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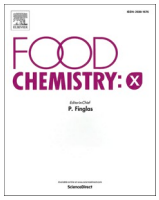

Effects of modification methods on the structural characteristics and functional properties of dietary fiber from cucumber

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ABSTRACT

Cucumbers produce by-products such as cucumber pomace during processing and most of them are discarded without being utilized. To effectively utilize the waste, cucumber pomace is used to extract both insoluble and soluble dietary fibers (DFs) using compound enzyme method (ME), High pressure processing assisted ME (HPP-ME), and dynamic high-pressure microfluidization-assisted ME (DHPM-ME). The results showed that DHPM-ME improved the extraction rate of soluble DFs most effectively, increasing it from 1.74 % to 4.08 %. The modified DFs exhibited enhanced hydration properties and functional properties after HPP-ME- and DHPM-ME-mediated auxiliary treatment. Additionally, the modified DFs exhibited improved thermal stability, increased absorption peaks in the infrared spectra, decreased crystallinity, improved glucose and cholesterol adsorption ability, and delayed glucose adsorption. The cucumber pomace-derived modified DFs can be used as a functional food additive in bakery, meat, dairy products, and beverages, and their effective use can further enhance the economic benefits.

1. Introduction

Cucumber (*Cucumis sativus* L.) is an annual climber belonging to the genus *Cucumis* in the family Cucurbitaceae (Min, Song, Lim, Yi, & Jin Lee, 2023). Cucumber is rich in nutrients (Alam & Albalawi, 2024), such as protein, calcium, phosphorus, iron, potassium, carotene, vitamin B2, vitamin C, vitamin E, and niacin. Cucumber has low calories, can lower blood sugar, and presents a broad market prospect and development potential. Presently, very few cucumber products are present in the market, mainly including pickled cucumber and cucumber juice concentrate. The production process of cucumber juice produces many by-products, such as cucumber pomace, which are used as feed, sold at low prices, or directly discarded, causing environmental pollution (Karim, Raji, Habibi, & Khalloufi, 2023). At present, the plant that is processing cucumber juice is processing 10,000 Kg of cucumber per hour, the proportion of cucumber pomace is 7 %, and the production is 20 h per day, which produces 14,000 Kg of cucumber pomace per day. At the same time, cucumber pomace is rich in dietary fiber, therefore, enhancing the processing and utilization of cucumber dietary fibers (DFs) can improve the added value of cucumber, presenting better ecological and economic benefits.

DFs primarily consist of carbohydrate polymers in plant cell walls and are classified into soluble dietary fiber (SDF) and insoluble dietary fiber (IDF) (Bhatt, Kumari, & Gupta, 2023). SDF is soluble in warm or hot water, and its main components are pectic compounds, mucilage and gum (Soleimanian, Sanou, Turgeon, Canizares, & Khalloufi, 2022); IDF is insoluble in warm or hot water, and its main components include cellulose, hemicellulose, and lignin (L. Huang et al., 2018). Both cannot be digested and absorbed by the human body, but they improve the intestinal environment (Y. L. Huang & Ma, 2016) and reduce blood sugar and lipids, exhibiting a certain positive effect. Additionally, proper DF intake in the daily diet is beneficial in reducing the chances of obesity. Therefore, people are focusing on DF intake in their daily lives, such as eating more coarse grains and whole grain nutritious rice, to retain more fiber nutrients in food and promote health.

SDF has better blood glucose adjustment ability compared with IDF, hence using the SDF content as an important indicator for evaluating DF quality, and the higher its content, the better the physiological efficacy

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Various raw materials have been modified to increase the SDF content in DFs. The main DF modification methods include the enzyme method (ME), ultra-micro pulverization, high pressure processing (HPP), and extrusion puffing (Goly Fayaz, Soleimanian, Mhamadi, Turgeon, & Khalloufi, 2022). ME utilizes IDF-degrading enzymes to promote partial IDF degradation and increase the SDF proportion (C. Wang et al., 2020). High-pressure processing (HPP) is a novel method in the field of DF modification, which uses a liquid medium or a gaseous medium to modify materials at a certain temperature and pressure (100–1000 MPa), improving the structural and functional properties of DF when applied to them. The dynamic high-pressure microfluidization (DHPM) technology is a highly efficient and low-time-consuming method of physical modification. DHPM modifies the material under high pressure utilizing the homogeneous cavity with a special structure, high-speed shear formation, convection collision, cavity effect, and other physical effects, to facilitate bond breakage in the macromolecule material and particle refinement (Calligaris, Foschia, Bartolomeoli, Maifreni, & Manzocco, 2012), simultaneously making the surface structure loose and enhancing the properties of the material, such as a higher water-holding capacity (WHC) and interfacial stability.

In this paper, dietary fiber was prepared from cucumber pomace as raw material, and the effects of ME, HPP-ME, and DHPM-ME on the structural and functional properties of cucumber dietary fiber samples were investigated; and the in vitro lipid-lowering activity of cucumber dietary fiber was elucidated through in vitro simulation experiments. This study not only provides a theoretical basis for the modification of cucumber dietary fiber but also is of great significance for the utilization of the by-products generated during the processing of cucumber.

2. Materials and methods

2.1. Materials and chemicals

Cucumbers were purchased from a local farmer's market (Tianjin, China). Glucose, cholesterol standard, α-amylase, protease, and glycolytic enzymes were purchased from Shanghai Yuanye Biotechnology Co., Ltd. (Shanghai, China). Ethanol, acetone, acetic acid, o-phthalaldehyde, concentrated sulfuric acid, 3,5-dinitrosalicylic acid (DNS), phenol, and other analytical reagents were purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China).

2.2. Cucumber DF processing technology

Cucumbers were washed, cut into pieces, pulped, and juiced to obtain the cucumber residue, which was then dried and ultra-finely powdered using a high-speed pulverizer (Tianjin Taisite Instrument Co., Ltd., Tianjin, China). Next, the samples were aliquoted into four portions as follows: (i) Control, (ii) ME, (iii) HPP-ME, and (iv) DHPM-ME. The laboratory pre-tested and determined that the optimal ratio of cucumber powder to water was 1:20. If the proportion of water increases, the subsequent dehydration experiment causes energy waste; if the proportion of water decreases and the material is sticky, which is easy to cause clogging of the pipeline of the DHPM machine, affecting the efficiency of the work, or even unable to work.

The cucumber pomace powder obtained from the HPP-ME group was added to distilled water at a ratio of 1:20 and mixed evenly in a vacuum bag. Following this, the bag was sealed after eliminating the air from the inside and placed into the HPP machine (HPPL2-800/2.5, Tianjin Huatai Bioengineering Technology Co., Ltd., Tianjin, China). The samples were processed for 15 min at 25 °C and under 400 MPa, following which they were then removed and centrifuging (4000*g*, 15 min), the precipitate was collected and dried and pulverized at 50 °C.

The cucumber pomace powder obtained from the DHPM-ME group was added to distilled water at a ratio of 1:20. To prevent blockage, the DHPM machine (ZH600-THW18, Wenzhou Binyi Technology Machinery, Wenzhou, China) pressure is set to 100 MPa. Slowly increase the pressure until it reaches 400 MPa and then processed twice. The sample was then removed and centrifuging (4000*g*, 15 min), the precipitate was collected and dried and pulverized at 50 °C.

Following a previous method (C. Tang, Wu, Zhang, Kan, & Zheng, 2022) with slight modifications, the three modified groups of cucumber pomace powder were mixed with phosphate buffer at a ratio of 1:25 in a beaker, and heat-stabilized α-amylase (40,000 u/g) was added at a ratio of 1:50 (g: μg). The mixture was stirred in a water bath at 95 °C for 30 min and then cooled to 60 °C. Alkaline protease (200 u/mg) was added at a ratio of 1:100 (g:μL), followed by stirring in a water bath at 60 °C for 30 min. Next, the pH was adjusted to 4.5, and saccharase (10,000 u/g) was added at a ratio of 1:100 (g:μg), followed by a 30-min incubation at 60 °C in a water bath. No enzymes were added to the control group, and the rest of the process was the same as the treatment of modified cucumber pomace powder. After mixing in the water bath and centrifugating (8000*g*, 15 min), the residue was washed twice with deionized water and the filtrate was collected, which was mixed with the supernatant after centrifugation. The supernatant was evaporated to 1/4th of the original volume using a rotary evaporator at 50 °C. After cooling to 25 °C, a 12-h precipitation was performed by adding 95 % ethanol at a ratio of 1:4 (v:v), and the precipitate was collected and dried to constant weight to obtain cucumber SDF. Following the centrifugation, the precipitate was washed twice with 78 % ethanol, 95 % ethanol, and acetone sequentially and dried to constant weight to obtain cucumber IDF.

2.3. Determination of water-holding capacity (WHC) and oil-holding capacity (OHC) of DFs

The WHC and OHC of DF samples were determined following a previous method (Xue et al., 2019), with slight modifications. DF (0.2 g) was placed in a 10-mL centrifuge tube and after adding 10 mL of distilled water or 5 mL of soybean oil, the tube was left to stand at room temperature for 24 h or 1 h, respectively. Following the centrifugation (5000*g* , 15 min), the supernatant was removed and weighted, and the WHC and OHC were calculated by Eq. (1) and Eq. (2):

- $$\mathrm{WHC}\ (\mathrm{g/g}) = \frac{M_2 - M_1 - M}{M} \quad (1)$$

- $$\mathrm{OHC}\ (\mathrm{g/g}) = \frac{M_2 - M_1 - M}{M} \quad (2)$$

where M is the weight of the sample (g); M_1 is the weight of the empty centrifuge tube (g); M_2 is the total weight of the wet sample and the centrifuge tube with the supernatant removed (g).

2.4. Determination of swelling capacity (SC)

The SC of DF samples was determined following a previous method (J. G. Zhang et al., 2024), with slight modifications. DF (0.2 g) was added to a 10-mL measuring cylinder, the volume was recorded, distilled water (5 mL) was added to remove air bubbles, and the sample was allowed to stand at room temperature for 24 h. The volume was recorded again, and the expansion rate was calculated per Eq. (3):

- $$\mathrm{SC}\ (\mathrm{mL/g}) = \frac{V_2 - V_1}{M} \quad (3)$$

where M is the mass of the sample (g); V_1 is the volume of the dry sample (mL); V_2 is the volume of the sample after water absorption (mL).

2.5. Scanning electron microscopy (SEM) analysis

The solid surfaces of DF samples were observed through SEM (S-3500 N, Hitachi, Japan). The DF sample powder was adhered to a specimen holder with double-sided adhesive carbon tape for gold spraying, and SEM was performed with an accelerating voltage of 5 kV.

2.6. Fourier transform infrared (FT-IR) spectroscopy analysis

Approximately 3 mg of DF samples were ground together with KBr samples (1:100) and then pressed into thin flakes (Z. Zhang et al., 2023). FT-IR spectra (scanning wavelength of 4000–400 cm^{-1} with a resolution of 4 cm^{-1}) were determined using an FT-IR spectrometer (LUMO, Bruker, Germany).

2.7. Differential scanning calorimetric (DSC) analysis

Following a previous method (Xiong et al., 2023) with slight modifications, The instrument was calibrated before experimenting. The calibration was mainly done by calibrating the temperature and heat flow using the standards In and Zn so that the measured values were consistent with the standard values. Approximately 2.0–5.0 mg of DF samples were weighed, sealed with an aluminum cap, and placed into the sample holder of a differential scanning calorimeter, with a sealed empty aluminum box as the reference, and subjected to DSC analysis. The heating rate was 10 °C/min, the temperature measurement range was 0–300 °C, and the rate of nitrogen gas introduction was 30 mL/min.

2.8. X-ray diffraction (XRD) analysis

DF samples were analyzed using an X-ray single crystal diffractometer (Xtal ABmini, Riqaku, Japan), as per a previous method (Kanwar, Yadav, & Yadav, 2023) with slight modifications. The operating voltage was 40 kV, the scanning angle 2θ was 5–60°, and the scanning rate was 2°/min. The crystallinity of the samples was calculated using the area ratio method.

2.9. Contact angle measurement

The contact angle of DF samples were measured using the droplet shape analyzer (DSA100, Kreuss, Germany).

2.10. Determination of hypolipidemic activity in vitro

2.10.1. Determination of glucose adsorption capacity (GAC)

Following a previous method (Shang, Zhang, Dang, & Gao, 2023) with slight modifications, 1 g of DF was added to 100 mL of glucose solution (50 mmol/L), mixed well, and subjected to a water bath at 37 °C for 6 h. Following this, centrifugation was performed at 4000*g* for 15 min. 1 mL of supernatant and 2 mL of DNS reagent were added to a 15 mL test tube and then heated in boiling water for 2 min. After cooling, filled the water to a 15 mlL scale, and measured the absorbance at 540 nm. Glucose solutions of different mass concentrations (0–1 mg/mL) were prepared, and the standard curve equation ($y = 0.5699\times$-0.0131, $R = 0.9981$) was obtained by using glucose concentration as the horizontal coordinate and absorbance as the vertical coordinate concerning the sample method. The change in glucose concentration in the sugar solution before and after adsorption was calculated according to the glucose standard curve, and the GAC was calculated per Eq. (4):

$$GAC = \frac{(C_2 - C_1) \times V}{M} \quad (4)$$

where M is the sample mass (1 g); C_1 is the glucose concentration in the system before DF adsorption (mg/mL); C_2 is the concentration of glucose in the system after DF adsorption (mg/mL); V is the volume of glucose solution (mL).

2.10.2. Glucose dialysis retardation index (GDRI)

Following a previous method (Daou & Zhang, 2012) with slight modifications, 0.5 g of DF was weighed and mixed with 15 mL of 100 mmol/L glucose solution and continuously stirred for 1 h. Following this, the solution was transferred into a 20-cm-long dialysis bag (Mw = 1000), with 15 mL of 100 mmol/L glucose as a reference. These dialysis bags were placed into a beaker containing 200 mL of deionized water, and the glucose content in the dialysate was determined at 30 min and 60 min, respectively, in a 37 °C constant temperature shocked water bath for 1 h. GDRI was calculated per Eq. (5):

$$GDRI\ (\%) = \left(1 - \frac{A}{A_0}\right) \times 100\% \quad (5)$$

where A is the amount of glucose dialyzed in the sample cup (mg/mL); A_0 is the amount of glucose dialyzed in the control cup (mg/mL).

2.10.3. Determination of cholesterol adsorption capacity (CAC)

The cholesterol standard curve was plotted following a previous method (Wu et al., 2024) with slight modifications. The commercially available egg yolk was diluted nine times with deionized water and mixed using a magnetic stirrer at 100 r/min for 10 min. After the yolk solution was sufficiently diluted and homogenized, the sample (50 mg) was added to a 200-mL beaker with 15 mL of stirred yolk solution, and the pH was adjusted to 2 and 7 to simulate the gastric and intestinal environments. After stirring at 37 °C for 2 h, centrifugation was performed at 8000*g* for 15 min, and 400 μL of supernatant was taken in a 50-mL colorimetric tube, supplemented with 1.5 mL of o-phthalaldehyde reagent and 1 mL of concentrated sulfuric acid, vortex-mixed, and then placed at room temperature for 10 min to develop the color. Finally, the absorbance was detected using an ultraviolet spectrophotometer (U-5100, Hitachi, Janpan) at OD540. The cholesterol concentration was derived from the cholesterol standard curve, and the CAC was calculated per Eq. (6):

$$CAC\ (mg/g) = \frac{M_2 - M_1}{M} \quad (6)$$

where M_1 is the cholesterol content after adsorption (mg); M_2 is the cholesterol content before adsorption (mg); M is the DF mass (g).

2.11. Statistical analysis

Data were plotted and analyzed by ANOVA using Origin 2021 and SPSS 27.0 software, and the experimental results were expressed as mean ± standard deviation, with different lowercase letters representing significant differences ($P < 0.05$). All experiments were repeated three times.

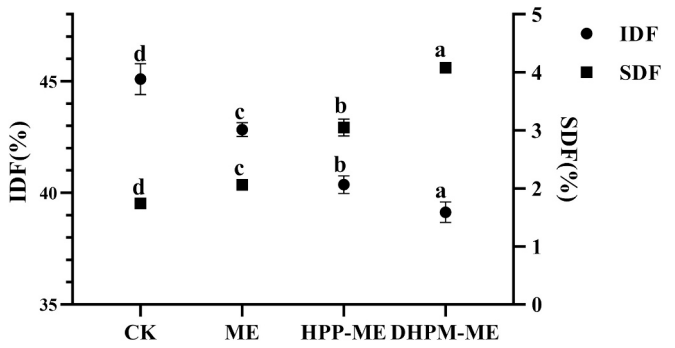

Fig. 2. Effect of different modification treatments on the extraction rate of IDF and SDF from cucumbers. Different letters in the figure indicate significant differences between the samples ($p < 0.05$).

3. Results and discussion

3.1. Analysis of the extraction rate of cucumber DFs

The extraction rate of SDF was significantly improved ($p < 0.05$) after the three modification treatments (Fig. 2), with the magnitude of DHPM-ME > HPP-ME > ME. The extraction of cucumber-derived SDF was increased by 0.31 %, 1.30 %, and 2.33 % after the modified treatments in the ME, HPP-ME, and DHPM-ME groups, respectively. This may be because the enzymatic modification degrades the cellulose and hemicellulose in the cucumber pomace powder. In addition, enzymatic digestion can break the glycosidic bonds in cucumber pomace powder, degrading IDF macromolecules, and releasing soluble small molecules (X. Zhao & Dong, 2016). HPP treatment causes the breakdown of the glycosidic bonds of dietary fiber to cause the dissolution of insoluble dietary fiber, which leads to the redistribution of dietary fiber from non-soluble to soluble fiber components. Appropriate treatment with DHPM technology possibly increased cleavage of the molecular structure in the cucumber pomace powder, resulting in the exposure of hydrophilic groups, which enhanced the increase in SDF. (See Fig. 1.)

3.2. Analysis of OHC, WHC, and SC

Fig. 3 shows that all three modification treatments significantly increased ($P < 0.05$) the OHC, WHC, and SC of cucumber IDF and SDF, the magnitude of which was characterized by the order DHPM-ME > HPP-ME > ME. DHPM-ME treatment increased OHC by 102.14 % ($p < 0.05$), WHC by 114.55 % ($p < 0.05$), and SC by 61.51 % ($p < 0.05$) in IDF when compared to that in CK. SDF showed 64.99 % ($p < 0.05$) higher OHC, 39.89 % ($p < 0.05$) higher WHC, and 64.55 % ($p < 0.05$) higher SC compared to CK, this may be because enzymatic modification breaks the glycosidic bonds of cucumber IDF and SDF, which makes the fiber structure relatively loose, thereby providing more storage space for water molecules or oil molecules. The main reason why HPP-ME treatment further improved the WHC, OHC and SC of cucumber IDF and SDF may be that HPP treatment destroyed the fiber structure. Tructural disruption causes the exposure of more hydrophilic groups. Therefore, the hydrogen bond network formed by water molecules on the particle surface was stronger to accommodate the fiber particles, enhancing the hydrophilic interaction and weakening the hydrophobic interactions between the molecules (Jiang et al., 2024). The increase in OHC may be due to structural rupture leading to the exposure of a large number of lipophilic sites. DHPM treatment of cucumber pomace powder, after a strong shear, dispersion, and impact effect, effectively reduced the force between the molecules of DF, so as to further destroy the structure and increase the specific surface area, so that its water and characteristics were significantly improved. WHC, OHC, and SC are important indicators of the physiological functions of DF, and the stronger water and other properties help enhance satiety and promote gastrointestinal motility. Therefore, the physiological functions of IDF and SDF of cucumbers were enhanced to some extent after the modification treatment.

3.3. Analysis of SEM

The cucumber CK-IDF presented a striped helical structure, typical of fibrous structures, and some lumpy material attached to the surface, presumably residual protein (Fig. 4[A–D]). Following the enzymatic treatment of IDF, the helical structure of the fibers was destroyed, presenting irregular strip and sheet structures and relatively smooth surfaces. The structures of the IDFs, which were further processed by the HPP and DHPM technology, became looser, forming an irregular lamellar structure with a rough surface and numerous folds. This loose structure facilitates the adsorption of small molecular particles such as water and glucose on IDF (Xia, Gu, Liu, Niu, & Yu, 2018), exhibiting advantages regarding hydration properties compared with that in SDFs, resulting in a higher WHC, OHC, and SC. SDFs presented an irregular blocky spherical structure (Fig. 4[a–d]). The SDF modified by the ME has a relatively smooth surface and a more loose structure. It is possible that the enzymatic digestion disrupts the glycosidic and hydrogen bonds of SDF, leading to a looser structure and exposure of more hydrophilic groups(Yang et al., 2024). The HPP treatment further breaks up the SDF structure and makes the SDF surface relatively rough, increasing its specific surface area. The shear force because of the DHPM technology reduced the particle size of SDFs, resulting in a rough particle surface and an uneven porous structure (Fig. 4d), which exposes more hydrophilic and lipophilic groups. This may be one of the reasons underlying the better physicochemical properties of modified SDF.

3.4. FT-IR analysis

The FT-IR spectra of IDF and SDF before and after modification were similar, and only the intensities of the absorption peaks were different. The absorption peaks at 3373 cm^{-1} (Fig. 5A) and 3344 cm^{-1} (Fig. 5B) are caused by the O—H stretching vibrations of cellulose and hemicellulose (Li, Wang, Yuan, Pan, & Chen, 2017). Herein, both HPP and

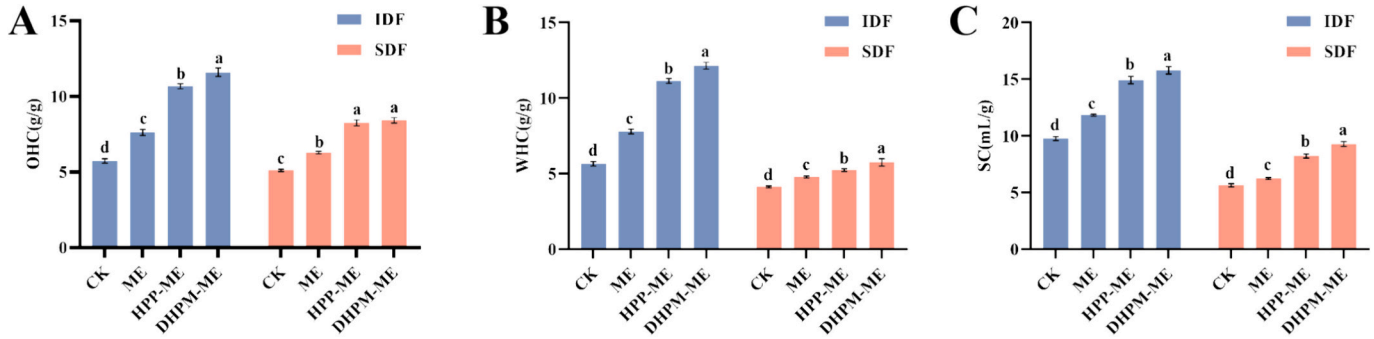

Fig. 3. Effect of different modification treatments on OHC(A), WHC(B), and SC(*C*)of dietary fiber from cucumbers.

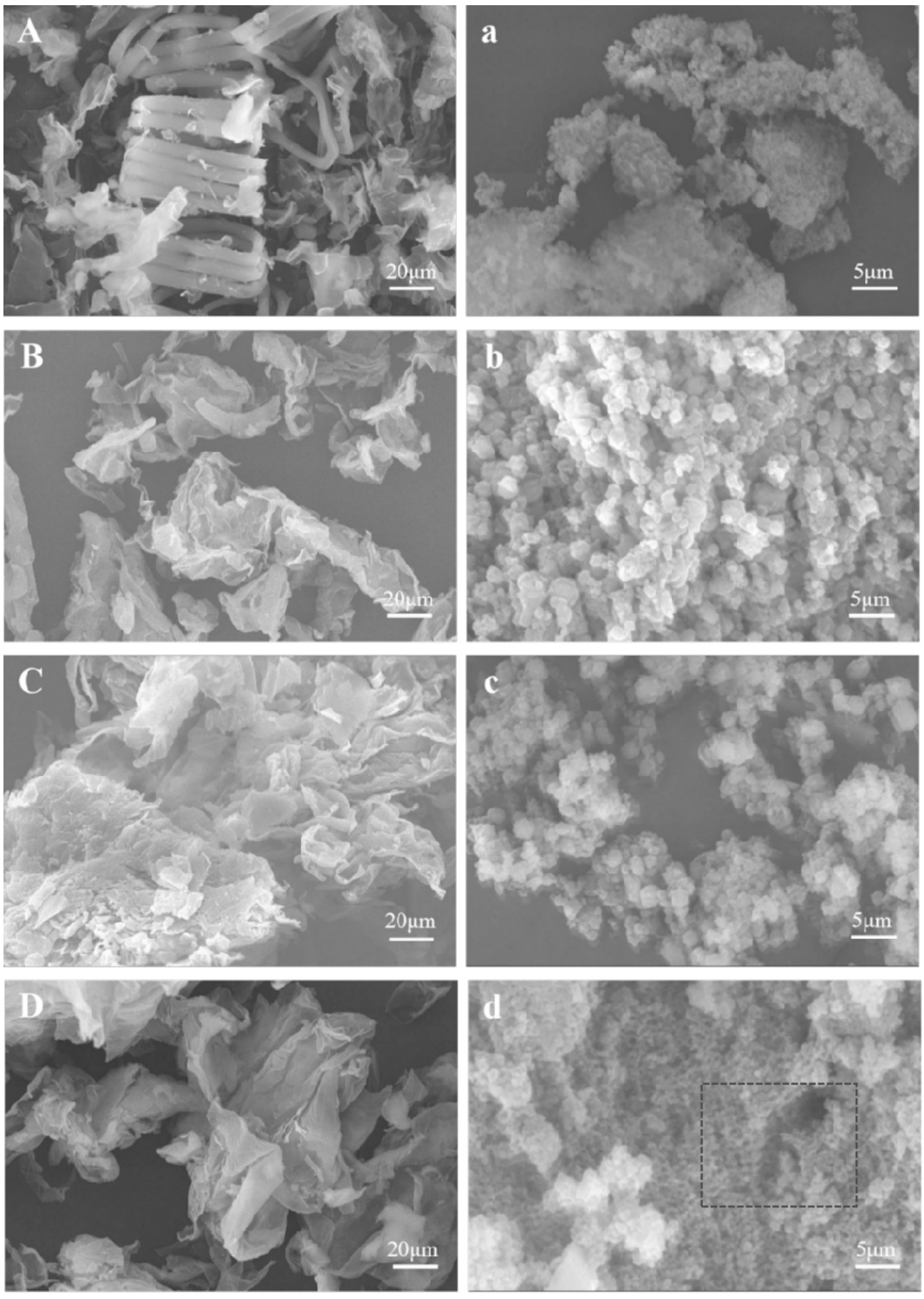

Fig. 4. SEM images of DF with different modification treatments. A, B, C, and D represent the control sample, ME, HPP-ME, and DHPM-ME samples of IDF; a, b, c, and d represent the control sample, ME, HPP-ME, and DHPM-ME samples of SDF, respectively. A–D images are at 2500× magnification, and a–d images are at 10,000× magnification.

DHPM treatments considerably increased the intensities of the absorption peaks, probably because under physical pressurization and shear, hydrogen bonds between cellulose break, leading to the formation of a rough folded structure on the DF surface, exposing many hydroxyl groups, and thus, increasing WHC, OHC, and SC (Moczkowska, Karp, Niu, & Kurek, 2019). The absorption peaks at 889 cm^{-1} (Fig. 5A) and 879 cm^{-1} (Fig. 5B) are contraction vibrations caused by β-glycosidic bonds in DFs (H. o. Wang et al., 2019); therefore, both IDF and SDF exhibited infrared absorption spectral characteristics of polysaccharides. The absorption peaks at 1609 cm^{-1} (Fig. 5A) and 1640 cm^{-1} (Fig. 5B) represent the stretching vibration of C═O, which is the characteristic absorption peak of hemicellulose; the peaks at 1033 cm^{-1} and 1092 cm^{-1} may be caused by the stretching vibration of C—O—C in cellulose and hemicellulose (Zheng & Li, 2018). The characteristic

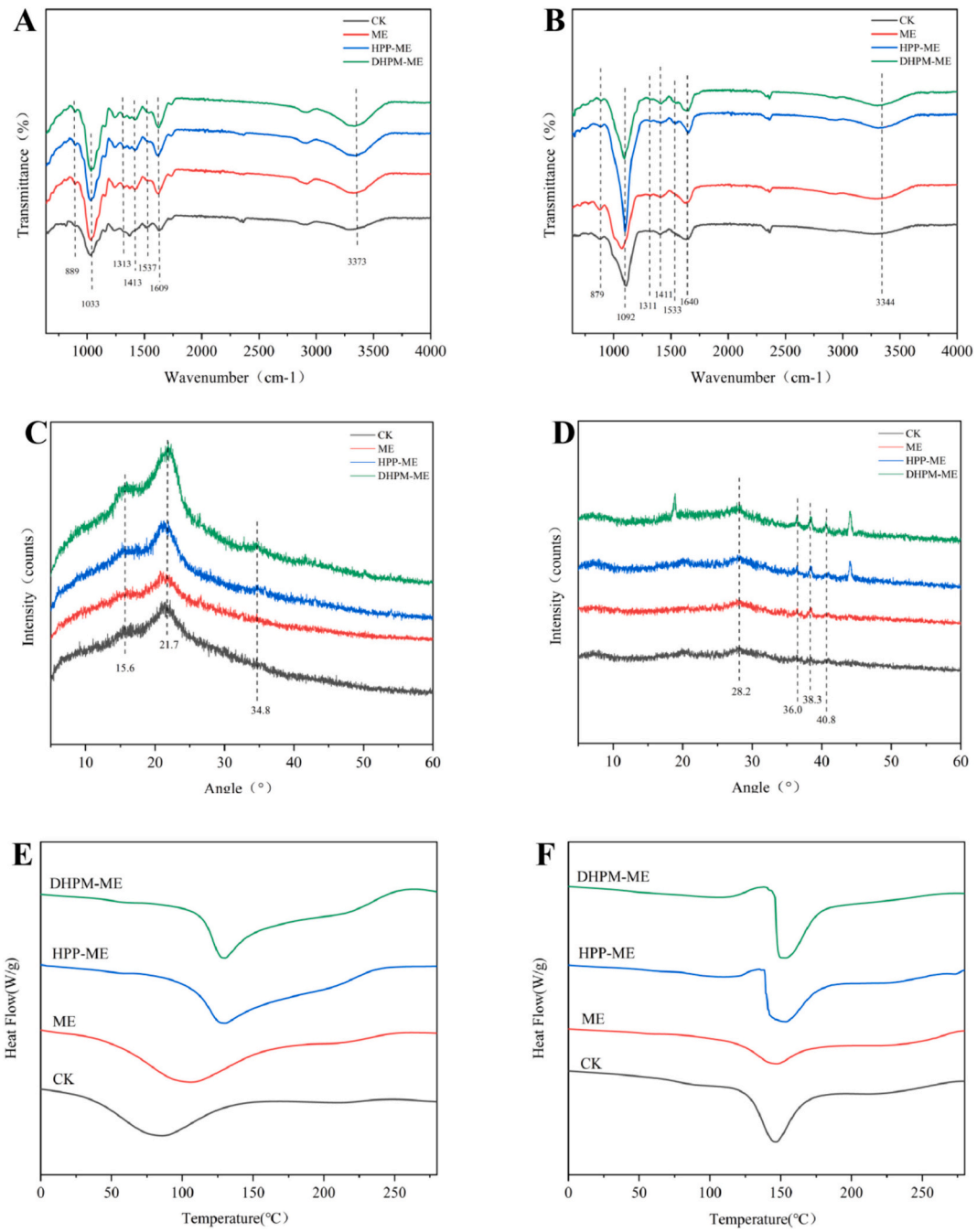

Fig. 5. FT-IR spectras for IDFs (A) and SDFs (B); X-ray diffraction diagrams for IDFs (C), SDFs (D); Thermal properties for SDFs (E) and IDFs (F).

absorption peaks at 1311–1537 cm^{-1} are caused by the bending vibrations of —CH and CH_2 in the fibers. The intensities of some absorption peaks of DFs were enhanced after different modification treatments, indicating that more glycosidic bonds of DFs were exposed after modification treatments, suggesting the improvement in their physicochemical and functional properties to some extent. Overall, the changes in the intensities of the characteristic absorption peaks of modified DFs indicated the redistribution of the cellulose fractions, but the similarity of their functional groups indicated that their basic chemical structure was not substantially altered.

3.5. XRD analysis

Notably, the positions of the diffraction peaks of all IDFs did not change much, and all presented more obvious crystal diffraction peaks near 15.6° and 21.7° and weak diffraction peaks at 34.8° (Fig. 5C). This indicated that there is no obvious difference in the crystallization type of the IDF, all of them possessed a cellulose I-type crystal structure (Khawas & Deka, 2016), and the crystalline region coexisted with the non-crystalline region. None of the three modification treatments changed the crystal structure of IDFs. The crystallinity of natural IDFs of cucumber was 10.27 %, and the relative crystallinities of DFs under ME, HPP, and DHPM treatment were 8.63 %, 8.18 %, and 5.89 %, respectively. The decrease in crystallinity may be because of the moderate degradation of amorphous materials such as enzymatic degradation of hemicellulose (Xi et al., 2023), which results in the solubilization or conversion of these structural components into water-soluble components for solubilization. HPP and DHPM treatments further disrupted the molecular linkages between compounds in cucumber IDF. Notably, the modification treatments weakened the intermolecular forces,

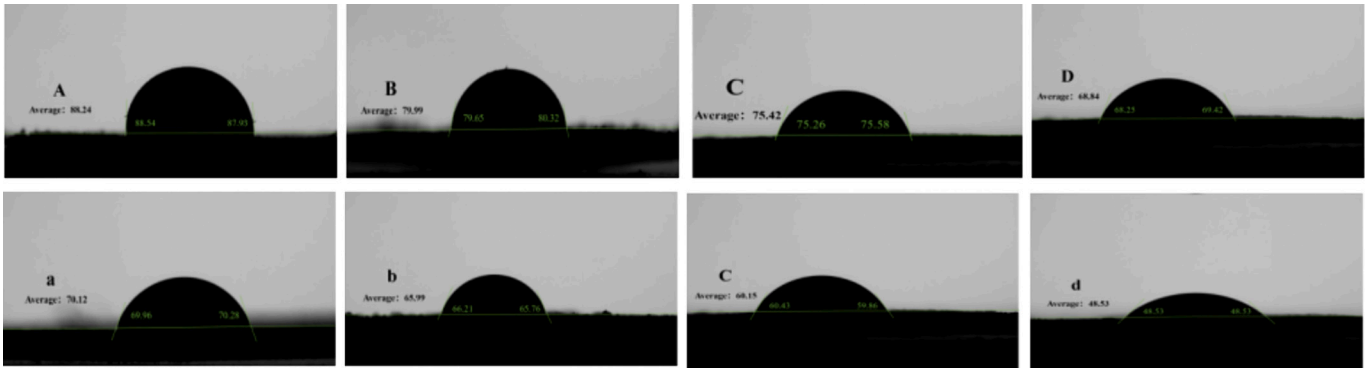

Fig. 6. The changes in the contact angle of DF with different modification treatments. A, B, C, and D show the IDF of CK, ME, HPP-ME, and DHPM-ME, respectively. a, b, c, and d show the SDF of CK, ME, HPP-ME, and DHPM-ME, respectively.

resulting in a more relaxed structure with better hygroscopicity, which enhanced its WHC and OHC and improved the SC (Lin et al., 2019). The XRD spectra of SDFs (Fig. 5D) show that the control SDF did not present any notable diffraction peaks in the range of 2θ from 5° to 60°. Although there is not much difference, a very weak broad diffraction peak appeared at 28.2° and new diffraction peaks appeared at 36.0°–38.3° and 40.8° for the modified SDFs. After calculation, the crystallinity of the natural SDF was obtained as 35.56 %, and the relative crystallinities of SDF after ME, HPP, and DHPM treatments were 28.3 %, 25.42 %, and 19.76 %, respectively. This may be because HPP and DHPM treatments cause cucumber compounds to polymerize less, and DF facilitates the breakage of hydrogen bonds under mechanical force, which destroys its crystalline and amorphous regions, leading to a decrease in the degree of crystallinity. Different modification treatments induced certain changes in the crystal structure and degree of crystallization of SDF.

3.6. Analysis of contact angle

The contact angle is used to describe wettability. Wetterability is the ability of a liquid to first moisten the solid phase surface in two kinds of heterogeneous solutions. The stability of DF in emulsions can be correlated to the size of the contact angle, the smaller the contact angle, the better the hydrophilic character and the greater the stability. Different modification treatments reduced the contact angle of DFs to different degrees (Fig. 6); the ME group presented no obvious effect on the contact angle, and the DHPM-ME group presented the most obvious effect. The contact angle of both IDF and SDF in the control group were larger, probably because of the occurrence of two drying and dehydration experienced during the preparation leading to hornification, which changed the fiber structure through the formation of hydrogen bonds, van der Waals interactions, and lactone bridges, resulting in low hydrophilicity (Aghajanzadeh et al., 2023). The IDF contact angle decreased from 88.24° to 68.84° and the SDF contact angle decreased from 70.12° to 48.53°. In the HPP-ME group, the IDF contact angle decreased from 88.24° to 75.42° and the SDF contact angle decreased from 70.12° to 60.15°. The stability of DF in an aqueous solution after HPP and DHPM treatments was effectively improved, and the DHPM-ME exhibited the best effect. Additionally, the contact angle of all sample groups was <90°, which suggested that both cucumber IDF and SDF are hydrophilic (T. Zhao & Jiang, 2018).

3.7. Analysis of thermal stability

The IDF in the CK, ME, HPP-ME and DHPM-ME groups all had an absorption peak from 50 °C to 150 °C, which was attributed to the breaking of chemical bonds in the IDF (Fig. 5E), indicating that the treatments considerably modified the thermodynamic properties of cucumber IDF and showed exothermic reactions. Compared with the CK group, the absorption peaks of the modified IDFs were all shifted to the right, and the absorption peaks of the ME, HPP-ME, and DHPM-ME groups were increased from 82.53 °C to 104.2 °C, 129.91 °C, and 130.41 °C, respectively. This may be attributed to the more loose and porous structure of IDF after the modification treatment, reducing the physical blockage during heating, which is consistent with the results of Zhang et al. (Y. Zhang, Qi, Zeng, Huang, & Yang, 2020). The peak exothermic peaks of IDF in the CK, ME, HPP-ME, and DHPM-ME groups ranged from 125 °C to 175 °C (Fig. 5F). Compared with IDF, the effect of the modification treatments on the thermal stability of SDF was relatively small. The absorption peaks of the modified SDFs were all shifted to the right, and the absorption peaks of the ME, HPP-ME, and DHPM-ME groups were increased from 145.06 °C to 146.54 °C, 151.67 °C, and 152.28 °C, respectively. Probably because the modified treatment enhances the compactness of the molecular structure arrangement within the SDF, thus improving the thermal stability. Altogether, the modification treatments improved the thermal stability of both IDF and SDF of cucumber, following the trend of DHPM-ME > HPP-ME > ME. The results also corroborate with those of OHC, WHC, and SC of IDF and SDF, which are not only related to the surface properties, total charge density, and viscosity of DFs, but are also positively correlated with the hydrophobic groups of the fiber particles (S. Wang et al., 2022). The greater the thermal stability, the more hydrophobic groups are exposed, allowing increased penetration of water and oil in the DF molecules, and resulting in greater OHC, WHC, and SC.

3.8. Determination of hypolipidemic activity in vitro

3.8.1. Effect of modification methods on the GAC of DF

The GAC of SDF was generally higher than that of IDF in cucumber (Fig. 7A), whereas that of modified, treatment-extracted IDF and SDF was considerably higher than that of untreated IDF and SDF. The DHPM-ME group presented optimal GAC, with an increase of 4.504 mmol/g and 4.211 mmol/g than that in the CK group. This was probably because of the creation of pores and folds among DFs under physical pressurization and strong shear forces, which loosened the tight tissue structure of DFs and increased the specific surface area (Zhai et al., 2022). The exposure of some functional groups encapsulated within the cellulose and the relatively easy access of internal solutes to the interior of the fibers increase the van der Waals and hydrogen bonding forces connecting them to the glucose molecules (X. Tang et al., 2023), which improves the GAC. Additionally, proper gaps and a loose, folded structure can act as a glucose adsorber.

3.8.2. Effect of modification methods on GDRI

As can be seen in Fig. 7 (B-E), for all DFs in cucumber samples, the GDRI value at 30 min of dialysis was greater than that at 60 min of dialysis. ME extracted cucumber dietary fiber had the lowest GDRI. After

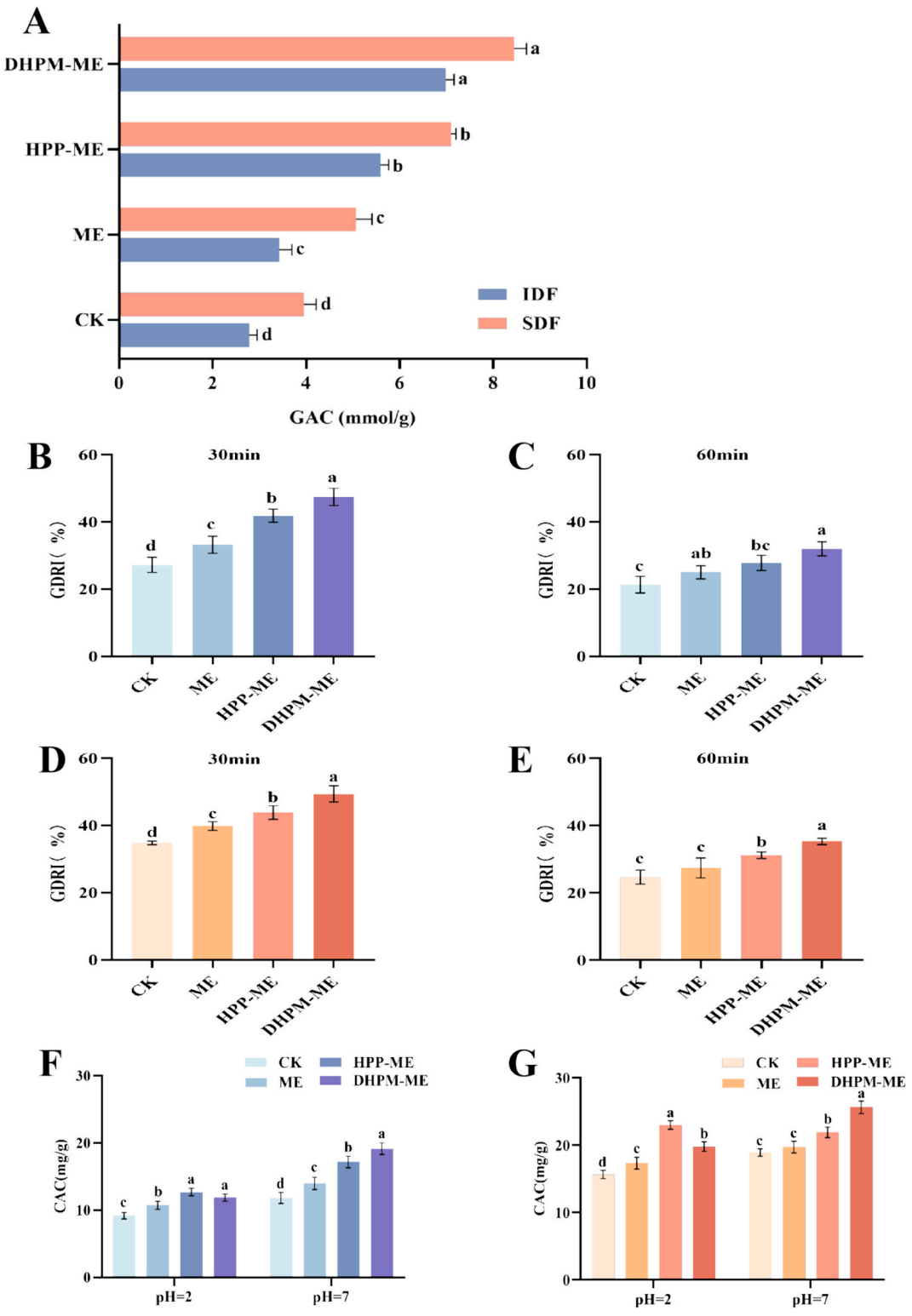

Fig. 7. Functional properties of DFs with different modification treatments. A: glucose-adsorption capacity of DFs. B and C: glucose delay indices for IDFs dialysis for 30 min and 60 min. D and E: glucose delay indices for SDFs dialysis for 30 min and 60 min. F and G: cholesterol-adsorption capacity of IDFs and SDFs.

30 min of dialysis treatment, IDF and SDF extracted by HPP-ME presented the highest GDRI values, the IDF of GDRI value reached 47.42 % ± 2.61 % and the SDF of GDRI reached 49.40 % ± 2.43 %. and those of all modified treatment groups were higher than those of the unpretreated DFs. The high GDRI of IDF may be because of its high GAC. SDF presented a greater GDRI value and a greater ability to bind glucose diffusion because it adsorbs enough glucose. This suggests that GDRI may be related to the characteristics, including the structure and hydration properties, of DF, which is consistent with the results of WHC, OHC, and SC. After 60 min of dialysis, there was no notable difference in GDRI of the modified-treated DFs compared with that of the unmodified-treated DFs. It may be because the prolongation of dialysis time resulted in the adsorption of glucose close to saturation and reached dynamic equilibrium for both IDF and SDF (Gupta & Premavalli, 2011).

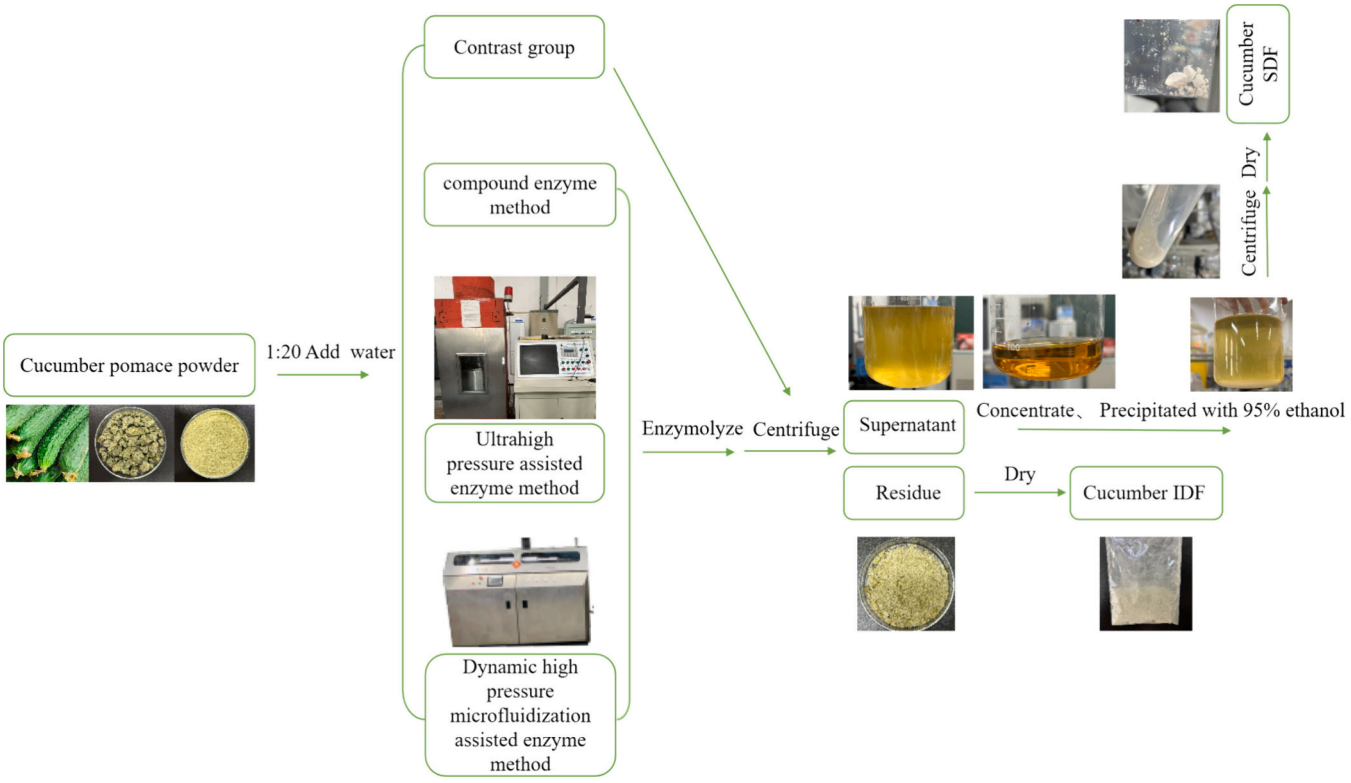

Fig. 1. Cucumber dietary fiber processing technology. SDF, soluble dietary fiber; and IDF, insoluble dietary fiber.

3.8.3. Effect of modification methods on the CAC of DF

The changes in the CAC of IDF and SDF before and after the modification treatments revealed that CAC was enhanced by the different modification treatments, but in general, the HPP-ME and DHPM-ME groups were superior to the other groups (Fig. 7[F-G]). Additionally, CAC at pH 7.0 was greater than that at pH 2.0, indicating that CAC of DF was affected by the acidity or alkalinity of the reaction system, with the adsorption capacity being better under neutral conditions than that under acidic conditions (Yan, Li, Liu, & Zheng, 2019). This may be because of the presence of a large number of hydrogen ions under acidic conditions, suggesting that both DF and cholesterol are attached to a certain degree of positive charge, and same-charge repulsive force weakens the binding force between them, decreasing the CAC of DF (Maqsood, Benjakul, Abushelaibi, & Alam, 2014). CAC of IDF and SDF after HPP or DHPM treatments were improved compared with those of the CK and ME groups. This may be because of the action of strong mechanical force, which further disrupted the tissue structure of DFs, resulting in the DF molecules becoming smaller, fewer microcrystalline bundles, in an amorphous state, and more exposure of the polar groups. Furthermore, the spatial barriers were small, which was more conducive to the adsorption of cholesterol (Tian, Sheng, Wu, Quan, & Wang, 2024).

4. Conclusion

In this study, ME, HPP-ME, and DHPM-ME modifications improved the functional properties of dietary fiber. Following different modification treatments, IDF and SDF structures notably changed compared with those before modification, and the OHC, WHC, and SC were significantly improved ($p < 0.05$). Among these, the hydration properties of HPP-ME- and DHPM-ME-modified IDF and SDF were the best and similar to each other. Structural characterization revealed that after the modification treatment, the particle size of DF became smaller, the surface structure became loose and porous, conversion to SDF increased, crystallinity was decreased and thermal stability was improved. In vitro simulation experiments yielded the best functional properties of IDF and SDF under DHPM-ME modification, with 114.09 % increase in GAC in IDF compared with the CK group. SDF showed an increase of 151.61 % in GAC. Altogether, the physicochemical and functional properties of the modified IDF and SDF were improved, and the DHPM-ME-modified DF presented excellent GAC, GDRI, CAC, OHC, WHC, and SC. The results of this study can provide insights into the method to improve the structure and functional properties of cucumber DFs, improve the added value of cucumber, and its precise application in functional food processing to lay a theoretical foundation. Since DFs needs to choose suitable modification methods according to the characteristics of the product itself, the study of the selective modification mechanism of DFs will be an important direction for future research.

CRediT authorship contribution statement

Zhiwei Zhang: Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization. **Xinyi Yang:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhenhong Gao:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Meiyue Zhang:** Writing – review & editing, Visualization, Investigation. **Shuaixue Mu:** Writing – review & editing, Visualization, Investigation. **Yuying Cheng:** Visualization, Investigation. **Kunsheng Qu:** Methodology, Investigation, Conceptualization.

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

Data will be made available on request.

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