Comparative evaluation of the properties and applications of soluble dietary fibers derived from natural plants

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Research Article

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Abstract

Plant-derived soluble dietary fibers (SDFs) have many important physiological functions and the applications of different SDFs vary based on their properties, which are worth further investigating for SDF-rich food production. In this study, SDFs with high industrialization derived from konjac, apple, chicory, flaxseed, orange, psyllium seed, soybean and oat were selected, and their structural properties, physicochemical properties, α-amylase inhibitory activity and cholesterol absorption capacity were systematically evaluated and compared. The results showed that the molecular weight of konjac glucomannan (KGM, 5.22×10^6 Da) was the highest, and inulin, soybean and oat SDFs had higher water solubility compared with the others. Moreover, KGM, apple, flaxseed and psyllium seed SDFs exhibited better water-holding capacity, swelling capacity, emulsifying activity and stability. Rheological studies and texture profile analysis suggested that KGM had the best viscosity and gelation ability. In addition, apple and orange SDFs showed better α-amylase inhibitory activity, while KGM and flaxseed SDF displayed fine cholesterol absorption capacity, illustrating the feasibility to regulate blood sugar and blood lipid levels.

Introduction

Dietary fibers can be defined as health beneficial carbohydrate polymers that resist digestion by small intestinal enzymes (Garcia-Amezquita et al. 2018). In recent years, dietary fibers have received great attention due to various health benefits such as hypoglycemic and hypolipidemic effects. However, because of the excessive emphasis on sensory and taste, bulk foods such as rice and flour products are over-processed, and lots of dietary fibers are removed, which results in insufficient intake in the human body and thus leads to many negative effects. Therefore, some manufacturers supplement the food with dietary fibers by exogenous addition to increase its health effects.

As the seventh essential nutrient (Waliullah et al. 2021), dietary fibers are conventionally classified into insoluble dietary fibers (IDFs) and soluble dietary fibers (SDFs) based on their solubility. IDFs include cellulose, hemicellulose, and lignin, etc., whereas SDFs include pectin, β-glucan, oligosaccharide, inulin, plant mucilage, etc. (Chawla and Patil 2010). It was found that SDFs had stronger physiological functions compared with IDFs in many aspects (Bader Ul Ain et al. 2019), including adjustment of blood cholesterol levels, reduction of cardiovascular disease risk, prevention of gastrointestinal problems, promotion of bacterial metabolic activities, prevention of type 2 diabetes, antioxidants and antitumor (Zhang et al. 2011b; Mudgil 2017; Ahmed et al. 2011; Cui and Zhu 2021). As far as functional food market is concerned, the development of SDF-fortified foods is more promising. Meanwhile, SDFs possess more advantages than IDFs in physicochemical properties (Gao et al. 2015), with higher ability to form gels and act as emulsifiers, and to impart texture, color, sensory, shelf life, thickening and stabilizing (Jia et al. 2019; Xie et al. 2017; Waliullah et al. 2021; Nandi and Ghosh 2015) properties to foods.

The properties of SDFs, including water solubility, water-holding capacity, emulsifying activity, swelling capacity, viscosity, absorption capacity, are decisive to their application scopes. Among them, water solubility, water-holding capacity and swelling capacity reveal the interaction between SDFs and water, and exert influences in the physiological functions and applications. SDFs with high water solubility can be used in beverages or formulated high-fiber foods. SDFs with high water-holding capacity can be applied in meat products, baked foods, flour products, or be used as fat substitutes in sausages (Kurek and Wyrwisz 2015; Yang et al. 2017; Kim and Paik 2012), and those with good emulsifying activity are suitable for cream and ice cream products. SDFs with favorable viscosity and swelling capacity increase satiety, which can be used in slimming products such as meal replacement shakes, solid beverages and chewable tablets. Furthermore, it is confirmed that SDFs can inhibit *α*-amylase activity, affect the release of glucose from starch (Cheng et al. 2017), and absorb cholesterol, which show their application potential in functional foods to lower or stabilize blood sugar and blood lipid levels.

Over the past few years, the demands for healthy food have stimulated the development of innovative fiber-rich foods and vastly broadened the application scopes of SDFs (Lopez-Marcos et al. 2015). However, the physicochemical and functional properties of SDFs from different plant sources are quite different, affecting their applications in food industry. Therefore, it is necessary to investigate the properties of SDFs so as to provide basic data for better utilization. However, so far very few studies have systematically compared the properties of different plant-derived SDFs. In this study, industrialized SDFs derived from konjac, apple, chicory, flaxseed, orange, psyllium seed, soybean and oat were selected, and the properties of the SDFs, including structural properties (molecular weight, monosaccharide composition, fourier transform infrared spectroscopy and X-ray diffraction), physicochemical properties (water solubility, water-holding capacity, swelling capacity, emulsifying activity and stability, rheological properties and gel properties), α-amylase inhibitory activity and cholesterol absorption capacity were systematically evaluated and compared, and thus, advantages and disadvantages of SDFs can be clarified, which can provide data to support the production of fiber-rich foods with higher consumer acceptability and health benefits.

Materials And Methods

Materials

Konjac glucomannan (KGM, ~ 76% purity) was purchased from Newstar Konajc Co., Ltd. (Chengdu, China). SDFs from apple (A-SDF, ~ 63% purity) and orange (O-SDF, ~ 86% purity) were bought from Zhengzhou Hongxing Food Additive Co., Ltd. (Zhengzhou, China). Inulin (~ 83% purity) was purchased from Weifang Meikaiwei Medical Technology Co., Ltd. (Chengdu, China). Flaxseed SDF (F-SDF, ~ 68% purity) was from Anhui Shujun Biotechnology Co., Ltd. (Anhui, China). Psyllium seed SDF (P-SDF, ~ 87% purity) was obtained from Xuzhou Nature Food Co., Ltd. (Xuzhou, China). SDFs derived from soybean (S-SDF, ~ 80% purity) and oat (OA-SDF, ~ 85% purity) were from Shandong Juyuan Biotechnology Co., Ltd. (Shandong, China). All other reagents were of analytical grade.

SDF purification and purity measurement

One gram of SDF sample was dissolved in 200 mL deionized (DI) water and stirred for 2 h, followed by centrifugation at 8000 rpm for 30 min to remove the insoluble materials. Subsequently, the supernatant was collected and the volume was reduced to 1/3 of the original volume by rotary evaporation. The concentrate was precipitated overnight with 4 times volume of 95% ethanol. The mixture was centrifuged, and the precipitation was washed twice with absolute ethanol before being vacuum-dried at 50°C. The dried material was ground and sieved through 40 mesh to obtain the purified sample.

The monosaccharide composition of KGM, inulin and OA-SDF was relatively simple, and thus the total carbohydrate content was determined according to phenol–sulphuric acid colorimetric assay (Dubois et al. 1956), while the reducing sugar content was measured by DNS colorimetric assay (Xu et al. 2014). As F-SDF, P-SDF, A-SDF, O-SDF and S-SDF were heteropolysaccharides, SDF content was determined following the enzymatic-gravimetric method (Horwitz 2010).

Molecular weight

Molecular weight was determined by high-performance gel filtration chromatography (HPGFC) equipped with differential refraction detector (Waters 2410) and Ultrahydrogel™ Linear column (7.8 mm × 300 mm, 40°C). The mobile phase was 0.1 M $NaNO_3$ at a flow rate of 0.5 mL/min. The SDF samples were dissolved in DI water (5 mg/mL), stirred for 4 h at room temperature, centrifuged at 6000 rpm for 15 min and filtered through 0.45 μm filter prior to analysis.

Monosaccharide composition

Monosaccharide composition was analyzed using a high-performance anion-exchange chromatograph with pulsed amperometric detection (HPAEC-PAD) system (Dionex ICS-5000 System, Dionex Corp.) coupled with a CarboPac™ PA20 column. The hydrolysis of SDF followed the method of Tang et al. (2019). 10 mg SDF sample was mixed with 8 mL of 2 mol/L trifluoroacetic acid (TFA). The mixture was hydrolyzed at 110°C for 5 h, and then TFA was evaporated. Anhydrous methanol was added and evaporated 3 times. The sample was finally dissolved in 10 mL DI water, followed by centrifugation at 8000 rpm for 10 min. The supernatant was filtered through 0.45 μm membrane before injection.

Fourier transform infrared spectroscopy

The structure of SDF samples was analyzed by fourier transform infrared spectroscopy (FTIR). Dry SDF samples were blended with potassium bromide at a ratio of 1:100, and the spectra were recorded ranging from 4000 to 400 cm^{-1} with 32 scans using a Nicolet IS10 spectrophotometer (Thermo-Scientific, Madison, USA).

X-ray diffraction

The crystallization parameters of SDF samples were analyzed by X-ray diffraction (XRD) using a D2 Phaser X-ray diffractometer (Bruker AXS, Karlsruhe, Germany). The samples were examined at scanning range of 5°-40° (2θ) with a scanning rate of 5°/min.

Hydration properties

Water solubility

SDF samples were mixed with DI water at the required temperature for 30 min. Then, the mixture was heated at the temperature for 1 h, followed by centrifugation at 9000 rpm for 20 min. The supernatant was dried at 105°C until weight remained constant. The water solubility was expressed as the quality of SDF dissolved in 100 g water.

Water-holding capacity

The water-holding capacity was determined as reported by Chen et al. (2014). Briefly, 0.1 g SDF sample was added to 30 mL DI water and mixed evenly, kept at room temperature for 1 h. After centrifugation at 9000 rpm for 30 min, the supernatant was removed and the residue was weighed. The water-holding capacity was expressed as g of water per g of dry sample.

Swelling capacity

The swelling capacity was measured on the basis of the approach by Huang et al. (2021) with slight modifications. 0.5 g SDF sample was put in 5 mL measuring cylinder, and then transferred to 50 mL measuring cylinder, gradually mixed with 20 mL DI water, hydrated at room temperature for 24 h. The volumes of the initial dry sample and final wet sample were recorded. Swelling capacity was defined as mL of water per g dry sample.

Emulsifying activity and stability

The emulsifying activity and stability were conducted using the method described previously by Lopez-Marcos et al. (2015). 0.25 g SDF sample was dispersed in 50 mL DI water, formulated into SDF aqueous suspension. 50 mL corn oil was added into sample solution, and the mixture was homogenized at 8000 rpm for 3 min. The emulsion was transferred into 15 mL graduated centrifuge tubes and centrifuged at 2000 rpm for 5 min. Emulsifying activity was calculated as the percentage of the volume of the emulsified layer to the total volume of content inside the centrifuge

tube. The above prepared emulsion was kept in an 80°C water bath for 30 min, and centrifuged at 2000 rpm for 5 min. Emulsifying stability was expressed as the percentage of the volume of the remaining emulsified layer to the volume of original emulsified layer.

Static rheological properties

The static rheological properties of SDF aqueous solution were performed by using a Discovery HR-3 rheometer (TA Instruments, New Castle, USA) equipped with a 40 mm diameter parallel plate at a gap of 1000 μm. SDF aqueous solution was prepared with various concentrations (0.5%, 1%, 1.5%, 2%, 2.5% and 5%, w/v) using DI water. The viscosity of all concentrations were recorded at the shear rate of 60 s^{-1}, and the steady shear flow properties of SDF solution with the concentration of 5% were measured at a 0.01 to 500 s^{-1} shear rate range.

Gel properties

Texture properties

SDF solution was prepared by directly dissolving SDF sample in 7.5 mmol $CaCl_2$ stock solution. The solution was stood to lead formation of gels and kept 24 h before subsequent test. The texture profile analysis (TPA) of the gels was determined by a Texture Analyzer TA XT plus (Stable Micro Systems, Surrey, UK) using a probe p/5 in TPA mode. The gels were tested at the pre-test speed of 1 mm/s, test speed of 1 mm/s, post-test speed of 2 mm/s with control force 5.00 g and compression depth of 50%.

Rheological properties

The rheological properties of the gels were determined by using a rheometer. For dynamic oscillatory experiments, frequency sweep was carried out to determine the values of storage modulus (G', Pa) and loss modulus (G", Pa) from 0.1 to 100 rad/s with 1% strain. Then, the strain sweep was ranged from 0.1 to 100% at 1 rad/s frequency. Finally, the steady flow properties were measured with the shear rate ranging from 0.01 to 500 s^{-1} at 25°C.

α -Amylase inhibitory activity

The *α*-amylase inhibitory activity was performed as the method described previously by Yan et al. (2019). 100 μL SDF solution with a concentration of 1.0 mg/mL and 200 μL 12.5 U/mL α-amylase solution (prepared with 0.1 mol/L PBS, pH = 6.8) were mixed and incubated at 60°C for 10 min. 500 μL of 1% (w/v) potato starch solution was then added to begin the reaction at 60°C for 10 min. The reaction was terminated by adding 500 μL DNS and the mixture was heated for 5 min in a boiling water. After cooling to room temperature, the mixture was diluted to 10 mL with 0.1 mol/L PBS. The absorbance was measured at 540 nm. The *α*-amylase inhibitory activity was calculated using the following equation.

$$\alpha\text{-amylase inhibitory activity } (\%) = (A_2 - A_1)/A_1 \times 100$$

1

Where, A_1 and A_2 mean the absorbance of the mixture with SDFs and the control, respectively.

Cholesterol absorption capacity

The cholesterol absorption capacity was evaluated by the procedure of Xu et al. (2015). Fresh egg yolks were diluted 10-fold in DI water and stirred. 0.10 g SDF sample was mixed with 25 mL diluted yolk solution, and then the pH was adjusted to 2.0 and 7.0, respectively. The mixture was shook at 37°C for 2 h, diluted yolk without SDF being the blank.

When the absorption was completed, absolute ethanol was blended to precipitate SDFs, followed by centrifugation. The supernatant was concentrated and 100 µL concentrate was diluted to 4 ml with glacial acetic acid. After the sequential addition of 0.1 ml o-phthalaldehyde reagent and 2 ml concentrated H_2SO_4, the mixture was allowed to let down for 20 min with color developing. The absorbance was measured at 550 nm. The cholesterol absorption capacity was calculated using the following equation.

$$\text{cholesterol absorption capacity (mg/g)} = (M_1\text{-}M_2)/m$$

2

Where, M_1 and M_2 mean the content of cholesterol in the yolk before and after absorption (mg), respectively, and m means the mass of dry SDF (g).

Statistical analysis

The experiments were carried out in triplicate. The data were analyzed by using the statistical analysis software SPSS and expressed as mean ± SD value. $p < 0.05$ indicated that the difference was statistically significant.

Results And Discussion

Structural properties of SDF

Molecular weight and monosaccharide composition

Generally speaking, purity was an indispensable parameter that affected the performance of SDFs. Based on the property of SDFs being soluble in water but not soluble in alcohol, alcohol extraction was used for purification, and the results are shown in Table 1. The purities of KGM, F-SDF, P-SDF and A-SDF were higher than 75% after purification. The effective substances content of purified KGM could reach 91.18%, while the purities of inulin, O-SDF, S-SDF and OA-SDF were more than 80%.

Table 1

Purity, molecular weight and monosaccharide compositions of SDF samples[a].

Sample	Purity (%, w/w)	Mw(Da)	Mn(Da)	Monosaccharide composition[b](%, w/w)							
				Glu	Man	Fru	Xyl	Gal	Ara	GalUA	GlcUA
KGM	91.18 ± 2.82	5.22×10^6	1.05×10^6	47.30	52.70	ND	ND	ND	ND	ND	ND
A-SDF	76.07 ± 2.31	1.01×10^6	1.39×10^5	17.54	ND	ND	2.78	6.32	1.50	21.42	49.90
Inulin	83.17 ± 1.45	1.79×10^3	797	57.55	ND	42.45	ND	ND	ND	ND	ND
F-SDF	76.83 ± 0.94	3.65×10^6	1.59×10^6	37.33	25.81	ND	ND	18.96	0.64	16.08	ND
O-SDF	86.13 ± 0.93	5.58×10^5	5.54×10^4	34.15	ND	2.88	2.18	36.73	11.99	8.38	ND
P-SDF	87.07 ± 1.57	1.82×10^6	1.07×10^6	ND	ND	ND	67.49	3.06	18.87	5.67	ND
S-SDF	80.48 ± 0.85	3.23×10^5	1.32×10^5	0.57	ND	ND	1.28	50.39	44.18	ND	2.7
OA-SDF	84.99 ± 0.67	1.26×10^5	2.68×10^4	81.92	0.36	ND	8.74	2.04	6.94	ND	ND

[a] SDF, soluble dietary fiber; KGM, konjac glucomannan; A-SDF, apple soluble dietary fiber; F-SDF, flaxseed soluble dietary fiber; O-SDF, orange soluble dietary fiber; P-SDF, psyllium seed soluble dietary fiber; S-SDF, soybean soluble dietary fiber; OA-SDF, oat soluble dietary fiber.

[b] Glu, Glucose; Man, Mannose; Fru, Fructose; Xyl, Xylose; Gal, Galactose; Ara, Arabinose; GalUA, Galacturonic acid; GlcUA, Glucuronic acid.

ND, not detected.

The weight-average molecular weight (Mw) and number-average molecular weight (Mn) varied greatly, which ranged from 10^3 to 10^6 Da, as shown in Table 1. The Mw of KGM was the highest (5.22×10^6 Da), followed by F-SDF, P-SDF, A-SDF, O-SDF, S-SDF, OA-SDF and inulin, which were 3.65×10^6 Da, 1.82×10^6 Da, 1.01×10^6 Da, 5.58×10^5 Da, 3.23×10^5 Da, 1.26×10^5 Da and 1.79×10^3 Da, respectively. The large differences in the Mw of SDF samples might lead to different physicochemical properties, such as higher viscosity and lower solubility of KGM, whereas lower viscosity and higher solubility of inulin.

The monosaccharide compositions of SDF samples are given in Table 1. The monosaccharide compositions of KGM and inulin were relatively simple, consisting of 47.30% glucose (Glu) and 52.70% mannose (Man), 57.55% Glu and 42.45% fructose (Fru), respectively. The A-SDF was composed of 17.54% Glu, 6.32% galactose (Gal), 21.42% galacturonic acid (GalUA) and 49.90% glucuronic acid (GlcUA). There was large amount of uronic acid in the A-SDF, which indicated that A-SDF should be considered as pectin. F-SDF was composed of 37.33% Glu, 25.81% Man, 18.96% Gal and 16.08% GalUA. O-SDF was mainly made up of four kinds of monosaccharides, namely Glu, Gal, arabinose (Ara) and GalUA. As for P-SDF, the main components were xylose (Xyl, 67.49%) and Ara (18.87%) with a

molar ratio of 3.5:1, which was basically consistent with the results reported by Yin et al. (2016). These results suggested that P-SDF should be arabinoxylan. S-SDF was mainly composed of 50.39% Gal and 44.18% Ara. Different from other SDFs, OA-SDF was mainly composed of Glu, which was referred to glucan. Many studies showed that polysaccharides containing more aldehyde acid (GalUA, GlcUA) had better biological activity (Lin and Huang 2022). In the quantitative structure-activity relationship of polysaccharides established by Li et al. (2016), it was found that polysaccharides rich in GalUA had significant antioxidant activity. In addition, polysaccharides containing more Glu and Man showed better antitumor activity (Chen et al. 2022).

FTIR and XRD analysis

FTIR spectrum of different SDF samples are depicted in Fig. 1-a. The results revealed that these SDF samples exhibited typical absorption peaks of polysaccharide. These main absorption peaks at around 3425 cm^{-1}, 2924 cm^{-1}, 1636 cm^{-1} and 1060 cm^{-1} were ascribed to the vibrations of O-H, C-H, C = O, and C-O, respectively. The strong and broad absorption bands at 3600 – 3200 cm^{-1} but below 3500 cm^{-1} were generated by the stretching vibration of –OH groups, which was demonstrated to be closely related to the formation of hydrogen bonds between the polysaccharide molecules (Safdar et al. 2019). The lower intensity of the peak at 2924 cm^{-1} corresponded to the C-H stretching band due to the presence of methyl or methylene, and band in the range of 1750 ~ 1700 cm^{-1} originated from C = O stretching vibration (Chua et al. 2012). At around 1746 cm^{-1}, the peak intensity of A-SDF and O-SDF were greater, which indicated that the contents of aldehyde acids in these two SDF samples were higher (Song et al. 2018). Moreover, the peak at 1636 cm^{-1} was ascribed to the angular O-H bending of water molecules (Moczkowska et al. 2019). In addition, absorption peaks between 1300 and 1000 cm^{-1} were attributed to the stretching vibration of C-O, and the band between 1200 and 800 cm^{-1} are recognized as the characteristic region (fingerprint) of carbohydrates (Safdar et al. 2019). At the same time, the peak at approximately 934 cm^{-1} was contributed to the symmetrical stretching vibration of pyranoid ring structure (Song et al. 2018).

The XRD patterns of the SDF samples are compared in Fig. 1-b. Except O-SDF, no apparent crystallinity peaks were found in SDF samples. These samples displayed diffuse and broad peaks, exhibiting amorphous features and typical diffraction pattern characteristics of polymers. The diffraction peaks of SDF samples appeared at 19.5° with slight difference. Moreover, a weak shoulder peak was observed at 10° in the pattern of A-SDF. It was suspected that these SDF samples were the amorphous material and provided with fairly low crystallinity. O-SDF exhibited strong diffraction peaks at 19° and 25°, and had a certain crystallinity. Results bore a resemblance to those of Li et al. (2021) who found that both KGM and ozone-degraded KGM displayed characteristics of amorphousness.

Physicochemical properties of SDFs

Hydration properties

The water solubility of SDF samples at different temperatures is present in Fig. 2-a. Overall, the water solubility of KGM, A-SDF, P-SDF, S-SDF and OA-SDF was positively correlated with temperature ($p < 0.05$). Inulin belongs to oligosaccharides with superior solubility. It was found in the pre-experiment that inulin solution with a concentration of 10% could be completely dissolved at room temperature. Among other SDF samples, S-SDF and OA-SDF had better solubility, reaching 3.95 g/100 g and 3.61 g/100 g at 20°C and 4.23 g/100 g and 4.64 g/100 g at 90°C, respectively. Interestingly, there was a negative correlation between molecular weight and solubility of SDFs (Ning et al. 2020). The molecular weights of F-SDF, A-SDF, KGM and P-SDF were all higher than 10^6 Da, and thus their solubility was lower, basically between 0.10 g/100 g and 0.25 g/100 g. Therefore, it can be inferred that inulin, S-SDF

and OA-SDF with lower molecular weights are more suitable for use as dietary fiber supplements in beverages to provide mellow flavor.

The water-holding capacity and swelling capacity of SDF samples are displayed in Fig. 2-b. The water-holding capacity of P-SDF was highest, up to 66.81 g/g, followed by A-SDF (42.13 g/g) and KGM (41.37 g/g). O-SDF had weak water-holding capacity of 2.79 g/g, while inulin, S-SDF and OA-SDF had better water solubility and were easily dissolved in water rather than held water. Water-holding capacity of SDF had been previously affirmed to increase with molecular weight, and the results of our case basically conformed to the relation (Li et al. 2017). The order of swelling capacity of SDF samples was F-SDF > P-SDF > KGM > A-SDF > O-SDF > OA-SDF ($p < 0.05$). The swelling capacity of F-SDF was up to 15.52 mL/g, followed by 14.38 mL/g of P-SDF and 9.70 mL/g of KGM, respectively, while O-SDF and OA-SDF expanded poorly. The inulin and S-SDF tended to dissolve in water and difficult to expand. It was found that SDFs with high water-holding capacity was able to hold more moisture in food and reduce mass loss (Jia-yi et al. 2021). With no calories but providing a feeling of fullness due to high water-holding capacity and swelling capacity, KGM, A-SDF, F-SDF and P-SDF are preferred by people who wish to lose weight (Debnath et al. 2019). In addition, they are suitable to be used in flour products and meat products to enhance the water retention capacity, reduce cooking losses and extend shelf life (Kurek and Wyrwisz 2015).

The emulsifying activity and stability of SDF samples are illustrated in Fig. 2-c. KGM, A-SDF, F-SDF, O-SDF, P-SDF, and OA-SDF showed high emulsifying activity and stability. However, inulin and S-SDF had poor emulsifying activity, and the emulsions were broken and stratified quickly after homogenization, and thus the results were not shown. As seen in Fig. 2-c, P-SDF showed the highest emulsifying activity and stability of 96.28% and 97.10%, respectively. The emulsifying activity of KGM was 82.79%, while A-SDF and F-SDF were 67.92% and 63.06%. Except O-SDF, the emulsifying activity of other SDF samples was all higher than 50%, indicating great potential for application in food processing. Moreover, emulsifying stability of the six SDF samples was greater than 80%, suggesting that these SDF samples were appropriated for foods to maintain the stability and prolong the shelf life. Thus, it can be implied that KGM, F-SDF and P-SDF are suitable to act as emulsifiers and stabilizers (Garcia-Amezquita et al. 2018).

Static rheological properties

Figure 3-a displays the viscosity of SDF solutions under different concentrations at a shear rate of 60 s^{-1}. Generally speaking, the viscosity gradually increased as concentration increased. KGM had the highest viscosity, while the viscosity of inulin solution was low and changed little with the increase of concentration. It was indicated that viscosity was related to molecular weight (Zhang et al. 2011a). The steady shear flow properties of SDF solutions at 5% are shown in Fig. 3-b. The viscosity of SDF solutions decreased with the increase of shear rate, which indicated that the SDF solutions belonged to pseudoplastic fluids with shear thinning phenomenon. When the shear rate was low, the viscosity was almost constant. This phenomenon could be explained that at low shear rate, the entanglement force among fiber molecules was sufficient to surmount the external stress (Chen et al. 2020), and thus the viscosity tended to become stabilizing at this stage. At high shear rate, the shear destruction rate was higher than the reconstruction rate, disrupting the aggregates formed by weak electrostatic interaction and van der Waals force (Gu et al. 2020). It was found that the extent of shear thinning effect was connected with molecular chain length and relative molecular mass of polymer (Cheng et al. 2017; Mudgil 2017). Therefore, high-viscosity SDFs can play a thickening role in food and be suitable for weight loss products to increase viscosity of gastric contents and enhance satiety.

Gel properties

The texture properties of the gels, including hardness, springiness, cohesiveness, adhesiveness and chewiness, obtained from the TPA curves, are listed in Table 2. The formation of the gels was closely related to the concentration of SDF samples. Except OA-SDF, inulin and S-SDF, other fibers could form gels when the concentration was up to 5%. OA-SDF could form a gel with a concentration of 10%, and inulin of 40%, but S-SDF failed to gelatinize at 40%. This might be due to that the molecular weights of these fibers were too low, and it was hard to form the spatial network structure of gels. For gels with the same concentration, KGM had the highest hardness, followed by P-SDF, F-SDF, A-SDF and O-SDF, and this relationship could also be applied to springiness and chewiness. Under the same condition, the higher the molecular weight, the faster the gelation rate. The longer molecular chains were more likely to interpenetrate and entangle with each other to form stable three-dimensional network structure, thereby increasing the springiness and stability of the gels (Zhang et al. 2001).

Table 2
The texture profile analysis of SDF samples[a].

Sample	Hardness (g)	Springiness	Cohesiveness	Adhesiveness (g□s)	chewiness
5% KGM	51.00 ± 0.41^{a}	0.93 ± 0.01^{a}	0.86 ± 0.01^{a}	247.03 ± 4.10^{a}	40.71 ± 0.80^{a}
5% A-SDF	9.41 ± 0.13^{e}	0.42 ± 0.10^{d}	0.42 ± 0.06^{d}	21.87 ± 5.73^{d}	1.72 ± 0.70^{e}
5% F-SDF	11.08 ± 1.20^{e}	0.74 ± 0.04^{c}	0.77 ± 0.06^{ab}	48.92 ± 14.81^{cd}	6.41 ± 1.32^{d}
5% O-SDF	5.47 ± 1.02^{f}	0.14 ± 0.01^{d}	0.57 ± 0.02^{c}	4.90 ± 1.38^{e}	0.34 ± 0.01^{e}
5% P-SDF	19.89 ± 0.05^{c}	0.83 ± 0.02^{bc}	0.75 ± 0.01^{b}	4.22 ± 0.46^{e}	12.38 ± 0.55^{c}
10% OA-SDF	15.95 ± 0.20^{d}	0.89 ± 0.01^{b}	0.65 ± 0.01^{c}	71.01 ± 4.07^{c}	9.10 ± 0.27^{d}
40% Inulin	39.21 ± 1.60^{b}	0.92 ± 0.01^{a}	0.46 ± 0.01^{d}	217.03 ± 1.17^{b}	16.67 ± 1.22^{b}

Values in the same column with different letters are significantly different ($p < 0.05$).

[a] SDF, soluble dietary fiber; KGM, konjac glucomannan; A-SDF, apple soluble dietary fiber; F-SDF, flaxseed soluble dietary fiber; O-SDF, orange soluble dietary fiber; P-SDF, psyllium seed soluble dietary fiber; S-SDF, soybean soluble dietary fiber; OA-SDF, oat soluble dietary fiber.

Dynamic rheology and steady shear flow properties of gels are shows in Fig. 4. Strain sweep was performed to ensure that 1% strain was in the linear viscoelastic region, where the G' and G" were independent of the strain. In Fig. 4-b, G' of all fiber gels was greater than G", which implied that the elasticity of the gels dominated the system, showing typical gel-like properties (Fang et al. 2021). The G' of all the gels was increased with the increase of frequency. Among the gels with 5% SDF samples, the gels containing KGM had the largest G', followed by F-SDF, P-SDF, A-SDF and O-SDF. It was confirmed by Yoshimura and Nishinari (1999) that the G' of gels increased with molecular weight increasing. Figure 4-c exhibits the relationship between the viscosity and shear rate of different SDF gels, where the viscosity of the gels decreased slightly at low shear rate, but decreased rapidly in the high shear rate range. The gel containing 5% KGM or 5% P-SDF had the higher viscosity, implying that the internal structure of the gel was more stable. In brief, KGM, F-SDF and P-SDF have good gel properties, which indicates that it is suitable for these fibers to act as gelling agents in food to provide smooth texture, increase springiness and hardness.

α -Amylase inhibitory activity

α-Amylase inhibitory activity of the SDF samples is presented in Fig. 5. Among the SDF samples, O-SDF and A-SDF were presented the stronger effects in restraining *α*-amylase activity than other SDF samples, reaching 23.65% and 22.97%, respectively. Inulin and OA-SDF had the weaker inhibitory ability, which were 15.54% and 14.19%, separately. In a study by Qiao et al. (2021), although *α*-amylase inhibitory activity of SDF from sweet potato residues increased from 5.40–10.59% by squeezing, it was still weaker than those of SDF samples revealed in this study. The inhibitory effect of SDF on *α*-amylase could be accounted for encapsulating starch and obstructing the starch-amylase contact, accordingly, reducing *α*-amylase activity. The *α*-amylase inhibitory activity might also be related to the molecular weight, monosaccharide composition and chemical structure of SDF, which requires further research and verification.

Cholesterol absorption capacity

The absorption capacity of SDF samples to cholesterol was performed by simulating the stomach (pH = 2) and small intestine (pH = 7) environments, the results are displayed in Fig. 6. Except A-SDF, absorption capacities of SDF samples at pH 7 were significantly higher than those at pH 2. It was generally believed that the intestinal tract was the primary place for the digestion and absorption of nutrients, where SDF could fully exert the function of reducing cholesterol uptake (Rideout et al. 2008). However, the cholesterol absorption capacity of different SDF samples at the same pH varied greatly. KGM, A-SDF, F-SDF and P-SDF showed higher absorbing capacity to cholesterol, which was most likely attributed to high expansibility. The volume of SDF increased after swelling, which improved contact area between fibers and cholesterol, thereby promoting the absorption to cholesterol. Among these SDF samples, KGM exhibited the highest effect on cholesterol absorption, with 44.94 mg/g at pH 7 and 40.35 mg/g at pH 2. This might be due to that the viscosity of KGM solution was the highest, which had the highest ability to limit the diffusion of cholesterol.

Conclusion

In this study, structural properties, physicochemical properties, *α*-amylase inhibitory activity and cholesterol absorption capacity of SDFs derived from konjac, apple, chicory, flaxseed, orange, psyllium seed, soybean and oat were systematically evaluated and compared. The results showed that the molecular weight of KGM was the highest, while that of inulin was the lowest. FIIR analysis revealed that these fibers had typical absorption peaks of carbohydrates. Inulin, S-SDF and OA-SDF displayed the better water solubility, and KGM, A-SDF, F-SDF and P-SDF exhibited better water-holding capacity, swelling capacity and emulsifying activity, which could be applied in flour, dairy and meat products to improving texture and sensory. Rheological analysis showed that all SDF solutions belonged to pseudoplastic fluids with shear thinning phenomenon, and KGM solution had the highest viscosity. Texture profile analysis suggested that KGM was the easiest to form gel, because it was more likely to form a stable spatial network structure for its high molecular weight and molecular chain. Moreover, A-SDF and O-SDF effectively inhibited *α*-amylase activity, while KGM and F-SDF exhibited higher cholesterol absorption capacity, testifying their potential to prevent chronic diseases. Based on above-mentioned results, SDFs can be selected according to their properties to produce SDF-rich foods with higher consumer acceptability and health benefits.

Declarations

Author Contribution Xiaoqiang Zou and Xiuli Xu designed the experiment, finished the study, collected test data, and drafted the original manuscript. Zhonghao Chao provided critical comments on draft of manuscript. Lei Zheng and Bangzhi Jiang revised the manuscript.

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Data Availability The data of the experiment are available upon request.

Conflict of Interest The authors declare no competing interests.

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Figures

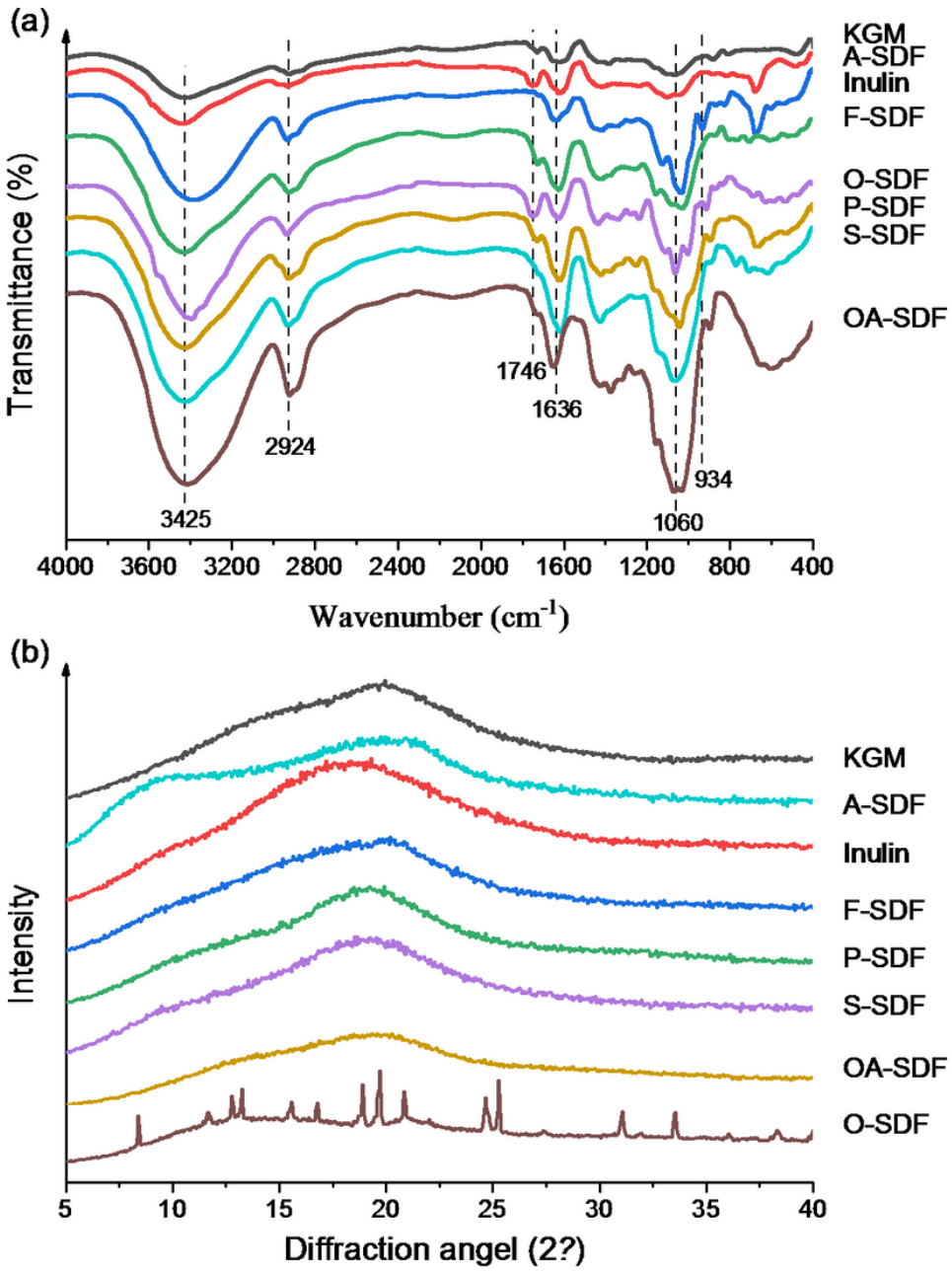

Figure 1

(a) FTIR spectra and (b) XRD patterns of SDF samples. (KGM, konjac glucomannan; A-SDF, apple soluble dietary fiber; F-SDF, flaxseed soluble dietary fiber; O-SDF, orange soluble dietary fiber; P-SDF, psyllium seed soluble dietary fiber; S-SDF, soybean soluble dietary fiber; OA-SDF, oat soluble dietary fiber).

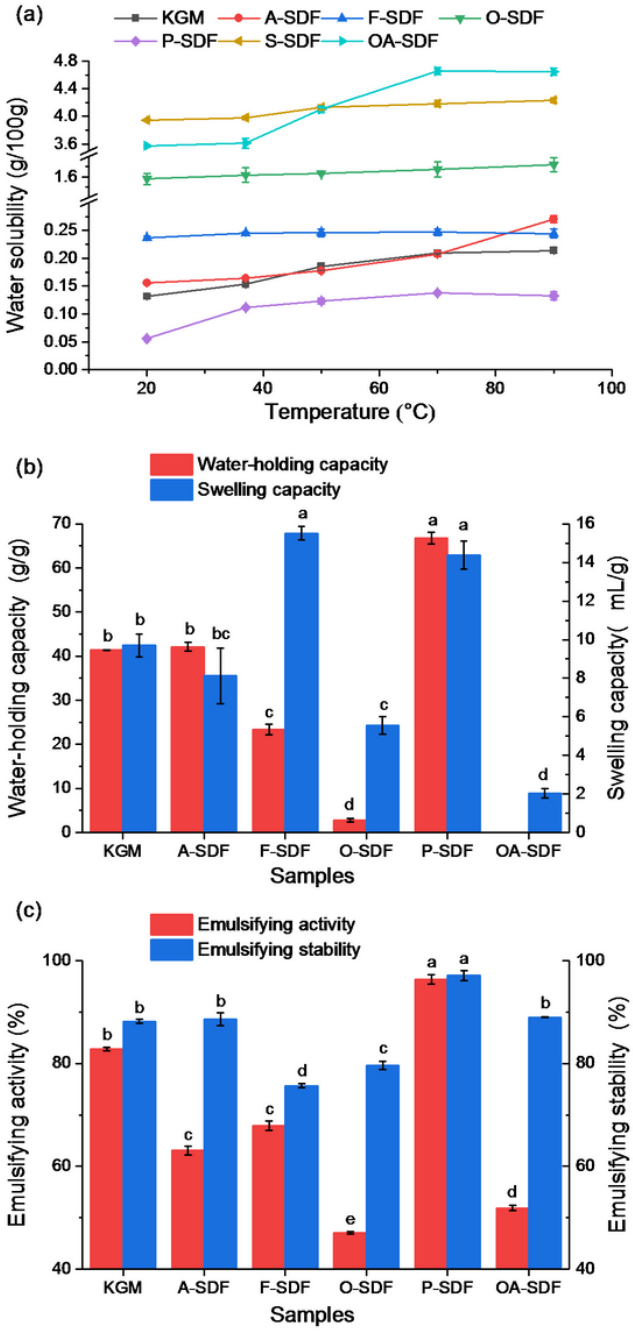

Figure 2

Hydration properties of SDF samples: (a) water solubility under different temperature, (b) water-holding capacity and swelling capacity, and (c) emulsifying activity and stability. Bars with different letters are significantly different ($p < 0.05$). (KGM, konjac glucomannan; A-SDF, apple soluble dietary fiber; F-SDF, flaxseed soluble dietary fiber; O-SDF, orange soluble dietary fiber; P-SDF, psyllium seed soluble dietary fiber; S-SDF, soybean soluble dietary fiber; OA-SDF, oat soluble dietary fiber).

Figure 3

(a) Viscosity of SDF solution under different concentrations at 25 °C, and (b) steady shear flow curves of 5% SDF solution at 25 °C. (KGM, konjac glucomannan; A-SDF, apple soluble dietary fiber; F-SDF, flaxseed soluble dietary fiber; O-SDF, orange soluble dietary fiber; P-SDF, psyllium seed soluble dietary fiber; S-SDF, soybean soluble dietary fiber; OA-SDF, oat soluble dietary fiber).

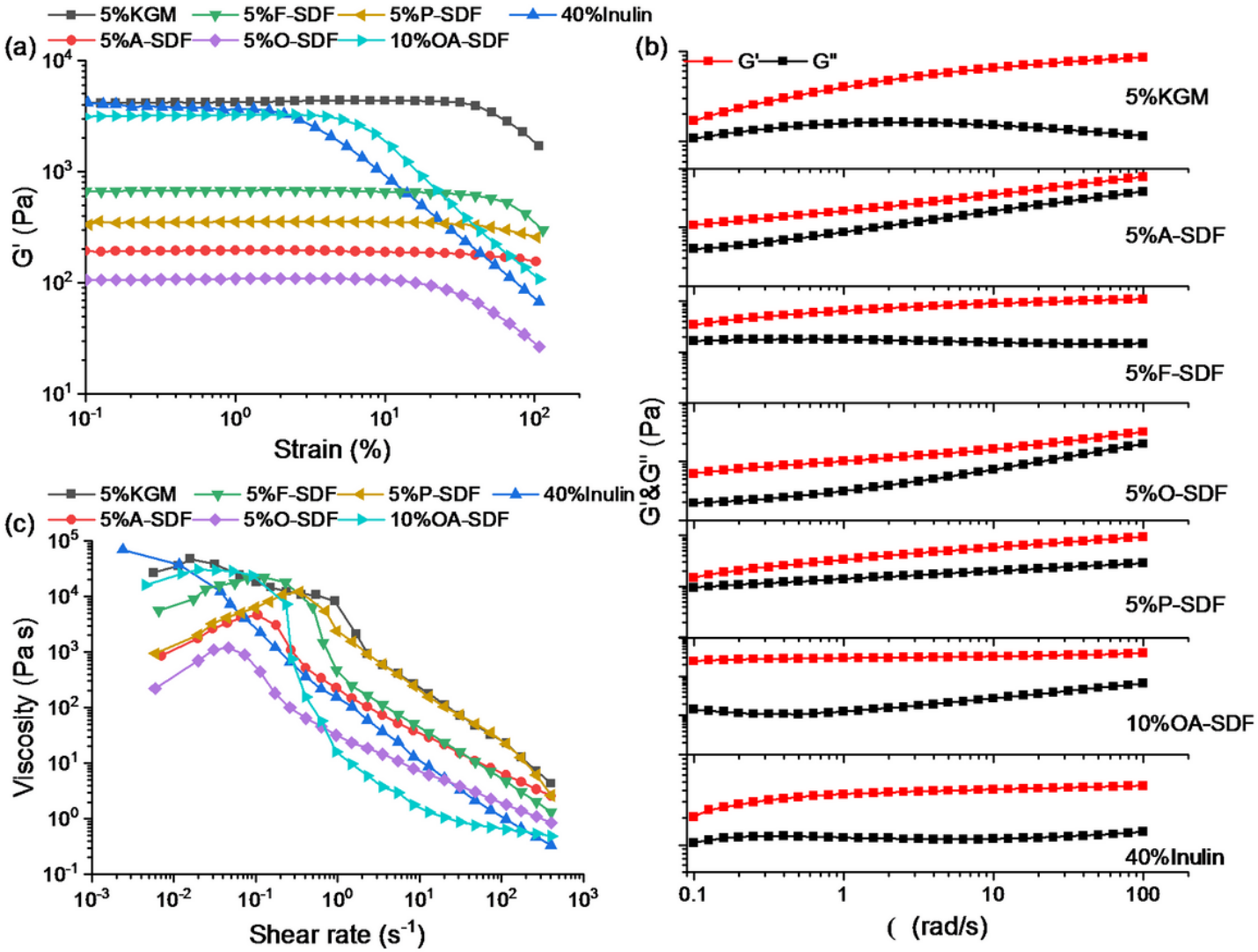

Figure 4

Dynamic rheology and steady shear flow curves of gels with different SDF samples: (a) G' vs strain (ω = 1 rad/s, T = 25 °C), (b) G', G" vs frequency (strain = 1%, T = 25 °C), and (c) viscosity vs shear rate (T = 25°C). (KGM, konjac glucomannan; A-SDF, apple soluble dietary fiber; F-SDF, flaxseed soluble dietary fiber; O-SDF, orange soluble dietary fiber; P-SDF, psyllium seed soluble dietary fiber; OA-SDF, oat soluble dietary fiber; G', storage modulus; G", loss modulus).

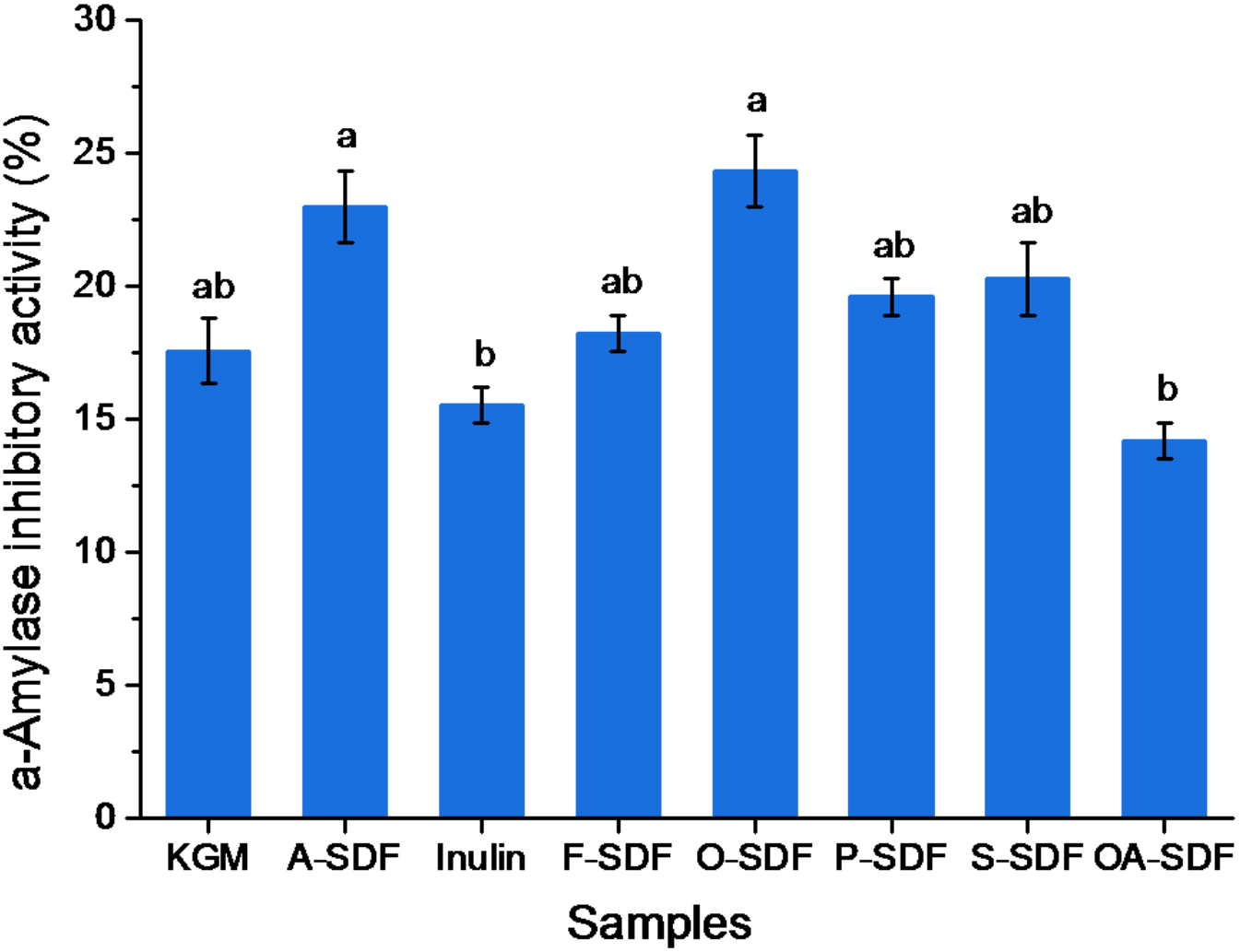

Figure 5

α-Amylase inhibitory activity of SDF samples. Bars with different letters are significantly different ($p < 0.05$). (KGM, konjac glucomannan; A-SDF, apple soluble dietary fiber; F-SDF, flaxseed soluble dietary fiber; O-SDF, orange soluble dietary fiber; P-SDF, psyllium seed soluble dietary fiber; S-SDF, soybean soluble dietary fiber; OA-SDF, oat soluble dietary fiber).

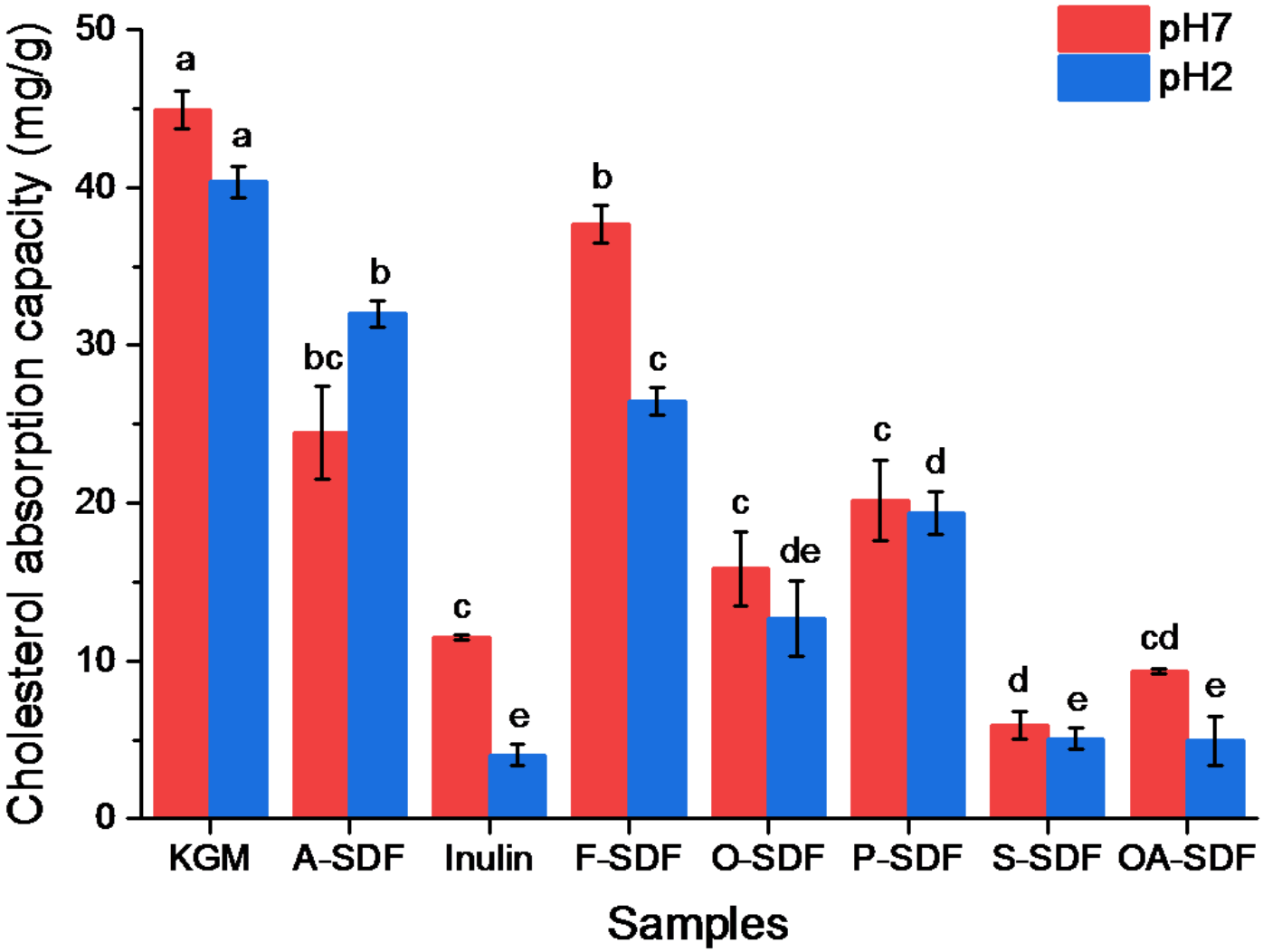

Figure 6

Cholesterol absorption capacity of SDF samples at pH 7 and pH 2. Bars with different letters are significantly different ($p < 0.05$). (KGM, konjac glucomannan; A-SDF, apple soluble dietary fiber; F-SDF, flaxseed soluble dietary fiber; O-SDF, orange soluble dietary fiber; P-SDF, psyllium seed soluble dietary fiber; S-SDF, soybean soluble dietary fiber; OA-SDF, oat soluble dietary fiber).