Decreasing the level of hemicelluloses in sow's lactation diet affects the milk composition and post-weaning performance of low birthweight piglets.

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Abstract

Hemicelluloses (HC) are polysaccharides constituents of the cell walls of plants. They are fermented in the gut to produce volatile fatty acids (VFA). The present study investigated the effects of decreasing HC level in sow's lactation diet on sow performances, offspring development and milk composition. From 110 days (d) of gestation until weaning (26±0.4 d post-farrowing), 40 Swiss Large White sows were assigned to one of the four dietary treatments: (1) ~~T12~~ T13 (HC: ~~121~~ 127g/kg), (2) T11 (HC: ~~107.6~~ 114g/kg), (3) T9 (HC: ~~86.4~~ 94g/kg) and (4) ~~T7~~ T8 (HC: ~~71.9~~ 80g/kg). Milk was collected at 3 and 17d of lactation. At birth, piglets were divided into two groups according to their birthweight (BtW): normal (N-BtW; BtW > 1.20 kg) or low (L-BtW; BtW ≤ 1.20 kg). Decreased HC levels in the maternal diet linearly increased ($P \leq 0.05$) the body weight of L-BtW piglets at two weeks post-weaning and linearly decreased ($P \leq 0.05$) diarrhoea incidence and duration in this category. The concentrations of copper, threonine and VFA, as well as the proportion of butyrate, in milk linearly increased ($P \leq 0.05$), whereas lactose content linearly decreased ($P \leq 0.05$) with decreased HC in the maternal diet. The present study provides evidence that decreasing HC level in sow's lactation diet can positively affect the composition and VFA profile of milk and ultimately favour the growth and health of L-BtW piglets.

Keywords: Dietary fibres, lactose, pigs, volatile fatty acids, butyrate

Introduction

Hemicelluloses (HC) represent a complex group of polysaccharides present in the cell walls of all plants, consisting mainly of pentoses (D-xylose and D-arabinose), hexoses (D-galactose, D-glucose and D-mannose) and uronic acids that can be estimated as the difference between NDF and ADF (Huang et al., 2021; Van Soest et al., 1991). As part of dietary fibres (DF), they can resist digestion by endogenous enzymes of the gut. Thus, they can reach the large intestine and promote the growth and activity of beneficial bacteria that produce volatile fatty acids (VFA) (Lattimer and Haub, 2010). These latter, namely, acetate, propionate and butyrate, provide up to 28% of the energy requirements in growing pigs and even more in sows, where they can be absorbed and transferred to the milk and serve as an energy source for milk synthesis (Noblet and Le Goff, 2001; Tian et al., 2020). A previous study focused on increasing the level of DF in sow's gestation diet showed that adding up to 20% DF increases colostrum fat content, as well as colostrum intake, of low birthweight (BtW) piglets ~~(L-BtW)~~ (0.6 kg ≥ BtW <0.9 kg) and decreases litter mortality during the suckling period (Loisel et al., 2013). To our knowledge, the effects of HC level have been investigated in growing pigs but never in lactating sows (Zhao et al., 2019).~~on lactating sows have~~

~~never been investigated~~ However, this aspect can be relevant, since ~~sow nutrition~~ inclusion of DF during lactation may also positively affect the development and gut health of piglets (Paßlack et al., 2015). Like all DF, HC can be differentiated according to their physiochemical properties such as their solubility in water and their intestinal fermentability. Indeed, depending on the plants, HC might be considered as a source of soluble dietary fibres (SDF) (Jiménez-Escrig et al., 2000). Compared to insoluble dietary fibres (IDF), SDF are easily fermented and may be completely degraded in the end of small intestine (Houdijk et al., 2002). Due to their slower fermentability, the majority of the IDF reach the large intestine, which acts as a fermentation chamber producing VFA (Lattimer and Haub, 2010). Therefore, the present study aims to fill this gap by comparing four diets characterised by similar total DF and crude fibre contents but different HC levels by varying the sources of DF. We hypothesised that decreasing the level of HC in sow's lactation diet may affect gut fermentation particularly in the large intestine and ultimately modify milk composition.

Materials and methods

Animals, housing and treatments

The experiment was conducted during late gestation and lactation of 40 Swiss Large White sows from five farrowing batches. Approximately 10 days before the expected time of farrowing, sows were moved to farrowing rooms arranged with individual 7.1 m^2 farrowing crates, consisting of a 5.89 m^2 concrete solid floor and a 1.21 m^2 concrete slatted floor. Each crate was equipped with an electronic sow feeder (Schauer Spotmix, Schauer Agrotronic GmbH, Austria), nipple drinker and a heated covered area for piglets. The ambient temperature was maintained at 24 °C, and artificial lights were on from 0800 h to 1700 h. On day 110 of gestation, the sows were randomly allocated to one of the four experimental lactation diets based on parity (mean ± SEM: 3.5 ± 0.7) and BW (mean ± SEM: 286.5 ± 13.6 kg). Parturition was induced when gestation period exceeded 116 days with an intramuscular injection of 1 ml (0.25 g/ml) of cloprostenol (Estrumate®, MSD Animal Health GmbH, Luzern, Switzerland). Within the first 24 h following birth, piglets were identified by an individual ear tag and received iron injection (Feridex® 10%, AMAG Pharmaceuticals, Inc., Waltham, USA). Piglets weighing less than 800 g at birth were excluded from the experiment. To adjust litter size to an average of 12 piglets per sow, cross-fostering was carried out only on male piglets 24 h post-farrowing. After anaesthetisation, the male piglets were castrated in the second week. Piglets were weaned on day 25.7 ± 0.44 (mean ± SEM) of age but were kept in their respective farrowing crates until 2 weeks post-weaning. The heating nest temperature was set at 40 °C following birth and then gradually decreased by 0.5 °C per day to reach a final temperature of 32 °C

Diets and feeding

The experimental diets were formulated to be isonitrogenous and isocaloric (Table 1) and to differ in DF sources and HC content: (1) ~~T12~~ T13 (HC: ~~121~~ 127 g/kg), (2) T11 (HC: ~~107.6~~ 114g/kg), (3) T9 (HC: ~~86.4~~ 94g/kg) and (4) ~~T7~~ T8 (HC: ~~71.9~~ 80g/kg). The daily feed allowance was calculated according to the current Swiss feeding recommendations for pigs (Agroscope, 2018). Sows had *ad libitum* access to water and were provided with moderate quantities of straw bedding, as required by the Swiss legislation. During the end of gestation, feed allowance was on average 3.04 ± 0.16 kg (mean ± SEM). While, during lactation, the feed allowance was gradually increased by 0.5 kg/day until *ad libitum* feeding on day 12 of lactation approximatively. All diets were delivered three times per day in three equal meals using a computerised feed delivery system (Schauer Spotmix, Schauer Agrotronic GmbH, Austria). Throughout the experiment, the feed refusals of the sows were weighed daily to calculate actual feed intake. From day 18.7 ± 0.44 of age (mean ± SEM) to 2 weeks post-weaning (mean ± SEM: day 39.7 ± 0.44 of age), piglets had *ad libitum* access to a post-weaning standard starter diet and water. The post-weaning starter diet contained 170 g/kg crude protein, 58 g/kg fat, 50 g/kg crude fibre and 14 MJ/kg digestible energy.

Table 1. Ingredients and composition of the sow's lactation diet

	Dietary Treatments[1]			
Item	~~T12~~ T13	T11	T9	~~T7~~ T8
Ingredients (%)				
Barley, ground	54.4	38.7		4.7
Oat flakes			4.0	18.2
Corn, ground	10.3		26.9	16.0
Rye		25.0	10.0	
Wheat, ground			13.1	15.0
Wheat starch	4.0	4.0	4.0	4.0
Molasses				4.0
Animal fat RS 65	2.4	2.4	3.0	3.8
Potato protein	10.0	10.0	10.0	10.0
Soybean meal	10.0	10.0	10.0	10.0
Flaxseed Meal	0.6			
Rapeseed meal		0.4		1.7
Oat hulls			4.0	8.0
Lupin			2.5	
Wheat bran			4.0	
Beet pulp	3.0	5.0	4.0	
L-lysine-HCL	0.070	0.057	0.057	0.056
DL-methionine	0.200			
L-threonine	0.050			0.050
L-tryptophan	0.020	0.006	0.013	0.003
Dicalcium phosphate	0.94	0.70	0.82	0.85
Calcium carbonate	1.57	1.38	1.39	1.47
Salt	0.59	0.52	0.42	0.41
Pellan[2]	0.40	0.40	0.40	0.40
Celite	1.00	1.00	1.00	1.00

Premix[3]	0.40	0.40	0.40	0.40
Natuphos 5000 G[4]	0.01	0.01	0.01	0.01
Gross chemical composition analysed (g/kg as fed)				
Dry matter	900	894	897	900
Crude protein	193	191	192	196
Fat	51	46	57	60
Crude fibre	43	43	47	46
Ash	63	61	60	63
NDF	184	174	163	154
ADF	~~63~~ 57	~~67~~ 60	~~76~~ 69	~~82~~ 79
Hemicelluloses[5]	~~121~~ 127	~~108~~ 114	~~86~~ 94	~~72~~ 80
Total dietary fibres	210	227	220	203
Low-molecular-weight dietary fibres	18	23	18	14
Soluble dietary fibres	43	44	35	28
Insoluble dietary fibres	149	160	167	161
IDF/SDF[6]	3.46	3.63	4.77	5.75
Calcium	9.4	9.4	9.3	8.7
Phosphorus	5.0	4.6	5.0	4.7
Gross chemical composition calculated				
Digestible energy (MJ/kg)	14.1	14.1	14.1	14.1
Digestible phosphorus (g/kg as fed)	3.1	2.8	2.8	2.8
Digestible essential amino acids (g/kg as fed)				
Lysine	9.6	9.6	9.6	9.6
Methionine	4.9	2.9	3.0	3.0
Threonine	6.9	6.3	6.4	6.9
Tryptophan	2.0	1.8	1.8	1.8

[1]~~T12~~ T13= Sow's lactation diet containing ~~12~~ 13% of hemicelluloses; T11 = Sow's lactation diet containing 11% of hemicelluloses; T9 = Sow's lactation diet containing 9% of hemicelluloses; ~~T7~~ T8 = Sow's lactation diet containing ~~7~~ 8% of hemicelluloses.

[2]Pellet binding aid: Pellan, Mikro-Technik, Bürgstadt, Germany.

[3]Supplied per kg of diet: vitamin A, 8000 IU; vitamin D3, 800 IU; vitamin E, 40 mg; menadione, 2 mg; thiamine, 2 mg; riboflavin, 5 mg; biotin, 0.1 mg; niacin, 20 mg; pantothenic acid, 20 mg; iodine (as calcium iodate), 0.55 mg; copper (as copper sulphate), 7 mg; manganese (as manganese oxide), 20 mg; zinc (as zinc oxide), 55 mg; selenium (as sodium selenite), 0.2 mg.

[4]Phytase supplemented with 500 units of *Aspergillus niger* phytase/kg diet.

[5]Hemicellulose: calculated as the difference between NDF and ADF.

[6]Ratio of insoluble to soluble dietary fibres

Sow and piglet performance

The BW of the sows, body condition score (BCS) and backfat thickness were recorded at the 110th day of gestation and ~~during~~ on the day of farrowing and weaning. Weight loss during lactation was calculated as the weight difference between farrowing and weaning. Based on visual observation and palpations, BCS was determined according to a scale ranging from 1 (*very thin*) to 6 (*obese*) points (Dourmad et al., 2001), including intermediate values of 0.33 points. Briefly, the trained personnel assessed sows by palpating the shoulders, ribs, backbone and hips, followed by a visual observation. Backfat thickness was measured on each side at 65 mm of the dorsal midline at the level of the last rib (P2) using a digital ultrasound back-fat indicator (Renco Lean Meter Digital Backfat Indicator, Renco Corporation, Minneapolis, Minnesota, USA). Backfat thickness loss during lactation was then calculated as the difference between backfat thickness measurements during farrowing and weaning. At farrowing, the number of born alive, stillborn and mummified piglets were recorded within each litter. Farrowing was recorded using a digital video recorder to estimate the farrowing duration, which is defined as the time span between the time of birth of the first and last piglet of the litter. ~~Furthermore, the time between the start of the farrowing and the first piglet suckling was also recorded.~~ At birth, the piglets were individually weighed, and crown-to-rump length and body circumference were recorded. Piglets were then individually weighed 5 and 16 days postpartum, during weaning (mean ± SEM: 25.7 ± 0.44 days of age) and at 1 (mean ± SEM: 32.7 ± 0.44 days of age) and 2 weeks post-weaning (mean ± SEM: 39.7 ± 0.44 days of age). The average daily gain (ADG) and litter weight during birth and weaning were calculated from these data. Milk yield was calculated as the individual piglet gain summed in the same litter multiplied by a numerical coefficient of 4.2 (Van der Peet-Schwering et al., 1998). The indices of body conformation were calculated based on the measurements of the individual

~~birthweight (~~BtW~~)~~ and the crown-to-rump length. The body mass index was calculated as the ratio of BtW to the squared value of the crown-to-rump length, and the ponderal index was calculated as the ratio of BtW to the cubic value of the crown-to-rump length (Hales et al., 2013). In addition, piglets were divided into two BtW groups: normal (N-BtW; BtW > 1.20 kg) or low (L-BtW; BtW ≤ 1.20 kg). From 1 week before weaning onwards, feed intake and refusals (including feed waste) per pen as well as the occurrence of diarrhoea were recorded daily. Diarrhoea incidence ~~percentage~~ was determined according to a daily faecal score assessed using a scale from 0 = *no diarrhoea* to 1 = *diarrhoea*. The percentage of diarrhoea per group was calculated as the sum of piglets with a faecal score of one divided by the total number of piglets.

Sample Collection

Within each farrowing series, feed samples of the four diets were collected weekly and pooled over the experimental period to determine the chemical composition. On days 3 and 17 of lactation, milk samples were manually collected from all functional teats after an intramuscular injection of 2 ml of oxytocin (Intertocine-S, MSD Animal Health GmbH, Luzern, Switzerland). Before milking, the piglets were temporarily isolated from the sow for 2 h, and the teats were cleaned with humid wipes. One aliquot of milk was refrigerated at 5 °C with 4 mg of bronopol to determine somatic cell concentration, and three aliquots were immediately stored at −20 °C for further analysis.

Analytical Methods

Feed Analysis

After being ground to pass a 1-mm screen (Brabender rotary mill; Brabender GmbH & Co. KG, Duisburg, Germany), feed samples were analysed for dry matter content by heating at 105˚C for 3h followed by incineration at 550°C until a stable mass was reached to determine the ash content according to ISO 5984:2002 (prepASH, Precisa Gravimetrics AG, Dietikon, Switzerland). An inductively coupled plasma optical emission spectrometer (ICP-OES, Optima 7300 DV; Perkin-Elmer, Schwerzenbach, Switzerland) was used to measure mineral content (European Standard EN 15510:2008). The CP content was calculated as nitrogen (N) content multiplied by a coefficient of 6.25, where N was determined with the Dumas method (ISO 16634–1:2008). Fat content was extracted with petrol ether after acid hydrolysis (ISO 6492:1999). Different categories of fibres were analysed by standard protocols. Crude fibre content was determined gravimetrically (ISO 6865:2000) by incineration of residual ash after acid and alkaline digestions using a fibre analyser (Fibretherm Gerhardt FT-12, C. Gerhardt GmbH & Co. KG, Königswinter, Germany). The NDF and ADF contents (ISO 16472:2006 for NDF and ISO 13906:2008 for ADF) were analysed with the same fibre analyser (Fibretherm Gerhard FT-12, C. Gerhardt GmbH & Co. KG, Konigswinter, Germany) and were expressed without residual ash. NDF determination was evaluated with heat stable amylase and sodium sulfite and expressed without residual ash after incineration at 600°C for 3 h. ~~Soluble (~~The contents of ~~(~~SDF~~)~~, ~~insoluble (~~IDF~~)~~ and low-molecular-weight DF ~~contents~~ were measured according to AOAC Method 2011.25, and the total DF content was calculated as the sum of the three aforementioned types of DFs.

Milk Analysis

The dry matter of the frozen milk samples was determined after freeze-drying (Christ DELTA 2-24 LSC, Kühner AG, Birsfelden, Switzerland) for 70 hours. Subsequently, freeze-dried samples were milled with a mortar. Residual dry matter, ash~~es~~, mineral and ~~CP~~ nitrogen contents were analysed as previously described for the feed chemical analysis, except that ~~a multiplicative coefficient of~~ that CP was expressed as N x 6.38 ~~was applied for the calculation of CP~~. Except for tryptophan, all amino acids were determined as described in ISO 13903:2005. Briefly, after oxidation, 24 h of acid hydrolysis occurred with 6M HCl and derivatization with AccQ-Tag Ultra reagent (Waters corporation, Milford, USA USA), the amino acid profile was determined by ultra-high-performance liquid chromatography (UHPLC) coupled with a UV detector (Vanquish, Thermo Scientific, Reinach, Switzerland. Tryptophan content was quantified by HPLC (LC 1290 Infinity II LC System, Agilent Technologies, USA) according to ISO 13904:2016. Gross energy content was determinate by combustion in a calorimetric vessel under pure oxygen condition using an adiabatic bomb calorimeter (AC600 Semi-Automatic Calorimeter, Leco Corporation, USA) (ISO 9831:1998). Lactose content was determined by enzymatic testing with β-galactosidase and galactose dehydrogenase (Enzytec TM Liquid Lactose/D-Galactose Ref. No. E8110, R-Biopharm AG, Darmstadt, Germany). Somatic cells count (ISO 13366-2) was determined by flow cytometry (Somacount FC, Bentley Instruments Inc., USA). Fatty acid methyl esters, as described by Kragten et al. (2014), and the VFA profile (ISO 15884:2002) (ISO 15885:2002) were determined by gas-liquid chromatography (Gaschromatograph Series II Agilent 6850, Agilent Technologies 2000, USA and Gaschromatograph Serie Agilent 6890, Agilent Technologies 2000, USA, respectively). Fat content was determined as total fatty acids multiplied by a coefficient of 1.05.

Statistical Analysis

Due to health problems that could not be related to the dietary treatment, one T9 sow was excluded from the experiment. Data were analysed by ANOVA using the 'lme' and the 'glmmPQL' function of the *nlme* package of R Studio (version 4.0.2 for Windows). Regarding sow performance, milk composition and VFA profile, the sow was the experimental unit; the pen was the experimental unit regarding piglet feed intake and litter performance; and the piglet was the experimental unit of piglet's individual performance, days and percentage of diarrhoea. Linear regression models, including the treatment and the farrowing batch as fixed effects, were used to fit data related to sow performance, litter performance, piglet feed intake and days with diarrhoea. Data related to piglets' individual performance were analysed using a linear mixed-effects model, including the treatment and the farrowing batch as fixed effects and the sow as random effects. Milk composition and VFA profile were analysed with a linear mixed-effects model and fitted in repeated measurements, including the treatment, the farrowing batch, the sampling day, and the interaction between the treatment and sampling day as fixed effects and the sow as random effect. Before analysis, logarithmic transformation was applied to the milk fatty acid and milk VFA data due to the non-normality of the residuals. The percentage of diarrhoea was analysed using a generalised linear mixed model using Penalized Quasi-Likelihood, including the treatment, the farrowing batch and the day as fixed effects and the piglet as a random factor. Orthogonal polynomial contrasts were implemented to evaluate the linear or quadratic effects of decreasing HC level. The results are expressed as the least square means ± SEM. Linear and quadratic effects were considered significant at $P \leq 0.05$.

Results

Sows' performance

The sow BW, BCS and backfat thickness on day 110 of gestation and during farrowing and weaning were not influenced by the dietary treatment, resulting in similar weight and backfat thickness losses during the lactation period. Daily feed intake in the pre-farrowing period and during lactation did not differ between treatments. Fibre intake was partially influenced by dietary treatments. In both the pre-farrowing and lactation periods, the NDF, HC, (linear effects; $P < 0.01$), low-molecular-weight DF and SDF intake decreased (linear and quadratic effects; $P < 0.01$), and the ADF intake increased (linear effect; $P < 0.01$) with decreasing HC levels in the diet. A quadratic effect ($P \leq 0.04$) of the HC level was found in the diets on the intake of total DFs in the pre-farrowing and lactation periods. At birth, litter traits, such as total born, born alive and stillborn piglets, did not differ, leading to comparable litter weights in the four treatments. Likewise, the dietary treatments had no effect on the total number of piglets weaned and, consequently, on litter weight at weaning. Farrowing duration ~~and the time between the start of the farrowing and the first piglet suckling were~~ was not influenced by dietary treatments. During the entire lactation period, milk yield was not influenced by the dietary treatments, with an average estimated production of 10.38 kg/day per sow (Table 2).

Table 2. Effect of decreasing hemicelluloses level in lactation diet on sow's performance

Item	[1]Dietary Treatments				SEM	[2]Contrasts	
	~~T12~~ T13	T11	T9	~~T7~~ T8		*L*	*Q*
Sows							
Number of sows, *n*	10	10	9	10			
Range of parity, *n*	3.8	3.8	3.5	3.5	0.69	0.51	0.99
Farrowing duration, min	308	337	321	262	70.7	0.54	0.44
Body weight, kg							
D110	284	291	284	287	13.6	0.71	0.89
Farrowing	264	267	269	272	14.1	0.67	0.99
Weaning	233	238	248	246	12.5	0.39	0.78

Weight loss in lactation, kg	30.6	28.7	20.9	26.1	2.58	0.19	0.30
BCS, *n*							
D110	4.09	4.10	4.03	3.83	0.129	0.79	0.18
Farrowing	3.58	3.59	3.40	3.64	0.148	0.96	0.40
Weaning	2.71	2.62	2.81	2.94	0.246	0.42	0.62
Backfat thickness, mm							
D110	13.8	~~15.8~~ 14.8	~~14.8~~ 12.7	~~12.7~~ 15.8	0.88	0.31	0.23
Farrowing	13.7	14.6	12.7	15.6	0.88	0.34	0.24
Weaning	11.3	11.9	11.5	12.9	0.71	0.18	0.52
Backfat thickness loss in lactation, mm	2.38	2.66	1.25	2.67	0.505	0.82	0.24
Milk yield, kg/day	10.61	10.85	10.09	9.97	0.720	0.41	0.79
Feed intake, kg/day							
Pre-farrowing	2.93	3.03	3.03	3.00	0.155	0.75	0.68
Lactation	5.67	5.93	5.77	5.87	0.237	0.69	0.73
Fibre intake, g/day							
Pre-farrowing							
Crude fibre	127	129	141	139	7.0	0.13	0.74
NDF	538	527	492	461	26.1	0.03	0.69
ADF	~~185~~ 168	~~202~~ 182	~~230~~ 208	~~248~~ 224	~~11.3~~ 10.3	<0.01	~~0.97~~ 0.90
Hemicelluloses	~~353~~ 370	~~325~~ 345	~~261~~ 284	~~213~~ 237	~~15.1~~ 16.1	<0.01	0.48
Total dietary fibres	614	688	667	610	33.1	0.82	0.04
Low-molecular-weight dietary fibre	53	70	55	42	2.8	<0.01	<0.01
Soluble dietary fibres	133	126	106	83	5.8	<0.01	<0.01
Insoluble dietary fibres	436	485	506	484	24.8	0.14	0.14
Lactation							
Crude fibre	246	254	269	272	10.4	0.06	0.81
NDF	1043	1033	937	903	41.3	<0.01	0.75
ADF	~~359~~ 325	~~396~~ 356	~~439~~ 396	~~484~~ 438	~~16.4~~ 14.8	<0.01	~~0.80~~ 0.71
Hemicelluloses	~~685~~ 718	~~638~~ 677	~~498~~ 541	~~418~~ 465	~~25.3~~ 26.8	<0.01	0.49
Total dietary fibres	1190	1350	1270	1190	51.1	0.76	0.02
Low-molecular-weight dietary fibre	102	137	104	82	4.6	<0.01	<0.01
Soluble dietary fibres	244	261	202	163	9.6	<0.01	<0.01
Insoluble dietary fibres	845	950	964	947	37.1	0.06	0.09
Suckling piglets							
~~First piglet suckling, min~~	~~35~~	~~28~~	~~20~~	~~38~~	~~11.0~~	~~0.98~~	~~0.23~~
Number of piglets per litter, *n*							
Total born[3]	13.5	13.7	13.5	14.3	1.12	0.65	0.76
Born alive[3]	12.8	12.4	11.4	12.7	1.27	0.82	0.49
Stillborn	0.7	1.3	2.1	1.6	0.65	0.22	0.40
After cross-fostering	11.4	11.4	11.5	11.6	0.79	0.85	0.91
Weaned	10.7	10.9	11.3	10.7	0.76	0.94	0.60
Litter weight, kg							

At birth	20.5	20.5	21.1	20.3	1.63	0.99	0.81
At weaning	81.9	83.9	78.0	79.4	5.50	0.59	0.96

[1]~~T12~~ T13 = Sow's lactation diet containing ~~12~~ 13% of hemicelluloses; T11 = Sow's lactation diet containing 11% of hemicelluloses; T9 = Sow's lactation diet containing 9% of hemicelluloses; ~~T7~~ T8 = Sow's lactation diet containing ~~7~~ 8% of hemicelluloses.

[2]Contrasts: L = Linear; Q = Quadratic.

[3] including piglets weighing less than 800g at birth.

Piglets' individual performance

Body characteristics, such as body circumference, crown-to-rump length, body mass index and ponderal index, were not affected by the lactation diet of the sows (Table 3). Similarly, piglet BW development, ADG and feed intake were not affected by the dietary treatments. During the first week post-weaning, the incidence of diarrhoea and the number of days with diarrhoea were similar among the treatments. By contrast, during the second week of post-weaning, a quadratic increase ($P \leq 0.05$) in the incidence of diarrhoea and the number of days with diarrhoea was observed with decreasing HC level. When focusing on the two BtW categories, the effect of the sow diets in the L-BtW group showed interesting observations (Table 4). ~~Excluding the incidence of diarrhoea and the number of days with diarrhoea that linearly increased during the second week post-weaning ($P < 0.01$) with decreased HC level, no dietary effects were observed in N-BtW piglets (Supplementary Table 1).~~ The BtW, the BWs until one week post-weaning and in accordance the ADG in this period were similar among the experimental treatments for L-BtW piglets. By contrast, the decrease in HC level in the sow diets increased (linear effect; $P \leq 0.04$) the BW and the ADG in the second week post-weaning and the overall ADG from birth to two weeks post-weaning of L-BtW piglets. ~~Likewise, the ADG of the L-BtW pigs remained similar among the dietary treatments in the suckling period.~~ ~~Nevertheless, decreasing the HC level in the maternal diet improved ($P \leq 0.05$) the ADG of L-BtW piglets in the second week post-~~

~~weaning and thereby the overall ADG of the L-BtW piglets during the experiment.~~ In the first week post-weaning, the dietary treatments did not affect either the incidence of diarrhoea or the days with diarrhoea of L-BtW piglets. In the second week post-weaning, the incidence of diarrhoea and days with diarrhoea linearly decreased ($P < 0.01$) with decreased HC level in the maternal diet. Except for the linear increase in the incidence of diarrhoea and increase in the number of days with diarrhoea in the second week post-weaning ($P < 0.01$) with decreasing HC level, no dietary effects on growth traits were observed in N-BtW pigs (Supplementary Table 1).

Table 3. Effect of decreasing hemicelluloses level in the maternal diet on the performance of piglets

	[1]Dietary Treatments					[2]Contrasts	
	~~T12~~ T13	T11	T9	~~T7~~ T8	SEM	*L*	*Q*
Body measurements at birth, cm							
Crown-to-rump length	28.7	28.9	28.8	28.4	0.53	0.60	0.56
Body circumference	25.5	25.6	25.8	25.3	0.49	0.81	0.57
Body mass index, kg/m^2	19.2	18.8	19.5	18.7	0.55	0.78	0.73
Ponderal index, kg/m^3	67.2	65.1	67.9	66.3	2.03	0.99	0.88
Body weight, kg							
At birth	1.61	1.60	1.63	1.52	0.083	0.55	0.50
5 days post-farrowing	2.38	2.37	2.45	2.22	0.126	0.49	0.36
16 days post-farrowing	5.36	5.28	5.25	4.94	0.272	0.29	0.65
Weaning	7.69	7.54	7.26	7.36	0.348	0.41	0.71
1 week post-weaning	7.82	7.69	7.42	7.48	0.371	0.55	0.92
2 week post-weaning	8.93	9.17	8.71	8.93	0.453	0.82	0.99
ADG, g/day							
Birth to 5 days post-farrowing	154	154	160	137	12.6	0.44	0.34
Birth to 16 days post-farrowing	235	230	225	212	13.9	0.25	0.74
Birth to weaning	237	232	222	222	11.5	0.29	0.82
Weaning to 2 weeks post-weaning	86	116	103	113	17.3	0.38	0.52
1 week to 2 weeks post-weaning	172	194	184	207	20.8	0.31	0.98
Birth-2 week post-weaning	185	191	180	184	9.9	0.73	0.90
Feed intake, g/piglet							
1 week pre-weaning	182	186	157	189	24.5	0.95	0.55
1 week post-weaning	753	883	760	786	121.0	0.96	0.65
2 weeks post-weaning	1428	1638	1436	1600	144.0	0.63	0.87
Post-weaning diarrhoea,%							
1 week post-weaning	26.1	29.3	27.0	29.6	2.47	0.47	0.77
2 weeks post-weaning	17.4	17.2	12.8	22.2	2.82	0.44	0.05
Days with diarrhoea, days							
1 week post-weaning	1.89	2.09	1.85	2.10	0.171	0.61	0.90
2 weeks post-weaning	1.45	1.40	1.11	1.80	0.172	0.34	0.02

[1]~~T12~~ T13= Sow's lactation diet containing ~~12~~ 13% of hemicelluloses; T11 = Sow's lactation diet containing 11% of hemicelluloses; T9 = Sow's lactation diet containing 9% of hemicelluloses; ~~T7~~ T8 = Sow's lactation diet containing ~~7~~ 8% of hemicelluloses.

[2]Contrasts: L = Linear; Q = Quadratic.

Table 4. Effect of decreasing hemicelluloses level in maternal diet on the performance of low birthweight piglets

	[1]Dietary Treatments					[2]Contrasts	
	~~T12~~ T13	T11	T9	~~T7~~ T8	SEM	*L*	*Q*
Number of piglets, *n*	25	23	15	20			
Body measurements at birth, cm							
Crown-to-rump length	25.0	25.4	25.5	26.0	0.56	0.22	0.97
Body circumference	22.3	21.8	21.9	22.3	0.42	0.98	0.16
Body mass index, kg/m^2	16.6	15.5	16.1	15.8	0.65	0.51	0.43
Ponderal index, kg/m^3	66.6	61.4	63.6	61.7	3.22	0.37	0.54
Body weight, kg							
At birth	1.04	1.01	1.04	1.06	0.047	0.64	0.46
5 days post-farrowing	1.61	1.59	1.58	1.54	0.095	0.53	0.86
16 days post-farrowing	3.94	3.78	3.59	3.85	0.287	0.70	0.39
Weaning	5.86	5.73	5.42	6.55	0.468	0.38	0.12
1 week post-weaning	5.92	5.96	5.56	6.95	0.498	0.20	0.12
2 week post-weaning	6.55	6.66	6.43	8.35	0.545	0.02	0.06
ADG, g/day							
Birth to 5 days post-farrowing	113	118	104	91	14.1	0.14	0.43
Birth to16 days post-farrowing	181	173	158	173	16.7	0.57	0.41
Birth to weaning	192	184	171	201	16.3	0.83	0.18
Weaning to 2 weeks post-weaning	50	62	74	113	27.0	0.09	0.56
1 week to 2 weeks post-weaning	91	103	125	187	27.0	0.01	0.25
Birth to 2 weeks post-weaning	141	143	135	177	11.5	0.04	0.05
Post-weaning diarrhoea,%							
1 week post-weaning	19.8	34.1	16.4	20.8	10.50	0.69	0.50
2 weeks post-weaning	36.4	16.7	6.5	5.2	8.31	<0.01	0.35
Days in diarrhoea, days							
1 week post-weaning	1.66	2.26	1.32	1.63	0.502	0.56	0.71
2 weeks post-weaning	2.36	1.22	0.55	0.87	0.512	<0.01	0.07

[1]~~T12~~ T13 = Sow's lactation diet containing ~~12~~ 13% of hemicelluloses; T11 = Sow's lactation diet containing 11% of hemicelluloses; T9 = Sow's lactation diet containing 9% of hemicelluloses; ~~T7~~ T8 = Sow's lactation diet containing ~~7~~ 8% hemicellulose.

[2]Contrasts: *L* = Linear; *Q* = Quadratic.

Milk Composition

Throughout lactation, no dietary treatment and sampling day interaction was found (data not shown). At days 3 and 17 of lactation, DM, ash, protein and somatic cell count, as well as milk yield estimated from farrowing to day 3 and from day 4 to day 17 of lactation, were similar among dietary treatments (Table 5). With a decreasing HC level, milk lactose content linearly decreased ($P < 0.01$). Regarding mineral levels in the sow milk, calcium, phosphorus, sodium, magnesium and zinc contents remained similar among experimental treatments, whereas the copper content linearly increased ($P = 0.02$) with decreasing HC content in the maternal diet. Excluding the linear increase ($P = 0.04$) in the threonine level and the quadratic increase ($P = 0.04$) in the monounsaturated fatty acid portion, decreasing HC level in the maternal diet had no impact on the amino acid and fatty acid profiles. Regardless of the dietary treatments, somatic cell counts did not differ between the sampling days. However, the sampling day influenced protein, mineral and lactose contents, as well as milk yield. Between days 3 and 17 of lactation, protein, phosphorus, potassium and zinc contents decreased ($P \leq 0.05$), whereas lactose and calcium contents and milk yield increased ($P \leq 0.05$). Furthermore, histidine, leucine, isoleucine, phenylalanine, threonine, tryptophan, tyrosine, valine, alanine, aspartic acid and serine decreased ($P \leq 0.05$), whereas glutamate and proline increased ($P \leq 0.05$) between days 3 and 17. The fatty acid profile in milk changed during lactation. Monounsaturated and polyunsaturated fatty acid portions decreased ($P \leq 0.05$) and saturated fatty acid content increased ($P \leq 0.05$) from day 3 to day 17. More precisely, the portions of C18:0, C18:1n-9, C18:2n-6, C18:3n-6, C18:3n-3, C20:4n-6, C20:5n-3 and C22:5n-3 decreased ($P \leq 0.05$), whereas C16:0 level increased ($P \leq 0.05$) between days 3 and 17.

Table 5. Effect of decreasing hemicellulose level in sow's lactation diet on gross composition, mineral content, amino acid profile and fatty acid profile of milk

Item	[1]Dietary Treatments				SEM	[2]Contrasts		[3]Stage of lactation		SEM	*P*-value
	~~T12~~ T13	T11	T9	~~T7~~ T8		*L*	*Q*	d3	d17		
Milk yield, kg/day	9.66	9.90	9.39	8.80	0.76	0.81	0.76	7.03	11.85	0.41	<0.01
Gross chemical composition											
Dry matter, %	19.5	20.7	19.9	20.6	0.60	0.25	0.49	20.7	19.7	0.40	0.06
Total protein, %	5.86	5.82	5.84	6.07	0.153	0.48	0.34	6.40	5.40	0.091	<0.01
Fat, %	7.50	8.65	8.07	8.69	0.533	0.15	0.38	8.50	7.96	0.364	0.27
Lactose, %	5.17	4.99	4.92	4.77	0.110	0.01	0.76	4.56	5.37	0.068	<0.01
Ash,%	0.86	0.86	0.88	0.85	0.150	0.29	0.89	0.89	0.83	0.098	<0.01
Somatic cells, log 10^3 cells/ml	6.99	6.92	7.40	7.71	0.325	0.18	0.41	7.40	7.11	0.248	0.93
Gross energy, MJ/kg	5.14	5.70	5.43	5.70	0.230	0.10	0.30	5.65	5.34	0.162	0.72
Minerals											
Calcium, g/kg	1.91	1.98	2.02	1.99	0.051	0.97	0.94	1.88	2.07	0.033	<0.01
Phosphorus, g/kg	1.57	1.58	1.57	1.53	0.026	0.09	0.63	1.61	1.52	0.017	<0.01
Potassium, g/kg	1.11	1.10	1.11	1.05	0.028	0.07	0.24	1.29	0.90	0.019	<0.01
Sodium, g/kg	0.37	0.35	0.35	0.34	0.016	0.21	0.89	0.36	0.34	0.011	0.93
Magnesium, g/kg	0.10	0.11	0.11	0.11	0.003	0.42	0.09	0.11	0.11	0.002	0.57
Copper, mg/kg	1.37	1.45	1.51	1.76	0.135	0.02	0.28	1.68	1.37	0.085	0.67
Zinc, mg/kg	6.04	6.64	6.02	5.44	0.363	0.16	0.07	6.38	5.69	0.213	<0.01
Amino acids, % of total protein											
Alanine	3.28	3.29	3.33	3.35	0.025	0.21	0.46	3.41	3.21	0.017	<0.01
Arginine	4.57	4.62	4.68	4.67	0.029	0.13	0.99	4.72	4.55	0.020	<0.01
Aspartic acid	7.70	7.68	7.75	7.74	0.035	0.78	0.29	7.83	7.61	0.025	<0.01
Cysteine	1.40	1.39	1.39	1.42	0.015	0.15	0.10	1.44	1.36	0.010	<0.01
Glutamate	17.8	17.6	17.8	17.6	0.16	0.29	0.99	17.5	17.9	0.11	<0.01
Glycine	2.98	3.02	3.12	3.05	0.030	0.10	0.40	3.06	3.03	0.019	0.15

Histidine	2.53	2.53	2.53	2.56	0.015	0.85	0.31	2.56	2.51	0.009	<0.01
Isoleucine	3.85	3.80	3.80	3.83	0.039	0.36	0.53	3.84	3.80	0.022	0.05
Leucine	8.03	8.12	8.02	8.15	0.049	0.74	0.83	8.18	7.99	0.030	<0.01
Lysine	6.86	6.79	6.82	6.86	0.049	0.61	0.36	6.85	6.82	0.029	0.22
Methionine	1.74	1.72	1.71	1.71	0.014	0.10	0.68	1.72	1.72	0.008	0.52
Phenylalanine	3.86	3.85	3.87	3.92	0.026	0.17	0.13	3.92	3.83	0.017	<0.01
Proline	10.2	10.3	10.4	10.2	0.11	0.37	0.15	10.1	10.5	0.07	<0.01
Serine	4.70	4.66	4.73	4.76	0.047	0.15	0.39	4.75	4.67	0.030	0.02
Threonine	3.88	3.88	3.90	3.98	0.036	0.04	0.19	3.99	3.83	0.023	<0.01
Tryptophan	1.18	1.18	1.21	1.20	0.017	0.17	0.94	1.23	1.15	0.011	<0.01
Tyrosine	4.02	3.97	3.99	4.05	0.050	0.43	0.20	4.05	3.96	0.028	<0.01
Valine	5.16	5.21	5.20	5.26	0.039	0.17	0.98	5.30	5.12	0.025	<0.01
Fatty acids, % of total fatty acids											
C16:0	27.2	27.4	26.4	27.8	0.70	0.52	0.38	24.9	29.5	0.48	<0.01
C18:0	4.29	4.43	4.33	4.41	0.143	0.70	0.70	4.78	3.95	0.089	<0.01
C18:1n-9	35.3	36.1	35.8	34.8	0.83	0.51	0.38	37.2	33.8	0.57	<0.01
C18:2n-6	11.45	9.63	12.08	11.74	0.412	0.09	0.09	12.20	10.30	0.245	<0.01
C18:3n-6	0.14	0.12	0.15	0.13	0.012	0.93	0.87	0.20	0.08	0.008	<0.01
C18:3n-3	1.08	1.12	1.16	1.32	0.057	0.06	0.53	1.25	1.09	0.036	<0.01
C20:3n-3	0.11	0.11	0.11	0.09	0.010	0.76	0.48	0.11	0.10	0.006	0.06
C20:4n-6	0.52	0.50	0.55	0.55	0.022	0.16	0.53	0.65	0.41	0.014	<0.01
C20:5n-3	0.09	0.09	0.08	0.08	0.006	0.55	0.74	0.09	0.07	0.003	<0.01
C22:5n-3	0.23	0.22	0.21	0.22	0.018	0.77	0.61	0.26	0.18	0.010	<0.01
n-3[4]	1.75	1.59	1.50	1.48	0.082	0.19	0.60	1.72	1.44	0.051	<0.01
n-6[5]	12.1	10.3	12.8	12.4	0.43	0.09	0.10	13.0	10.8	0.26	<0.01
Saturated	36.1	36.4	35.3	37.1	0.76	0.57	0.40	33.8	38.6	0.52	<0.01
Mono-unsaturated	49.1	50.8	49.5	48.1	0.61	0.71	0.04	50.4	48.3	0.42	<0.01
Poly-unsaturated	14.8	12.8	15.2	14.9	0.53	0.22	0.14	15.7	13.1	0.32	<0.01

[1]~~T12~~ T13 = Sow's lactation diet containing ~~12~~ 13% of hemicelluloses; T11 = Sow's lactation diet containing 11% of hemicelluloses; T9 = Sow's lactation diet containing 9% of hemicelluloses; ~~T7~~ T8 = Sow's lactation diet containing ~~7~~ 8% of hemicelluloses.

[2]Contrasts: *L* = Linear; *Q* = Quadratic.
[3] Days: d3 = Day 3 of lactation; d17 = Day 17 of lactation;
[4]*n*-3: sum of C18:3n-3, C20:3n-3, C20:5n-3, C22:5n-3.
[5]*n*-6: sum of C18:2n-6, C18:3n-6 and C20:4n-6.

Volatile fatty acid concentrations in milk

The VFA concentration and the proportion of butyrate linearly increased ($P < 0.01$; Table 6) with decreased HC content in the maternal diet, resulting in an increased in total VFA by 25% and butyrate proportion by 60%. Regardless of the dietary treatment, total VFA concentration decreased ($P \leq 0.05$) by 71% between days 3 and 17. The proportion of methanoate increased ($P < 0.01$), and the proportion of acetate decreased ($P < 0.01$) between days 3 and 17, whereas the levels of propionate, isobutyrate, butyrate and isovalerate remained unchanged.

Table 6. Effect of decreasing hemicellulose levels in sow's lactation diet on the volatile fatty acid profile of milk

	[1]Dietary Treatments					[2]Contrasts		[3]Stage of lactation			
Item	~~T12~~ T13	T11	T9	~~T7~~ T8	SEM	*L*	*Q*	d3	d17	SEM	*P*-value
Total volatile fatty acids, mmol/kg	3.07	3.58	3.60	3.86	0.28	0.03	0.60	4.12	2.94	0.19	<0.01
Proportion of individual VFA, %											
Methanoate	9.41	9.50	9.38	9.93	0.287	0.94	0.28	9.16	9.95	0.187	<0.01
Acetate	88.90	89.00	88.90	88.30	0.353	0.31	0.17	89.21	88.36	0.220	<0.01
Propionate	0.30	0.30	0.25	0.20	0.041	0.19	0.84	0.25	0.28	0.026	0.29
Isobutyrate	0.04	0.04	0.05	0.03	0.007	0.86	0.79	0.04	0.05	0.004	0.17
Butyrate	0.53	0.60	0.75	0.86	0.153	<0.01	0.64	0.68	0.69	0.104	0.29
Isovalerate	0.76	0.55	0.57	0.57	0.080	0.80	0.21	0.61	0.61	0.043	0.81

[1]~~T12~~ T13 = Sow's lactation diet containing ~~12~~ 13% of hemicelluloses; T11 = Sow's lactation diet containing 11% of hemicelluloses; T9 = Sow's lactation diet containing 9% of hemicelluloses; ~~T7~~ T8 = Sow's lactation diet containing 7% of hemicelluloses.

[2]Contrasts: *L* = Linear; *Q* = Quadratic

[3]d3 = Day 3 of lactation; d17 = Day 17 of lactation

Discussion

Effect of decreasing the level of hemicelluloses on sows' performance

Excluding fibre intake, the sow's performances were not affected by dietary HC. As expected, due to similar feed intake during the pre-farrowing and lactation periods, decreasing the level of HC also reduced the intake of the low-molecular-weight DF and SDF fractions. ~~Renteria-Flores et al. (2008) found that increasing the SDF level in the gestation diet increased BW loss during lactation. However, the adverse effects may be related to the inclusion level of SDF.~~ Similar to the present study, ~~Li et al. (2019b) found no effect on sow's performance when the SDF level was decreased from 38.7 g/kg to 17.7 g/kg in the gestation diet during the whole gestation period~~ Shang et al. (2021) found no effect either on sow's BW or backfat thickness at farrowing and weaning when the dietary SDF level was decreased from 40.6 g/kg to 13.9 g/kg in the late gestation and from 27.2 g/kg to 14.3 g/kg during lactation. In addition, considerably high SDF intake can negatively affect litter performance. Indeed, Liu et al. (2020) reported that from day 90 of gestation to farrowing, a daily intake of 215 g of SDF (SDF: 45.7 g/kg as fed), compared with 138 g/day (29.7 g/kg as fed) and 96 g/day (17.8 g/kg), decreases the number of piglets and litter weight at weaning. In the present study, sows received between 133 and 83 g/day of SDF according to the diets, from day 110 of gestation to farrowing. ~~This setup can explain the lack of differences in these traits between the dietary treatments.~~ Therefore, compared to the study of Liu et al. (2020), the SDF intake during this period for the four treatment groups was not sufficiently elevated to negatively impact litter performances.

Effect of decreasing hemicelluloses levels on milk composition and milk VFA profile

Milk yield and composition play a crucial role in the growth of suckling piglets to reach an adequate weaning weight. In the present study, decreasing the level of HC in the maternal diet affected milk composition but did not affect milk yield. Furthermore, lactose content decreased, whereas copper and threonine proportions increased with decreased HC level. A previous study showed that glucose, glycerol and other glucose precursors play an important role in the synthesis of lactose in sow's milk (Boyd et al., 1995). Houdijk et al. (2002) reported that the fermentation of SDF occurs already at the end of the ileum. As decreasing the level of HC also decreased the intake of SDF, one can hypothesize that lowering the HC supply reduced the absorbed HC fermentation products available for lactose synthesis.~~, the fermentability of organic matter in the small intestine might have decreased. Moreover, a recent study showed that a 3:1 ratio of IDF to SDF increases the fermentability of organic matter in the small intestine (Hoogeveen et al., 2021). Therefore, a higher level of HC could be related to the higher fermentability of the organic matter in the small intestine~~. ~~Given~~ Moreover, due to the osmotic power of lactose (Costa et al., 2019), milk yield may drop together with lactose as the HC level decreases ~~(Costa et al., 2019)~~. Surprisingly, milk yield only decreased numerically, and this result could be due to the differences in lactose concentration between the experimental groups, which were not sufficiently large to affect milk yield. A further interest in the present study is the linear increase in copper in milk with a decreased HC level. Copper is an essential microelement for animals, with many biological functions, including iron metabolism, immunity, protection from oxidative stress and improvement in the activity of digestive enzymes (Huang et al., 2015). The milk concentration of copper is affected by the source of the micromineral (Peters et al., 2010). However, as the same micromineral source was used among the four dietary treatments, the mechanism underlying the increase in copper concentration remains unclear. Similarly, with decreased HC levels in the diet, the proportion of threonine in the milk increased. This effect remains unclear, as the calculated digestible threonine levels were similar between the ~~T12~~ T13 and ~~T7~~ T8 diets. Besides a similar DF content, hypothetically, decreasing the HC level using several DF sources may affect the fermentation patterns in the gut, namely, the concentration and proportion of VFA. As VFA can be absorbed, transported through the blood and finally reach the mammary glands, modifications in the milk composition are expected (Tian et al., 2020). Decrease in HC level increased total VFA concentration and butyrate proportion in milk. Zhao et al. (2019) showed a positive correlation between VFA concentration in pig's ileum and decreased HC level. Given that sows can ferment DFs better than growing pigs, a similar phenomenon may have occurred in the ileum of sows fed with a low HC level (Noblet and Le Goff, 2001). Furthermore, this effect on VFA in milk may also be due to differences in the intake of other DF fractions. As previously mentioned, decreasing HC level concomitantly increased ADF intake and decreased SDF intake. A positive correlation was reported between the ADF level in pig's diet and butyrate concentration in the faeces (Zhao et al., 2019). In the present study, hypothetically, increased ADF intake in sows fed with decreasing level of HC might have increased the butyrate proportion in the faeces and then in the milk. Compared with IDF, SDF is rapidly fermented by bacteria, thereby enhancing the production of VFA (Jha and Berrocoso, 2015). Therefore, with decreased SDF intake, VFA production should be lowered. However, the present study showed that this concept was not evident and confirmed the importance of the source of DF, as reported by some authors (Theil et al., 2014). Therefore, to understand the effects of DF on milk composition, different fractions of DF, including HC and ADF contents, must be considered.

Effects of the lactation diet on piglets' performance

In the present study, modifying the level of HC in the maternal diet did not enhance litter performance. This result is consistent with the results of Loisel et al. (2013), which showed that modifying the maternal diet is easier to positively affect the performances of L-BtW piglets than the performance of the litter overall. Therefore, decreasing the HC level improved post-weaning performance and reduced the occurrence of diarrhoea in the L-BtW piglets. By contrast, why the performance of N-BtW was unaffected by the HC level even though the occurrence of diarrhoea increased in this group remains unclear. The L-BtW piglets usually exhibit poor performances, such as a high mortality rate and low ADG, which represents high economic costs for farmers due to reduced slaughter weight and increased occupancy of the stables (López-Vergé et al., 2018). Girard et al. (2021) highlighted the importance of early-life interventions to improve the post-weaning development and health of this sub-population of piglets. ~~Therefore, t~~ In the present study, the beneficial effects observed in L-BtW piglets during post-weaning period like the improved growth performance and the lower incidence of diarrhoea may be related to the combination of an increased relative abundance of butyrate, threonine and copper and to an increased concentration of total VFA in milk. ~~Indeed~~ Given that piglets are highly susceptible to intestinal bacterial disorders during the post-weaning period, butyrate, due to its recognised role in gut health, could have been useful in increasing gut impermeability, alleviating diarrhoea in L-BtW piglets during the second week post-weaning (Feng et al., 2018). In addition, ~~given that piglets~~

~~are highly susceptible to intestinal bacterial disorders during the post-weaning period~~, increasing threonine and copper proportions in the milk in the pre-weaning period can help accelerate the gut maturation of those piglets (Lalles et al., 2009). Threonine plays a critical role in the regulation of intestinal mucosal integrity, as it is required for the production of mucins and immunoglobulins, improving the physical protection from the attachment of microbes to the mucosal surface (Van Klinken et al., 1995). By contrast, copper can help against pathogenic bacteria because of its bacteriostatic properties, which affect the community structure of microorganisms in the caecum and colon (Højberg et al., 2005). A lower relative abundance of *Alistipes*, *Lachnospiraceae*, *Ruminococcaceae* and *Prevotellaceae* has been reported in the colon and ileum of L-BtW piglets compared with N-BtW piglets (Li et al., 2019~~a~~). These genera enhance gut health and immune functions in the host (Den Besten et al., 2013). Given that, colostrum and mature milk are key components in shaping piglet microbiota (Trevisi et al., 2021), the modification of milk composition induced by decreased HC level in the sow diet might have changed the gut microbiota of L-BtW piglets and improved their health and growth.

Effect of lactation stage on milk composition

Sow's milk composition is strongly affected by changes throughout the lactation period. ~~Colostrum (0–24 h after parturition) and~~ Transitional milk (48–72 h after parturition) contain higher amounts of lipids, protein and dry matter compared with mature milk (from day 10 of lactation) (Csapó et al., 1996). In the present study, the passage from transitional milk to mature milk was characterised by a decrease in protein and ash contents and an increase in lactose content. Nevertheless, the contents of fat, dry matter and gross energy decreased only numerically from day 3 to day 17. Indeed, in the present experiment, the lack of statistical differences on those traits is in disagreement with several studies (Csapó et al., 1996; Theil et al., 2014), ~~could be due to the~~ where differences between the sampling days were reported~~, which were not large enough to affect dry matter, fat and gross energy contents in the sow's milk~~. This might be related to differences in sow genotypes, sow management and litter size between the present study and the previous ones. Similarly, the decrease in amino acid proportion follows the same trend as protein content, except for glycine, lysine and methionine, which remained stable over lactation, and for glutamate and proline, which increased from day 3 to day 17. Therefore, the high level of amino acids in transitional milk reflects the protein level, mainly because of the high content of immunoglobulins (Klobasa et al., 1987). The mineral content ~~and fatty acid profile were~~ was also affected by the stage of lactation with an increase in the calcium level and a decrease in the potassium and zinc levels from transitional milk to mature milk in agreement with Csapó et al. (1996). ~~Calcium and phosphorus play a key role in improving piglet's growth (Hu et al., 2019 These changes are consistent with a previous study (Csapó et al., 1996) that also reported an increase in the calcium level and a decrease in the potassium and zinc levels from transitional milk to mature milk. The present experiment also showed~~ . Moreover, the phosphorus content decreased between days 3 and 17. The reason for this decrease over lactation remains unclear but might be related to a dilution effect, as it follows the numerical decrease in dry matter. When expressed per kilogram of dry matter, the phosphorus concentration was similar between days 3 and 17. Moreover, from transitional milk to mature milk, the decrease in the proportion of mono- and polyunsaturated fatty acids and the increase in the proportion of saturated fatty acids are related to changes in the proportion of individual fatty acids. The increase in C16:0 proportion and decrease in the proportions of C18:0, C18:1n-9, C18:2n-6, C18:3n-6, C18:3n-3, C20:4n-6 and C20:5n-3 observed in the present study have already been described in a previous study (Hu et al., 2019). Furthermore, Hu et al. (2019) reported a positive correlation between calcium and C16:0 fatty acid. ~~Indeed, long-chain saturated fatty acids can form calcium salts in the piglet's intestine, which can improve dry matter digestibility and enhance growth performance (Kluge et al., 2006). However, the mechanism by which calcium affects the synthesis of C16:0 remains unknown.~~

In conclusion, ~~as shown in the present study,~~ when the DF level is the same, feeding lactating sows with a lower HC level can positively affect the milk composition and ~~offspring~~ the development of L-BtW piglets. As HC content decreased, the growth performance of the L-BtW piglets improved after weaning, and the occurrence of diarrhoea decreased, particularly in the second week post-weaning. Moreover, it increased the proportion of butyrate, copper and threonine and increased the VFA concentration in the milk. Therefore, this study highlighted the importance of the maternal diet in lactation to positively affect the development and health of L-BtW piglets in the post-weaning period.

Ethics approval

The experiment was conducted in accordance with the Swiss Guidelines for Animal Welfare, and the Swiss Cantonal Committee for Animal Care and Use approved all procedures involving animals (approval number: 2019_25_FR).

Data accessibility

The data that support the findings of this study are publicly available in Zenodo (https://doi.org/10.5281/zenodo.5814624).

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Author contributions

Francesco Palumbo and Marion Girard validated the data and carried out the main statistical analyses. Marion Girard and Giuseppe Bee conceived the study design and secured substantial funding. Francesco Palumbo and Marion Girard performed the animal experiment, recorded the data and collected and processed the milk samples. Marion Girard, Francesco Palumbo, Giuseppe Bee and Paolo Trevisi supervised analyses and drafted and critically reviewed the manuscript. All authors read and approved the final manuscript.

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Declaration of interest

The authors declare they have no conflict of interest relating to the content of this article.

Supplementary materials

The Supplementary Table S1 and the statistical codes used can be found in the Supplementary Materials.

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