Heliyon 9 (2023) e17699

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Influences of wheat bran fiber on growth performance, nutrient digestibility, and intestinal epithelium functions in Xiangcun pigs

Jiahao Liu [a,b], Yuheng Luo [a,b], Xiangfeng Kong [c,**], Bing Yu [a,b], Ping Zheng [a,b], Zhiqing Huang [a,b], Xiangbing Mao [a,b], Jie Yu [a,b], Junqiu Luo [a,b], Hui Yan [a,b], Jun He [a,b,*]

[a] Institute of Animal Nutrition, Sichuan Agricultural University, Sichuan Province, Chengdu, 611130, PR China
[b] Key Laboratory of Animal Disease-resistant Nutrition, Sichuan Province, Chengdu, 611130, PR China
[c] Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, Hunan 611130 410125, PR China

ARTICLE INFO

Keywords:
Dietary fiber
Nutrition
Intestinal health
Bacteria
Pigs

ABSTRACT

Dietary fiber (DF) has long been looked as an essential "nutrients" both for animals and humans as it can promote the intestinal tract development and modulate the intestinal epithelium functions and the gut microbiota. This study was conducted to investigate the influences of wheat bran fiber (WBF) on growth performance and intestinal epithelium functions in Xiangcun pigs. Twenty Xiangcun pigs with 60 days of age were divided to two groups and exposed to a basal diet (BD) or BD containing 4.3% wheat bran fiber (WFD). WFD improved the average daily gain (ADG) and feed-to-gain ratio (F:G) ($p < 0.01$). Moreover, WFD lowered the serum triglyceride (TC), D-lactate, and malonicdialdehyde (MDA) concentrations, but significantly improved the glutathione (GSH) activity and total antioxidant capacity (T-AOC) ($p < 0.05$). Interestingly, WFD observably improved the villus height (VH) and the villus height to crypt depth ratio (V/C) in the small intestine ($p < 0.05$). The jejunal sucrase and ileal maltase activities were higher in the WFD group ($p < 0.05$). WFD markedly elevated the tight junction protein ZO-1 and claudin-1 expression levels in the jejunum and ileum ($p < 0.05$). The sodium/glucose co-transporter 1 (*SGLT1*), glucose transporter 2 (*GLUT2*), and fatty acid transport proteins 4 (*FATP-4*) expression levels in jejunum and ileum were also elevated under WFD ($p < 0.05$). WFD decreased the IL-6 impression level in the duodenum and ileum, but significantly increased the IL-10 expression levels in jejunum and ileum ($p < 0.05$). Moreover, WFD reduced the abundance of *E. coli*, but elevated the abundances of beneficial microorganisms (e.g. *Lactobacillus* and *Bacillus*) and the production microbial metabolites (e.g. propionic acid and butyrate acid) in the cecum ($p < 0.05$).

1. Introduction

The intestinal epithelium is composed of a single layer of columnar epithelium cells, which is not only responsible for nutrients absorption but also acts as a barrier to prevent harmful substances from entering [1,2]. In weaned piglets, hypoplasia or disruption of the intestinal epithelial is usually followed by retarded growth and an increased risk of developing diarrhea and inflammations [3–5].

* Corresponding author. Institute of Animal Nutrition, Sichuan Agricultural University, Chengdu, Sichuan 611130, PR China.
** Corresponding author. Institute of Animal Nutrition, Sichuan Agricultural University, Chengdu, Sichuan 611130, PR China.
E-mail addresses: comnnkxf@isa.ac.cn (X. Kong), hejun8067@163.com (J. He).

https://doi.org/10.1016/j.heliyon.2023.e17699
Received 6 March 2023; Received in revised form 21 June 2023; Accepted 26 June 2023
Available online 28 June 2023

In last decades, various antibiotics have been utilized to improve growth performance and gut health of animals. However, the use in animal production has been prohibited due to resistance or residue, and alternative pathways to improve the intestinal health have attracted considerable research interest from scientists around the word [6].

DF is a type of non-digestible carbohydrates with more than three monomeric units, such as fructan, arabinoxylan, inulin, lignin, etc [7]. Although DF cannot be digested through endogenous digestive enzymes, microbiota in the hindgut can partially or fully degrade and ferment it [8]. The advantage influence of DF on animals health have been well documented [9]. For instance, DF can increase the expression and secretion of mucin in porcine distal small intestine through boosting the goblet cells number [10]. Zhao also found that addition of 5% corn bran or wheat bran had positive effects on the posterior intestinal microbes and feed efficiency of piglets [11]. Importantly, the DF can be fermented by vast quantities of hindgut bacteria to produce SCFAs, which can lower the intestinal lumen pH and restrain the pathogenic bacteria growth [8,12]. Fiber-fermented SCFAs have been linked to the promotion of intestinal growth epithelial mucosal growth through the elevation of the tight-junction protein (TJPs) expressions (e.g. *claudin-7*, *occludin*, *claudin-1*) [13,14]. Interestingly, butyric acid can function as an important energy source for intestinal epithelial cells (IEC), and protect against colon cancer and intestinal inflammation through the inhibition of histone acetyltransferases (HDACs) [15]. Moreover, the butyrate-induced HDAC inhibition in small intestinal stem cells can promote the stem cell population [16,17]. Additionally, the fiber-deprived SCFAs may also act as a potent anti-inflammatory agent. For instance, butyrate and propionate inhibit bone marrow-derived dendritic cells (BMDC) activation via suppression of lipopolysaccharide-induced expression of co-stimulatory molecule CD40 and secretion of IL-6 and IL-12 [18].

Xiangcun pig is one of most famous lean-meat pig breeds in southern China [19], which is characterised by tender meat, high intramuscular fat, homogenous marbling, and improved juiciness of flavor [19,20]. While quite a few of researches have reported a beneficial influence of DF supplementation on lots of aspects in a range of animal species [21–23], the specific relationship between the dose and action of DF has not been clearly demonstrated, since the influence of DF on animals are closely linked to the source of DF and the species, sex, and the physiological stage of animals. Wheat bran fiber (WBF), a by-product of wheat processing is composed of various dietary fibers such as the arabinoxylan, lignin, cellulose, β-glucan and fructans, and more than 90% of which is insoluble dietary fiber (IDF) [24,25]. Arabinoxylan is the main fiber constituent in WBF with a content of 42% to 57% of dry matter, which is abundant in phenolic components that may help eliminate toxic-free radicals and prevent colon cancer [25,26]. While beta-glucan is a soluble dietary fiber (SDF) which has been reported to has anti-lipaemic, anti-oxidant, and anti-cancer effects [27]. This research investigated the influences of WBF on growth performance and gut health in Xiangcun pigs. Xiangcun Pigs were exposed a normal diet (BD) or BD supplemented with 4.3% WBF (WFD). We observed increases in the ADG and F:G in Xiangcun pigs upon WBF supplementation. Importantly, WBF improved the intestinal epithelium functions, as well as the microbial fermentation in the pigs. This study suggested that DF played a beneficial role in improving the growth performance and intestinal barrier function in Xiangcun pigs, but also provided insight into the mechanisms underlying the DF-regulated intestinal health.

2. Materials and methods

The animal experiment in this study was carried out after approval by the Animal Care and Use Committee of Sichuan Agricultural University (Chengdu, China, No.20210911). The WBF (total dietary fiber of the raw material ≥95%; Insoluble dietary fiber of the WBF ≥98%) used was purchased from Chengdu Tubaite Technology Co. Ltd.

2.1. Experimental design, diet, and animal housing

Twenty Xiangcun pigs (average weight 11.47 ± 0.15 kg) pigs age were divided into two treatments, exposed to a normal basal diet (BD) or BD containing 4.3% WBF (WFD) 28 days. The diet (Table S1) was formulated in accordance with National Research Council (NRC, 2012) [28]. WBF (DF ≥ 95%) was used to adjust the DF level. Pigs were housed in a metabolism cage (2.55 m^2) and provided with food and water ad libitum with room temperature (27 ± 2 °C) and relative humidity (60 ± 5%).

2.2. Sample collection

Fecal samples were collected during the d 25–28 of the study. On the day 29 morning, the serum were obtained through centrifuging the bloods after 12 h fasting. Then pigs were slaughtered through electrical stunning to obtain the intestinal and digest samples. After removing the intestine from the pig's body, the small intestine were immediately isolated, and fixed in paraformaldehyde solution (about 4 cm) to be made into sections and analysis intestinal morphologic. Last, the remained small intestinal were made into mucosal samples through a scalpel and stored in ultra low temperature refrigerator.

2.3. Growth performance evaluation

The feed intake every pig was recorded daily. The body weight was determined at the initial (IBW) and the final (FBW) of this study. The growth performance results can be calculated based on IBW, FBW and average daily feed intake (ADFI), including average daily gain (ADG) and feed-to-gain ratio (F:G). The piglet fresh excreta that were semi-liquid and liquid were considered diarrhea. Diarrhea rates were calculated based on previous formula [29].

2.4. Apparent total tract nutrient digestibility analysis

The nutrients digestibility were detected by the dried and pulverized diets and fecal samples, and the Cr_2O_3 was served as an external indicator. The dry matter (DM), crude protein (CP), ether extract (EE), acid detergent fiber (ADF), neutral detergent fiber (NDF), crude fiber (CF) and Ash contents were detected based on AOAC standard [30]. The gross energy was detected by adiabatic bomb calorimeter.

2.5. Serum parameter analysis

The D-lactate and diamine oxidase (DAO) were detected by enzyme-linked immunosorbent assay kits (Jiangsu Meimian industrial Co., Ltd.). The commercial kits were used to detect the catalase (CAT), malondialdehyde (MDA), glutathione (GSH), total superoxide dismutase (T-SOD), total antioxidant capacity (T-AOC), urea nitrogen (BUN), glucose (GLU), triglyceride (TG), and total cholesterol (TC). All procedures and special information of those assay kit were based on previous study [31,32,33].

2.6. Intestinal morphologic analysis

The intestinal segments fixed were dewaxed by graded anhydrous ethanol, dyed through haematoxylin and eosin (H&E), sealed by a neutral resin size. Finally, the sections of each intestinal sample was measured for crypt depth (CD) and villus height (VH) using an image processing and analysis system (Image-ProPlus 6.0), then, VH:CD (V:C) could be calculated from those data [34].

2.7. Enzyme activity

The small intestinal mucosa was homogenized with cold saline, and centrifugated (3500 g) 15 min for the supernatant separation for the determination of the disaccharidase activities. The enzyme were measured by commercial assay kits: sucrase, lactase and maltase (Jiancheng Biotechnology Ltd., nanjing, China). All procedures and special information of those assay kit were based on previous study were [32].

2.8. Real-time quantitative PCR and caecal microbiological analysis

The RNA of mucosal samples of duodenum, jejunum and ileum were extracted using Trizol (TAKARA, Japan). The mRNA levels of critical genes of pattern recognition receptor related barrier related genes, such as *ZO-1*, *Occludin*, *Claudin-1*, nutrient transporters, such as sodium/glucose cotransporter-1 (*SGLT-1*), sodium/glucose cotransporter-1 (*GLUT-2*), fatty acid transport proteins-4 (*FATP-4*), inflammation response, such as interlukin-6 (*IL-6*), interlukin-10 (*IL-10*), interleukin1-β (*IL-1β*) and cell apoptosis, such as caspase3, caspase8, caspase9 were quantified by real-time PCR and the relative expression of each gene was calculated using the $2^{-\Delta\Delta Ct}$ method [12]. All procedures were based on previous methods [35].

The total DNA of caecal digesta were extracted using Stool DNA Kits (Omega Bio-Tex). The DNA levels of caecal microbial populations, such as *Escherichia coli*, *Bacillus* and *Bifidobacterium* were performed through the Quant Studio 5 Flex real-time PCR system (Bio-Rad) [25]. All procedures were based on previous methods [36]. The primers information were shown in Table S2.

2.9. Statistical analysis

All results were presented as the means and structural equation model (SEM). Data were subjected to *t*-test to determine significant

Table 1
Effects of WBF on the performance and nutrient digestibility in Xiangcun pigs.

Items	Treatments		SEM	*P* value
	BD	WFD		
IBW (kg)	11.47	11.46	0.15	0.97
FBW (kg)	18.94	20.48	0.54	0.03
ADFI (g/d)	713.07	730.84	19.41	0.21
ADG (g/d)	300.00	360.81	13.79	0.02
F:G	2.38	2.03	0.06	<0.01
diarrhea rate%	26.00	10.80	0.04	0.04
DM%	85.03	78.37	0.95	<0.01
EE%	65.52	67.82	0.02	0.41
GE%	86.04	78.50	0.01	0.01
CP%	80.03	73.61	0.01	0.01
ASH%	39.92	38.36	0.02	0.62
ADF%	54.87	42.45	2.67	0.02
NDF%	68.44	54.14	2.08	<0.01
CF%	50.62	49.77	2.37	0.87

BD, basal diet; WFD, BD supplemented with 4.3% WBF. Mean and total SEM are list in separate columns, n = 10.

differences between the groups at $p < 0.05$ with SPSS 27.0 (IBM, Chicago, IL, USA).

3. Results

3.1. Effect of WBF on growth performance and nutrient digestibility

As compared to the BD group, WFD improved the ADG and feed efficiency (F:G) in Xiangcun pigs ($p < 0.05$). ADFI did not differ between the two groups ($p > 0.05$); however, WFD observably reduced the diarrhea rate in xiangcun pigs (Table 1). In the BD group, the nutrition digestibility of DM, GE, CP, ADF, NDF were greater than those of the WFB group. The EE and CF digestibilities did not differ between the two treatments ($p > 0.05$).

3.2. Effect of WBF on serum metabolites and antioxidative capacity

As shown in Table 2, WFD markedly raised the serum GSH and T-AOC concentrations in Xiangcun pigs ($p < 0.05$). The serum MDA, TC, and D-lactate concentrations were lower in the WFD group ($p < 0.05$). WFD also tended to lower the serum TG concentration in Xiangcun pigs ($p = 0.07$).

3.3. Effect of WBF on intestinal morphology and mucosal enzyme activity

WFD elevated the VH and V/C in the small intestine (Table 3 and Fig. 1, $p < 0.05$). In addition, WFD improved the jejunal sucrase, and the ileal maltase activity ($p < 0.05$).

3.4. Effect of WBF on expression of intestinal epithelial functions genes

As shown in Fig. 2 (A-F), WFD increased the expression levels of *ZO-1* and *Claudin-1* in the jejunum and ileum, and *Caludin-1* in duodenum ($p < 0.05$). Meanwhile, the *SGLT-1*, *GLUT-2*, and *FATP-4* expression levels were higher in the WFD group ($p < 0.05$). WFD also increased the jejunal *SGLT-1* expression level ($p < 0.05$).

3.5. Effect of WBF on inflammation and apoptosis in the intestinal epithelial cells

As shown in Fig. 3 (A-H) WFD greatly decreased the *IL-6* expression levels in the duodenum and ileum; but significantly increased the *IL-10* expression levels in jejunum and ileum ($p < 0.05$). Furthermore, WFD greatly decreased the expression levels of *caspase-8* in duodenum and *caspase-9* in duodenum, jejunum and ileum ($p < 0.05$). Interestingly, WFD decreased the *Bax* expression level in the duodenum and jejunum ($p < 0.01$).

3.6. Effect of WBF on intestinal microbiota and microbial metabolites

As shown in Table 4, WFD significantly reduced the *E. coli* abundance, but raised the *Lactobacillus* and *Bacillus* abundances in the caecal digesta ($p < 0.05$). Meanwhile, the caecal acetic acid, propionic acid, butyrate acid, and the total VFA concentrations were higher in the WFD group ($p < 0.05$).

4. Discussion

Dietary fiber has long been looked as an essential “nutrients” both for animals and human as it can promote the intestinal tract

Table 2
Effects of WBF on serum metabolites and antioxidative capacity.

Items	Treatments		SEM	*P* value
	BD	WFD		
BUN(mmol/mL)	3.55	4.32	0.32	0.24
GLU (mmol/mL)	4.69	4.97	0.13	0.30
TC (mmol/mL)	2.48	1.89	0.11	<0.01
TG (mmol/mL)	0.48	0.42	0.02	0.07
DAO (pg/mL)	67.64	71.27	1.08	0.09
D-Lactate (pg/mL)	303.72	239.66	9.78	<0.01
CAT(U/mL)	13.14	11.17	1.02	0.35
GSH-PX (U/mL)	608.53	769.54	32.77	<0.01
MDA (U/mL)	2.50	1.88	0.12	<0.01
T-AOC(U/mL)	1.76	2.35	0.13	0.02
T-SOD (U/mL)	126.92	121.98	2.87	0.40

BD, basal diet; WFD, BD supplemented with 4.3% WBF. Mean and total SEM are list in separate columns, n = 10.

Table 3
Effects of WBF on intestinal morphology.

Items	Treatments		SEM	*P* value
	BD	WFD		
Duodenum				
VH (μm)	355.07	435.02	20.17	0.04
CD (μm)	320.53	232.19	20.77	0.03
V/C	1.18	1.89	0.12	<0.01
Jejunum				
VH (μm)	337.18	388.39	9.46	<0.01
CD (μm)	230.11	196.59	7.29	0.02
V/C	1.48	2.00	0.08	<0.01
Ileum				
VH (μm)	265.87	357.33	16.66	<0.01
CD (μm)	212.00	205.71	6.97	0.66
V/C	1.26	1.75	0.07	<0.01

BD, basal diet; WFD, BD supplemented with 4.3% WBF. Mean and total SEM are list in separate columns, n = 10.

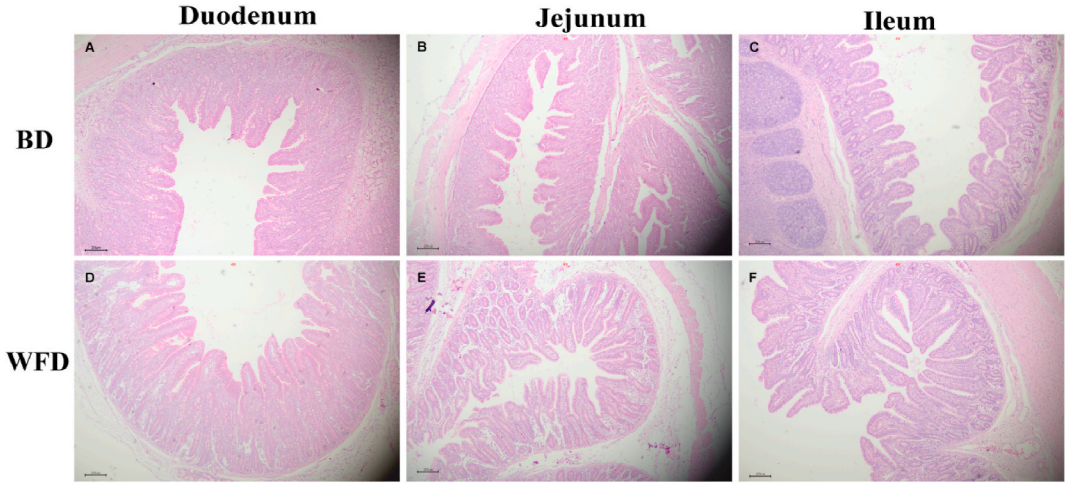

Fig. 1. Effect of WBF on intestinal morphology in Xiangcun pigs (H&E; × 40). BD, basal diet; WFD, BD supplemented with 4.3% WBF (A–F).

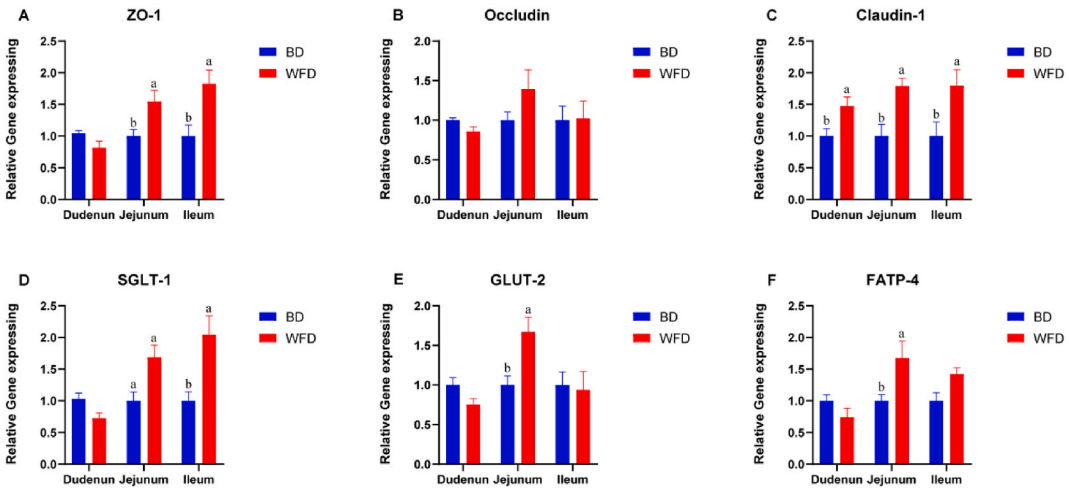

Fig. 2. Effect of WBF on expressions of intestinal epithelium functions genes (A–F). a, b mean values within a row with unlike superscript letters were significantly different ($p < 0.05$). BD, basal diet; WFD, BD supplemented with 4.3%WBF.

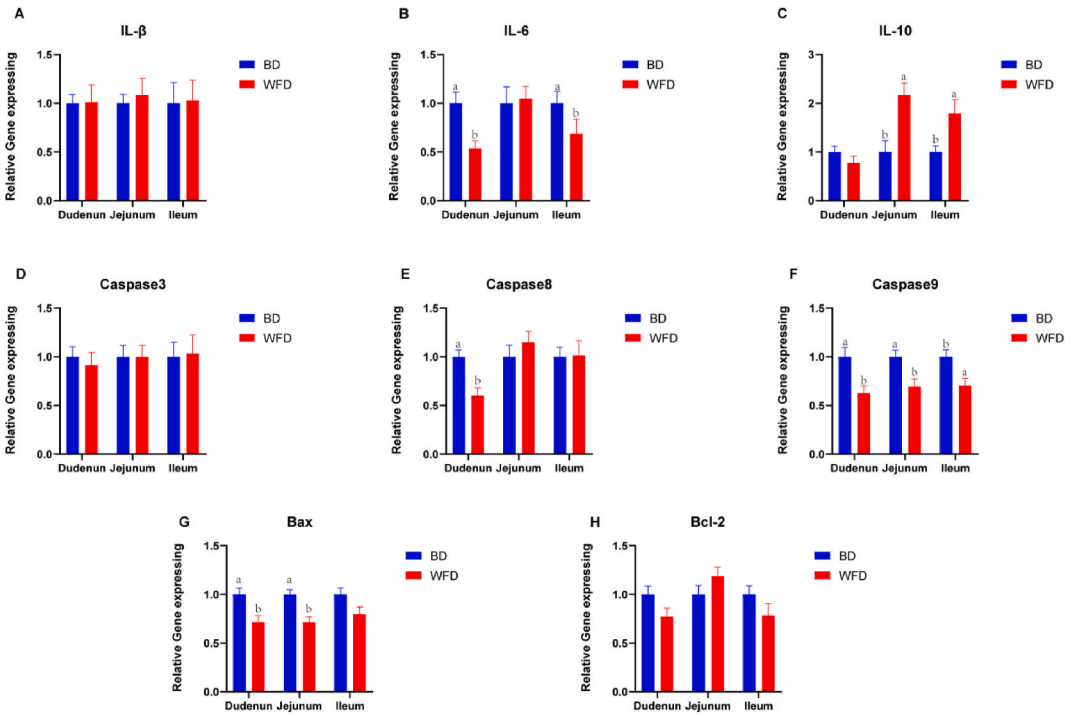

Fig. 3. Effect of WBF on critical genes related to intestinal inflammation (A, B, C) and apoptosis (D–H) in Xiangcun pigs. a, b mean values within a row with unlike superscript letters were significantly different ($p < 0.05$). BD, basal diet; WFD, BD supplemented with 4.3%WBF.

Table 4
Effect of WBF on caecal microbiota and microbial metabolites.

Items	Treatments		SEM	*P* value
	BD	WFD		
Microbial populations (lg(copies/g))				
Escherichia coli	9.23	8.31	0.20	< 0.01
Lactobacillus	7.66	8.15	0.10	0.01
Bifidobacterium	6.47	6.20	0.13	0.32
Bacillus	8.58	8.93	0.08	0.02
Total bacteria	11.75	11.91	0.04	0.07
VFA (g/g)				
Acetic acid	3.32	4.64	0.20	< 0.01
Propionic acid	1.44	1.92	0.08	< 0.01
Butyrate acid	0.36	0.52	0.03	< 0.02
Total acid	5.53	7.06	0.27	< 0.01

BD, basal diet; WFD, BD supplemented with 4.3% WBF. Mean and total SEM are list in Separate columns, n = 10.

development and regulate the intestinal epithelium functions and gut microbiota [31,35,37]. Importantly, DF and many oligosaccharides are capable of reducing the adhesion of pathogenic bacteria to the intestinal epithelium, which subsequently attenuates the inflammation and injury of the intestinal barrier [32,38,39]. Wheat bran (WB) is composed of about 53% DF [40], and other components include protein, lipids, vitamins, minerals, and bioactive components such as alkylresorcinols and carotenoids [26,41]. Previous research suggested that dietary supplementation of WB deceased the diarrhea ratio and improved the growth performance in pigs [30,31]. Our research found that WBF supplementation resulted in same results, as indicated by increases in ADG and final body weight, and decreases in diarrhea incidence and F:G ratio. However, a study on DLY pigs researched that DF had no observably influence on their ADG and F:G ratio [37]. This is may due in part to differences in animal species, fiber level, and physiological stages [11,42,43]. Previous study indicated that fiber components in the diet may increase the digesta viscosity, which ultimately affect gastric emptying or slow the diffusion/mobility of nutrients to the absorptive surface [44,45]. In this study, the digestibilities of some nutritions were lower in the WFD group, which was agreed with previous research that DF could significantly reduced nutrient digestibility [46].

Triglyceride and cholesterol are two important clinical blood lipid indicators, provide information for the diagnosis of lipid metabolism disorders and related metabolic diseases [47]. In current research, WFD observably reduced the serum TC concentration

and tended to reduce the TG concentration, indicating dietary WBF supplementation improved lipid metabolism. Reactive oxygen species (ROS) overproduction is a vital inciting factor in intestinal inflammation or mucosal injury in animals including the swine [48]. Various antioxidative enzymes produced in animals body (e.g. CAT, T-AOC and GSH) are responsible for ROS removal and play a crucial role in maintenance of redox homeostasis [49]. In this research, WFD improved the serum GSH and T-AOC concentrations, and reduced the MDA concentration in Xiangcun pigs, indicating an improved antioxidative capacity. Those are consist with previous researches on rats and sows, in which DF supplementation significantly elevated their antioxidative capacity through regulating antioxidant enzymes activity [50,51]. It is also noteworthy that certain DF components (e.g. ferulated arabinoxylan) can terminate the free radical chain reactions through electron-donating groups on their benzene rings [52].

Intestine is the primary digest and absorb nutrients site for animals, and the normal function of the intestinal epithelium is pretty importance for their digestive capacity. Numerous of investigations have showed a beneficial role for DF in regulating the gut barrier functions [53]. For instance, DF might enhance the thickness and integrity of mucus layers lining the interior of the tract, thereby protecting against inflammation from pathogens that penetrate the intestinal wall [54]. Moreover, supplementation of fructo-oligosaccharides fermented by DF, induces IgA production in rat and suppresses a decrease in intestinal permeability induced by carbohydrates-deficient diet [55]. In our research, WFD improved the VH and V/C in the small intestine, which showed an improved absorption capacity and an enhanced integrity of the intestinal epithelium [56]. These results are consistent with the serum D-lactate concentration. D-lactate, a metabolite fermented by gastric and intestinal bacteria, is almost not be absorbed into the bloodstream under normal conditions, except through damaged intestinal mucosa [57–59]. In present research, WFD obvervably lower the serum D-lactate concentration, indicating an enhanced intestinal barrier function in Xiangcun pigs. Change in gut morphology are companied with variations in brush border enzyme activities [60]. Sucrase and maltase not only serve as important disaccharidases participating in carbohydrate digestion, but also can serve as critical markers monitoring the development or maturation of intestinal epithelium [36]. In our research, WFD obvervably improved the jejunal sucrase and ileal maltase activities. These results were also similar to previous finding that a diet rich in DF components improved the disaccharidase enzymes activity in intestinal mucosa [33].

Intestinal epithelial cells are joined by the apical junctional complex, which is made up of the tight junction and TJPS [53]. TJPs such as ZO-1 and Claudin, showed a momentous character in maintenance of the integrity of intestinal barrier, which may effectively prevent the paracellular diffusion of bacteria and other gut antigens through the epithelium [53]. In this study, WFD elevated the ZO-1 and Claudin-1 expression levels in jejunum and ileum. Moreover, the critical functional genes expression levels such as the SGLT-1, GLUT-2 and FATP-4 were both elevated in jejunal epithelium upon WFD. SGLT-1 and GLUT-2 are two primary glucose transporters, and FATP-4 is distinctly important for the transportation of long chain fatty acids into the enterocytes [61,62]. These results showed that epithelial function in Xiangcun pigs were improved upon WFD.

Pro-inflammatory cytokines, such as *IL-6* and *IL-1β*, have been proved to adjust host immune function and induce immune responses following pathogen infection [63]. At the same time, macrophages activated by inflammatory response can produce the anti-inflammatory cytokine such as *IL-10* to regulate the secretion of inflammatory cytokines [64]. In this study, WFD decreased the *IL-6* impression level, but significantly increased the *IL-10* expression levels in intestinal epithelium. These results are consistent with previous studies, and indicated an anti-inflammatory effect of WBF on xiangcun pigs [65,66]. Apoptosis, the programmed cell death, is controlled by genes to mediate body development and maintain internal environmental stability in multicellular organisms [67]. Apoptosis is mainly triggered through the activation of Caspase-mediated (e.g. *caspase-8*, *caspase-9*) intrinsic pathways (mitochondria-dependent) or extrinsic pathways (death receptor-dependent) [68]. These activated caspases can transmit intracellular apoptotic signals to effector caspases (e.g. *caspase-3*, *caspase-7*), thus inducing cell apoptosis [69]. Bcl-2 family is important for regulation of mitochondrial pathways, and can be divided into anti-apoptotic genes (e.g. *Bcl-2*, *Bcl-xL*) and pro-apoptotic genes (e.g. *Bax*, *Bid*, *Bad*) according to structure and function, in which *Bcl-2* and *Bax* are directly related to apoptosis regulation [70]. In present study, WFD significantly decreased the *caspase-9* and *Bax* expression levels in duodenal jejunal epithelium. Similarly, Arabinogalactan, a major fiber component in WBF, has been shown to block the apoptotic cascade through decreasing Bcl/Bax ratios to inhibiting the conversion of procaspase-3 to *Caspase-3* in rats [71].

DF is highly resistant to digestion in the foregut and can serve as a critical substrate for microbes inhabiting the distal gut [72]. Numerous previous studies have indicated that DF inhibits the growth of pathogenic bacteria but promotes the growth of beneficial bacteria in animals [73–75]. Similarly, WFD significantly increased the caecal *Lactobacillus* and *Bacillus* abundance, but reduced the caecal *E. coli* abundance. In spite of their capabilities to utilize the DF, the reduced *E. coli* abundance may be also resulted from the elevated production of metabolites such as the SCFA, which offers an acidic environment that is unfavorable for most harmful bacteria [76]. Moreover, the elevated production of volatile fatty acid (VFA) upon WFD may also contribute to improving gut barrier functions. For instance, the propanoic acid was reported to elevate the expressions of TJPs (e.g. *Claudin-7, Occludin* and ZO-1) [77]. Whereas, the butyric acid can increase the secretion of regulatory T cell in the intestinal epithelium via stimulating of GPCR [78], which subsequently promotes the secretion of *IL-18* or *IL-10* and decreases inflammatory response of the intestinal epithelium [79].

5. Conclusions

Dietary WBF supplementation can improve the growth performance and gut health in Xiangcun pigs. The mechanisms behind its action may be connected with improved antioxidative capacity and intestinal epithelium functions, as well as microbial fermentation in the intestine. The advantage effect of WBF in pigs may allow it an attractive source of dietary fibers in the utilization of animal nutrition and feed industry.

Author contributions

JH conceived and designed the experiments. JHL performed the experiments and wrote the paper. JQL, XFK, BY, XBM, PZ, JY, ZQH and HY contributed reagents, materials, analysis tools or data. All authors have read and approved the final manuscript.

Funding

This work was supported by the National Natural Science Foundation of China (no. U20A2056) and the Key Research and Development Program of Sichuan Province (no. 2020YFN0147).

Data availability statement

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

Consent for publication

Not applicable.

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.

Acknowledgments

We thank HFW, FlW, EY and SJD for their help during the animal trial.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17699.

References

[1] A.T. Blikslager, A.J. Moeser, J.L. Gookin, Restoration of barrier function in injured intestinal mucosa, Physiol. Rev. 87 (2007) 545–564.
[2] K. Kunzelmann, M. Mall, Electrolyte transport in the mammalian colon: mechanisms and implications for disease, Physiol. Rev. 82 (2002) 245–289.
[3] J.C. Kim, C.F. Hansen, B.P. Mullan, Nutrition and pathology of weaner pigs: nutritional strategies to support barrier function in the gastrointestinal tract, Anim. Feed Sci. Technol. 83 (2001) 3–16.
[4] F. Smith, J.B. Clark, Early weaning stress impairs development of mucosal barrier function in the porcine intestine, Am. J. Physiol. Gastrointest. Liver Physiol. 298 (2010) 352–363.
[5] S.R. Shiou, Y. Yu, S. Chen, Erythropoietin protects intestinal epithelial barrier function and lowers the incidence of experimental neonatal necrotizing enterocolitis, J. Biol. Chem. 286 (2011) 12123–12132.
[6] C. hosh, P. Sarkar, R. Issa, Alternatives to conventional antibiotics in the era of antimicrobial resistance, Trends Microbiol. 27 (2019) 323–338.
[7] H. Wang, X. Huang, H. Tan, Interaction between dietary fiber and bifidobacteria in promoting intestinal health, Food Chem. 1 (2022), 133407, 393.
[8] B. Williams, L. Grant, M. Gidley, Gut fermentation of dietary fibres: physico-chemistry of plant cell walls and implications for health, Int. J. Mol. Sci. 18 (10) (2017) 2203, 2017.
[9] S.K. Gill, M. Rossi, B. Bajka, Dietary fibre in gastrointestinal health and disease, Nat. Rev. Gastroenterol. Hepatol. 18 (2) (2021) 101–116.
[10] A. El Kaoutari, F. Armougom, J.I. Gordon, The abundance and variety of carbohydrate-active enzymes in the human gut microbiota, Nat. Rev. Microbiol. 11 (2013) 497–504.
[11] J. Zhao, P. Liu, U. Wu, P. Guo, Dietary fiber increases butyrate-producing bacteria and improves the growth performance of weaned piglets, J. Agric. Food Chem. 1 (30) (2018) 7995–8004, 66.
[12] Y. Zhou, Y. Luo, B. Yu, Effect of β-glucan supplementation on growth performance and intestinal epithelium functions in weaned pigs challenged by enterotoxigenic Escherichia coli, Antibiotics 11 (4) (2022).
[13] H. Wang, P. Shi, L. Zuo, Dietary non-digestible polysaccharides ameliorate intestinal epithelial barrier dysfunction in IL-10 knockout mice, J. Crohn's Colitis 10 (9) (2016) 1076–1086.
[14] T.V. Hung, T. Suzuki, Dietary fermentable fibers attenuate chronic kidney disease in mice by protecting the intestinal barrier, J. Nutr. 148 (4) (2018) 552–561.
[15] D. Haenen, J. Zhang, SilvaAC. Dasouza, Diet high in resistant starch modulates microbiota composition, SCFA concentrations, and gene expression in pig intestine, J. Nutr. 143 (3) (2013) 274–283.
[16] Y. Furusawa, Y. Obata, S. Fukuda, Commensal microbe-derived butyrate induces the differentiation of colonic regulatory T cells, Nature 504 (2013) 446–450.
[17] N. Arpaia, C. Campbell, X. Fan, Metabolites produced by commensal bacteria promote peripheral regulatory T-cell generation, Nature 504 (2013) 451–455.
[18] C. Nastasi, M. Candela, C.M. Bonefeld, The effect of short-chain fatty acids on human monocyte-derived dendritic cells, Sci. Rep. 5 (2015), 16148.
[19] Y. Chen, Y. Wei, J. Chen, Growth, carcass characteristics and meat quality of Chinese indigenous Yanan pig crossbred with Duroc and Berkshire genotypes, Anim. Prod. Sci. 59 (6) (2019) 1147.
[20] W. Chen, Q. Zeng, H. Xu, Comparison and relationship between meat colour and antioxidant capacity of different pig breeds, Anim. Prod. Sci. 58 (11) (2018) 2152.
[21] S.M. Lin, X.M. Zhou, Y.L. Zhou, Intestinal morphology, immunity and microbiota response to dietary fibers in largemouth bass, Micropterus salmoide, Fish Shellfish Immunol. 103 (2020) 135–142.

[22] H.Y. Han, K.Y. Zhang, X.M. Ding, Effect of dietary fiber levels on performance, gizzard development, intestinal morphology, and nutrient utilization in meat ducks from 1 to 21 days of age, Poultry Sci. 1 (12) (2017) 4333–4341, 96.
[23] Y.H. Samuel, D.Q. Wu, Lin, Effects of wheat fiber addition on emulsion and lipid/protein stabilities of an omega-3 fatty acid-fortified chicken surimi product, Poultry Sci. 100 (2) (2021) 1319–1327.
[24] W. Cheng, Y. Sun, M. Fan, Wheat bran, as the resource of dietary fiber: a review, Crit. Rev. Food Sci. Nutr. 62 (26) (2022) 7269–7281.
[25] Y. Luo, Y. Liu, H. Li, Y. Zhao, Differential effect of dietary fibers in intestinal health of growing pigs: outcomes in the gut microbiota and immune-related indexes, Front. Microbiol. 22 (13) (2022), 843045.
[26] G.G. Mateos, F. Martin, M.A. Latorre, Inclusion of oat hulls in diets for young pigs based on cooked maize or cooked rice, Anim. Sci. 82 (2007) 57–63.
[27] J.C. Kim, B.P. Mullan, D.J. Hampson, Addition of oat hulls to an extruded rice-based diet for weaner pigs ameliorates the incidence of diarrhoea and reduces indices of protein fermentation in the gastrointestinal tract, Br. J. Nutr. (2008) 1217–1225.
[28] National Research Council (U.S.), Nutrient Requirements of Swine, eleventh ed., National Academies Press, Washington D.C, 2012.
[29] C. Huang, S. Qiao, D. Li, X. Piao, Effects of lactobacilli on the performance, diarrhea incidence, VFA concentration and gastrointestinal microbial flora of weaning pigs, Asian-Australas. J. Anim. Sci. 17 (2004) 401–409.
[30] J. Wan, J. Zhang, D. Chen, Alginate oligosaccharide-induced intestinal morphology, barrier function and epithelium apoptosis modifications have beneficial effects on the growth performance of weaned pigs, J. Anim. Sci. Biotechnol. 9 (2018) 58.
[31] W. Wang, D. Chen, B. Yu, Effects of dietary inulin supplementation on growth performance, intestinal barrier integrity and microbial populations in weaned pigs, Br. J. Nutr. 14 (3) (2020) 296–305, 124.
[32] Q. Duan, D. Chen, B. Yu, Z. Huang, Effect of sialyllactose on growth performance and intestinal epithelium functions in weaned pigs challenged by enterotoxigenic Escherichia Coli, J. Anim. Sci. Biotechnol. 3 (1) (2022) 30, 13.
[33] X. Wu, D. Chen, B. Yu, Effect of different dietary non-starch fiber fractions on growth performance, nutrient digestibility, and intestinal development in weaned pigs, Nutrition 51–52 (2018) 20–28.
[34] H. Kissow, B. Hartmann, J.J. Holst, Glucagon-like peptide-1 as a treatment for chemotherapy-induced mucositis, Gut 62 (12) (2013) 1724–1733.
[35] P.M. Becker, P.G. Wikselaar, A.J. Jansman, Pea dietary fiber for adhesion and excretion of enterotoxigenic E.coli K88 to prevent intestinal colonization, J. Anim. Sci. 87 (2009) 172–189.
[36] A. Pyner, H. Nyambe-Silavwe, G. Williamson, Inhibition of human and rat sucrase and maltase activities to assess antiglycemic potential: optimization of the assay using acarbose and polyphenols, J. Agric. Food Chem. 65 (39) (2017) 8643–8651.
[37] J. He, H. Xie, D. Chen, Synergetic responses of intestinal microbiota and epithelium to dietary inulin supplementation in pigs, Eur. J. Nutr. 60 (2) (2021) 715–727.
[38] Liu Lei, Chen Daiwen, Yu Bing, Fructooligosaccharides improves growth performance and intestinal epithelium function in weaned pigs exposed to enterotoxigenic Escherichia coli, Food Funct. 11 (2020) 9599.
[39] O.O. Onipe, A.I.O. Jideani, and D. Beswa, Composition and functionality of wheat bran and its application in some cereal food products. Int. J. Food Sci. Technol.. 50: 2509-2518.
[40] A.A.M. Andersson, L. Dimberg, P. Aman, D. Landberg, Recent findings on certain bioactive components in whole grain wheat and rye, J. Cereal. Sci. 59 (2014) 294–311.
[41] S. Apprich, O. Tirpanalan, J. Hell, Wheat bran-based biorefinery 2: valorisation of products, LWT–Food Sci. Technol. 56 (2013) 222–231.
[42] A.K. Agyekum, C.M. Nyachoti, Nutritional and metabolic consequences of feeding high-fiber diets to swine: a review, Engineering 3 (5) (2017) 716–725.
[43] L.F. Wang, E. Beltranena, R.T. Zijlstra, Diet nutrient digestibility and growth performance of weaned pigs fed sugar beet pulp, Anim. Feed Sci. Technol. 211 (2016) 145–152.
[44] F. Molist Gasa, M. Ywazaki, Administration of loperamide and addition of wheat bran to the diets of weaner pigs decrease the incidence of diarrhoea and enhance their gut maturation, Br. J. Nutr. 103 (6) (2010) 879–885.
[45] C.M.E. Heyer, L.F. Wang, E. Beltranena, Nutrient digestibility of extruded canola meal in ileal-cannulated growing pigs and effects of its feeding on diet nutrient digestibility and growth performance in weaned pigs, J. Anim. Sci. 99 (5) (2021).
[46] H. Li, J. Yin, B. Tan, Physiological function and application of dietary fiber in pig nutrition: a review, Ani. Nutr. 7 (2) (2021) 259–267.
[47] M. Woo, Y.O. Song, K.H. Kang, Anti-obesity effects of collagen peptide derived from skate (Raja kenojei) skin through regulation of lipid metabolism, Drugs 16 (2018) 306.
[48] Yan Honglin, Cao Shanchuan, Li Yan, Reduced meal frequency alleviates high-fat diet-induced lipid accumulation and inflammation in adipose tissue of pigs under the circumstance of fixed feed allowance, Eur. J. Nutr. 59 (2) (2020) 595–608.
[49] E. Cabiscol, J. Tamarit, J. Ros, Oxidative stress in bacteria and protein damage by reactive oxygen species, Int. Microbiol. 3 (1) (2000) 3–8.
[50] J. Wang, B. Sun, Y. Cao, C. Wang, Wheat bran feruloyl oligosaccharides enhance the antioxidant activity of rat plasma, Food Chem. 123 (2) (2010) 472–476.
[51] H.L.Z. Yu, D.L. Peng, Bamboo vinegar powder supplementation improves the antioxidant ability of the liver in finishing pigs, Livest. Sci. 211 (2018) 80–86.
[52] Y. Li, H. Liu, L. Zhang, Y. Yang, Maternal dietary fiber composition during gestation induces changes in offspring antioxidative capacity, inflammatory response, and gut microbiota in a sow model, Int. J. Mol. Sci. 19 (1) (2019) 31, 21.
[53] H. Usuda, T. Okamoto, K. Wada, Leaky gut: effect of dietary fiber and fats on microbiome and intestinal barrier, Int. J. Mol. Sci. 16 (14) (2021) 7613, 22.
[54] B.O. Schroeder, G.M.H. Birchenough, M. Stahlman, Bifidobacteria or fiber protects against diet-induced microbiota-mediated colonic mucus deterioration, Cell Host Microbe 23 (2018) 27–407.
[55] T. Genda, Y. Sasaki, T. Kondo, Fructo-oligosaccharide-Induced transient increases in cecal immunoglobulin A concentrations in rats are associated with mucosal inflammation in response to increased gut permeability, J. Nutr. 147 (2017) 1900–1908.
[56] D.P. O'Brien, L.A. Nelson, F.S. Huang, Intestinal adaptation: structure, function, and regulation, Semin. Pediatr. Surg. 10 (2) (2001) 56–64.
[57] N. Nieto, Experimental ulcerative colitis impairs antioxidant defense system in rat intestine, Dig. Dis. Sci. 45 (9) (2000) 1820–1827.
[58] S.M. Smith, R. H, g En, F. Buccini, Use of D-lactic acid measurements in the diagnosis of bacterial infections, JID (J. Infect. Dis.) 154 (4) (1986) 658–664.
[59] E. Wertz, L.L. Berge, P.M. Walker, Early weaning and postweaning nutritional management marbling score to feed efficiency. J. Anim. Sci.. 79(7).
[60] J. Wan, F. Jiang, Q. Xu, D. New insights into the role of chitosan oligosaccharide in enhancing growth performance, antioxidant capacity, immunity and intestinal development of weaned pigs, RSC Adv. 7 (16) (2017) 9669–9679.
[61] Ulluwishewa Dulantha, C. Rachel, C. Anderson Warren, Roy, regulation of tight junction permeability by intestinal bacteria and dietary components, J. Nutr. (2011) 769–776.
[62] P.T. Sangild, K.A. Tappenden, C. Malo, Glucagon-like peptide 2 stimulates intestinal nutrient absorption in parenterally fed newborn pigs, J. Pediatr. Gastroenterol. Nutr. 43 (2) (2006) 160–167.
[63] S. Macfarlane, G.T. Macfarlane, Regulation of short-chain fatty acid production, Proc. Nutr. Soc. 62 (1) (2003) 67–72.
[64] M. Zenhom, A. Hyder, M. de, Vrese, Prebiotic Oligosaccharides Reduce Proinflammatory Cytokines in Intestinal Caco-2 Cells via Activation of PPARγ and Peptidoglycan Recognition Protein 3, 141(5), 2011, pp. 971–977.
[65] M. Saraiva, A. O'Garra, The regulation of IL-10 production by immune cells, Nat. Rev. Immunol. 10 (3) (2010) 170–181.
[66] T. Fang, X. Wu, W. Cao, G. Jia, Effects of dietary fiber on the antioxidant capacity, immune status, and antioxidant-relative signaling molecular gene expression in rat organs, RSC Adv. 7 (32) (2007) 19611–19620.
[67] H. Kang, M.G. Lee, J.K. Lee, Enzymatically-processed wheat bran enhances macrophage activity and has in vivo anti-inflammatory effects in mice, Nutrients 8 (4) (2016) 188.
[68] S. Elmore, Apoptosis: a review of programmed cell death, Toxicol. Pathol. 35 (4) (2007) 495–516.
[69] Y. Fuchs, H. Steller, Programmed cell death in animal development and disease, Cell 11 (4) (2011) 742–758, 147.
[70] S.J. Riedl, Y. Shi, Molecular mechanisms of caspase regulation during apoptosis, Nat. Rev. Mol. Cell Biol. 5 (11) (2004) 897–907.
[71] M. Giam, D.C. Huang, P. Bouillet, BH3-only proteins and their roles in programmed cell death, Oncogene 27 (2008) S128–S136.

[72] S.H. Lim, Larch arabinogalactan attenuates myocardial injury by inhibiting apoptotic cascades in a rat model of ischemia-reperfusion, J. Med. Food 20 (7) (2017) 691–699.
[73] E.D. Sonnenburg, J.L. Sonnenburg, Starving our microbial self: the deleterious consequences of a diet deficient in microbiota-accessible carbohydrates, Cell Metabol. (2014) 1–8.
[74] J. Walter, Murine gut microbiota—diet trumps genes, Cell Host Microbe 17 (2015) 3–5.
[75] Y. Honglin, Z. Pan, Z. Yong, Short-chain fructo-oligosaccharides alleviates oxidized oil-induced intestinal dysfunction in piglets associated with the modulation of gut microbiota, J. Funct.Foods 64 (2020), 103661.
[76] A. Singh, R.C. Zapata, A. Pezeshki, Inulin fiber dose-dependently modulates energy balance, glucose tolerance, gut microbiota, hormones and diet preference in high-fat-fed male rats, J. Nutr. Biochem. 59 (2018) 142–152.
[77] E.R.C. Maria, C. Desirée, A. Belén, The combination of fructooligosaccharides and resistant starch shows prebiotic additive effects in rats, Clin. Nutr. 29 (6) (2010) 832–839.
[78] Z. Xia, Y. Han, K. Wang, Oral administration of propionic acid during lactation enhances the colonic barrier function, Lipids Health Dis. 16 (2017) 62.
[79] L. Macia, J. Tan, A.T. Vieira, Metabolite-sensing receptors GPR43 and GPR109A facilitate dietary fibre-induced gut homeostasis through regulation of the inflammasome, Nat. Commun. 6 (2015) 6734.