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Effects of yeast culture supplementation from late gestation to weaning on performance of lactating sows and growth of nursing piglets

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ABSTRACT

Dietary yeast culture supplementation can contribute to the performance and health of sows and piglets, but few studies have focused on the relationships between the effects of yeast culture and gut microbiota. This study investigated the effect of yeast culture (*Saccharomyces cerevisiae*) supplementation from late gestation to weaning on the reproductive performance of lactating sows and their faecal microbiota. One hundred and six purebred Landrace sows, of parities two to six were selected and randomly assigned to a control (**CON**) and yeast culture supplementation (**YC**) groups based on parity and back fat thickness. The YC sows were individually fed with yeast culture at a dose of 24 g/d from day 90 of gestation to parturition and 40 g/d during lactational period. Blood samples were collected from sows on d 110 of gestation and at weaning at day 21 of lactation for plasma hormone and immunoglobulin analysis. Colostrum and milk on day 20 of lactation were collected for composition analysis. Faecal samples from sows on day 110 of gestation and day 20 of lactation were collected for short-chain fatty acid and faecal microbial analysis. Results showed that the farrowing performance of YC sows did not differ significantly from the CON group ($P > 0.05$). The average daily feed intake by the YC group during the lactation period was significantly increased by 9.98% ($P = 0.004$), the weaning-to-oestrus interval was shortened by 0.96 d ($P = 0.046$) and average daily weight gain of piglets increased by 7.14% ($P = 0.036$) compared with the CON group. Yeast culture supplementation also significantly improved the average daily milk yield in the first week of lactation ($P = 0.035$), lactose content in colostrum ($P = 0.046$), protein ($P = 0.033$) and DM ($P < 0.001$) content of milk. In the YC group, concentrations of plasma ghrelin ($P = 0.02$) and IgG ($P = 0.015$) were increased compared with the CON group, while that of glucagon-like peptide-1 was decreased ($P = 0.006$) on d 110 of gestation. The 16S rRNA gene sequencing showed that faecal microbiota changed at taxonomic levels with yeast culture addition ($P < 0.05$). Dietary yeast culture supplementation from late gestation to lactation improved feed intake, immunity status, milk yield, milk quality and faecal microbiota of sows, resulting in the improved growth performance of piglets.

Implications

Diet supplemented yeast culture was an effective means to promote the performance and health of sows and piglets, but few studies have focused on its effect on gut microbiota. This study was undertaken to investigate the effects of adding yeast culture to diets on sow performance and its underlying possible mechanisms. The results showed that feed intake, milk quality, faecal microbiota of sows, and maternal health status were altered by yeast culture supplementation, suggesting *Saccharomyces cerevisiae* yeast culture products may be a promising functional additive to improve the performance of sows and their piglets.

Introduction

Due to genetic selection for prolificacy, modern sows undergo a huge metabolic nutrient demand for milk production to satisfy a large litter size (Zhou et al., 2018), so insufficient nutrient intake will lead to mobilisation of their body reserves during lactation (Kim et al., 2008). The growth performance of the piglets is determined by the sow's health status and milk yield during lactation (Szyndler-Nędza et al., 2013), which can be altered by maternal

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diets (Jang et al., 2013; Hasan et al., 2018), so nutritional manipulations using dietary supplements are direct and effective means to improve sow productivity and litter performance.

Yeast cultures have been widely used as either a probiotic using a small amount of live yeast cells or prebiotic with yeast metabolites or cell wall components as additives to enhance swine performance. Improvements in piglets' numbers weaned (Czech et al., 2010), litter weight at weaning (Czech et al., 2010; Kim et al., 2010; Shen et al., 2011; Zhang et al., 2020) and piglet average daily gain (Shen et al., 2011) have all been noted when sows were fed with yeast products such as dry yeast, yeast cell walls or purified β-glucan and mannan-oligosaccharides from yeast during lactation. This effect may be due to an improvement in the digestibility of DM, gross energy and CP in pigs (Shen et al., 2009). Sow diet supplementation with yeast culture or live yeast has also been demonstrated to have positive effects on the immunological status of their progeny (Shen et al., 2009; Monroy-Salazar et al., 2012; Jang et al., 2013; Zanello et al., 2013). In contrast, no improvements in sows' feed intake during lactation and litter weight at weaning were reported when sows were supplemented with dry yeast (*Saccharomyces cerevisiae*) during gestation and the lactation period (Jurgens et al., 1997). The improvements in immunological state could be due to probiotic components such as β-glucan and mannan-oligosaccharides, which exist in yeast culture, which have shown not only to bind to pathogenic bacteria and facilitate their flushing from the intestinal lumen (Spring et al., 2000) but also to promote the growth of beneficial bacteria (Davis et al., 2004). Immunopotentiation effected by the binding of a (1,3) + glucan molecule or particle includes activation of cytotoxic macrophages, helper T cells, and NK cells, promotion of T cell differentiation, and activation of the alternative complement pathway (Bohn and Bemiller, 1995). Milk yield and quality not only provide nutrients to support the growth of neonates (Theil and Hurley, 2016) but also ultimately impact the growth performance and gut health of offspring (Leonard et al., 2010; Chu et al., 2016). The milk-derived immunity involves mostly IgA derived from the maternal intestine and directed against various pathogens from the mother's intestinal microbiota (Hanson et al., 1979; Salmon et al., 2009). However, evidence of how yeast culture supplementation affects the gut microbiota of sows is still scarce.

The objective of this study was to supplement sow diets with a novel type of yeast culture *Saccharomyces cerevisiae* (CGMCC No. 6120) and measure the subsequent performance of the sows and their offspring, along with effects on sow milk quality and gut microbiota.

Material and methods

Animals, feeding and management

A total of 106 purebred Landrace multiparous sows of parities two to six were selected and allocated to a control (**CON**) or a yeast culture group (**YC**) based on parity (3.50 ± 0.31 and 3.62 ± 0.33) and back fat thickness (15.52 ± 0.55 mm and 15.67 ± 0.56 mm). From d 90 of gestation to parturition, all sows were kept in individual stalls and offered 3.0 kg/d of standard gestation diet (Table 1). Sows in the YC group were individually fed a pellet including ten grams of wheat flour, two grams of dextrin and twenty-four grams of Saccharomyces cerevisiae yeast culture with moisture 4.87%, CP 18.41%, ash 7.69%, β-glucan and mannan-oligosaccharides 0.82%, and others 69.03% (Enhalor Biotechnology Company, Beijing, China) . Sows in the CON group were fed a placebo pellet including ten grams of wheat flour and two grams of dextrin.

Sows were moved into the farrowing house on d 112 of gestation and kept in individual farrowing crates measuring 200 × 80 cm. After farrowing, the feed allowance was 2 kg initially and increased by 0.5 kg/d until the fifth day of lactation. From day six, all sows had free access to standard lactation diet until weaning and similarly, YC sows were individually daily fed a pellet including ten grams of wheat flour, two grams of dextrin and forty-five grams of *Saccharomyces cerevisiae* yeast culture and a placebo pellet including ten grams of wheat flour, two grams of dextrin for the CON group. If needed, cross-fostering was completed within 24 h of parturition to standardise litter size to 10–12 piglets within treatment. The postnatal care of piglets including teeth clipping, tail docking and iron injection was administered within the first 12 h after birth. During lactation, piglets had free access to water via nipple drinkers until weaning on d 21.

Table 1
Ingredients and chemical composition of basal diets provided to the sows.

Items	Gestation	Lactation
Ingredients, %		
Corn	56.00	63.40
Wheat bran	10.00	–
Rice bran meal	8.56	–
Soybean meal[1]	9.70	21.20
Extruded-soybean	–	5.30
Flaxseed	–	2.00
Sugar beet pulp	3.00	3.20
Soybean hull	8.50	–
Soybean oil	–	0.50
Limestone	1.00	0.90
Dicalcium phosphate	1.20	1.70
NaCl	0.40	0.40
Sodium bicarbonate	0.20	–
Magnesium oxide	0.18	0.16
L-Lysine sulphate[1]	0.13	0.20
DL-Methionine[1]	0.03	–
L-Threonine	0.11	0.06
L-Tryptophan[1]	0.14	0.13
Choline chloride[1]	0.10	0.10
Mineral premix[2]	0.43	0.43
Vitamin premix[3]	0.32	0.32
Total	100.00	100.00
Nutritional level[4]		
DM, %	87.10	87.10
ME, Mcal/kg	2.81	3.20
CP, %	12.5 (12.34)	16.50 (16.52)
Ca, %	0.85 (0.82)	0.90. (0.91)
AP, %	0.32	0.37
Total Lysine, %	0.7 (0.68)	1.08 (1.06)
SID Lysine	0.58	0.96
SID Methionine	0.19	0.25
SID Threonine	0.45	0.61
SID Tryptophan	0.12	0.18

Abbreviations: ME = metabolisable energy; AP = available phosphorus; SID = standardised ileal digestible.
[1] 42% CP content of soybean meal; 70% L-Lysine sulphate content; 99% DL-Methionine content; 20% L-Tryptophan content; 60% Choline chloride content.
[2] Mineral mixture supplied per kilogram of diets: Fe 120 mg; Cu 20 mg; Mn 60 mg; Zn 120 mg; Se 0.3 mg; I 0.5 mg.
[3] Vitamin mixture supplied per kilogram of diets: vitamin A 10000 IU; vitamin D_3 2000 IU; vitamin E 60 IU; vitamin K_3 5.0 mg; vitamin B_1 5.0 mg; vitamin B_2 10.0 mg; vitamin B_6 6.0 mg; vitamin B_{12} 50 μg; nicotinic acid 40 mg; d-pantothenic acid 20 mg; folic acid 2.0 mg; biotin 0.2 mg.
[4] Calculated according to China Feed Database (2018). The measured values are in parentheses, and others are calculated values.

Performance measurements and sample collection

Backfat thickness of sows was measured at 6.5 cm to the left side of the dorsal midline at the level of the last rib using an ultrasound device (Renco, Manchester, MA, USA) on d 90, d 112 of gestation and d 21 of lactation. Piglets were weighed individually at birth and on d 7, 14, and 21 of lactation to calculate weight gain and to estimate milk yield. Colostrum samples were collected

within two hours after the first piglet was born, and milk samples were collected in the morning of d 21 of lactation. During milk sampling, the sow was injected intravenously with 0.3 mL of oxytocin to induce milk let-down, and 20 mL of milk was collected and stored at −20 °C until further analysis. Sow blood samples on d 110 of gestation and d 21 of lactation were drawn by jugular vein puncture two hours after the morning meal and collected in heparinised tubes. Plasma was obtained by centrifuging blood samples at 1 000*g* at 4 °C for 10 min and then stored at −20 °C until analysis. Fresh faecal samples on d 110 of gestation and d 20 of lactation were individually collected from the rectum of sows using sterile tubes, flash-frozen in liquid nitrogen and stored at −80 °C until analysis.

Milk and plasma sample analysis

Milk composition was analysed in triplicate for DM, fat, protein, lactose, and non-fat solid (**SNF**) with an Automatic milk analyzer (CombiFoss FT+, Foss, Denmark). Plasma metabolites including neuropeptide Y (**NPY**), peptide tyrosine-tyrosine (**PYY**), glucagon-like peptide-1 (**GLP-1**), Ghrelin, IgG, IgM of sows were determined using respective commercial kits (Jiangsu Meimian Industrial Co., Ltd China) according to the manufacturer's protocols.

Faecal metabolites and microbial analysis

One of the duplicate faecal samples was analysed for short-chain fatty acids (**SCFA**) including acetate, propionate, butyrate, valerate, isobutyrate and isovalerate using the gas chromatographic method as previously reported by Zhou et al. (2018). Another faecal sample was subjected to microbial analysis. Microbial DNA was extracted using the E.Z.N.A. ®Stool DNA Kit (D4015, Omega, Inc., Norwalk, CN, USA) according to the manufacturer's protocol. The extracted genomic DNA was measured for purity and integrity before sequencing (LC-Biotechnology Co., Ltd, Hang Zhou, Zhejiang Province, China). The V4 hypervariable region of the 16S rRNA gene was amplified using 515F and 806R primer (5′-GTGCCAGCMGCCGCGGTAA-3′ and 5′-GGACTACHVGGGTWTC TAAT-3′, respectively). The 16sRNA gene sequencing was performed on NovaSeq PE250 platform.

Statistical analysis

This study was a completely randomised design with sow or litter as the experimental unit and yeast culture treatment as the main effect. Milk yield was calculated as litter weight gain and litter size according to Hansen et al (2012). The statistical analysis was performed by the MIXED procedure of SAS (version 9.4) and excluded stillborn piglets, mummified foetuses, piglets' mortality, total born piglets born, live-born piglets, litter size after cross-fostering, litter size at weaning and wean-to-oestrus. The percentage of stillborn piglets, mummified foetuses and piglets' mortality during lactation were analysed using the GLIMMIX procedure and fitted with the assumption that the data exhibited a binomial distribution. Total born piglets born, live-born piglets, litter size after cross-fostering, litter size at weaning and wean-to-oestrus interval were analysed using the GLIMMIX procedure with the Poisson distribution.

For analysis of intestinal microbiota, data of relative abundance at phylum and genus levels were log-transformed before statistical analysis. Difference in α-diversity was presented by Shannon index, and differential abundance between the dietary groups of specific genus or phylum were evaluated by the non-parametric Wilcoxon sum rank test. Differences were considered significant when $P < 0.05$ and $0.05 < P < 0.1$ were considered as showing a trend.

Results

Sow and litter performance

Two sows from the CON and the YC group were removed from the study due to low consumption of feed during the experimental period, and two sows from the YC group were excluded due to postpartum paralysis. Supplementation of yeast culture from late gestation to lactation did not change the farrowing performance of YC sows compared with the CON group ($P > 0.05$) as seen in Table 2. The YC sows had higher weekly average daily feed intake (**ADFI**, $P < 0.05$) as seen in Fig. 1A, whole-lactation ADFI at 5.95 compared with 5.41 kg for the CON group ($P = 0.004$) and a tendency to lose less back fat as −0.06 compared with −1.15 mm ($P = 0.083$) during lactation as shown in Table 3. Yeast culture supplementation improved the weaning-to-oestrus interval of YC sows compared to CON sows at 5.16 d compared with 6.12 d ($P = 0.046$), and piglet average daily gain (**ADG**) was improved at 1.65 compared with 1.54 kg ($P = 0.036$) as seen in Table 3.

Milk yield and milk composition

As shown in Table 3, milk yield during the whole lactation was not changed by yeast culture supplementation ($P > 0.05$), except that the average daily milk yield (ADMY) in the first week of lactation was markedly increased compared with the CON group ($P = 0.035$), as seen in Fig. 1B. The contents of lactose ($P = 0.046$), protein ($P < 0.001$), DM ($P = 0.033$) and urea N contents in milk ($P = 0.017$) were significantly improved in the YC group compared with the CON group as seen in Table 4.

Concentration of faecal short-chain fatty acids, appetite-related hormone and immunological parameters in plasma

As shown in Table 5, consumption of yeast culture did not change faecal SCFA concentrations. However, a significant reduction of isovalerate, a branched-chain fatty acid (**BCFA**) in the faeces of YC sows, was detected on d 21 of lactation compared with the CON group ($P = 0.043$). Yeast culture supplementation significantly increased concentration of plasma ghrelin ($P = 0.02$) and decreased GLP-1 ($P = 0.006$) on d 110 of gestation and tended to enhance concentration of NPY on d 21 of lactation ($P = 0.074$) as seen in Fig. 2. The plasma IgG level of YC sows was greater than that of CON sows at weaning ($P = 0.015$).

Changes of gut microbial composition

Yeast culture supplementation did not change faecal microbial α- or β-diversity of sows as seen in Fig. 3A and B. The relative abundance of *Bacteroidetes* was lower ($P = 0.047$), while the *Firmicutes*/*Bacteroidetes* ratio was higher ($P = 0.046$) for YC sows compared to those of the CON sows, as shown in Fig. 3E. During gestation, yeast culture addition remarkably increased the abundances of *Ruminococcaceae_UCG-005*, *Ruminococcus_1*, *Prevotellaceae_UCG-001*, *Family_XIII_AD3011*, *Acetitomaculum* and *Lachnospiraceae_NK4B4* ($P < 0.05$) while decreasing the abundance of *Bacteroidales* and *Lachnospiraceae_UCG-010* at genus level ($P < 0.05$) as shown in Fig. 3C. For the lactation period, the relative abundance of genera *Eggerthella* and *Alistipes* were significantly higher ($P < 0.05$), while the relative abundances of genera *Anaerostipes*, *Saccharimonadaceae*, *Oscillospira* and *Eubacterium eligens* were significantly lower in the YC group than those in the CON group ($P < 0.05$) as shown in Fig. 3D.

Table 2
Effect of yeast culture supplementation from late gestation to lactation on farrowing performance of sows.

Items	CON	YC	SEM	*P*-value
No. of Sows	53	53		
Litter size				
Total born piglets, n	11.96	12.33	0.752	0.538
Live-born piglets, n	11.30	11.25	0.447	0.934
Stillborn piglets, %	3.34	5.13	0.013	0.103
Mummified foetuses, %	1.20	1.67	0.010	0.372
Piglet weight				
Average piglet weight at birth, kg	1.46	1.41	0.033	0.244
Litter weight at birth, kg	16.39	15.53	0.561	0.275
CV of piglet birth weight, %	20.96	23.53	2.356	0.173

Abbreviations: CON = control group; YC = yeast culture group.

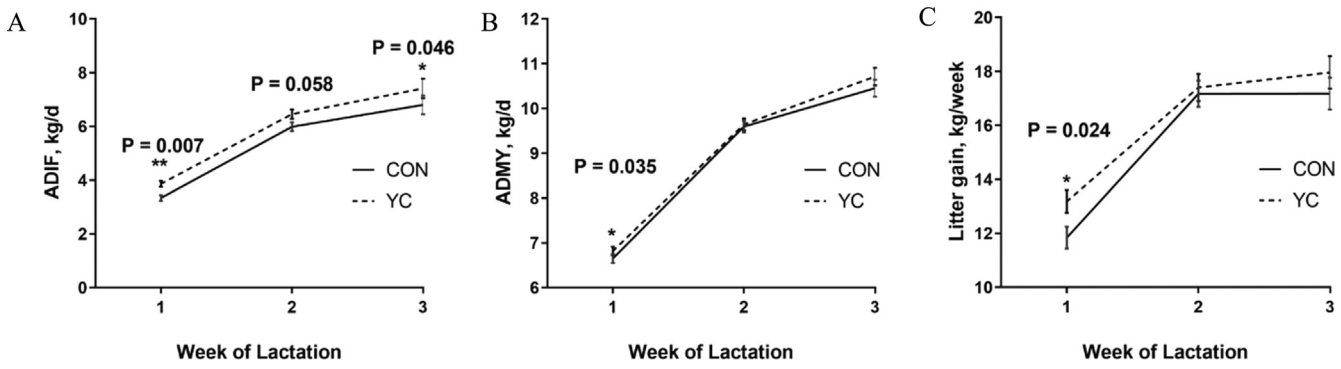

Fig. 1. The weekly ADFI (A), ADMY (B) and litter gain (C) of sows from control and yeast culture group during lactation. * $P < 0.05$, ** $P < 0.01$. Abbreviations: CON = control group; YC = yeast culture group; ADFI = average daily feed intake; ADMY = average daily milk yield.

Table 3
Effects of yeast culture supplementation from late gestation to lactation on lactational performance of sows.

Items	CON	YC	SEM	*P*-value
No. of sows	52	50		
Sow back fat thickness change, mm				
G 90–G 112 d	2.51	1.52	0.658	0.14
G112–L21 d	−1.15	−0.66	0.224	0.083
Weaning-to-oestrus interval, d	6.12	5.16	0.206	0.046
Litter size after cross-fostering, n	10.17	10.24	0.114	0.68
Litter size at weaning, n	9.83	10	0.12	0.329
Piglet mortality, %	2.65	2.93	0.267	0.782
Litter weight after cross-fostering, kg	14.79	14.75	0.321	0.923
Piglets weight after cross-fostering, kg	1.46	1.45	0.031	0.825
Average daily feed intake (0–21 d), kg/d	5.41[b]	5.95[a]	0.159	0.004
Milk yield, kg/d	8.88	9.08	0.116	0.19
Litter weight gain per week, kg	15.31	16.54	0.498	0.063
Piglet average daily gain per week, kg	1.54[b]	1.65[a]	0.039	0.036

Abbreviations: CON = control group; YC = yeast culture group; G 90- G 112 d = from day 90 of gestation to day 112 of gestation; G112-L21 d = from day 112 of gestation to day 21 of lactation.
[a–b]Values within a row with different superscripts differ significantly at $P < 0.05$.

Discussion

To meet the continuous need for nutrients for foetal and mammary gland development, sows undergo metabolic and physiological changes during late gestation (Luan et al., 2014). These changes can cause insulin resistance (Barbour et al., 2007) and elevated systemic pro-inflammatory cytokines and oxidative stress (Saltiel and Olefsky, 2017). This study found that dietary yeast culture supplementation from late gestation to weaning appeared beneficial for sows and piglet performance, which could be due to improved sow feed intake, milk quality, maternal immune status and altered intestinal microbiotal homeostasis.

In this study, supplementing sow diets with 24 g/d yeast culture from late gestation did not affect gestational backfat thickness change and farrowing performance. These results are in agreement with Kim et al. (2008) and Shen et al. (2011) who supplemented sows with Saccharomyces cerevisiae fermentation products throughout the whole gestation period. Czech et al. (2010) reported increased live-born piglets and piglet birth weight when sows' diet was supplemented with yeast cell wall product or manna-oligosaccharides beginning on d 28 before farrowing. Similarly, a recent study found that the number of live-born piglets was increased and IUGR percentage was decreased with increasing inclusion of *Pichia guilliermondii* in sow diet throughout gestation (Bass et al., 2019). The inconsistent results suggested that improved farrowing performance may be associated with breed of sow, duration and dose of yeast supplementation, as well as diets that varied in ingredients.

Table 4
Effects of yeast culture supplementation from late gestation to lactation on colostrum and milk composition of experimental sows.

Items	CON	YC	SEM	*P*-value
Colostrum				
Fat, %	4.52	3.71	0.428	0.162
Protein, %	14.59	14.66	0.658	0.912
Lactose, %	2.82[b]	3.13[a]	0.145	0.046
DM, %	25.15	24.85	0.717	0.768
SNF, %	21.53	21.01	0.482	4.457
Urea N, mmol/L	66.66	58.76	2.993	0.075
Milk on day 21 of lactation				
Fat, %	7.76	9.6	0.992	0.066
Protein, %	4.86[b]	5.44[a]	0.212	0.009
Lactose, %	5.7	5.74	0.28	0.922
DM, %	21.06[b]	24.00[a]	1.182	0.033
SNF, %	14.02	14.95	0.342	0.066
Urea N, mmol/L	64.27[a]	51.77[b]	4.344	0.017

Abbreviations: CON = control group; YC = yeast culture group; SNF = solid of not-fat in milk.
[a–b]Values within a row with different superscripts differ significantly at $P < 0.05$.

Table 5
Effects of yeast culture supplementation from late gestation to lactation on faecal SCFA concentration of sows.

Items	CON	YC	SEM	*P*-value
Day 110 of gestation, μ mol/g				
Total SCFA	100.41	104.66	9.059	0.744
Acetate	69.81	74.12	6.095	0.622
Propionate	18.62	18.41	2.161	0.945
Butyrate	9.71	9.89	1.144	0.911
Valerate	2.27	2.24	0.164	0.896
Total BCFA	8.32	7.79	0.8	0.952
Isobutyrate	3.24	3.08	0.326	0.671
Isovalerate	5.07	4.71	0.479	0.486
BCFA/SCFA	0.082	0.076	0.001	0.355
Day 21 of lactation, μ mol/g				
Total SCFA	96.28	98.4	7.587	0.845
Acetate	67.25	68.18	5.046	0.897
Propionate	17.27	18.58	1.502	0.545
Butyrate	9.64	9.53	1.168	0.948
Valerate	2.13	2.12	0.146	0.964
Total BCFA	8.09	7.1	0.415	0.107
Isobutyrate	3.07	2.92	0.161	0.529
Isovalerate	5.03[a]	4.18[b]	0.276	0.043
BCFA/SCFA	0.086	0.075	0.005	0.097

Abbreviations: CON = control group; YC = yeast culture group; SCAF = short-chain fatty acid; BCFA = branched-chain fatty acid.
[a–b]Values within a row with different superscripts differ significantly at $P < 0.05$.

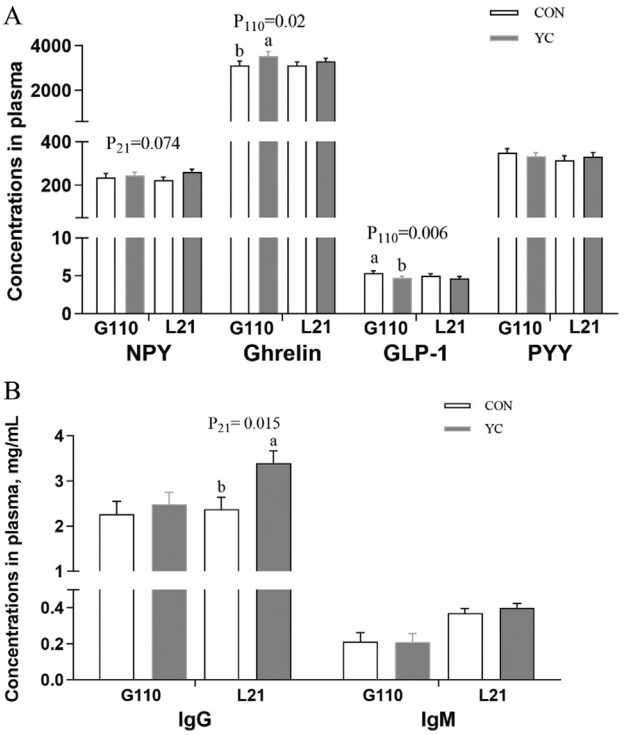

Fig. 2. Concentration of plasma hormones and immunoglobulin in sows. (A) Concentration of plasma NPY (ng/L), Ghrelin (ng/L), GLP-1 (pmol/L) and PYY (pg/ml). (B) Concentration of plasma IgG and IgM. (a–b) Values with different superscripts differ significantly at $P < 0.05$. Abbreviations: CON = control group; YC = yeast culture group; G 110 = day 110 of gestation; L21 = day 21 of lactation; NPY = neuropeptide Y; GLP-1 = glucagon-like peptide-1; PYY = peptide tyrosine-tyrosine; IgG = immunoglobin G; IgM = immunoglobin M.

Feed intake is regarded as a major limiting factor for nutrients available for milk production in lactating sows (Strathe et al., 2017), which may be due to the hormonal regulation of appetite (Zhou et al., 2018). The underlying reason for the increased lactational feed intake of YC sows could be explained by altered plasma gut hormones with reduced concentration of GLP-1, which suppresses feeding desire by relaying meal-related information on nutritional status to the brain (van Bloemendaal et al., 2014) and increased concentration of ghrelin and NPY. Neuropeptide Y is one of the most active stimulating agents for food intake, and ghrelin released from the stomach is the only known hormone which transmits hunger signals to the brain (Nogueiras et al., 2010; Zhang et al., 2012). Despite it, the hormone was changed by supplementation of yeast culture in late gestation and lactation compared to the CON group which had a higher ghrelin (G_{110}), a lower GLP-1(G_{110}) concentration and a trend to increased NPY concentration (L_{21}) in the plasma of sows. Although the mechanisms of yeast culture supplementation are still unclear, this result might be due to improved sow health condition by the positive actions of yeast culture in their intestinal tract. Some slowly fermentable probiotic components such as β-glucan and mannan-oligosaccharides exist in yeast culture, which may not only have the potential to modulate the secretion of GLP-1 (Qin et al., 2021) but could also be associated with enriched beneficial bacteria. The lactation process is generally accompanied by extreme loss of body fat and minor protein catabolism, resulting in a decline in sow BW (Hoving et al., 2012). Excessive loss of BW can increase the weaning-to-oestrus interval and cause reduced ovulation rate and embryonic survival, which will reduce the subsequent reproductive performance of affected sows (Van den Brand et al., 2000; Thaker and Bilkei, 2005; Vinsky et al., 2006). The tendency of decline in backfat loss and weaning-to-oestrus interval in YC sows was closely related to the higher feed intake due to yeast culture supplementation and the results are in agreement with whose of Jang et al. (2013). The probiotic components such as β-glucan and mannan-oligosaccharides exist in yeast culture, which could reduce the interval from weaning to next oestrus (Pettigrew et al., 2005), but the mechanisms by which yeast culture reduces weaning-to-oestrus interval have not been fully determined, but will be at least in part to better sow health resulting from the positive actions of yeast culture in their gastrointestinal tract.

The improvements in piglet performance in YC sows are similar to results obtained by Kim et al. (2008) and Song et al. (2017). It is well established that yield and composition of milk are major determinants for piglet growth (Lewis et al., 1978), so the higher milk yield in the first week of lactation, as well as improved colostrum, and milk composition in YC sows are likely to be the main reasons for improved individual piglet ADG.

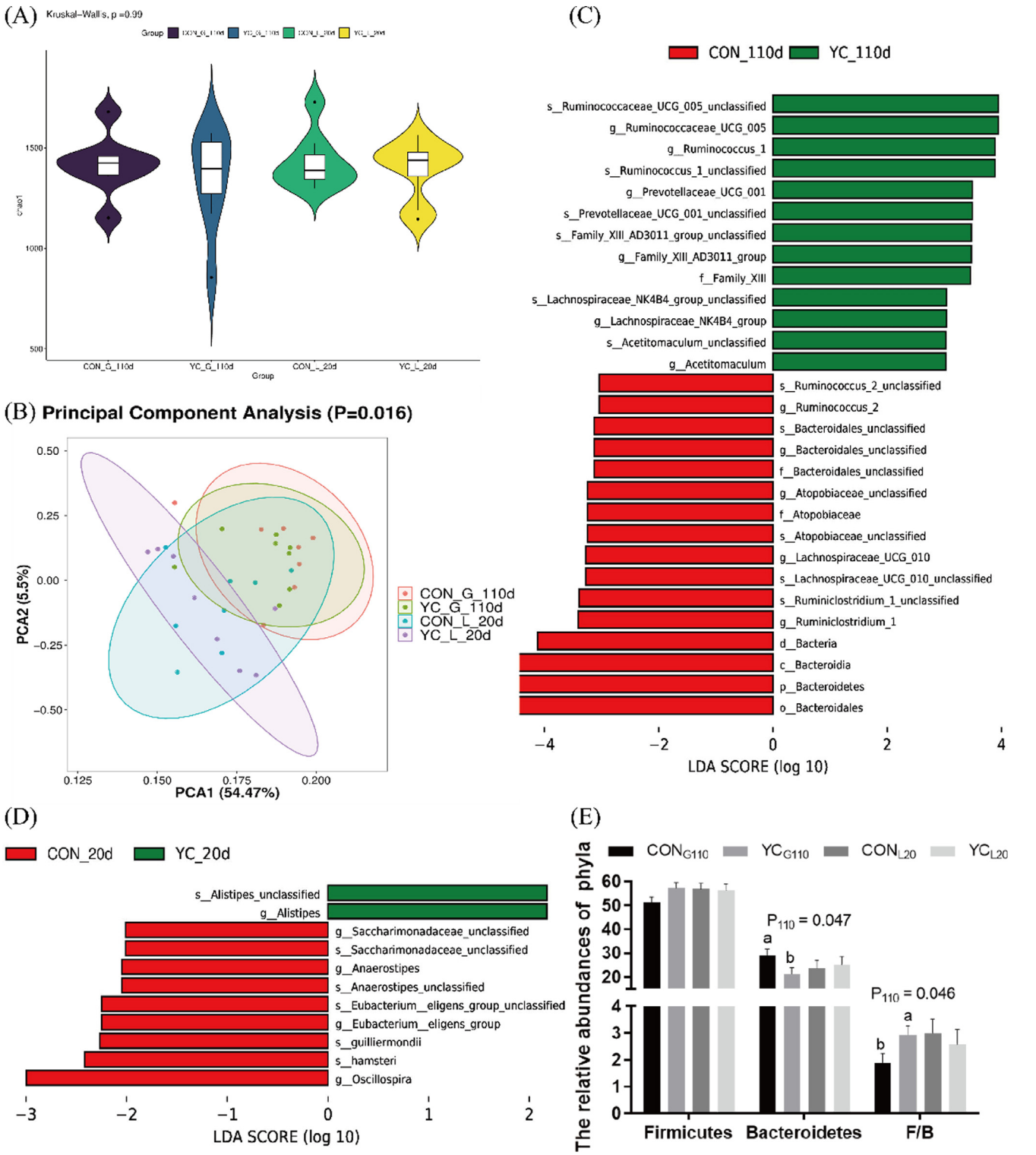

Fig. 3. Effects of yeast culture supplementation from late gestation to lactation on sows' faecal microbial diversity and relative abundance at different taxonomic levels. (A) α-Diversity (Shannon index) of the faecal microbial community; (B) β-diversity (Principal Component Analysis) of faecal microbial community; (C) LDA score of significantly differential bacterial taxa on d 110 of gestation; (D) LDA score of significantly differential bacterial taxa on d 20 of lactation; (E) The relative abundance of phyla *Firmicutes* and *Bacteroidetes* and *Firmicutes/Bacteroidetes* ratio(F/B). (a–b) Values with different superscripts differ significantly at $P < 0.05$. Abbreviations: CON = control group; YC = yeast culture group; G 110 = day 110 of gestation; PCA = principal component analysis; L20 = day 20 of lactation; LDA = linear discriminant analysis.

The reduction of specific BCFA concentration detected on d 21 of lactation may be indicative of a lower colonic protein fermentation (Windey et al., 2012; Korpela, 2018) and a higher protein digestion and absorption in the foregut (Shen et al., 2009).

Supplementation with yeast culture to the gestation and lactation diet did elevate sow serum IgG concentration at weaning, suggesting a better maternal immunological state. Similarly, Czech et al. (2010) reported that serum IgG on d 110 of gestation and IgA on d 21 of lactation were increased when sows consumed yeast

cell walls from d 84 of gestation to d 28 of lactation. The improvements in maternal immunological state could be due to probiotic components such as β-glucan and mannan-oligosaccharides that exist in yeast culture, which were not only proven to bind to pathogenic bacteria and flush them away from the intestinal lumen (Spring et al., 2000) but also to promote the growth of beneficial bacteria (Davis et al., 2004).

Although yeast culture supplementation showed no effect on faecal bacteria diversity in the present study, a higher *Firmicutes*/*Bacteroidetes* ratio and more abundant beneficial and fermentative bacteria, such as *Prevotellaceae_UCG-001*, *Ruminococcaceae_UCG-005*, *Ruminococcus_1,* were observed on d110 of gestation. A high *Firmicutes*/*Bacteroidetes* ratio has been directly related with promoting obesity (Ley et al., 2006; Zou et al., 2018) and according to Jumpertzx et al. (2011), an increase in *Firmicutes* and a corresponding decrease in *Bacteroidetes* was associated with an increased energy harvest. The results indicated some degree of increased energy harvest with yeast culture, which may be associated with increased milk yield and quality in the first week of lactation. Yue et al. (2019) reported that *Prevotellaceae_UCG-001* was associated positively with faecal moisture but negatively with gastrointestinal transition time, and related to glycolipid metabolism disorders (Song et al., 2019). Genus *Ruminococcaceae_UCG-005* and *Ruminococcus_1*, both belonging to family *Ruminococcaceae*, have been demonstrated to participate in degradation of diverse polysaccharides (Shang et al., 2018) with a negative correlation with lipopolysaccharide biosynthesis, and a lower abundance had been reported to lead to inflammatory response (Kang et al., 2017; Shao et al., 2020). All of those mentioned above indicate that yeast culture treatment contributed to improving energy utilisation for milk composition and increased storage in body reserves, as well as improved systemic inflammatory status. Differences of *Firmicutes*/*Bacteroidetes* ratio with yeast culture supplementation vanished in lactation and genera *Eggerthella* and *Alistipes* were significantly enriched. Decreased body fat content leads to a lower Firmicutes/Bacteroidetes ratio (Turnbaugh et al., 2006; Zou et al., 2018). Lower *Firmicutes*/*Bacteroidetes* ratio indicated some degree of increased energy expenditure, as well as a catabolic metabolic state during lactation. *Eggerthella* and *Alistipes* can degrade dietary fibres, produce polyphenols and suppress microbial pathogenicity to barrier function (Li et al., 2009; Whisner and Aktipis, 2019).

Conclusion

The present study showed that dietary yeast culture supplementation from late gestation to weaning improved ADG of piglets and weaning-to-oestrus interval, which could be due to improved sow feed intake, milk yield and composition, maternal health status as well as gut microbiota. *Saccharomyces cerevisiae* yeast culture products may be a promising functional additive to improve the performance of sows and their offspring.

Ethics approval

The animal study protocol was reviewed and approved by the Animal Care and Use Committee of Sichuan Agricultural University under ethic approval number 20 180 082. Animal study was conducted on a commercial pig farm in southwest of China (TIE QI LI SHI, Mian Yang) from October 2018 to January 2019 and was in accordance with the Guidelines on Ethical Treatment of Experimental Animals (2006) No. 398 of the Ministry of Science and Technology of China.

Data and model availability statement

The sequencing data have been uploaded to NCBI, which can be accessed with NO. PRJNA815319.

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Declaration of interest

All authors have read, approved the final manuscript, and declared no competing interests existed.

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