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Effect of milling and defatting treatment on texture and digestion properties of oat rice

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ABSTRACT

Oat rice with great sensory acceptance was developed based on the combination method of milling and defatting (petroleum ether) treatment. In this study, the effect of milling and defatting treatment on the texture and digestion properties of oat rice was investigated. Results showed that milling and defatting treatment enhanced stickiness, enthalpy, and starch digestibility. The pasting temperature and hardness of oat rice were reduced. The lipid content of oat rice was significantly reduced by milling and defatting treatment, leading to a decrease in the formation of starch-lipid complex. Fourier transform infrared spectroscopy and X-ray diffraction analyses revealed that the application of milling and defatting treatments led to a reduction in the content of starch-lipid complexes in oats during the cooking process. Milling and defatting significantly enhanced both the rapid and slow digestion rates of oat rice. Specifically, the rapid digestion rate was found to be 2.5 times higher than the slow digestion rate. The nutritive components of oat rice were properly preserved, and the viscosity and elasticity of oat rice reached the maximum when milling for 40 s and defatting. This study provides a theoretical basis for oat products.

1. Introduction

Oat (*Avena sativa*) is an annual herb of the Gramineae avena oat. As a worldwide cultivated crop, oat is well known for its rich nutrients (Zhu et al., 2020). In oats, starch is the main content, accounting for about 60 %, followed by fiber (17 % ~ 21 %), protein (13 % ~ 20 %), and oil (2 % ~ 12 %) (Aro, Jarvenpaa, Konko, Huopalahti, & Hietaniemi, 2007). In addition, oats also contain active substances such as β-glucans (2 % ~ 7.5 %) and polyphenols (Mirmoghtadaie, Kadivar, & Shahedi, 2009). Oats have a significant effect on preventing obesity, hypertension, hyperlipidemia, and hyperglycemia (Izydorczyk & Dexter, 2008). Oats are favored by consumers for their high nutritional value. Oats are often added to dough, noodles, biscuits, bread, and yogurt to improve nutrient absorption because oats have a poor taste when cooked and roasted (Bruckner-Guhmann, Vasil'eva, Culetu, Duta, Sozer, & Drusch, 2019; Zou, Wang, Zhang, Peng, Ma, & Hu, 2023). In Western countries, oatmeal is more popular as a meal replacement. According to the dietary preferences observed in China, rice, porridge, steamed bread, and noodles are considered staple foods in our country. In the process of cooking, naked oats have some problems, such as long cooking time, firm taste, and poor viscoelasticity. Hence, investigators have developed some methods to improve oats' processing properties and taste.

Milling is a commonly used method in grain processing to remove the hard shell and other fibrous tissue on the outer surface of the grain, properly retain nutrients, and improve the taste of the grain (H. Y. Li et al., 2021). Milling can increase the whiteness of oat rice and effectively improve the color of oat products, which is more conducive to consumer acceptance. Some studies have shown that milling can augment the amount of rice solid extract dissolved, and the amylopectin content in the solid is positively correlated with the viscosity of rice (H. Y. Li et al., 2021). Milling effectively removes the bran layer of rice, reduces processing time, increases water absorption and swelling, and improves texture. Oat rice contains a lot of starch (about 60 %). During boiling, oat starch absorbs water and swells. The structure of the starch is closely correlated with cereal processing and palatability. Studies have shown that milling can reduce the rapidly digestible starch (RDS), and increase the resistant starch (RS) content of brown rice starch, thus affecting the starch digestion rate (F. Li, Guan, & Li, 2021).

Oat rice has the characteristics of high oil content and poor storage performance, which is the main problem in the application of oat

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products. Oats contain large amounts of polyunsaturated fatty acids, which undergo drastic lipid oxidation reactions during storage. Lipid oxidation during storage can cause adverse effects such as unpleasant odor and food safety issues (Huang, Huang, Guan, Zhang, & Zhang, 2022). There are many methods used to pretreat oat flour to delay lipid oxidation, such as superheated steam, extrusion, and microwave, which inactivate or reduce the activity of many enzymes. However, high-temperature treatment can change the microstructure and functional properties of oat rice nutrients and affect the quality of oat rice (Jia, Yang, Guo, & Zhu, 2021). Food processing enhances the sensory attributes, such as flavors, textures, and appearance of products, while also improving their overall properties (Utpott, Rodrigues, de Oliveira Rios, Mercali, & Flôres, 2022). Metabolomics techniques offer a comprehensive analysis of the nutritional value and sensory characteristics of food items. The integration of metabolomics technology plays a pivotal role in establishing the intricate relationship between food quality and processing methods (Diez-Simon, Mumm, & Hall, 2019). Gas chromatography-mass spectrometry (GC–MS) is commonly employed to identify volatile substances in food samples and investigate the key factors influencing aroma components (S. Li, Tian, Jiang, Lin, Liu, & Yang, 2021). Previous studies have shown that defatting oat flour reduces the fat oxidation reaction (Liu et al., 2019). At the same time, oat rice by-products were processed and utilized through concentration and refining to prepare oat oil products. Over the past few years, investigators have studied the interaction between oat starch and oat fat and observed their effects on the physical and chemical characteristics of oat flour. Research has shown that oat lipids are negatively associated with the peak viscosity and storage modulus of oat flour (Y. T. Li, Obadi, Shi, Xu, & Shi, 2021). Starch-lipid complexes are formed during the processing of starch and oil in oats, which affects the texture and digestibility of oats (Chao, Huang, Yu, Copeland, Wang, & Wang, 2020). Milling and defatting are milder than microwave or superheated steam and have less effect on grain structure.

At present, milling and defatting treatment oat rice are popular with consumers. However, the impacts of milling and defatting treatments on the texture and starch digestion of oat rice are not well understood. This paper mainly researched the effects of defatting treatment on the texture and gelatinization characteristics of oat rice with different milling degrees. Scanning electron microscope (SEM), fourier transform infrared (FTIR) spectroscopy, Rapid Visco Analyzer (RVA), differential scanning calorimeter (DSC), and rheology were accustomed to analyzing the changes in microstructure, crystalline structure, gelatinization properties, and viscoelasticity of oat rice with different milling and defatting treatments. Combined with the changes in water absorption and swelling and water migration of oat rice during cooking, the mechanism of milling and defatting method on the texture and starch digestion of oat rice was explored. To provide theoretical guidance and basis for oat rice in food processing and sensory acceptance. Regarding the persisting issue of residual petroleum ether, it has been observed that immersing degreased oat rice in anhydrous ethanol can effectively eliminate any remaining traces of petroleum ether due to its solubility in ethanol.

2. Materials and methods

2.1. Materials

The milling oat rice was made in the laboratory (Shen et al., 2023). Amylose/amylopectin, β-glucan, and total starch kits were purchased from Megazyme International Ireland Ltd. (Bray Co., Wicklow, Ireland). In this experiment, all chemical reagents were at least analytical grade.

2.2. Milling and defatting treatment and sample preparation

Preparation of oat rice: Petroleum ether (boiling point: 30 ℃~60 ℃) was added according to the ratio of solid to liquid is 1:3 (w/v, g/mL) and placed in a closed container for 4 days (temperature 25 ℃), and the oat rice was soaked in anhydrous ethanol for three times and cleaned for 0.5 h each time (Petroleum ether and ethanol are subjected to rotary evaporation for distillation and subsequent recovery). The oat rice was placed in an oven at 45 ℃ for 48 h and stored in a sealed bag at 4 ℃. The different degrees of milling and defatting (DOMD) treatment samples prepared were named DOMD-0, DOMD-20, DOMD-40, DOMD-60, and DOMD-80, respectively (milling time was 0 s, 20 s, 40 s, 60 s, and 80 s, and rate of milling was 0.00 %, 15.63 % ± 0.60, 35.41 % ± 0.39, 53.75 % ± 0.19, and 69.54 % ± 0.40, respectively). The oat rice milled sample utilized in this paper was subjected to processing methods established in prior published research (Shen et al., 2023). After drying, the defatted oat rice was ground, screened at 100 mesh, transferred to hermetic bags, and stored at 4 ℃.

2.3. Composition, water absorption index (WAI), and swelling power (SP) analysis of milled and defatted oat rice

The amounts of protein and oil were measured using the Kjeldahl method and Soxhlet extraction method, respectively (Dewanto, Wu, Adom, & Liu, 2002). Corresponding kits were used for total starch, β-glucan, and amylose (Huang et al., 2022; McCleary & Codd, 1991).

Add oat rice and distilled water at a 1:15 (w/v, g/mL) ratio. After 10 min at 95 ~ 100 ℃ and 10 min in the ice water bath, centrifuge at 7000 × g for 10 min and record the weight of dry supernatant and precipitation (F. Li et al., 2021):

$$\mathrm{SP}\ (\mathrm{g/g}) = \frac{W_1}{W_2\text{-}W_3}$$

$$\mathrm{WAI}\ (\mathrm{g/g}) = \frac{W_1}{W_2}$$

Where W_1 is residual solids weight, W_2 is oat rice weight, and W_3 is dry supernatant weight.

2.4. SEM and FTIR

The oat rice samples were randomly selected for SEM analysis. In brief, the cross-sections of oat rice were observed at an accelerating voltage of 30 kV (500 ×) by SEM (TM-1000, Hitachi, Japan) as described previously (N. Wang, Wu, Zhang, Kan, & Zheng, 2022).

FTIR spectrometers (Nicolet IS10, Thermo Fisher Scientific, Waltham, MA, USA) were accustomed to measuring the milling and defatting treatment of oat rice. The oat rice powder was mixed with KBr and then pressed for test scanning (400 cm^{-1} ~ 4000 cm^{-1}) analysis (Su et al., 2020).

2.5. X-ray diffraction (XRD) analysis

XRD (D2 Phaser, Bruker-AXS, Germany) was used to determine the crystal structure of the sample. The scanning area of the diffraction angle (2θ) was 3° ~ 4° and the scanning rate was 2°/min (Su et al., 2020).

2.6. Pasting and thermal properties

The pasting characteristic was determined by the RVA (TecMaster, Perten Instruments, NSW, Australia) analyzer. Accurately weigh 3 g (dry basis) sample mixed with distilled water to control the total weight of the sample and distilled water to 28.0 g. Heating procedure: temperature 50 ℃ for 1 min, then heating at 12 ℃/min to 90 ℃, holding at 90 ℃ for 2.5 min, then cooling at 12 ℃/min to 50 ℃, holding at 50 ℃ for 2 min. The first 10 s is 960 rpm, and the rest is 160 rpm. Each sample was analyzed in duplication (Su et al., 2020).

The thermal properties of oat rice were determined by DSC (200F3, Netzsch, Germany). Place 3.0 mg (dry base) and 6 μL of deionized water in a crucible. At 25 ℃ equilibrium for 12 h, the heating rate is 5 °C/min from 30 °C to 100 °C. Record onset temperature (T_o), peak temperature (T_p), conclusion temperature (T_c), and enthalpy (ΔH) (Abdel-Aal, Hernandez, Rabalski, & Hucl, 2020).

2.7. Determination of rheological properties

A rheometer (DISCOVERY HR-3, USA) was used to measure the rheological characteristics of oat rice. The viscosity of the oat rice was determined in the shear rate range of 0.1 s^{-1} ~ 100 s^{-1}. The oscillating frequency is scanned, the storage modulus (G') and loss modulus (G″) are recorded as a function of the angular frequency (0.1 rad/s ~ 100 rad/s), and the strain is 5 % (Y. T. Li et al., 2021).

2.8. Transverse relaxation time (T_2) measurement

The water distribution of cooked oat rice under different milling and degreasing treatments was surveyed by a low-field nuclear magnetic resonance (LF-NMR) spectrometer (Niumag Co., Ltd., Shanghai, China). The instrument parameter settings are the same as in the previous manuscript (Shen et al., 2023). CPMG sequence parameters are set as spectrometer frequency (SF) 23 MHz, offset frequency (O1) 312.3755 kHz, 90° pulse time P90 14 μs, 180° pulse time P180 28 μs, number of sampling points (TD) 40020, repeated sampling waiting time (TR) 4500 ms, scanning number (NS) 64, echo time (TE) 200 μs, echo number Echo Count 1000, analog gain (RG) 20.0 dB, digital gain (DRG) 3.

2.9. Total solids leached analysis from cooked oat rice with milling and defatting treatment

The extraction of the total solids leached was slightly modified according to the previous research method (F. Li et al., 2021). The oat rice was washed three times with distilled water to remove any remaining bran and other adhesive substances. Then weighing exactly 2.5 g oat rice was put into a 25 mL beaker, added distilled water was at 1:6 (w/v, g/mL), and cooked for 60 min in an induction cooker (1600 W). The surface substance of cooked oat rice was rinsed with 50 mL hot distilled water (about 95 ℃) three times, and filtered through a 250 μm sieve to collect the extracted substance. Solids leached were freeze-drying and stored at −4 ℃. The method for determining the content of components in the solids leached is the same as that in 2.3.

2.10. Texture profile analysis (TPA)

The oat rice was accurately weighed at 2.5 g and mixed with distilled water by a solid–liquid ratio of 1:6 (w/v, g/mL). Induction cooker 1600 w cooked for 60 min, and the top and bottom layers of oat rice were abandoned, and the rest of the oat rice was mixed for determination.

TPA (TA-XT2i, Shanghai Bosin Industrial Development Co., Ltd, Shanghai, China) determination using a P/36R cylindrical probe. TPA program settings are the same as in the previous manuscript (Shen et al., 2023). Pre-test speed 10.0 mm/s, Test speed 1.0 mm/s, Post-test speed 1.0 mm/s, Target mode Strain, Strain 75 %, Time 5.0 s, Trigger force 5.0 g.

2.11. In vitro digestion of cooked oat rice

The effect of digestibility of starch *in vitro* was determined by the glucose oxidase/peroxidase reagent (GOPOD) enzyme chromogenic method. After oat rice flour was hydrolyzed by trypsin and starch glycoside enzyme. Starch digestibility was detected at different digestion times (0, 5, 10, 15, 20, 30, 45, 60, 90, 120, 180, 240, and 300 min). For specific operations refer to references (F. Li et al., 2021; Shen et al., 2023).

2.12. Logarithm of slope plot (LOS) and combination of parallel and sequential digestion kinetics (CPS) analysis

The results show that the LOS logarithm formula can be used to fit the starch digestion map (Butterworth, Bajka, Edwards, Warren, & Ellis, 2022).

$$ln\frac{dC_t}{dt} = \ln(C_\infty - C_0) - kt$$

C_t is the starch fraction digested at time t (min), while C_0 is the starch fraction digested at t = 0. C_∞ is the estimated maximum starch digestibility, and k is the digestion rate constant.

The LOS curve can determine the number of starch components with different digestible rate constants. The CPS model can distinguish various digestive patterns in the starch digestive system (Butterworth et al., 2022; C. Li & Hu, 2020).

$$C(t) = C_0 + (C_{\infty1}) \times \left(1 - e^{-k_1 t}\right) + \mathrm{If}\left(t \geq t_{2start}, \left((C_{\infty2}) \times \left(1 - e^{-k_2(t - t_{2start})}\right)\right), 0\right)$$

In the formula, k_1 and k_2 are the two starch digestion rate constants, and $C_{\infty1}$ and $C_{\infty2}$ represent the maximum starch digestibility of the two starch components, respectively. t_{2start} is the beginning time for the digestion of the second starch.

2.13. Statistical analysis

All data results in this paper are represented by mean ± SD. SPSS software was employed for conducting variance and correlation analyses. Statistical significance was determined at a $p < 0.05$, indicating the presence of significant differences. Origin 2021 was used for drawing.

3. Result and discussion

3.1. Oat rice composition, WAI, and SP analysis

Milling removed the seed coat and destroyed the aleurone layer. Defatting oat rice with petroleum ether was beneficial to removing oat rice oil. It can be seen from Table S1 that milling and defatting could effectively reduce the oil content in oat rice, especially the greater the DOM, the easier the oil removal. Compared to the DOMD-0, there were no statistically significant differences in oil content of DOMD-20 and DOMD-40. This lack of significance can be attributed to the limited degree of milling, resulting in minimal damage to the oat seed coat and aleurone layer. Consequently, this limited damage hinders the effective immersion of petroleum ether. Oil and β-glucan were distributed in the seed coat, and starch and protein were distributed in the aleurone layer and endosperm (H. Y. Li et al., 2021). The levels of starch and β-glucan exhibited a gradual increase, while protein initially showed an increment followed by a subsequent decline. Additionally, an alteration was observed in the amylose/amylopectin ratio (Sandhu, Singh, Kaler, Kaur, & Shevkani, 2018). The content of β-glucan increased slowly due to the uneven milling of the seed coat and aleurone layer of oat rice.

Milling and defatting can significantly increase the WAI and SP of oat rice during cooking (Table S2). Compared to DOMD-0, the WAI of DOMD-20, DOMD-40, DOMD-60, and DOMD-80 exhibited significant increases of 40.82 %, 48.47 %, 64.80 %, and 98.47 % respectively. Similarly, when compared with DOMD-0, the SP values for DOMD-20, DOMD-40, DOMD-60, and DOMD-80 demonstrated substantial enhancements of 43.48 %, 50 %, 63.59 %, and 101.63 % correspondingly. When the milling time is 20 s and 40 s, the defatting treatment does not significantly affect the WAI and SP of oat rice. This can be attributed to a similar level of damage inflicted on the seed coat and aleurone layer of oats after milling for 20 s and 40 s. Consequently, no significant differences were observed in terms of oil content, WAI, and SP indices of oat rice. Milling and defatting oat rice is conducive to water entry during cooking. Meanwhile, starch has more gelatinization and expansion space (F. Li et al., 2021).

3.2. Oat rice SEM analysis

As depicted in Fig. 1, the cross-sectional SEM images exhibit the impact of milling and defatting treatments on oat rice. It is evident from the visual representation that milling treatment disrupts the seed coat and aleurone layer, while defatting treatment induces pore formation alongside oil removal. Compared with DOMD-0, DOMD-20, DOMD-40, DOMD-60, and DOMD-80, the oat rice aleurone layer was damaged more severely, and the pores were noticeable. The aleurone layer was more conducive to forming pore channels of petroleum ether on the surface of oat rice (H. Y. Li et al., 2021). With the increase of DOM and defatting treatment, the roughness of the surface area of oat rice was more remarkable, and the damage was more serious. Moreover, the WAI and SP in the cooking process of oat rice were increased, which was consistent with the results in Table S1.

3.3. Oat rice FTIR analysis

Fig. 2 (a) shows FTIR spectra of oat rice milling and defatting. The characteristic absorption peak at 2850 cm^{-1} is caused by the asymmetric tensile vibration of the fatty acids –CH_3 and –CH_2. The characteristic absorption peak at 1750 cm^{-1} is due to the vibration of fatty acid C=O, and the peak shift is due to the formation of hydrogen bonds between the C=O of the fatty acid and the –OH of amylose in the sample (Q. Li, Dong, Gao, Du, Li, & Yu, 2021). When the degree of milling and defatting increased, the absorption peaks at 1735 cm^{-1} and 2850 cm^{-1} showed a decreasing trend. Previous research has shown that the starch-lipid complex can affect the texture and pasting characteristics of oat rice. The defatting treatment decreased the oil and starch-lipid complex content in oat rice (Y. T. Li et al., 2021). The formation of a stable starch-lipid complex between starch and oil can increase the structural order of oat starch, restrict its swelling capacity, and augment the resistance to enzyme digestion of oat rice (Y. Zhang et al., 2023). No new absorption peaks appeared and disappeared in the spectrogram, indicating no chemical change in oat rice during milling and defatting procedures.

3.4. Oat rice crystalline structures analysis

Fig. 2 (b) shows that the milling and defatting oat rice starch had special diffraction peaks at 15°, 17°, 18° and 23°, which is the typical A-type crystalline structure. There were weak diffraction peaks at 12.8° and 19.8°, and the nearby peaks showed a V-type structure as starch-lipid complexes (Y. T. Li et al., 2021). Oats contain a lot of starch and oil, which can form resistant starch in natural grains. With the milling and defatting treatment, the crystallinity at 20° gradually decreased (Table S3), and the starch-lipid content gradually reduced. There may be two reasons for this: the starch-lipid complex is also known as RS. Milling destroys the seed layer and aleurone layer of oat rice kernels, reducing the content of RS (Zhen et al., 2022); the reduction of oil content in oat rice reduces the presence of starch-lipid complexes (Chao et al., 2020). The findings were in line with the outcomes obtained from FTIR analysis.

3.5. Oat rice pasting properties analysis

Pasting characteristics of oat rice after milling and defatting (Table 1). With the increase of milling and defatting degree, the peak viscosity, trough viscosity, breakdown viscosity, and final viscosity enhanced significantly ($p < 0.05$), the pasting time was increased from 6.14 min to 6.40 min, and the pasting temperature was reduced from 67.00 ℃ to 59.20 ℃ ($p < 0.05$). The peak viscosity of starch is affected by the swelling force of water absorption. The oil and starch in oat rice formed a starch-lipid complex (Chao et al., 2020). Some studies have shown that the peak viscosity of corn starch decreased when mixed with 10 % corn oil (Ai, Hasjim, & Jane, 2013). The starch-lipid complex can inhibit the WAI and SP of starch particles, thus affecting starch pasting. The breakdown viscosity showed a trend of first decreasing and then increasing, while the setback viscosity was the opposite. Along with the decrease in oil content, the decrease of setback viscosity in oat rice was attributed to the increase in β-glucan content during milling and defatting treatments, and the increase in setback viscosity was attributed to the enhanced rebinding of amylose. Under heating conditions, a stable starch-lipid complex between starch and lipid is formed in oat rice (X. B. Li, Luo, Hou, Liu, Hu, & Liu, 2020). The starch-lipid complex will reduce the WAI and SP of starch particles, increase the pasting temperature, and decrease the pasting (Gomez-Aldapa, Velazquez, Gutierrez, Castro-Rosas, Jimenez-Regalado, & Aguirre-Loredo, 2020).

3.6. Oat rice thermal properties analysis

The thermal properties of milled and defatted oat rice samples were tested by DSC, and the results obtained for the T_o, T_p, T_c, and ΔH of the endothermic peak are shown in Table 1. The sample had an absorption peak at 63 ℃, which was the result of starch gelatinization. As the degree of milling and defatting increased, the T_o did not decrease significantly, and ΔH increased significantly and slowly ($p > 0.05$). The decrease in oil content and the increase in ΔH value in the sample may be related to the content of starch-lipid complexes. A lesser extent may reflect the change of order degree of the internal structure of the starch-lipid complex. T_p can reflect the structural stability and gelatinization resistance of starch particles, and the crystallinity inside starch particles can be reflected by pasting temperature range (ΔT) (Su et al., 2020). As milling and defatting treatments increased, ΔT increased, indicating that both milling and defatting treatments improved the uniformity or perfection of the grains, thereby limiting the hydration/plasticization of the crystals. ΔH can measure the crystallinity of starch in terms of mass and quantity. In addition, it can also reflect the degree of molecular order destruction of hydrogen bond breakage. The principle of starch-lipid complex formation is that the single helical hydrophobic cavity of amylose binds to lipids through hydrogen bonding and hydrophobic force (Y. T. Li et al., 2021). The hydrophobic radical is located on the inner side of the spiral cavity, and the hydrophilic hydroxyl radical is located on the outer side of the spiral cavity. The hydrophobic carbon chain of the lipid is connected with the inner part of the spiral cavity by hydrogen bond and hydrophobic force to form a complex. The formation of starch-lipid complexes was correlated with amylose content and the proportion of lipid content and type (Q. Li et al., 2021; Qin, Yu, Li, Copeland, Wang, & Wang, 2019). In this study, a reduction in the content of the starch-lipid complex was observed, while an upward trend in the thermal stability of oats was demonstrated. Although the protein content of oats surpasses that of β-glucan, it is noteworthy that both starch and β-glucan significantly impact the gelatinization process and thermal properties of oat flour (Grundy et al., 2017). With the augmentation of β-glucan content, oat flour will establish a compact and uninterrupted honeycomb-like network structure, resulting in an elevation in the enthalpy of gelatinization while exhibiting commendable stability (Nguyen, Gilbert, Gidley, & Fox, 2020). It is evident from this study that the β-glucan content significantly influences the thermal stability of oat flour, thereby assuming a prominent role.

3.7. Oat rice viscoelasticity analysis

The changes in the viscoelasticity of oat rice with the milling and defatting treatment were studied using the swept-frequency method. The storage modulus (G') reflects the elasticity of oat rice and its ability to return to its original state after deformation. The loss modulus (G″) represents the viscous ability of oat rice. The Tanδ (G″/G') value represents the viscoelasticity of oat rice. When $\tan\delta < 1$, it indicates that the

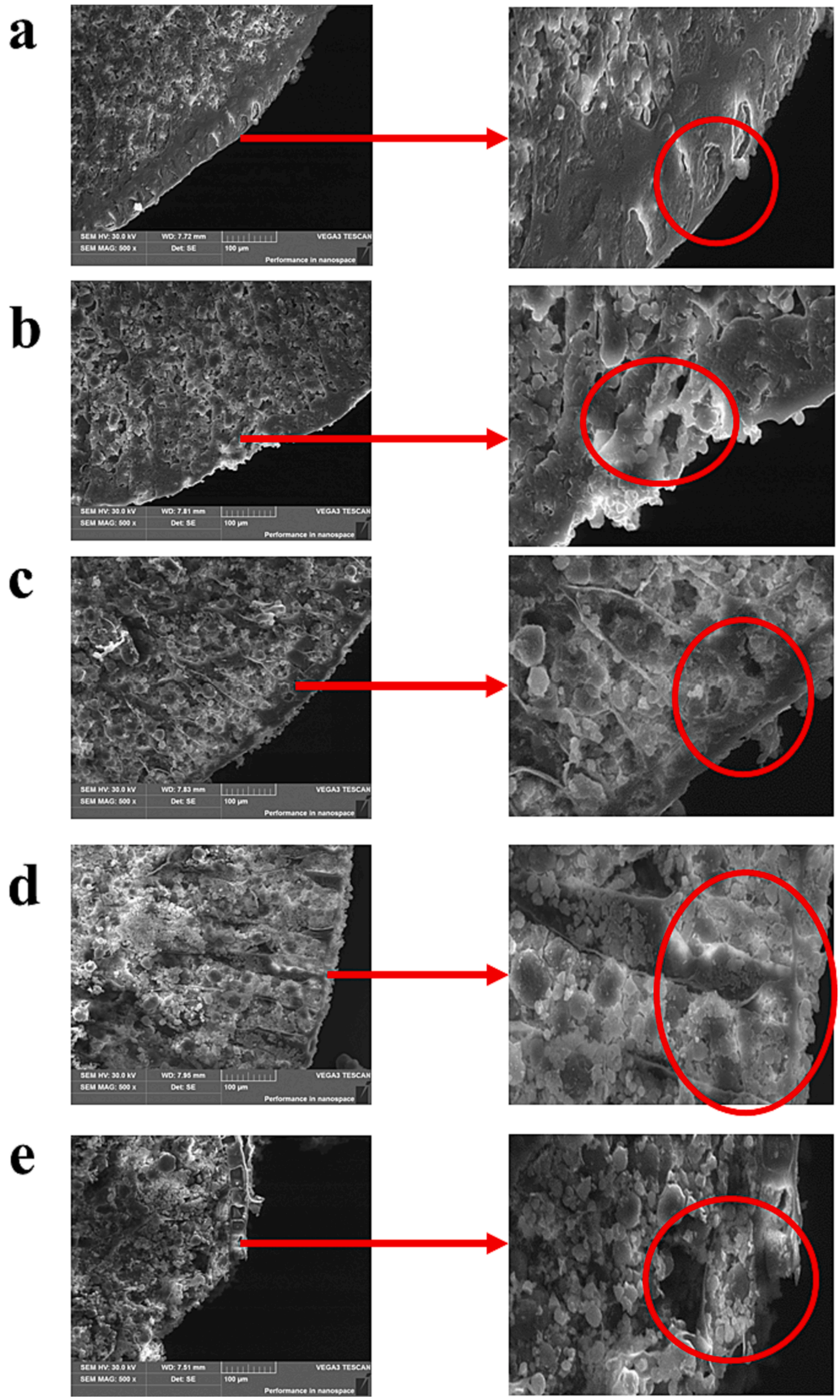

Fig. 1. Observation of cross-section ultrastructure of oat rice by milling and defatting treatment (a: DOMD-0, b: DOMD-20, c: DOMD-40, d: DOMD-60, e: DOMD-80).

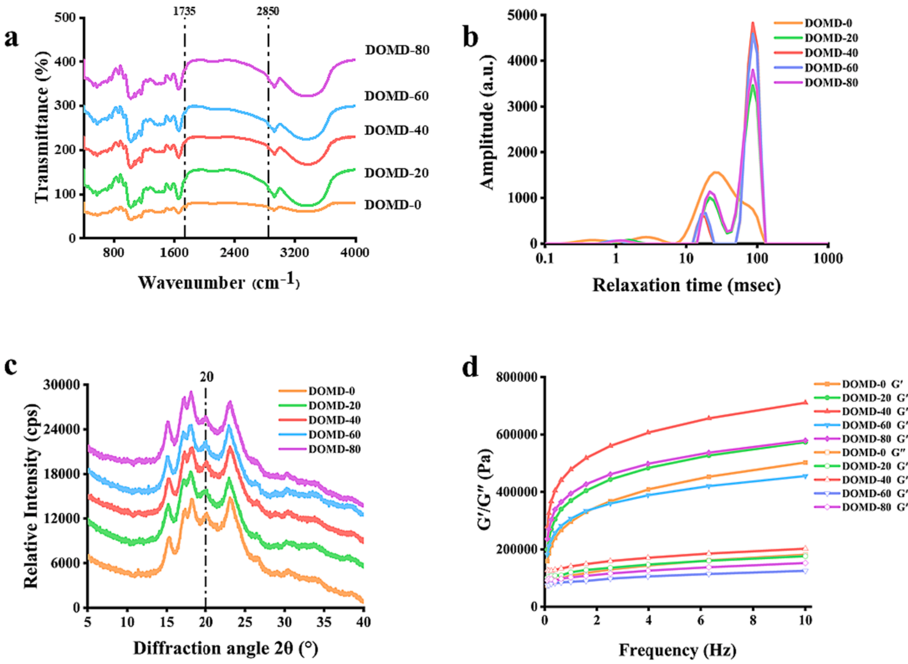

Fig. 2. FTIR (a), proton distribution (b), XRD (c), and viscoelasticity changes (d) of oat rice were analyzed after milling and defatting treatment.

Table 1
Effect of milling and defatting treatment on pasting and thermal properties of milled oat rice.

	Pasting properties							Gelatinization peak			
	Peak viscosity (cP)	Trough viscosity (cP)	Breakdown viscosity (cP)	Final viscosity (cP)	Setback viscosity (cP)	Pasting time (min)	Pasting temperature (°C)	T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)
DOMD-0	1,981.00 ± 11.31[d]	1,229.50 ± 10.61[b]	751.50 ± 0.71[c]	4,171.00 ± 107.48[c]	2,941.50 ± 96.87[b]	6.14 ± 0.09[b]	67.00 ± 0.07[a]	58.18 ± 0.51[a]	63.32 ± 0.51[a]	72.28 ± 0.61[a]	5.59 ± 0.09[b]
DOMD-20	2,723.00 ± 43.84[c]	2,133.00 ± 22.63[a]	590.00 ± 21.21[d]	5,579.00 ± 131.52[a]	3,446.00 ± 108.89[a]	6.57 ± 0.05[a]	61.45 ± 0.64[b]	56.56 ± 0.88[a]	62.98 ± 0.72[a]	72.42 ± 1.55[a]	5.77 ± 0.27[ab]
DOMD-40	2,818.00 ± 22.63[bc]	2,031.00 ± 12.73[a]	787.00 ± 9.90[c]	5,595.00 ± 168.29[a]	3,564.00 ± 155.56[a]	6.47 ± 0.00[a]	60.98 ± 0.04[bc]	56.62 ± 0.65[a]	62.67 ± 0.38[a]	71.58 ± 0.58[a]	5.79 ± 0.31[ab]
DOMD-60	2,851.00 ± 4.24[b]	2,014.50 ± 26.16[a]	836.50 ± 21.92[b]	4,93 0.00 ± 14.14[b]	2,915.50 ± 12.02[b]	6.50 ± 0.04[a]	60.58 ± 0.67[bc]	56.34 ± 0.84[a]	62.54 ± 0.15[a]	72.00 ± 1.45[a]	6.19 ± 0.35[a]
DOMD-80	3,028.00 ± 89.10[a]	2,070.00 ± 117.38[a]	958.00 ± 28.28[a]	4,154.00 ± 164.05[c]	2,084.00 ± 46.67[c]	6.40 ± 0.18[a]	59.20 ± 1.20[c]	56.31 ± 0.99[a]	62.33 ± 0.40[a]	72.08 ± 1.31[a]	6.32 ± 0.13[a]

Note: DOMD-0, DOMD-20, DOMD-40, DOMD-60, and DOMD-80 represent milling times of 0 s, 20 s, 40 s, 60 s, and 80 s followed by defatting. The values of different letters in each column indicated a significant difference between milling and defatting treatment with oat rice ($p < 0.05$).

elasticity of the sample is higher than the viscosity, and elasticity is the main property. With the increase in milling and defatting, oat rice showed a clear increase in G' except for DOMD-60 (Fig. 2c). It is indicated that a decrease in oil content leads to an increased propensity to form gel networks (Y. T. Li et al., 2021; Nguyen et al., 2020). The oat rice showed the strongest viscous behavior when the milling time was 40 s for the defatting treatment, which was in accord with the oat rice RVA results in Table 1. The tanδ value of oat rice decreased significantly, showing the viscoelastic behavior of the dough, and the elastic state gradually increased (Fig. S1). Adding lipids to natural rice and wheat starch gels increases its G'. Milling and defatting treatment, which increases the starch content of oat rice while reducing the oil content, amylose content, and lipid type affect the starch-lipid formation, thereby affecting the elastic behavior (Gu, Qian, Sun, Wang, & Ma, 2023). Monoglyceride in oat oil increases G 'in oat flour, whereas the addition of lecithin or soybean oil to cornstarch reduces G' (Punia et al., 2020).

3.8. Oat rice T_2 analysis

LF–NMR can dynamically monitor the distribution and interconversion of water in oat rice. Fig. 2 (d) shows the inversion spectrum of T_2 of milling and defatting oat rice during cooking processing. The NMR T_2 inversion spectrum of oat rice had three peaks representing three different moisture states of the oat. $Peak_1$, $Peak_2$, and $Peak_3$ represent bound water (T_{21} 0.1 ms − 1 ms), non-flowing water (T_{22} 1 ms − 10 ms), and free water (T_{23} 10 ms − 1000 ms), respectively. As the degree of milling and defatting treatment increased, the T_2 peak shifted to the right, the area of $Peak_1$ and $Peak_3$ decreased, and the area of $Peak_2$ increased (Table S3), indicating that the water content and mobility of boiled oat rice decreased. During the cooking process of oat rice after milling and defatting treatment, the bound water transferred to the non-flowing water, and the non-flowing water moved to the free water. During cooking, water permeates the oat rice kernels, resulting in a decrease in bound and free water content and an increase in non-flowing water content. Water penetrates the center of the rice grain, which contains a high concentration of starch particles, which can be connected to free water by hydrogen bonding (Iskandar et al., 2021). At the same time, the protein is usually located at the periphery of the rice grain, and the surface contains many hydrophilic groups, which have a strong affinity for water (Zhang, Sun, Gao, & Luo, 2022).

3.9. Total solids leached analysis and TPA of oat rice

Starch, protein, and oil are the three main components of oats. Milling and defatting were beneficial to the total solids leached during the cooking process (Table S4). In particular, compared with DOMD-0, the starch content of DOMD-60 and DOMD-80 of total solids leached increased significantly, meanwhile the protein and β-glucan content also increased. Milling destroys the seed coat and aleurone layer of the oat rice. The defatting treatment may form small gaps on the surface of oat rice, which is more conducive to starch, protein, and glucan dissolving out and increasing the viscosity of oat rice (H. Y. Li et al., 2021).

Milling and defatting treatment changed indicators such as hardness, viscosity, chewiness, and elasticity of oat porridge. Table 2 shows the texture characteristics of oat porridge. It can be seen that with the increase of milling and defatting, the hardness, chewing force, and elasticity of oat rice show a significant decreasing trend ($p < 0.05$), while the viscosity increases significantly ($p < 0.05$). As the DOM increased, the seed layer and aleurone layer of oat rice were destroyed, and cellulose, protein, and oil were removed, which reduced the hardness and chewiness of oat porridge. Defatting can reduce the oil content and form tiny pores on the surface of oat rice, which is more conducive to the total solids leached from oat rice during cooking. It has been reported that the content of amylose in solid leaches is positively correlated with the viscosity of rice (H. Y. Li et al., 2021). During cooking, starch pastes form starch-lipid complexes with oil (Y. T. Li et al., 2021). The decrease in hardness and elasticity of oat rice may be due to the regeneration and complexity of the starchy-lipid complex. Starch and protein undergo hydrophobic, hydrogen bonding, and electrostatic interactions during food processing to form a starch-lipid complex. The presence of a larger mesh composed of protein and starch molecules within the gel network significantly influences the textural properties of food products (J. Wang et al., 2021). Simultaneously, the augmentation of β-glucan concentration will diminish hardness and augment elasticity (Nguyen et al., 2020).

3.10. Oat rice in vitro starch digestion analysis

Fig. 3 (a) shows the digestion curve of oat rice under different milling and defatting treatments. The digestion curves all show exponential growth, where 0–30 min is the rapid digestion fraction (RDF). After the digestion time of 120 min, the digestibility of starch slowly reached the maximum. All the samples showed high starch digestibility (more than 90 %), this phenomenon was caused by the destruction of the starch crystal structure during the cooking process. Milling and defatting treatment increased the final starch digestibility of oat rice, and the digestion rate was increased. It has been pointed out that milling will destroy the bran layer of brown rice, increase the WAI of brown rice, starch gelatinization, and the distance between starch molecules, which will increase the digestibility of brown rice (F. Li et al., 2021; Shen et al., 2023). This study may be due to the high amount of oil contained in oats, and the soaking and defatting operation after milling treatment, while effectively removing oil, will also change the distribution of oat oil (Zhen et al., 2022). During the cooking process, the amount of amylose–lipid complexes formed by starch and oil decreases, increasing the rate of starch digestion (Sun et al., 2021).

Researchers often use first-order kinetic models to evaluate the digestive system of starchy food systems. To visually observe the difference between milling and defatting treatment on the digestive process of oat rice, LOS and CPS kinetic models were used for fitting calculation. The CPS digestive kinetics model can be used to analyze the digestion of food systems containing multiple starch components. Sequential digestion patterns are generally applicable to food systems containing a protective layer with an outer layer with an RDF and an inner part with a slow digestion fraction (SDF) (Zhen et al., 2022). In this case, SDF does not begin to digest until the RDF is fully digested (X. X. Wang, Lao, Bao, Guan, & Li, 2021). The parallel digestion mode is usually used in systems with two starch fractions and different simultaneous starch digestion rate constants (Huang et al., 2022). There are two continuous components in the digestion process of oat rice starch, and the starch digestion rate is different in Fig. 3 (b ~ f). According to the digestibility of oat rice, the starch of oat rice can be divided into RDF and SDF. CPS kinetic model fitting showed that the digestion patterns of the two starch fractions were parallel and sequentially combined. The fitted R^2 of all samples was higher than 0.99, indicating that the fitting results were real and highly reliable. In the fitting process of the CPS model, t_{2start} refers to the beginning of digestion of the second starch fraction after the end of digestion of the first starch fraction. Milling and defatting treatments had a significant effect on the RDF (k_1) rate and SDF (k_2) rate constant but had little effect on the DOMD-40 k_1, which was similar to DOM-0 k_1 (Table S5). In the CPS fitting model, the maximum starch digestibility of RDF ($C_{\infty 1}$) increases first and then decreases, while the maximum starch digestibility of SDF ($C_{\infty 2}$) decreases, and the RS content also shows a decreasing trend. Milling and defatting treatment can reduce the oil content of oat rice, reduce the formation of starch-lipid complex during cooking, and reduce the content of RS and the digestibility of SDF (Qin et al., 2019; Zhen et al., 2022).

Research findings have demonstrated the formation of starch-lipid complexes during the heating process (Q. Li et al., 2021). Gelatinization disrupts the crystalline structure of starch and untwists its double helix configuration (H. Zhang et al., 2023). The lipophile groups within the V-type amylose cavity can interact with lipids, forming a starch-lipid complex (Q. Li et al., 2021). This complex formation enhances the ordered arrangement of starch molecules, diminishes its swelling capacity, and reduces the contact area between starch and enzymes, thereby augmenting resistance to enzymatic degradation (H. Zhang et al., 2023). Starch undergoes digestion in the human body through a sequential process involving the oral cavity, stomach, and small intestine. RDS is efficiently broken down, absorbed, and metabolized during this process. Conversely, RS exhibits limited susceptibility to enzymatic breakdown and thus proceeds undigested into the colon (Chang, Jin, Lu, Qiu, Sun, & Tian, 2021). Resistant starch generates a diverse array of metabolites *via* fermentation by intestinal microbes, thereby promoting the maintenance of intestinal homeostasis, mitigating inflammation, and enhancing intestinal barrier integrity (Chang et al., 2021). Hence, it is imperative to investigate the impact of milling and defatting treatment on the in vivo digestion of oat rice as well as the intestinal microorganisms in mice. This aspect of the research will be incorporated into future research papers.

Table 2
Effect of milling and defatting treatment on texture properties of oat rice.

	Hardness (gf)	Stickiness (gf*s)	Chewiness (gf)	Elasticity (gf*s)
DOMD-0	1,277.84 ± 255.04^{a}	0.30 ± 0.08^{b}	778.51 ± 185.93^{a}	0.83 ± 0.07^{a}
DOMD-20	710.09 ± 63.65^{b}	3.69 ± 0.61^{a}	295.01 ± 51.80^{b}	0.72 ± 0.06^{b}
DOMD-40	626.09 ± 111.98^{bc}	3.93 ± 1.00^{a}	223.07 ± 39.55^{bc}	0.66 ± 0.04^{bc}
DOMD-60	576.56 ± 132.90^{bc}	4.04 ± 0.70^{a}	198.16 ± 36.14^{bc}	0.63 ± 0.05^{c}
DOMD-80	487.74 ± 117.28^{c}	4.26 ± 0.80^{a}	148.59 ± 50.39^{d}	0.63 ± 0.11^{c}

Note: DOMD-0, DOMD-20, DOMD-40, DOMD-60, and DOMD-80 represent milling times of 0 s, 20 s, 40 s, 60 s, and 80 s followed by defatting. The values of different letters in each column indicated a significant difference between milling and defatting treatment with oat rice ($p < 0.05$).

3.11. Correlation analysis

In this paper, the effects of milling and defatting treatment on texture characteristics and starch digestibility of oat rice were established by selecting the nutrient composition and related indexes of oat rice. As can

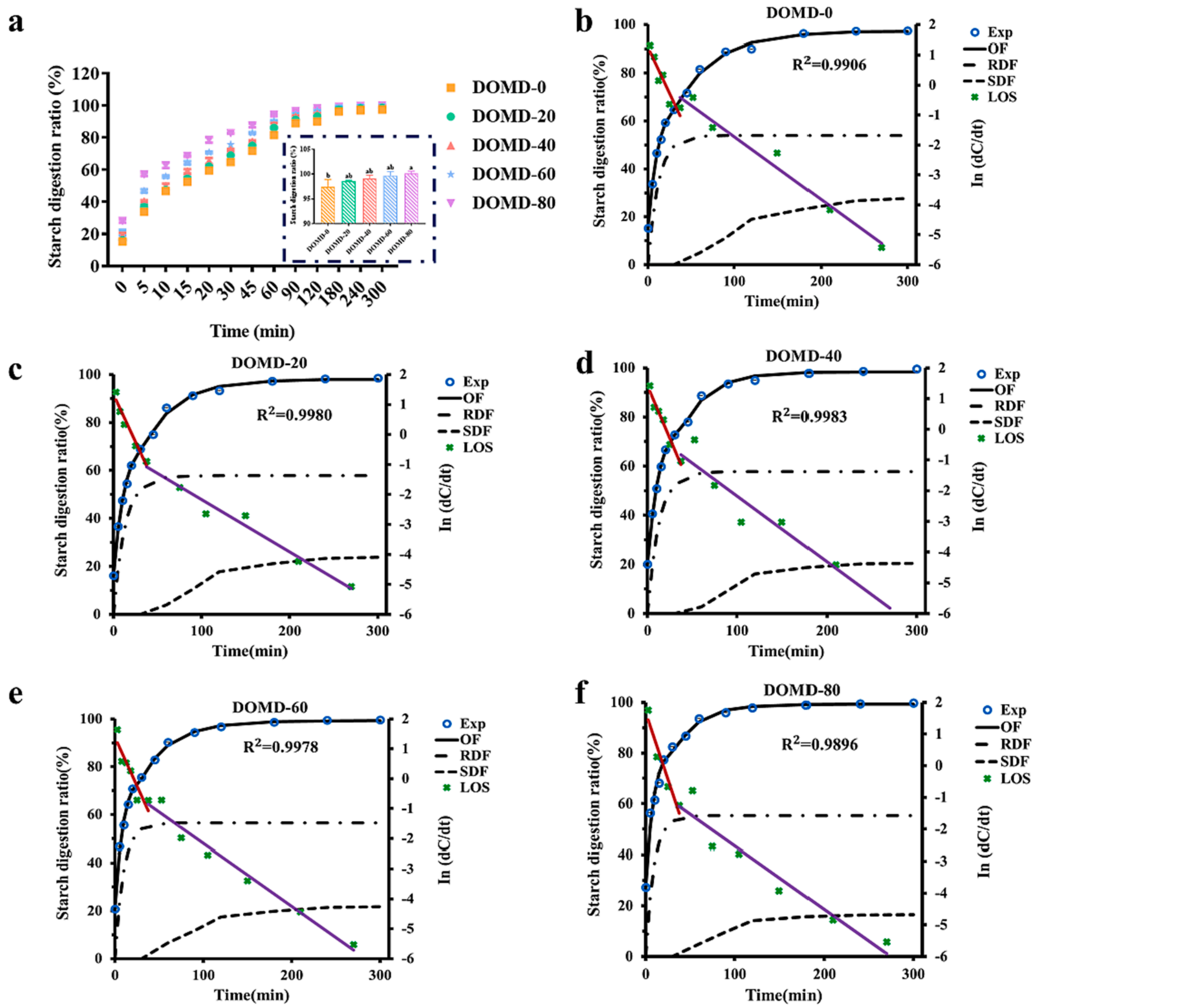

Fig. 3. Starch digestion curve (a) and LOS/CPS kinetic model fitting (b-f) were obtained by milling and defatting treatment of oat rice. Exp is experimental data. OF is the overall fit curve.

be seen in Table 3, the starch content was significantly positively correlated with the WAI, SP, and k_1 of oat rice. β-glucan was negatively correlated with hardness, chewiness, and elasticity, and positively correlated with stickiness. Solids leached were negatively correlated with hardness, chewiness, and elasticity ($p < 0.05$), and significantly positively correlated with k_2. There was a positive correlation between oil content and starch digestion rate k_1. Starch, amylose, β-glucan, and solids leached were positively correlated with WAI and SP of oat rice, while oil content was negatively correlated with WAI and SP. Milling can effectively remove the bran layer of oat rice, and defatting treatment can decrease the oil content of oat rice. These combined treatments effectively increase WAI and SP, thereby improving the texture of oat rice and accelerating the starch digestion rate. During the cooking process, starch and oil will form a V-shaped starch-lipid complex at high temperatures, reducing the content of RS and increasing the rate of k_2 digestion. β-glucan increases the viscosity of the system, inhibits enzymatic accessibility to gelatinized starch particles, and has an inhibitory effect on starch digestibility (Zhuang et al., 2017).

4. Conclusion

In this paper, the defatting of oat rice with milling was used to research the effect on the texture characteristics of oat rice. SEM results showed that milling and defatting treatment destroyed the bran and abalone layers of oat rice. The decreased hardness of the oat rice might be attributed to the reduced fiber, oil, and protein contents. At the same

Table 3
Correlation analysis of the nutrient composition of milling and defatting oat rice with WAI, SP, texture properties, and starch digestion rate.

	WAI	SP	Hardness	Stickiness	Chewiness	Elasticity	k_1	k_2
Starch	0.90*	0.90*	−0.67	0.57	−0.63	−0.72	0.84	0.95*
Oil	−0.85	−0.83	0.62	−0.52	0.58	0.70	−0.99**	−0.71
Amylose	0.82	0.82	−0.72	0.64	0.70	−0.77	−0.59	0.93*
protein	−0.45	−0.44	0.13	0.01	0.08	0.27	−0.73	−0.56
β-glucan	0.76	0.76	−0.96**	0.99**	−0.97**	−0.91**	0.30	0.64
Solids leached	0.92*	0.91*	−0.82	0.74	−0.80	−0.91*	0.80	0.88*

Note: * represents significant, $p < 0.05$; ** represents extremely significant, $p < 0.01$.

time, it can effectively increase the content of total solids leached from oat rice and increase the viscosity of oat porridge. The final viscosity, ΔH, and starch digestibility of oat rice were increased by milling and defatting while the pasting temperature was decreased. The content of bound water and free water was reduced and the content of non-flowing water was enhanced during cooking. The results of XRD showed that from DOMD-0 to DOMD-80, milling and defatting treatment increased the content of starch-lipid complexes in oat rice. At DOMD-40, the nutrient content of oat rice was properly retained, and the viscosity and elasticity of oat rice reached the maximum. At the same time, in the digestive stage, k_1 was low, and k_2 and t_{2start} were the highest. In this study, the effects of the combination of the two processing methods on the structure and texture characteristics of oat rice were investigated, and the reasons for the differences in the texture characteristics of oat rice were analyzed. To provide a theoretical basis and guidance for oats in food processing and production.

CRediT authorship contribution statement

Meng Shen: Writing – review & editing, Writing – original draft, Project administration, Methodology, Data curation. **Kai Huang:** Writing – review & editing, Visualization, Validation, Supervision. **Zhu Sun:** Writing – review & editing, Visualization, Validation, Supervision. **Zhiquan Yu:** Writing – review & editing, Validation, Supervision. **Hongwei Cao:** Writing – review & editing, Validation, Supervision. **Yu Zhang:** Writing – review & editing, Validation, Supervision. **Xiao Guan:** Writing – review & editing, Supervision, Funding acquisition.

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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Appendix A. Supplementary data

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