Journal of Food Engineering 338 (2023) 111255

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Fabrication of edible special wettability coating on polystyrene substrate and application in yogurt storage

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A R T I C L E I N F O

Keywords:
Edible coating
Special wettability
Yogurt residual rate
Quality index
Polystyrene sheet substrate

A B S T R A C T

The yogurt adherence always caused enormous waste of food sources due to sticking onto the package inner walls. So, carnauba wax, silica, and carboxymethylcellulose (CMC) were mixed together as an emulsion to be sprayed, and fabricated an edible special wettability coating on the polystyrene substrate for reducing the yogurt residual rate. The contact angle, slide angle and yogurt residual rate on the coating were respectively (141.32 ± 3.48) °, (7.51 ± 1.65) ° and (3.77 ± 1.99) %, revealing a good application in yogurt package. The coating was fabricated compactly and robustly through element mapping, functional groups recognition, and crystalline analysis. The coating could also tolerate the acid circumstance at a wide pH range with little yogurt residual. Afterwards, the emulsion was sprayed onto the inner wall of commercial cups to fabricate the coating for yogurt storage. It could be observed that the yogurt residual rate was (7.40 ± 0.36) % in coated cups, which was significantly less than the control cups (9.64 ± 0.83) % ($p < 0.05$) after 21 days storage. Besides, the coating had no negative effects on the yogurt qualities, and none of the coating ingredients released into the yogurt during storage. It could be found that there was no significant relationship between the viscosity and the residual rate ($p > 0.05$) due to the coating, but the viscosity and the contact angle on the coating had a positive correlation ($R = 0.701$, $p < 0.01$). Thus, an edible special wettability coating was fabricated for solving the adherence problems generally existing in the yogurt industry.

1. Introduction

In dairy consumption, there can be a significant (up to 15%) waste of yogurt as the residue sticks onto the package inner walls (Karkantonis et al., 2020). For alleviating the waste phenomena, the superhydrophobic coatings were tentatively fabricated through a combination of surface microstructure and low solid surface energy chemicals (Wang et al., 2016). Recently, it gradually turned to research the natural special wettability coating which was repellent to the complex food hydrocolloids system (Kouhi et al., 2020; Wang et al., 2020). For example, Li et al. (2018) initially took advantage of the hydrogen bonds which were formed between the edible elastic film and honeycomb wax to fabricate bioinspired surface on polypropylene substrate, and then Zhang et al. (2019) added coffee lignin into the honeycomb wax for enhancing the coating robustness. Wang et al. (2021b) achieved an eco-friendly nano-starch-based superhydrophobic coating by combining starch nanoparticles with polydimethylsiloxane. Liu et al. (2019) adopted edible candelilla wax and rice bran wax melt in hot ethanol solution to fabricate superhydrophobic coatings on polypropylene substrates via one step spraying. Thus, the coatings were widely studied in repelling various non-Newtonian liquid food like yogurt. However, the influences of the coating on the yogurt in subsequent storage were not been fully explored. Especially, the release of the coating ingredients into yogurt or not was already unclear after a long storage time. Hence, it needs to study the feasibility of the edible special wettability coating for yogurt during a long storage, which means an extreme environment for the coating.

It is really desired to create a robust coating for meeting the long storage requirement in yogurt industry. Among the methods improving the coating robust (Wang et al., 2021c), crosslink between the coating

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https://doi.org/10.1016/j.jfoodeng.2022.111255
Received 28 May 2022; Received in revised form 30 July 2022; Accepted 19 August 2022
Available online 26 August 2022

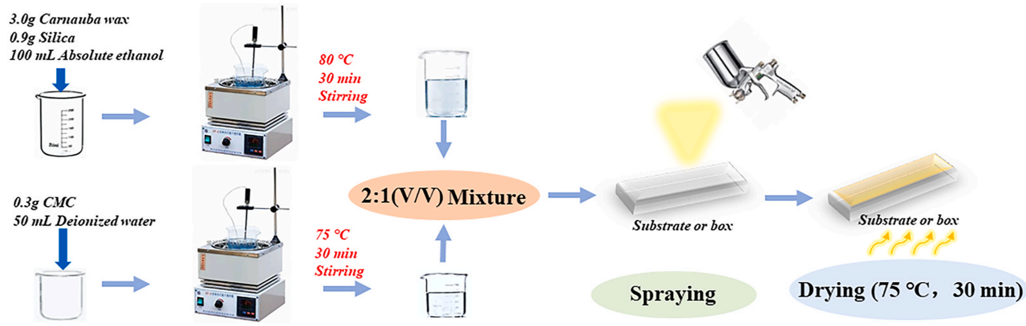

Fig. 1. Fabrication of a special wettability coating on polystyrene sheet and into yogurt cup.

ingredients could improve the robustness conveniently and quickly through a step of spraying. It was just critical that to seek out the appropriate crosslink substances. Wang et al. (2021a) fabricated a stretching superhydrophobic coating through adjusting the ratio between carnauba wax and bee wax to produce various crosslink statuses. Carnauba wax was a general accepted food additive in food industry, but it already lacks robust due to weak intermolecular reaction. It should not endure the extreme storage condition for yogurt during a long storage. As a result, it was worthy to explore another edible adhesive which could generate crosslinks among carnauba wax and substrate in arbitrary conditions. Carboxymethylcellulose (CMC) was a common food additive usually used as binder in film formation. And hydrogen bonds could be formed between the carnauba wax and CMC to enhance the coating integrity. Furthermore, the –COOH group in CMC molecular could provide a special wettability surface with stability for food applications (Wang and Guo, 2020). So, CMC is an ideal component to enhance the coating stability with yogurt repellent in a long storage.

In this study, the edible special wettability coating was fabricated by spraying carnauba wax, silica and CMC emulsion onto the polystyrene sheet. Then, the microstructure and components of the coating were observed and analyzed for verifying the integrity. Since the coating would be used in yogurt storage, the coating resistance to pH value, time, and temperature were also tested. In addition, the effects of the coating on the yogurt quality were evaluated for confirming the practical application in yogurt cup package during a long storage. It would help understanding the coating durability in a long shelf-life for yogurt. Besides, the feasibility of the coating in some common commercial yogurt brands were also studied. It is hoped that the edible special wettability coating could provide a theory basis for solving the large waste of sticky fluid food.

2. Material and methods

2.1. Materials

Carnauba wax (1#, fusion point >83 °C) was purchased from Aladdin company. Silica (food grade) was bought from Guangdong Xingrong Biological Technology Co., LTD. Carboxymethylcellulose (CMC, food grade) was obtained from Shanghai Shenguang Edible Chemicals Co., LTD. While, the other reagents including lactic acid, absolute ethyl alcohol, sodium hydroxide, petroleum ether and brilliant blue G-250 were all analytically pure and used as received. Besides, polystyrene sheets were used as substrate, and 15 species of yogurts (Fig. S1) were bought from a local supermarket and storage at 4 °C for further usage. Among of these yogurts, Yili Natural Yogurt was used as the model yogurt because it was at a low price and the lid should be easily peeled off. The commercial yogurt cups from Yili Natural Yogurt were carefully cleared and dried for fabricating the coating to store the yogurt.

2.2. Fabrication of special wetting coating

The special wettability coating was fabricated as shown in Fig. 1. Solution A was prepared by adding 3 g carnauba wax and 0.9 g silica into 100 mL absolute ethyl alcohol, and mixed in water bath at 80 °C for 30 min in a Magnetism Msier (DF-101 S, Kerui Yiqi limited company, Gongyi, Henan). Meanwhile, Solution B was obtained by dissolving 0.3 g CMC into 50 mL deionized water, and mixed in water bath for 30 min at 75 °C in the Magnetism Msier. Afterwards, the solution A and B (A:B = 2:1, V/V) were mixed fully to form an emulsion for a step spray to fabricate the special wetting coating onto the polystyrene sheets substrate or cup inner walls. When spraying at 60 psi, the distance between the nozzle and the substrate was set as 120 mm to fabricate a coating on the substrate. After spraying, the substrate with coating were placed in an air oven for 30 min at 75 °C to eliminate the ethyl alcohol and enhance the coating stability. Thus, a special wetting coating on the substrate (64.467 g m^{-2}) was fabricated for further usage.

2.3. Characteristics and components analysis of the special wettability coating

2.3.1. Contact angle and slide angle test

The contact angle and slide angle of the yogurt on the special wetting coating were tested using a contact angle meter (SL200KS, Shanghai Solon Information Technology Co., LTD). 5 μL yogurt was dropped on the surface to test the contact angle and slide angle of the coating. 5 different points on a coating sample were detected and averaged as the contact angle or slide angle results of a coating sample, and the results of 3 coating samples were averaged as the contact angle and slide angle values.

2.3.2. Scanning electron microscopy (SEM) and energy disperse spectroscopy (EDS)

The special wettability coating samples were cut down to be adhered on the microstat for a further gold sputtering in ion sputtering apparatus at 5 mmHg vacuum degree and 6 mA electric current. After that, the microstructure of the coating at 100 × and 500 × magnification was observed in a SEM (EVO 18, ZEISS, Germany) at 20.00 kV. Energy disperse spectroscopy (EDS) was used to detect the C, O, Na, and Si elements on the coating by scanning electron microscopy (SEM). The test mode was map scan, voltage was 15 kV and current PC was about 80 when the cps reached to 6000–8000.

2.3.3. Fourier-transform infrared spectroscopy (FTIR) of the coating and yogurt

The groups of the coating constitute substances were test using Fourier-transform infrared spectroscopy (FTIR) (Thermo Fisher Scientific, America) at wavelength between 500 and 4000 cm^{-1}. The powder samples with KBr were stacked into discs separately as reference substance for the coating. For exploring whether the coating constitutes diffused into yogurt or not, the yogurt after 21 days storage in the cups

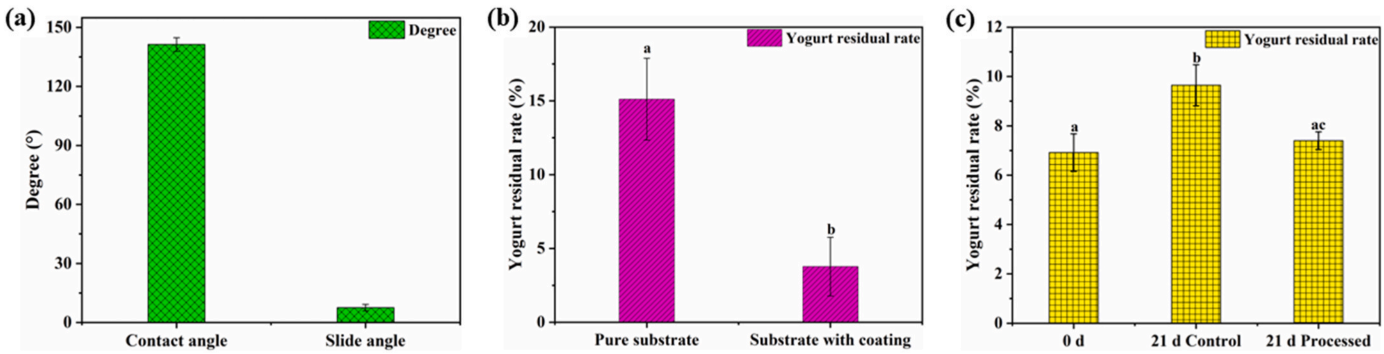

Fig. 2. (a) Contact and slide angles of yogurt on the special wettability on the polystyrene sheet. (b) Residual rate of yogurt on the polystyrene with or without the special wettability coating. (c) Residual rate of yogurt on the inner wall of the cup with or without the special wettability coating. The different lower cases on each subgraph means significant for the index ($p < 0.05$).

with or without coating was dried to be tested using FTIR at wavelength between 500 and 4000 cm^{-1}.

2.3.4. X-ray diffraction (XRD) analysis

The crystalline characteristics of carnauba wax, silica, and CMC and the coating samples were measured using a Shimadzu XRD-6100 X-ray Diffractometer (Shimadzu Corporation, Japan) with Cu-Kα radiation at 40 kV target voltage and 30 mA electric current. The XRD data were obtained at a range of 5–40° with scanning speed of 2°/min and step of 0.02°.

2.4. Coating robustness analysis

The special wettability coatings were immersed in a series of lactate solution with pH ranging from 1 to 7. After 24 h, a lot of deionized water was used to flush the immersed coatings, which were then dried in an oven at 75 °C for 24 h to test pH tolerance. Besides, the special wettability coatings were placed in air for 0, 6, 12, 16, 24 and 30 days to verify the time stability. Meantime, the special wettability coatings were also placed in an oven with different temperatures (20, 40, 60, 80 and 100 °C) for 12 h to the thermostability test. Then, the yogurt contact angle and residual rate on all the processed coating samples were tested at room temperature as before.

2.5. Detection of yogurt residual rate on the coating

All the yogurt was taken from the refrigerator at 4 °C and immediately dropped onto the coating on the polystyrene sheet to test the residual rates at room temperature. For the model yogurt, it was poured into the cups with coating and kept at 4 °C for 21 days, and the residual rates were then tested when taken out of the refrigerator. The yogurt residual rate was calculated as below by dropping or pouring the yogurt onto the special wettability coating and pouring away.

$$\omega = \frac{m_3 - m_1}{m_2} \times 100\%$$

Where.

ω is the yogurt residual rate, %;
m_1 is the weight of the substrate polystyrene sheet or the cup with coating, g;
m_2 is the weight of yogurt poured onto the coating or into the cup, g;
m_3 is the weight of the substrate polystyrene sheet or the cup with residual yogurt and coating, g.

2.6. Yogurt quality index evaluation in the cup with or without the coating

For investigating the effects of the coating on the storage qualities after a long storage, the yogurt quality index in the cup with or without the special wettability coating were obtained at 0 and the 21st day.

2.6.1. Content of main nutrient substances

The titratable acid test was performed by fully mixing 0.1 mL yogurt and 5 mL deionized water together as a diluent, in which 0.8 mL was dropped onto the sugar-acid machine (PAL-BX/ACID, ATAGO, Japan) for getting the titratable acid. The fat content of yogurt was obtained by Soxhlet extraction method, while the protein content by Coomassie brilliant blue method. The standard curve of the protein content was shown in Fig. S2. Three replicates were performed and averaged as a nutrient substance result.

2.6.2. Water hold capacity

At room temperature, 10 g yogurt was added into a tube and centrifuged at 5000 r·min^{-1} for 30 min. Then the supernatant was discarded, and the tube was immediately weighed after inversely placed for 10 min. The water hold capacity was obtained as follow,

$$WHC = \frac{m_2 - m_1}{10g} \times 100\%$$

WHC is the water hold capacity, %;
m_1 is the pure weight of the tube, g;
m_2 is the weight of tube with yogurt sediment after centrifugation, g.

2.6.3. Viscosity

The viscosity of yogurt was tested using the rheometer (RSO, Brookfield, USA). The rotor RPTO-25 was used to acquire the viscosity of yogurt at 25 °C, with shearing rate 120 s^{-1} and standing time 10s. Three replicates was tested and averaged as a viscosity result of a yogurt sample.

2.7. Feasibility of the coating in other yogurts

At room temperature, the parameters including the viscosity, contact angle, residual rate for 15 species of common commercial yogurts (Fig. S1), which were all dropped onto the special wettability coating on the polystyrene sheet as substrate, were acquired to explore the feasibility probability of the coating for the other yogurts.

2.8. Statistics analysis

Differences were determined using Tuckey HSD multiple tests at a level of 0.05 by R Language (Version 4.0.3, The R Foundation for Statistical Computing). All data were presented as mean values with standard deviations. And the relationship between viscosity, contact angle, and residual rate of yogurts were explored using Pearson's comparison.

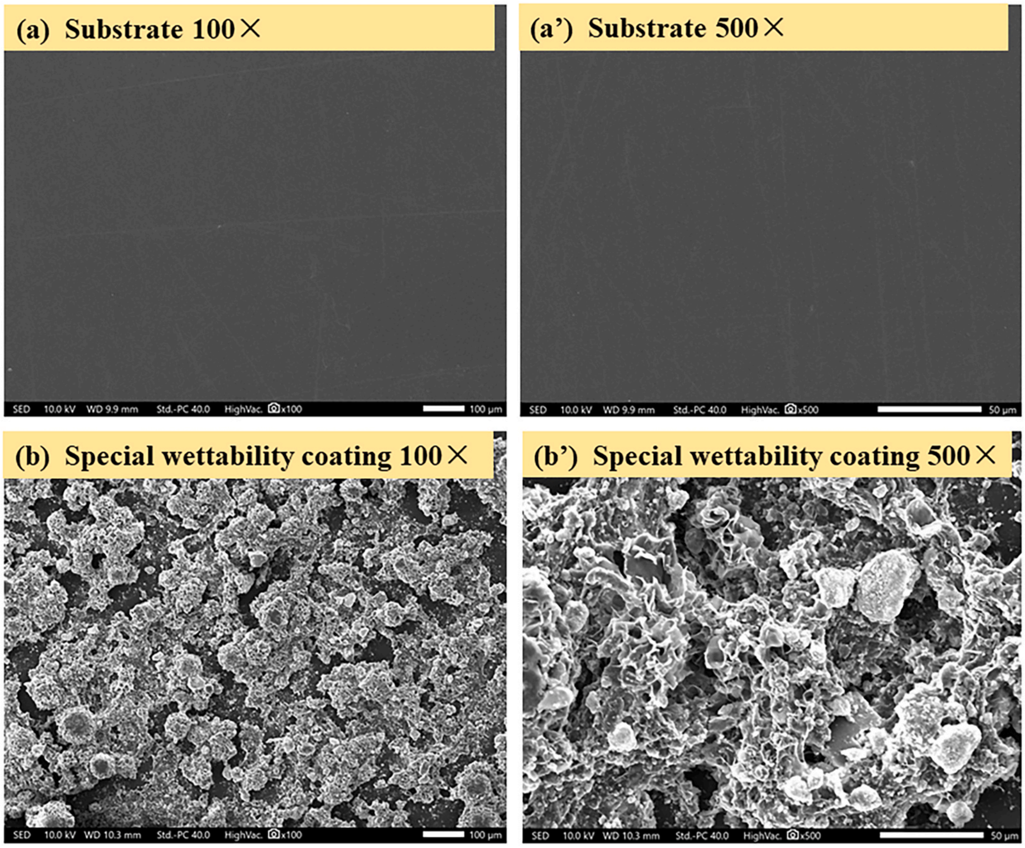

Fig. 3. SEM of the polystyrene with or without the special wettability coating.

3. Results and discussion

3.1. Coating wettability

The coating wettability was shown in Fig. 2. The contact angle and slide angle of yogurt on the coating of polystyrene sheets were (141.32 ± 3.48) ° and (7.51 ± 1.65) °, respectively (Fig. 2 (a)). The contact angle was approximately close to (145.93 ± 1.12) ° of the nano-starch-based superhydrophobic coatings (Wang et al., 2021b) and approached to (150.41 ± 2.3) ° of the edible superhydrophobic coating (Yang et al., 2019). And the slide angle was much lower than (12–16) ° for some yogurt brands (Li et al., 2021). It is because that the coating is contained chemically inert long-chain alkanes of carnauba wax (Shen et al., 2020; Zhao et al., 2018). Besides, the polar groups of the protein, fat, and water in yogurt tended to possess hydrophilic characteristics and increased the surface energy of yogurt drop, so the cohesion forces between the yogurt molecules are higher than the adhesion forces between the yogurt and air molecules at the yogurt-air interface (Ghasemi and Niakousari, 2020), leading to formation of a spherical shape of yogurt droplet and easily rolling off the coating in the air. So, the yogurt residual rate on the coating was (3.77 ± 1.99) %, which was significantly less than on the uncoated polystyrene sheet (15.12 ± 2.77) % ($p < 0.05$) (Fig. 2 (b)). The yogurt residual rates during storage in control (uncoated) and processed (coated) cups were shown in Fig. 2(c). The yogurt residual rate in the commercial cup was (6.92 ± 0.76) % at initial storage (Fig. 2 (c)). After 21 days storage, the yogurt residual rates of the processed cups were (7.40 ± 0.36) % which was significantly less than the control cups (9.64 ± 0.83) % ($p < 0.05$). The coating fabricated could already cut down the yogurt residual rate compared with the original commercial cup package after a long storage. But it was slightly more than the yogurt residual rate (5%) of the cups which were coated by sunflower oil layer to reduce the sliding resistance via liquid-liquid sliding (Hao et al., 2022). Probably because the carnauba wax was the coating major components including wax acid, wax alcohol and wax ester, which were easy to adsorb protein after a long storage (Song et al., 2021). However, it was well known that protein could act as emulsifier to stabilize oil-in-water system. Thus, there was still a risk for the sunflower oil on the oleogel layer to be emulsified by the yogurt itself, reducing the slide ability. As a result, the coating fabricated with common food stuffs had a potential ability to repellent yogurt in storage.

3.2. Coating microstructure and components

The structure of the hierarchically structured coatings possessed typical micro-nano structure (Fig. 3(b')), compared with the pure substrate (Fig. 3(a')). It was concluded that the special wettability was induced due to the synergistic effects between the constitutes and structures of the coating. As for further affirming the coating constitutes, EDS (Fig. 4), FTIR (Fig. 5(a)) and XRD (Fig. 5(b)) spectrums were all shown. In Fig. 4, it was verified that the elements of the coating included C ((71.86 ± 0.05) %), O ((19.18 ± 0.06) %), Na ((0.76 ± 0.01) %), Si ((8.20 ± 0.02) %), which all uniformly appeared in the coating element mapping (Fig. 4). So, carnauba wax, silica, and CMC mixed and fused together to form the special wettability coating. In Fig. 5(a), the FTIR results of the coating possessed abundant $-CH_3$ and $-CH_2$ group stretching vibrations at wavenumbers of 2920 and 2848 cm^{-1}, and ester group C=O stretching vibrations at 1731 cm^{-1} corresponding to carnauba wax, which provided the carnauba wax with hydrophobic chemical property (Wang et al., 2021a). The absorption bands of the coating at 1613 cm^{-1} could be assigned to carboxyl group C=O symmetric stretching vibration of CMC. The absorption bands of the coating at the wavenumbers of 1080 and 797 cm^{-1} conformed to the Si–*O*–Si antisymmetric stretching vibration peak and Si–O symmetric stretching vibration peak of silica, respectively. Thus, the FTIR spectrums (Fig. 5

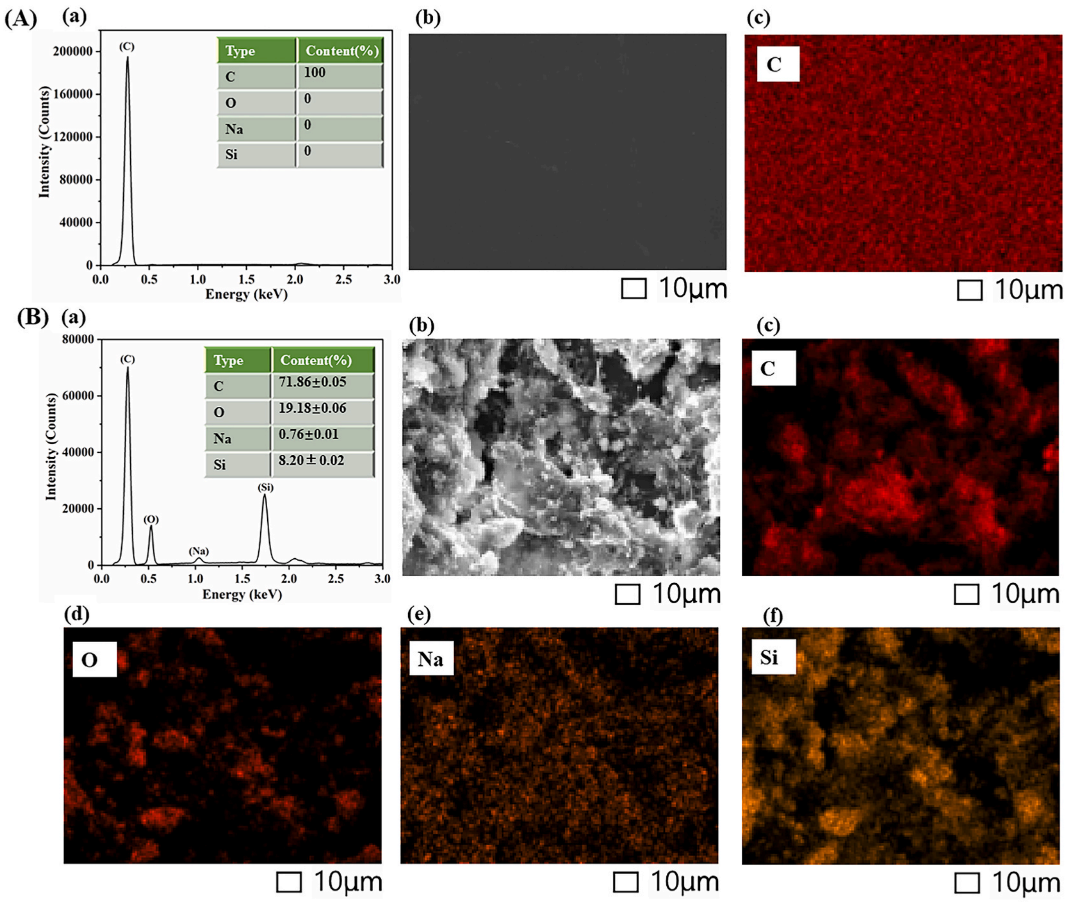

Fig. 4. EDS mapping of the polystyrene sheet (A) and the special wettability coating (B).

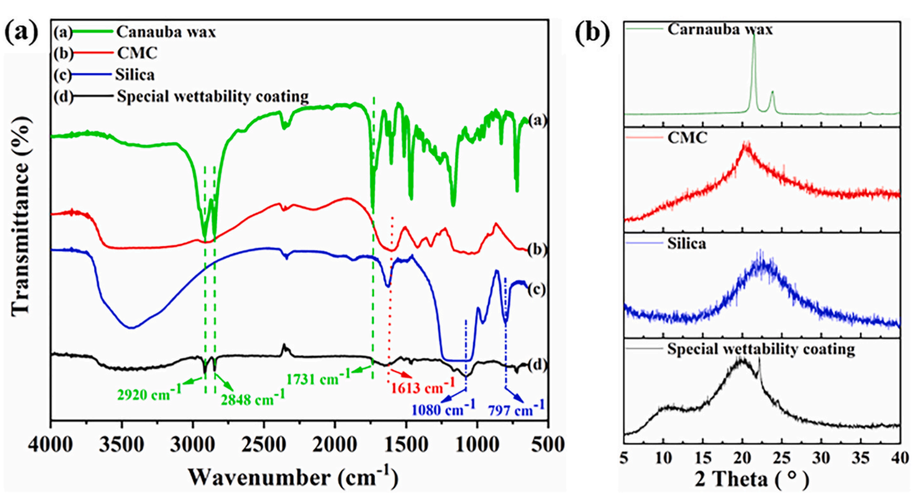

Fig. 5. (a) FTIR of the polystyrene with or without the special wettability coating. (b) XRD of the components and the special wettability coating.

(a)) confirmed the successful presence of carnauba wax, silica, and CMC in the special wettability coating. In Fig. 5(b), the XRD spectrum diagram shown that the coating appeared a peak at nearly 10° because silica and CMC overlapped with each other. The coating should be corresponded to CMC at 20°. While, the peak of the coating could be the crystallization of the silica at 22°. And the coating should be corresponded to the second peak of carnauba wax at 24°. So, the special wettability coating was compactly and integrally formed on the polystyrene sheet according to the element mapping, functional groups analysis, and crystallization results.

3.3. Coating robustness

The acid tolerance of the coating was shown in Fig. 6 (a) and (d). The contact angle of yogurt on the coating decreased significantly from (145.70 ± 3.16) ° at pH1.0 to (135.71 ± 4.08) ° at pH6.0 ($p < 0.05$). While, the yogurt residual rate was respectively (0.00 ± 0.00) % at pH3.0 and (3.93 ± 0.39) % at pH5.0, which located at the general yogurt pH from 3.85 to 4.50 (Aryana and Olson, 2017). The yogurt droplet could already roll with a slide angle (14.58 ± 2.60) ° at pH4 (Table S1). The microstructure of the coating should be reformed by

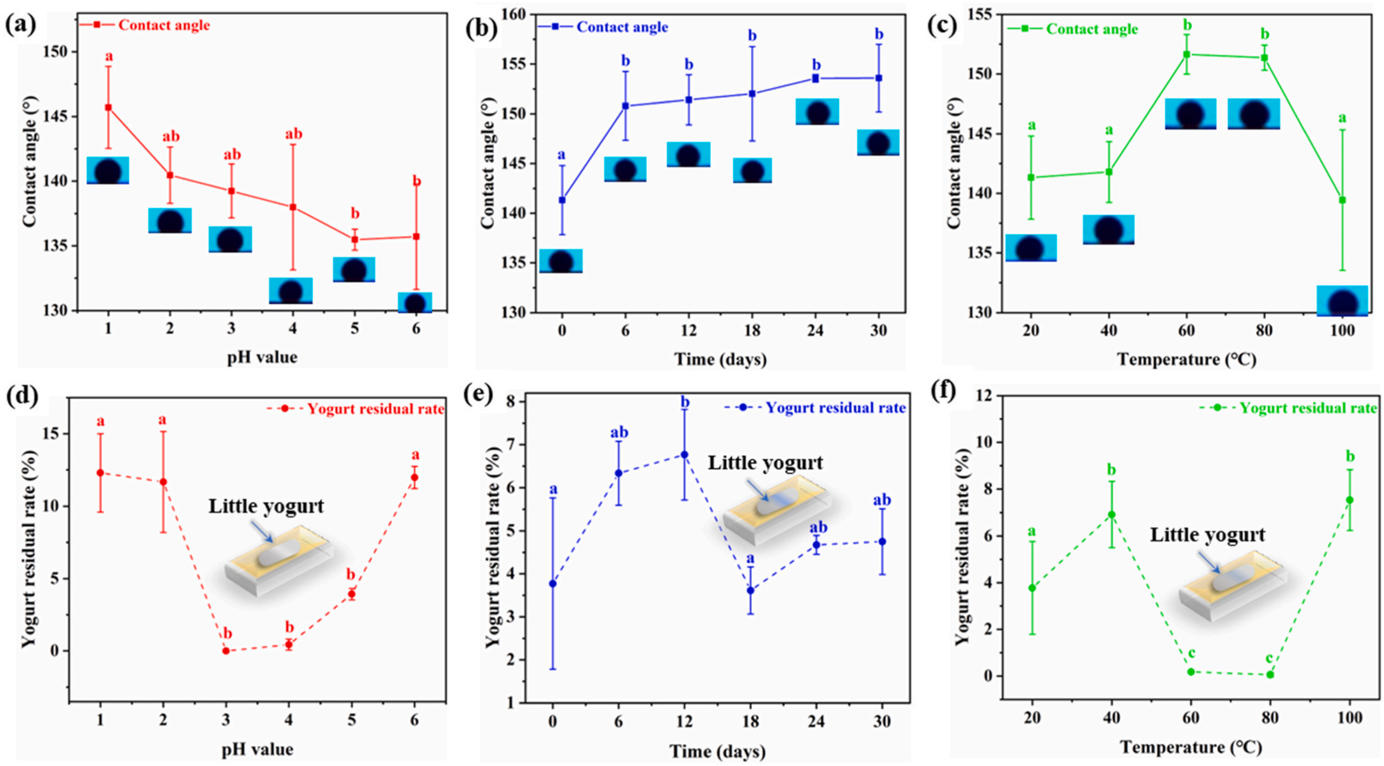

Fig. 6. Contact angle (a) and yogurt residual rate (d) for coating pH stability, contact angle (b) and yogurt residual rate (e) for coating time stability, contact angle (c) and yogurt residual rate (f) for coating temperature stability during robust test on polystyrene sheet. The different lower cases on each subgraph means significant different for the index ($p < 0.05$).

lactic acid at pH3.0 and could repel the yogurt adherence onto the coating. Besides, the carnauba wax possessed chemical reactive groups that could form hydrogen bonds with other coating ingredients to resist an acid environment, leading to strong coating integrity (Wang et al., 2019). The effects of time on the coating were shown in Fig. 6 (b) and (e). With the storage time prolonged, the contact angle of the coating firstly increased to (150.80 ± 3.45) ° at 6 days ($p < 0.05$), and then kept stable ($p > 0.05$). The yogurt residual rate held significantly variation

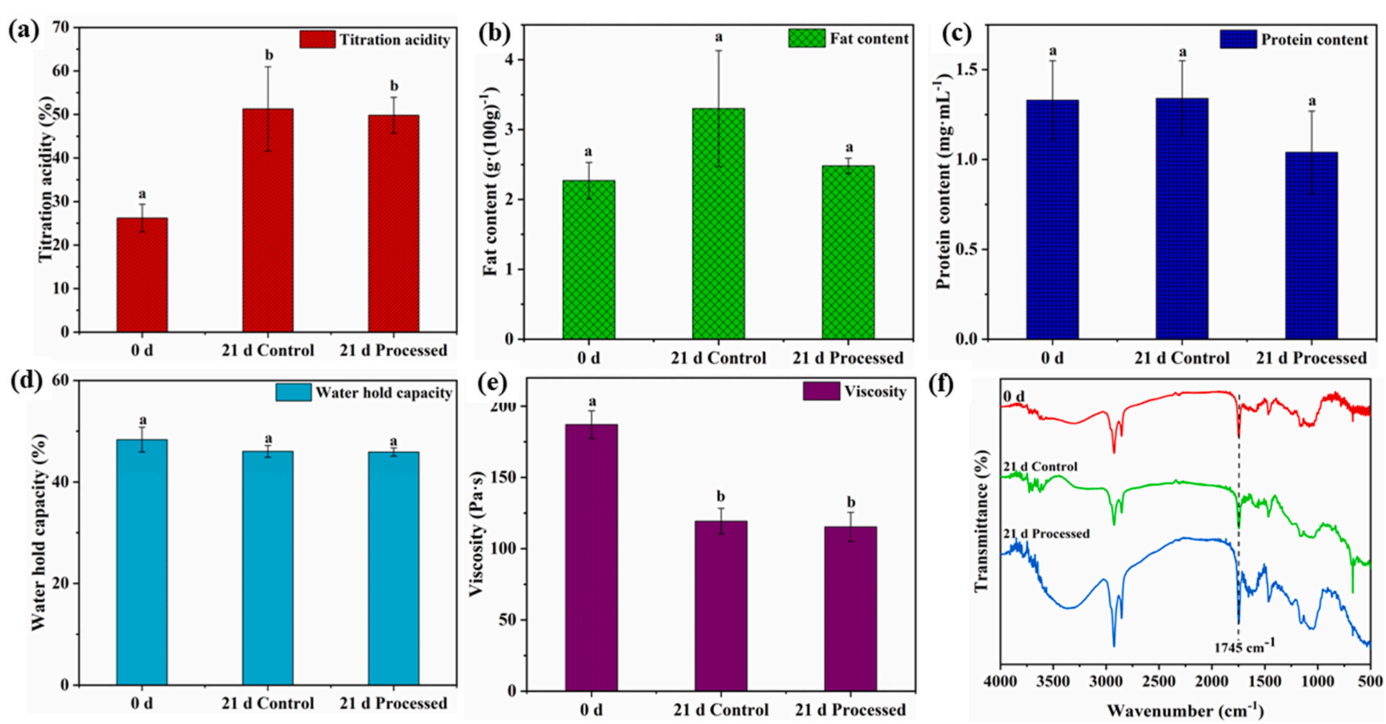

Fig. 7. Titratable acid (a), fat content (b), protein content (c), water hold capacity (d), viscosity (e) and FTIR (f) of yogurt in the cup with or without the special wettability coating at 0 day and 21 days. The different lower cases on each subgraph means significant different for the index ($p < 0.05$).

ranging from (3.77 ± 1.99) % at 0 day to (6.77 ± 1.05) % at 12 days ($p < 0.05$), maintaining relatively stable tendency in the subsequent storage days. As for slide angle, the yogurt almost did not roll (Table S1), probably due to the absorption between the protein and coating. However, it already shown little residual on the coating once the yogurt droplet was large enough to roll easily. The effects of temperature on the coating were shown in Fig. 6 (c) and (f). The contact angle significantly increased from (141.79 ± 2.56) ° to (151.36 ± 1.05) ° ($p < 0.05$) as the temperature increased from 40 °C to 80 °C. Nevertheless, the contact angle notably decreased to (139.43 ± 5.90) ° at 100 °C ($p < 0.05$), since the polystyrene sheets had thermoplastic deformation. As for the yogurt residual rate, it was (0.06 ± 0.10) % at 80 °C, significantly less than the other processed temperature ($p < 0.05$) except 60 °C. Meanwhile, the slide contact of the yogurt on the processed polystyrene sheet with special wettability coating was (13.78 ± 3.37) ° at only 80 °C (Table S1). Probably because the carnauba wax melt at nearly 80 °C and cured again with a phase transition during cooling (Zhang et al., 2014), causing bigger contact angle and less yogurt residual. Generally, the coating could endure the temperatures at which the yogurt was generally stored. It was because that the CMC and carnauba wax could form more hydrogen bonds than only carnauba wax with the polystyrene substrate. Inner the coating itself, the structures became more robustness with the CMC binding action. As a result, the special wettability coating possessed robust properties to resist pH, time and temperature for yogurt package.

3.4. Effects of the coating on yogurt quality index after storage

3.4.1. Titratable acid

The effects of coating on the yogurt titratable acid were shown in Fig. 7(a). The titratable acid of yogurt in the control and processed cups at 21st days were respectively (51.28 ± 9.65) % and (49.83 ± 4.10) % with insignificantly different ($p > 0.05$), and all notably increased than the initial titratable acid (26.22 ± 3.18) % ($p < 0.05$), because of lactic acid accumulation in post-acidification. It could be concluded that there were no effects of the coating on the yogurt titratable acids.

3.4.2. Fat content

The effects of coating on the yogurt fat content were shown in Fig. 7 (b). At initial, the fat content of yogurt was (2.27 ± 0.26) %. At the end of storage, the fatty acid content of control yogurt was (2.88 ± 0.39) %, and the processed yogurt (2.45 ± 0.04) %. It could be shown that the coating had no prominent effects on the fat content of yogurt ($p > 0.05$) (Fig. 7(b)).

3.4.3. Protein content

The effects of coating on the yogurt protein content were shown in Fig. 7(c). At initial, the protein content of yogurt was (1.33 ± 0.22) %. At the end of storage, the protein content of control yogurt was (1.34 ± 0.21) %, and the processed yogurt (1.04 ± 0.23) %. However, the yogurt protein content had no significant difference with each other after storage ($p > 0.05$). It could be shown that the coating had no effects on the protein content of yogurt.

3.4.4. Water hold capacity

The effects of coating on the water hold of yogurt was shown in Fig. 7 (d). At 0 day, the water hold of yogurt was (48.33 ± 2.44) %. After 21 days storage, the water hold of the control and processed yogurt were respectively (46.01 ± 1.18) % and (45.89 ± 0.80) %, without significant different ($p > 0.05$). The yogurt water hold capacity were lower than the study (62.86%) of Ding et al. (2022), due to the different centrifugal force. Thus, the coating had no effects on the water hold capacity of yogurt.

3.4.5. Viscosity

The effects of coating on yogurt viscosity were shown in Fig. 7(e). At initial, the yogurt viscosity was (187.17 ± 9.71) Pa·s. While at the end of storage, the viscosity of the control yogurt was (119.32 ± 9.03) Pa·s, and the processed yogurt (115.30 ± 10.24) Pa·s, without significantly different ($p > 0.05$). It appeared that the viscosity decreased dramatically at end, but the coating had no effects on the yogurt viscosity.

Table 1
Viscosity, contact angle and residual rate of 15 species of yogurt on the special wettability coating fabricated onto the polystyrene sheet.

Yogurt code	Viscosity (Pa•s)	Contact angle (°)	Residual rate (%)	Yogurt names
a	95.19 ± 4.78	140.66 ± 1.64	8.21 ± 0.98	Aochun Youlaoru
b	96.99 ± 14.79	143.80 ± 0.45	9.09 ± 2.20	Mengniu Guanyiru
c	116.88 ± 12.93	137.60 ± 1.17	11.39 ± 2.58	Jincai Flavor Yogurt
d	134.90 ± 2.37	146.37 ± 3.26	9.71 ± 0.97	Yili 25% Calcium
e	137.50 ± 7.46	138.62 ± 0.83	7.72 ± 1.34	Mengchun Yiqiniu
f	158.86 ± 6.47	136.90 ± 1.32	12.03 ± 1.58	Langege Mengshibinglao
g	164.94 ± 3.63	150.96 ± 1.52	9.91 ± 0.96	Xinxiwang Muchang
h	167.52 ± 21.22	154.88 ± 1.37	9.72 ± 1.31	Guangze Flavor Yogurt
i	230.31 ± 5.39	150.42 ± 1.80	9.39 ± 0.58	Yili Changqing
j	254.82 ± 10.94	163.76 ± 4.86	15.28 ± 3.56	Junlebao Jianchun
k	257.91 ± 24.63	169.65 ± 7.45	6.62 ± 0.74	Mengniu no sucrose
l	277.10 ± 13.57	151.17 ± 0.29	9.67 ± 1.16	Wandashan 0% sucrose
m	295.02 ± 20.48	141.32 ± 3.48	3.77 ± 1.99	Yili Natural Yogurt
n	385.73 ± 12.72	177.45 ± 1.66	9.33 ± 1.97	Mengniu Chunzhen
o	801.85 ± 65.45	175.56 ± 8.23	10.47 ± 0.87	Yili Anmuxi

3.4.6. Release ability of the coating components into yogurt

The yogurt FTIR image in the control and processed cups was shown in Fig. 7(f). To further explore the release of the carnauba wax, silica and CMC into the yogurt or not, the FTIR spectra of yogurt sample shown characteristic stretch vibration peaks at 1745 cm^{-1} which means the specific flavor substance acetaldehyde. There was no characteristic absorption of functional group of carnauba wax, silica and CMC after the yogurt fully held in the processed cups for 21 days. Furthermore, the FTIR spectrums of the yogurt at 0 days, 21 days control, and 21 processed shown the same tendency. Therefore, the release of the carnauba wax, silica and CMC of the coating did not occur in the yogurt. It could satisfy long-term leaching behavior of the coating in practically yogurt storage (Ruzi et al., 2022).

3.5. Broad feasibility of the coating in other yogurts

The yogurt viscosity, contact angle and residual rate on the coating were listed in Table 1. In Table 1, it could be seen that the viscosity of 15 species yogurts ranged from (95.19 ± 4.78) Pa·s to (801.85 ± 65.45) Pa·s, contact angles from (136.90 ± 1.32) ° to (177.45 ± 1.66) °, and yogurt residual from (3.77 ± 1.99) % to (15.28 ± 3.56) %. For example, the Yili Anmuxi yogurt had the largest viscosity (801.85 ± 65.45) Pa·s, the Mengniu Chunzhen possessed the largest contact angle (177.45 ± 1.66) °, and the Junlebao Jianchun yogurt had the maximal residual rate (15.28 ± 3.56) %. It was revealed that the residual rate of 11 species of common yogurt could be less than 10% on the coating (Table 1). So, the coating had a broad feasibility in other yogurts. For exploring the relationship between viscosity, contact angle and yogurt residual rate on the

Table 2
Pearson's comparison results of viscosity, contact angle and residual rate of 15 species of yogurt on the special wettability coating fabricated onto the polystyrene sheet. ** means $p < 0.01$.

	Viscosity (Pa•s)	Contact angle (°)	Residual rate (%)
Viscosity (Pa•s)	1.000	0.701**	0.025
Contact angle (°)		1.000	0.100
Residual rate (%)			1.000

coating, a Pearson's comparison was performed (Table 2). The viscosity and the contact angle had a positive correlation ($R = 0.701$, $p < 0.01$). However, the yogurt residual rate was not entirely determined by viscosity, probably because the coating could eliminate the viscosity effects on the residual rate. At the same time, the yogurt residual rate was also not significantly correlated with the contact angle, maybe due to the complex components of the yogurt, especially high protein content, could pin the yogurt drop onto the coating.

4. Conclusion

An edible special wettability coating consisting of carnauba wax, silica and CMC was fabricated via spraying on the polystyrene substrate to restrain the yogurt adherence. The special wettability coating had typical micro-nano structure and could tolerate the acid environment, long time storage, and high temperature, which was suitable for yogurt storage in a coated cup package. The quality index of yogurt could not be influenced when stored in the processed cup. What's more, the relationship between viscosity and contact angle of yogurt was revealed to understand the effects of yogurt drop property on the contact angle, which disclosed another influence factor from the liquid property, rather than only from the coating itself. At the same time, it was desired how the polar substance in yogurt affected the coating wettability. Totally, it was provided a basis for fabricating the special wettability coating on the package surface to eliminating the waste of sticky fluid foods based on surface wettability theory.

Funding

This work was supported by the 65th Postdoctoral Science Foundation of China [grant number 2019M651212], the Climbing Project of Changchun University [grant number zkp202029/2020JBD26L45], the ChunLei Project of Changchun University [grant number zkc201909/2019JBC26L35].

Credit author statement

Jumin Hou are responsible for manuscript written, statistic data and figures plotting. Shuqiu Liu and Mengqi Su are responsible for designing and performing the trial. Yuyan Fan are responsible for plotting the figures. The corresponding authors Yan Liu and Xiaoxia Yan are responsible for ensuring that the descriptions are accurate and agreed by all authors.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

I have uploaded the data and .R file as supplementary materials.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jfoodeng.2022.111255.

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