA}
	MFFYC	7.86 ± 0.03^{bA}	8.33 ± 0.09^{bB}	9.61 ± 0.04^{cD}	9.02 ± 0.18^{cC}	7.38 ± 0.06^{cA}
	SKYPHM5	8.16 ± 0.09^{cA}	9.45 ± 0.09^{cB}	10.53 ± 0.12^{cdC}	9.19 ± 0.04^{dB}	8.37 ± 0.19^{dA}
Acidity (%)	SKYC	0.93 ± 0.14^{aA}	0.95 ± 0.21^{aB}	0.98 ± 0.25^{aB}	1.03 ± 0.19^{aB}	1.07 ± 0.24^{abC}
	FFYC	0.97 ± 0.19^{bA}	1.02 ± 0.10^{bAB}	1.05 ± 0.14^{bB}	1.11 ± 0.21^{cC}	1.15 ± 0.29^{bD}
	MFFYC	0.95 ± 0.04^{bA}	1.05 ± 0.12^{bB}	1.06 ± 0.09^{bB}	1.09 ± 0.07^{cC}	1.12 ± 0.15^{bC}
	SKYPHM5	0.84 ± 0.17^{aA}	0.86 ± 0.08^{aA}	0.92 ± 0.20^{aB}	0.93 ± 0.25^{bB}	0.95 ± 0.34^{aC}

Data are presented as mean ± SD (n = 3). Mean values with different lowercase (a-d) letters within a column and uppercase (A-E) letters within a row represent significantly different values within the samples and days, respectively. (Skimmed yogurt control (SKYC), Full-fat yogurt control (FFYC), Market full-fat yogurt control (MFFYC), PHM: *Psyllium* husk mucilage.

mucilage, showed a more distinct acidity, likely due to the presence of additional fermentable substrates in the mucilage, which can enhance microbial activity and acid production. The pH value of MFFYC was found to be 4.81 ± 0.02 on 0 days and it was slightly decreased up to 4.54 ± 0.06 on 16 days. Likewise, Quintero-García et al. (2021) determined that fat-content gums and mucilage significantly impact on acidity and stability of yogurt. Furthermore, hydrocolloids such as PHM can offer additional nutrients for microbial fermentation, leading to increased acidity, while high-fat content can shield acid production and maintain a more stable pH. Consequently, the results suggest that while PHM mucilage effectively enhances texture and water retention, it also contributes to increased acidity, which may influence the overall flavor profile of the yogurt.

3.5.3. Acidity

The acidity of the yogurt samples increased over the 16-day storage period, with distinct patterns observed among the different formulations. For skimmed milk yogurt (SKYC), the acidity increased from 0.93 ± 0.14 % to 1.07 ± 0.24 %, reflecting a gradual increase in sourness, consistent with the observed decrease in pH. Full-fat yogurt (FFYC) exhibited a similar trend, with acidity increased from 0.97 ± 0.19 % to 1.150.29 %. In contrast, the yogurt with PHM (SKYPHM5) detected a smaller increase in acidity, from 0.84 ± 0.17 % to 0.95 ± 0.34 %, indicating that the mucilage might have a moderating effect on the acidification process (Table 2C). This observation suggested that while all yogurt samples become more acidic over time, the PHM-based yogurt tends to maintain a relatively lower acidity, potentially due to the mucilage's buffering properties. SKYPHM5, with added PHM mucilage, had a moderate increase in acidity, which aligns with its pH trend and suggested that the mucilage provided additional fermentable substrates, enhancing microbial activity and acid production. Consequently, the results proved that PHM effectively enhances texture and water retention, it also contributes to moderate acidity, influencing the overall flavor profile of the yogurt (Ribes et al., 2021).

3.6. Microbial analysis

The total viable count (TVC) of yogurt samples was evaluated over a 16-day period. The SKYC control sample exhibited an initial TVC of 6.08 ± 0.09 log CFU/mL on Day 0, which significantly increased up to 8.25 ± 0.10 log CFU/mL on Day 8. Full-fat yogurt (FFYC) showed higher microbial counts throughout the study, starting at 7.35 ± 0.12 log CFU/mL and increasing maximum up to 9.36 ± 0.15 log CFU/mL on Day 8, followed by a reduction to 7.12 ± 0.10 log CFU/mL on Day 16 (Table 2C). MFFYC exhibited a similar trend, with the highest TVC (9.61 ± 0.04 log CFU/mL) on Day 8 and a final count of 7.38 ± 0.06 log CFU/mL on Day 16. SKYPHM5, the sample containing PHM, consistently had the highest viable counts, starting at 8.16 ± 0.09 log CFU/mL and reaching a peak of 10.53 ± 0.12 log CFU/mL on Day 8. On Day 16, SKYPHM5 maintained a relatively high count of 8.37 ± 0.19 log CFU/mL The results indicated that the addition of PHM effectively enhanced microbial viability, potentially due to its probiotic properties, contributing to sustained bacterial growth throughout the storage period.

3.7. Texture profiling

The texture analysis of various yogurt samples over a 16-day storage period reveals notable differences in hardness, adhesiveness, and gumminess. Full-fat yogurt (FFYC) demonstrated consistently high hardness values, increasing from 238.49 ± 0.34 g on Day 0 to 243.66 ± 0.34 g on Day 16, and showed a firm texture attributed to its higher fat content (Table 2D). In contrast, skimmed milk yogurt (SKYC) exhibited lower hardness, starting at 181.28 ± 0.53 g and reaching 197.38 ± 0.21 g, reflecting its softer texture. The yogurt with PHM (SKYPHM5) showed the highest hardness, rising from 231.80 ± 0.81 g to 256.45 ± 0.65 g, proved that mucilage contributes to a significant increase in firmness. Adhesiveness data revealed that FFYC had the highest initial adhesiveness of 319.57 ± 0.73 g/mm, which decreased to 305.68 ± 0.40 g, and showed reduced stickiness over time. SKYC had lower adhesiveness, starting at 185.66 ± 0.62 g/mm and decreasing to 161.09 ± 0.38 g/mm, while SKYPHM5 also had reduced adhesiveness, from 269.41 ± 0.43 g/mm to 237.27 ± 0.66 g/mm, though it remained higher than SKYC. Gumminess values for FFYC increased from 203.76 ± 0.16 N to 221.43 ± 0.46 N which enhanced chewiness with storage. Conversely, SKYC displayed lower gumminess, from 172.05 ± 0.27 N to 159.37 ± 0.34 N, and SKYPHM5 exhibited the highest gumminess, escalating from 189.33 ± 0.51 N to 160.72 ± 0.73 N showed a marked improvement in chewiness. The firmness of selected yogurt was increased across all samples, with SKYC showed the lowest firmness (1.35 ± 0.24 N at Day 0) and SKYPHM5 demonstrated the highest firmness (2.84 ± 0.08 N at Day 16), likely due to water-binding capacity of PHM. FFYC and MFFYC, with higher fat content, exhibited greater firmness, cohesiveness, and springiness than the low-fat SKYC sample. Cohesiveness decreased for all samples, with SKYC showing the sharpest decline, indicating a weakening gel structure over time. FFYC and MFFYC maintained higher cohesiveness, suggesting a role of fat in structural stability, while SKYPHM5 retained moderate cohesiveness due to the stabilizing effect of PHM (Ribes et al., 2021). These results suggest that while fat content significantly enhances textural attributes such as hardness and adhesiveness, the addition of PHM mucilage can effectively mimic these properties, providing a stable and desirable texture in low-fat yogurt formulations. Similarly, Mudgil et al. (2017) highlighted the role of PHM in improving the textural properties of yogurts due to their higher water-holding capacity. Therefore, SKYPHM5 demonstrates the potential of mucilage as an effective fat replacer, maintaining texture quality and stability without the need for added fat.

Table 2D
Textural profiling of selected yogurt.

Parameter	Samples	Storage Period (Days)				
		Day-0	Day-4	Day-8	Day-12	Day-16
Hardness (g)	SKYC	181.28 ± 0.53^{aA}	183.75 ± 0.60^{aB}	187.98 ± 0.76^{aC}	192.43 ± 0.44^{aD}	197.38 ± 0.21^{aE}
	FFYC	238.49 ± 0.34^{cA}	239.05 ± 0.43^{cB}	240.51 ± 0.81^{cBC}	241.14 ± 0.69^{bC}	243.66 ± 0.34^{bD}
	MFFYC	240.17 ± 0.47^{dA}	242.24 ± 0.82^{cdB}	243.77 ± 0.43^{dBC}	244.68 ± 0.35^{cC}	245.91 ± 0.42^{bcD}
	SKYPHM5	231.80 ± 0.81^{bA}	234.19 ± 0.34^{bB}	236.05 ± 0.55^{bC}	244.43 ± 0.72^{cD}	256.45 ± 0.65^{dE}
Adhesiveness (g/mm)	SKYC	185.66 ± 0.62^{aE}	178.63 ± 0.72^{aD}	174.12 ± 0.34^{aC}	168.41 ± 0.54^{aB}	161.09 ± 0.38^{aA}
	FFYC	319.57 ± 0.73^{cE}	317.33 ± 0.66^{cD}	314.73 ± 0.46^{cC}	309.45 ± 0.39^{cB}	305.68 ± 0.40^{dA}
	MFFYC	317.12 ± 0.95^{cD}	316.49 ± 0.49^{cD}	313.02 ± 0.67^{cC}	307.88 ± 0.40^{cB}	291.53 ± 0.27^{cA}
	SKYPHM5	269.41 ± 0.43^{bE}	261.02 ± 0.83^{bD}	254.66 ± 0.29^{bC}	242.19 ± 0.84^{bB}	237.27 ± 0.66^{bA}
Gumminess (N)	SKYC	172.05 ± 0.27^{aE}	168.44 ± 0.44^{aD}	164.33 ± 0.38^{aC}	161.83 ± 0.61^{aB}	159.37 ± 0.34^{aA}
	FFYC	203.76 ± 0.16^{cA}	205.35 ± 0.25^{cB}	211.08 ± 0.70^{cC}	215.67 ± 0.47^{cD}	221.43 ± 0.46^{cE}
	MFFYC	201.82 ± 0.35^{cA}	206.40 ± 0.17^{cB}	209.76 ± 0.35^{cC}	211.44 ± 0.32^{cD}	216.94 0.81^{cE}
	SKYPHM5	189.33 ± 0.51^{bE}	186.12 ± 0.39^{bD}	184.61 ± 0.27^{bC}	176.58 ± 0.67^{bB}	160.72 ± 0.73^{bA}
Firmness (N)	SKYC	1.35 ± 0.24^{aA}	1.53 ± 0.15^{aB}	1.81 ± 0.15^{aC}	1.98 ± 0.43^{aD}	2.05 ± 0.13^{aE}
	FFYC	1.94 ± 0.11^{bA}	2.26 ± 0.27^{bB}	2.47 ± 0.26^{bC}	2.80 ± 0.35^{bD}	2.94 ± 0.18^{cE}
	MFFYC	1.90 ± 0.09^{bA}	2.20 ± 0.30^{bB}	2.53 ± 0.32^{bC}	2.87 ± 0.14^{bD}	3.02 ± 0.24^{cE}
	SKYPHM5	2.14 ± 0.25^{cA}	2.27 ± 0.18^{bB}	2.42 ± 0.21^{bB}	2.55 ± 0.33^{bC}	2.84 ± 0.08^{bD}
Cohesiveness (N)	SKYC	0.247 ± 0.02^{cE}	0.184 ± 0.05^{bD}	0.135 ± 0.03^{aC}	0.117 ± 0.09^{aB}	0.97 ± 0.05^{bA}
	FFYC	0.216 ± 0.01^{bE}	0.207 ± 0.02^{cD}	0.187 ± 0.05^{bC}	0.152 ± 0.02^{bB}	0.134 ± 0.07^{cA}
	MFFYC	0.231 ± 0.03^{bE}	0.219 ± 0.01^{dD}	0.206 ± 0.07^{cC}	0.191 ± 0.04^{cB}	0.173 ± 0.09^{dA}
	SKYPHM5	0.186 ± 0.04^{aE}	0.151 ± 0.03^{aD}	0.134 ± 0.09^{aC}	0.117 ± 0.07^{aB}	0.83 ± 0.10^{aA}
Springiness (mm)	SKYC	5.06 ± 0.29^{aA}	7.34 ± 0.51^{aB}	9.19 ± 0.19^{aC}	11.03 ± 0.27^{aD}	13.55 ± 0.41^{aE}
	FFYC	8.24 ± 0.21^{bA}	10.03 ± 0.37^{bB}	14.75 ± 0.24^{bC}	18.49 ± 0.43^{bD}	21.87 ± 0.33^{cE}
	MFFYC	9.73 ± 0.35^{bA}	12.61 ± 0.46^{cB}	15.02 ± 0.44^{cC}	19.33 ± 0.19^{bcD}	23.46 ± 0.52^{dE}
	SKYPHM5	13.49 ± 0.43^{cA}	15.50 ± 0.28^{dB}	17.38 ± 0.30^{dC}	18.43 ± 0.34^{bD}	19.66 ± 0.13^{bD}

Table 3
Color value of the selected yogurts at different day interval.

Color value	Samples	Day-0	Day-4	Day-8	Day-12	Day-16
L*	SKYC	91.68 ± 0.15^{bE}	87.52 ± 0.25^{bD}	84.05 ± 0.23^{bC}	80.67 ± 0.27^{bB}	78.83 ± 0.79^{bA}
	FFYC	93.05 ± 0.2^{cE}	89.22 ± 0.19^{cD}	86.34 ± 0.15^{cC}	82.91 ± 0.34^{bB}	79.24 ± 0.66^{bA}
	MFFYC	93.56 ± 0.08^{cE}	91.08 ± 0.11^{dD}	87.55 ± 0.32^{cC}	82.80 ± 0.43^{bB}	79.34 ± 0.19^{bA}
	SKYPHM5	87.19 ± 0.43^{aE}	85.76 ± 0.28^{aD}	81.09 ± 0.41^{aC}	75.88 ± 0.17^{aB}	71.43 ± 0.42^{aA}
a*	SKYC	−1.38 ± 0.55^{aD}	−1.32 ± 0.24^{aD}	−1.21 ± 0.35^{aB}	−1.11 ± 0.41^{aB}	−1.05 ± 0.31^{aA}
	FFYC	−0.65 ± 0.68^{bA}	−0.58 ± 0.09^{bB}	−0.85 ± 0.19^{bC}	−0.97 ± 0.27^{bD}	−1.09 ± 0.84^{aBE}
	MFFYC	−0.66 ± 0.17^{bA}	−0.60 ± 0.35^{bA}	−0.82 ± 0.24^{bB}	−0.95 ± 0.12^{bC}	−1.07 ± 0.09^{aD}
	SKYPHM5	−1.35 ± 0.34^{aD}	−1.29 ± 0.05^{aC}	−1.21 ± 0.13^{aB}	−1.14 ± 0.25^{aB}	−1.03 ± 0.66^{aA}
b*	SKYC	3.11 ± 0.29^{aE}	3.01 ± 0.38^{bD}	2.93 ± 0.21^{aC}	2.85 ± 0.30^{aB}	2.80 ± 0.49^{aA}
	FFYC	3.85 ± 0.38^{bE}	3.60 ± 0.42^{cD}	3.51 ± 0.17^{bC}	3.42 ± 0.19^{bB}	3.33 ± 0.82^{bA}
	MFFYC	3.86 ± 0.10^{bE}	3.61 ± 0.18^{cD}	3.48 ± 0.27^{bC}	3.40 ± 0.31^{bB}	3.35 ± 0.21^{bA}
	SKYPHM5	3.12 ± 0.91^{aE}	2.89 ± 0.31^{aD}	2.82 ± 0.12^{aC}	2.79 ± 0.17^{aB}	2.76 ± 0.73^{aA}

Data are presented as mean ± SD (n = 3). Mean values with different lowercase (a-d) letters within a column and uppercase (A-E) letters within a row represent significantly different values within the samples and days, respectively. (Skimmed yogurt control (SKYC), Full-fat yogurt control (FFYC), Market full-fat yogurt control (MFFYC), PHM: *Psyllium* husk mucilage.

3.8. Color analysis

The color analysis of the selected yogurt samples was evaluated over a 16-day storage period and revealed changes in lightness (L^*), redness (a^*), and yellowness (b^*) values. SKYC presented a decrease in L^* value from 91.68 ± 0.15 on the 1st day to 78.83 ± 0.79 by the 16th day, indicating a reduction in lightness over time (Table 3). The a^* value slightly increased from −1.38 ± 0.55 to −1.05 ± 0.31, indicating a minor shift towards redness, while the b^* value decreased from 3.11 ± 0.29 to 2.80 ± 0.49, showing a reduction in yellowness. FFYC also exhibited a decrease in L^* value from 93.05 ± 0.69 on Day 1 to 89.22 ± 0.19 on the 4th and 79.24 ± 0.66 by the 16th day, reflecting a reduction in lightness. The a^* value decreased slightly from −0.65 ± 0.68 to −1.09 ± 0.84, indicating a slight shift towards more greenish hues. The b^* value decreased from 3.85 ± 0.38 to 3.33 ± 0.82, and reducted the yellowness but maintained a relatively higher b^* value compared to SKYC and SKYPHM5. Whereas, SKYPHM5 showed the most significant decrease in L^* value from 87.19 ± 0.43 on 1st day to 71.43 ± 0.42 by the 16th day, indicated a distinct reduction in lightness. The a^* value increased slightly from −1.35 ± 0.34 to −1.03 ± 0.66, showing a minor shift towards redness. The b^* value decreased from 3.12 ± 0.91 to 2.76 ± 0.73, indicating a reduction in yellowness. The reduction in L^* values across all samples suggested a decrease in lightness over the storage period, likely due to ongoing fermentation and pigment degradation (Ribes et al., 2021). The minor shifts in a^* and b^* values indicated slight changes in the red-green and yellow-blue hues, respectively. The higher fat content in FFYC may have contributed to a slower change in color compared to the control and mucilage-enhanced samples, likely due to the protective effect of fat on pigment stability. These findings are consistent with the literature, which indicates that yogurt color can change over time due to fermentation and storage conditions. The hydrocolloids like PHM mucilage can impact color stability by affecting the microstructure and light-scattering properties of the yogurt (Leal et al., 2024). The significant decrease in lightness in SKYPHM5 suggested that mucilage addition may influence color stability, possibly due to its interaction with yogurt components and its impact on light scattering. Thus, the results suggest that addition of mucilage in yogurt can influence the color stability of product. The selection of appropriate concentrations and types of additives is crucial for maintaining the desired color attributes of yogurt during storage (Sofu & Ekinci, 2007).

3.9. Consumers perceptions

The market acceptance study of mucilage-based low-fat yogurt revealed a strong consumer response, particularly in terms of perceived health benefits, which achieved the highest mean score of 97.16 ± 1.58 %. This finding suggests that a significant proportion of consumers are aware of the health-promoting attributes of the yogurt, likely attributable to the use of organic, plant-derived ingredients (Fig. 3A). The assessment of mouthfeel and texture yielded positive results (85.49 ± 2.55), indicated that the mucilage effectively compensated for the reduced fat content by providing adequate viscosity and creaminess key factors in consumer satisfaction with low-fat dairy products. Although still favorable, the taste and flavor evaluation showed greater variability (80.32 ± 3.98), suggested that further optimization of the flavor profile may be necessary to enhance the product's appeal to a broader range of consumers. The yogurt received a high score of 91.11 ± 2.49 in the category of ingredient perception, indicating a consistently favorable consumer view of using plant-based components as a healthier alternative to traditional additives. This aligns well with consumer preferences for natural and clean-label products. However, the perception of price and value scored somewhat lower (78.16 ± 2.76), proving that consumers may perceive the product as less cost-effective, which could pose a barrier to market adoption. The visual images of formulated yogurts are illustrated in Fig. 3B. This highlighted the importance of strategic pricing to enhance market appeal and consumer acceptance. The product achieved a high overall acceptability score of 92.76 ± 2.99, demonstrating strong consumer approval. However, the variability in responses suggests that there may be differences in consumer preferences that could be addressed through targeted product improvements. These findings indicated that mucilage-based low-fat yogurt holds significant potential to meet the demands of modern consumers who seek natural, sustainable, and health-conscious food products.

3.10. Sensory analysis

The sensory analysis of the three yogurt formulations including low-fat with *psyllium* husk mucilage (SKYPHM5), full-fat control (FFYC), and low-fat based on skimmed milk (SKYC) revealed distinct variations in consumer perception across key characteristics, including appearance, flavor, mouthfeel, and overall acceptability. The full-fat yogurt (FFYC) received the highest ratings for mouthfeel (7.9 ± 0.68), appearance (7.42 ± 0.15), and overall acceptability (7.68 ± 0.19), confirmed its superior sensory attributes related to its rich flavor and texture (Fig. 3C). The addition of PHM in the low-fat yogurt formulation (SKYPHM5) also showed good performance, particularly in appearance (6.68 ± 0.87) and mouthfeel (7.12 ± 0.77). This purposed that the mucilage effectively enhanced the texture and overall sensory experience, making it more comparable to the full-fat version. MFFYC showed higher sensory scores compared to SKYC, FFYC, and SKYPHM5. Additionally, the SKYPHM5 formulation received a relatively high score for scent (6.87 ± 0.91), indicated a positive impact on the overall sensory profile of the product.

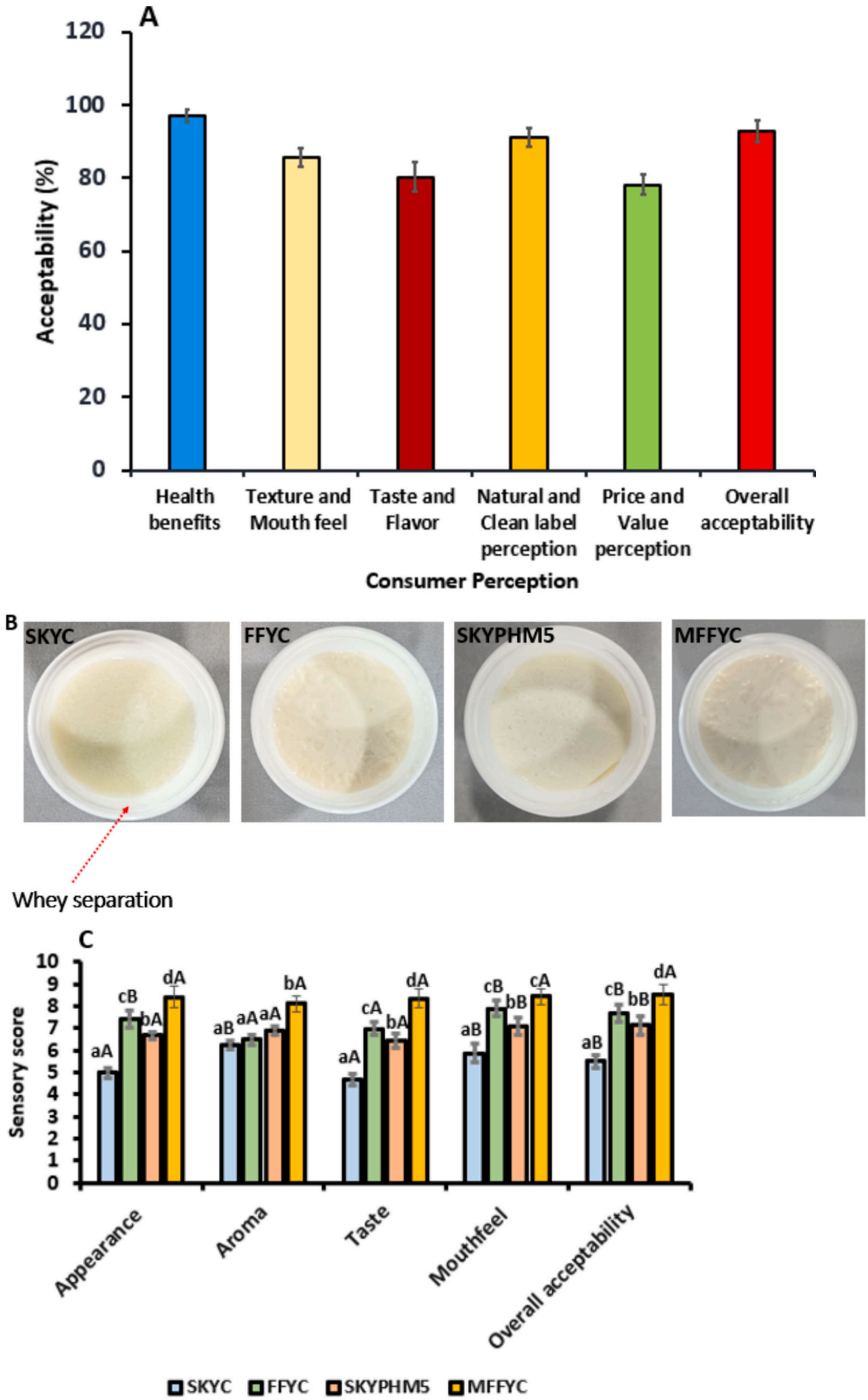

Fig. 3. (A) Consumer's perception on the formulated yogurt, (B) pictorial representation of formulated yogurt, (C) Sensory analysis, (D) Protein bioavailability after *in vitro* digestion, (E) Reducing sugar release of yogurt after *in vitro* digestion. Different error bars represent the standard deviation from the mean values (n = 3) and lower case (a-d) represent the significantly different among the samples (SKYC, FFYC, MFFYC, and SKYPHM5), Uppercase (A-C) shows the significant difference within the different sensory parameters. (Skimmed yogurt control (SKYC), Full-fat yogurt control (FFYC), Market full-fat yogurt (MFFY), PHM: *Psyllium* husk mucilage.

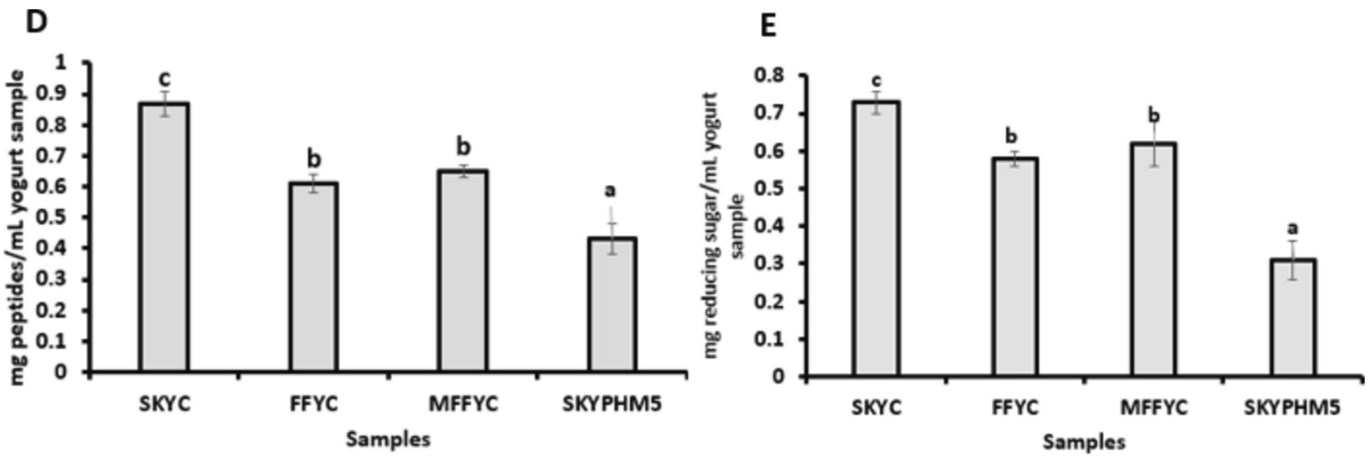

Fig. 3. (*continued*).

In contrast, the conventional low-fat yogurt (SKYC) scored the lowest in flavor (4.68 ± 0.19) and overall acceptability (5.51 ± 0.43), highlighted the challenges associated with maintaining sensory quality in reduced-fat products. However, the sensory improvements observed in SKYPHM5 suggested that plant-derived mucilage can significantly enhance the sensory appeal of low-fat yogurt, making it a viable alternative for health-conscious consumers without compromising on flavor or texture.

3.11. *In vitro digestion*

The protein bioavailability wasmeasured as the concentration of peptides released (mg peptides/mL yogurt sample), varied across the different yogurt formulations. The SKYC showed the highest peptide release of 0.87 ± 0.02 mg/mL, indicated better protein hydrolysis compared to other samples. This can be attributed to the absence of fat, which may have allowed easier access for digestive enzymes to hydrolyze the proteins. On the other hand, the FFYC and MFFYC exhibited lower peptide release at 0.61 ± 0.08 mg/mL and 0.65 ± 0.06 mg/mL, respectively (Fig. 3D). The presence of fat in these samples likely inhibited enzyme access to proteins, reducing hydrolysis (Ye et al., 2022). Interestingly, the SKYPHM5 represented the lowest peptide concentration of 0.43 ± 0.11 mg/mL, which suggested that the mucilage may have formed a barrier or network that hindered enzymatic activity, thereby reducing the protein bioavailability.

In terms of carbohydrate digestion, the reduced sugar content followed a similar trend. SKYC exhibited the highest release of reducing sugars (0.73 ± 0.16 mg/mL), likely due to the absence of fat and the easier breakdown of lactose and other carbohydrates. Both FFYC and MFFYC showed moderately lower reducing sugar levels at 0.58 ± 0.09 mg/mL and 0.62 ± 0.13 mg/mL, respectively as illustrated in Fig. 3E. The fat content in these samples may have impeded the action of digestive enzymes on the carbohydrates. The SKYPHM5 sample displayed the lowest reducing sugar release (0.31 ± 0.08 mg/mL), likely due to the presence of PHM, which may have trapped carbohydrates and delayed their breakdown by digestive enzymes. The viscosity and gel-forming properties of mucilage have been previously detected to slow down the enzymatic hydrolysis of carbohydrates (Aswathy et al., 2024).

4. Conclusion

The addition of nano-mucilage derived from plants such as *Psyllium* husk, *Cordia dichotoma* fruits, and *Colocasia esculenta* rhizomes significantly enhances the texture, viscosity, and overall sensory quality of low-fat yogurt, while also meeting consumer demand for more natural and health-conscious food options. The findings of study suggest that these plant-based nano-mucilages can effectively replicate the functional properties of the fat, leading to improved mouthfeel, stability, and consumer acceptability. Furthermore, the positive consumer perception of these products, particularly regarding their health benefits and sensory attributes, underscores their strong market potential. However, the study also identifies areas that require further optimization, particularly in flavor enhancement and pricing strategy, to ensure broader consumer acceptance and commercial success. Overall, this research influences the functional benefits of plant-derived nano-mucilage to offer valuable insights into the development of low-fat yogurt that meets contemporary consumer expectations for flavor, texture, and health benefits.

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CRediT authorship contribution statement

Mansuri M. Tosif: Investigation, Methodology, Visualization, Validation, Software, Writing – original draft. **Aarti Bains:** Resources, Project administration, Methodology, Investigation, Data curation. **Gulden Goksen:** Conceptualization, Writing – original draft, Visualization, Data curation, Validation, Formal analysis, Writing – review & editing. **Mohd Ziaur Rehman:** Visualization, Funding acquisition, Writing – review & editing. **Nemat Ali:** Visualization, Project administration, Writing – review & editing. **Gulsah Karabulut:** Validation, Software, Data curation, Writing – review & editing. **Prince Chawla:** Conceptualization, Visualization, Validation, Data curation, Software, Resources, Methodology, Funding acquisition, Project administration, Writing – review & editing.

Declaration of competing interest

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

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101920.

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