

Effects of *Amaranthus hypochondriacus* supplementation during gestation and lactation on the apparent total tract digestibility of nutrients, lactational feed intake, and litter performance in SOWS

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Abstract

The purpose of this study was to investigate the effects of *Amaranthus hypochondriacus* (AH) inclusion in the diets of gestating and lactating sows on the lactational feed intake, nutrient digestibility, and growth performance of suckling piglets. During gestation, 40 multiparous Landrace sows were restrictively fed with either a control diet or a diet including 30% AH. Both diets had similar levels of digestible energy and crude protein, but the 30% AH diet had higher crude fibre levels than the control diet. After breeding, lactating sows were fed ad libitum with one of two isoenergetic and isonitrogenous diets, either a control diet or a diet containing 10% AH. In gestating sows, AH supplementation was found to be associated with decreased digestibility of crude protein and dry matter ($p < .001$), resulting in lesser backfat depth ($p < .001$). However, in lactating sows, AH supplementation had little effect on digestibility and milk composition; moreover, it increased the feed intake ($p < .001$) and decreased backfat loss ($p < .001$) in sows. On the 21st day of lactation, suckling piglets in AH group showed significantly greater average daily gains ($p < .001$), and average body weight and litter weight significantly increased compared with sows fed the control diet. In conclusion, AH-supplementation increased lactational feed intake in sows and improved the growth performance of suckling piglets.

KEYWORDS

Amaranthus hypochondriacus, growth performance, lactational feed intake, sows, suckling piglets

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1 | INTRODUCTION

Considering the relationship between lactational feed intake in sows and growth performance of pre-weaning piglets, reduced lactational feed intake is a serious problem in pig rearing. For lactating sows, litter growth rate is not only an indicator of milk yield, but also the most important factor for determining nutrient requirements (Farmer, 2015). Research has shown that approximately 50%–60% of the nutrients in the bodies of lactating sows are secreted into milk (Theil et al., 2004). Body condition is an important proxy for milk production, and low feed intake in lactating sows is compensated by body tissue mobilization (Beyer et al., 2007). Consequently, the feed intake of lactating sows should be high as possible to minimize backfat loss at all stages of lactation, especially as excessive backfat loss resulting from low feed intake negatively impacts subsequent reproductive performance. Studies have shown that low feed intake during lactation prolongs the weaning-to-oestrus interval and increases the chance that the sow will return to oestrus, resulting in excessive weight loss (Lewis & Bunter, 2011a, 2011b). Throughout the entire lactation phase, sows are vulnerable to negative nutrient balance (van den Brand & Kemp, 2006). Nutrient deficiency resulting from low feed intake also affects the survival and development of embryos, with consequences for litter size and birth weight in the next pregnancy (Krogh et al., 2017; Tan et al., 2018; Walsh et al., 2012). Therefore, preventing feed insufficiency during lactation is of great significance to sow reproductive performance and piglet growth performance.

Numerous studies have shown that dietary supplementation with green forage (GF) has positive effects on the satiety process, behaviour and performance of sows during gestation and lactation (Benelam, 2009; Courboulay & Gaudré, 2002; De Leeuw et al., 2008). Such an effect can be explained by an increase in size and capacity of the digestive tract induced by the GF diets provided during pregnancy. Therefore, GF is usually added to the diet to improve sow health and reduce feed costs. *Amaranthus hypochondriacus* (AH) is a GF with high yield and rich nutrient content. It is one of several crop species in the genus *Amaranthus*, which originates in tropical and subtropical regions such as Central America and Southeast Asia. Because AH has high photosynthetic efficiency and strong stress resistance, it grows rapidly in many parts of the world. AH can be reaped three to five times a year, yielding up to 400–500 t/hm² of fresh forage (Barba de la Rosa et al., 2009). AH has a high nutritional value, with a gross energy (GE) close to that of corn, but a higher crude protein (CP) content. For the present study, AH was obtained from Zhongxian-Shengtai Limited Company. The nutrient composition of dried crude AH is 5.1% water, 26.0% ash, 26.2% CP, 3.7% ether extract (EE), 34.7% crude fibre (CF) and 4.3% nitrogen free extract (Pony Testing International Group Co. Ltd.). In fact, in their evaluation of the mineral content of 15 species of *Amaranthus*, Jiménez-Aguilar and Grusak (2017) provided the following ranges of macroelement content (mg/g fresh weight): Ca, 1.5–3.5; K, 5.5–8.8; Mg, 1.8–4.5; and P, 0.53–0.93. They also provided the following

ranges of microelement content (ug/g fresh weight): Cu, 0.56–2.4; Fe, 8.4–22; Mn, 3.8–11; and Zn, 8.1–16.

Based on the advantages of GFs and the characteristics of AH, we believe that dietary supplementation of AH may have positive effects on satiety process, behavioural activity or performance of sows during gestation and lactation. Accordingly, the purpose of this study was to investigate the effects of AH inclusion in the gestation and lactation diets of sows on nutrient digestibility, lactational feed intake and litter performance.

2 | MATERIALS AND METHODS

2.1 | Animals and experimental treatments

The experimental protocol in this study was approved by the Animal Care and Use Committee of Hunan Normal University, Changsha, Hunan, China. We followed EU feed legislation and EU standards for the protection of animals used for scientific purposes. AH that had been cradled at the beginning of flowering was naturally aired and then pulverized into powder. AH powder and basal diet were evenly mixed to create different experimental pelleted diets. The percentage of AH was decided based on nutrient requirements and fibre tolerance levels during pregnancy and lactation, as well as preliminary experiments on AH. The experiment was conducted in the breeding base of the Yongan branch of Hunan Xinwufeng Co., Ltd., which is a commercial farm. A total of 40 multiparous Landrace sows were selected for the study, with an average parity of 3.9. After mating, sows of mixed parity were divided into two groups based on breeding, parity, and body weight (BW). Two isoenergetic and isonitrogenous diets were formulated (Table 1): the control diet and the AH-supplemented diet, the latter containing 30% AH. Although there were no differences indigestible energy (DE) and CP levels between the two diets, the AH diet had a higher level of CF. Feed intake was strictly restricted during pregnancy with two meals per day (07:00 and 14:30). After breeding, lactating sows were fed ad libitum with one of two isoenergetic and isonitrogenous diets, either a control diet or a diet containing 10% AH. During lactation, all sows in both gestational treatments were fed diet providing them with 12.6 MJ DE/kg, 13.5% CP and 0.70% lysine. To ensure free feeding, lactating sows were provided with feed three times daily (07:00, 11:00 and 17:30). All sows and piglets had free access to water during the experiment.

2.2 | Performance measurement

The backfat thickness of sows was measured on days 0 and 106 of pregnancy, within 24 hr after farrowing, and at weaning. An ultrasound scanner (China) was used to measure the backfat at the last rib (P2). The number and weight of live and dead piglets born in each litter were recorded within 12 hr of farrowing. The number of live pigs per litter and the total litter weight were recorded for each sow

TABLE 1 Ingredient and nutrient composition of gestation and lactation diets of sows

Item	Gestation		Lactation	
	C ^a	AH ^a	C ^b	AH ^b
Ingredient (%)				
Corn	63.00	48.00	61.00	51.00
Wheat bran	20.00		5.00	
Soybean oil		3.00	2.50	7.00
Soybean meal	12.00	14.00	24.00	27.00
Fish meal			2.50	
AH		30.00		10.00
Premix ^c	5.00	5.00	5.00	5.00
Nutrient composition				
DE (MJ/kg) ^d	12.60	12.94	13.85	13.81
CP (%) ^e	13.50	13.63	18.00	18.20
CF (%) ^e	3.85	10.18	3.00	4.66
Lysine (%) ^d	0.70	0.69	1.13	1.10
Calcium (%) ^d	0.82	0.81	0.87	0.93
Phosphorus (%) ^d	0.71	0.70	0.65	0.67
Methionine (%) ^d	0.20	0.20	0.30	0.28
Threonine (%) ^d	0.43	0.43	0.64	0.64

Abbreviations: AH, *Amaranthus hypochondriacus* supplementation group; C, control group; CF, crude fibre; CP, crude protein; DE, digestible energy.

^aC and AH, the control diet and the AH-diet containing 30% AH.

^bC and AH, the control diet and the AH-diet containing 10% AH.

^cProvided per kg of diet: Fe 90 mg; Zn 60 mg; Mn 20 mg; Cu 10 mg; Ca 5 g; P 2.5 g; NaCl 3 g; vitamin A 5,000 IU; vitamin D 300 IU; vitamin E 30 IU; vitamin K 1 mg; vitamin B₁ 1.5 mg; vitamin B₂ 4 mg; vitamin B₆ 1.5 mg; vitamin B₁₂ 0.017 mg; D-pantothenic acid 15 mg; nicotinic acid 40 mg; choline chloride 400 mg; folic acid 0.7 mg; Biotin 0.2 mg.

^dCalculated chemical concentrations using values for feed ingredients from the NRC (2012). Amino acid content of AH protein (Dry Matter basis): CP 26.2; Asp 1.9; Ser 0.9; Glu 2.4; His 0.4; Arg 1.1; Gly 1.0; Ala 1.1; Pro 0.8; Met <0.01; Lys 1.4; Ile 0.7; Phe 0.9; Val 0.9; Leu 1.4; Thr 0.8; Tyr 0.6; Cys <0.01.

^eAnalysed compositions were measured according to the Association of Official Analytical Chemists.

at weaning. The daily feed intake of lactating sows was measured by weighing daily feed refusals each morning.

2.3 | Determination of apparent total tract digestibility of nutrients

Apparent total tract digestibility (ATTD) of nutrient was tested in 20 sows at day 60 of pregnancy and day 10 of lactation. The mean parity was 3.9 (SEM ± 1.1). To enable ATTD measurement, sows were fed diets containing 0.3% chromium oxide as an indigestible marker. We specially customized a batch of this kind of feed, which was administered for a 7-day adaptation period, followed by

a 3-day collection period. Faecal samples were collected twice a day at 08:00 and 16:00. A plastic basin was used to collect the faeces as they were discharged from the anus. The samples were then placed in plastic bags and frozen at -20°C. After collection, faeces were dried at 60°C in a forced ventilation oven for three consecutive days. The dried faeces were ground through a sieve with 1-mm mesh, and a subsample was retained for determination of chromium oxide content, CP, dry matter (DM), GE and CF. Chemical analyses of the selected feed and faecal samples were conducted according to the method prescribed by the Association of Official Analytical Chemists (AOAC, 1999): method 934.01 for determination of DM, method 955.04 for CP and method 962.09 for CF. GE was measured with an isothermal autocalorimeter (5E-AC8018, CKIC) using benzoic acid as the calibration standard. Chromic oxide was measured using a flame atomic absorption spectrometer (nova 350, Analytik Jena). ATTD was calculated using the following formula:

$$\text{Digestibility of T (\% of intake)} = \left[1 - \frac{(\text{Cr}_2\text{O}_3)_{\text{diet}} \times T_{\text{(feces)}}}{(\text{Cr}_2\text{O}_3)_{\text{(feces)}} \times T_{\text{(diet)}} \right] \times 100,$$

where T is the concentration of energy or of a given nutrient.

2.4 | Colostrum and milk analyses

Colostrum was collected immediately after farrowing and 24 hr after farrowing. Milk was collected on the 7th and 21st days of lactation. Colostrum and milk were collected from all functional teats after intramuscular injections of oxytocin. Colostrum and milk samples were immediately filtered through gauze and stored at -80°C. Analyses were conducted to determine the amount of total solids, CP, EE and lactose in colostrum and milk. Total solids were determined according to the method prescribed by the AOAC (1990). CP was estimated using the Kay's nitrogen method. EE was measured using the Soxhlet extractor method. Lactose was assayed using a lactose assay kit (K624-100, Biovision).

Levels of immunoglobulin G and immunoglobulin A (IgG and IgA) in colostrum were measured at T0 (start of labour) and T24 (24 hr after labour), and levels of IgA in milk were measured on day 7 and 21 of lactation. Both IgG and IgA levels were determined using ELISA kits (references E026-1-1 and E027-1-1, respectively; intra-assay CV ≤5.0%; Nanjing Jiancheng Bioengineering Institute) according to the manufacturer's instructions.

2.5 | Statistical analysis

Data were evaluated using the MIXED procedure of SAS (SAS Institute Inc.). Data analysis was performed for 40 sows (20 in the control group and 20 in the AH-supplemented group) through two consecutive reproductive cycles. In all statistical analyses, the experimental unit was the individual sows. Prior to analysis, the normality and homoscedasticity of the data were tested using the Kolmogorov-Smirnov and Levene tests, with the significance level set at 5%. Repeated measures ANOVA was performed

using the MIXED procedure of SAS in order to compare the two groups with regard to lactational feed intake, litter performance, backfat thickness, ATTD of nutrients, and composition of colostrum and milk. The model treated diet as a fixed effect and the individual sow as a random effect. Differences were considered significant at $p \leq .05$, highly significant at $p \leq .01$, and as trending towards to significance at $.05 < p \leq .10$. Data are presented as least-squares means with standard error (SEM).

3 | RESULTS

3.1 | Apparent total tract digestibility of nutrients of sows

As shown in Table 2, in lactating sows, control and AH-supplemented did not differ in the digestibility of DM, GE, CP or CF. However, in gestating sows, the AH-supplemented diet was associated with highly significantly lower ($p < .001$) digestibility of DM and CP than the control group diet. In addition, the digestibility of GE was trending towards significance lower ($p = .073$) for gestating sows fed the AH-supplemented diet.

3.2 | Backfat thickness and feed intake of sows

As shown in Table 3, AH supplementation during gestation highly significantly reduced ($p < .001$) backfat gain during gestation, but

TABLE 2 Effects of inclusion of AH in gestation and lactation diets on apparent total tract digestibility of nutrients of sows

Items (%)	C ^a	AH ^a	SEM	p-value
No. of sows	20	20		
ATTD of nutrients during gestation				
DM	75.58	70.49	1.30	<.001
GE	77.30	75.41	1.02	.073
CP	78.57	73.45	1.27	<.001
CF	60.12	59.79	1.19	.668
NFE	70.37	69.42	1.32	.732
ATTD of nutrients during lactation				
DM	81.44	80.23	1.26	.408
GE	78.62	79.55	1.44	.740
CP	80.31	79.96	1.33	.455
CF	64.06	65.81	1.28	.132
NFE	75.34	75.02	1.12	.541

Note: Differences were considered significant at $p \leq .05$, highly significant at $p \leq .01$, and as trending towards to significance at $.05 < p \leq .10$.

Abbreviations: ATTD, apparent total tract digestibility; CF, crude fibre; CP, crude protein; DM, dry matter; GE, gross energy; NFE, nitrogen-free extract.

^aC and AH, the control diet and the AH-diet containing *Amaranthus hypochondriacus*.

highly significantly reduced ($p < .001$) backfat loss during lactation. As also shown in Table 3, AH supplementation was likewise associated with greater lactational feed intake in sows, with highly significant differences ($p < .001$) during the first week, the second week, the third week and the overall lactation period.

3.3 | Growth performance of suckling piglets

As shown in Table 4, there was no difference between two groups with regard to the mean total number of piglets born per litter or the mean number of live born piglets per litter, but the mean number of weaned piglets was trending towards significance greater ($p = .070$) in the AH group. Piglet weights at birth did not differ between the two groups, but the AH group showed significantly greater weaned piglets weight and piglet average daily gain.

3.4 | Colostrum and milk compositions

AH supplementation did not affect the concentrations of protein and lactose in colostrum (day 1) or milk (days 7 and 21), but the

TABLE 3 Effects of AH inclusion in gestation and lactation diets on body composition and feed intake during lactation of sows

Items	C ^a	AH ^a	SEM	p-value
No. of sows	20	20		
Average sow parity	3.9	3.9		
Sow backfat thickness (mm)				
Mating	12.9	12.6	0.36	.374
Day 106 of gestation	15.6	14.3	0.38	.002
Gain during gestation	2.7	1.7	0.06	<.001
Parturition	15.8	14.5	0.50	.020
Weaning	14.6	14.0	0.65	.364
Loss during lactation	1.2	0.5	0.03	<.001
Average daily feed intake (kg)				
1st week of lactation	5.0	5.8	0.20	<.001
2nd week of lactation	6.2	7.0	0.19	<.001
3rd week of lactation	6.2	7.8	0.17	<.001
Mean of 1st week to 3rd week	5.8	6.9	0.16	<.001

Note: Differences were considered significant at $p \leq .05$, highly significant at $p \leq .01$, and as trending towards to significance at $.05 < p \leq .10$.

^aC and AH, the control diet and the AH-diet containing *Amaranthus hypochondriacus*.

TABLE 4 Effects of AH inclusion in gestation and lactation diets on growth performance of suckling piglets

Items	C ^a	AH ^a	SEM	p-value
No. of sows	20	20		
No. of piglets per litter				
Total born	12.68	12.49	0.35	.503
Born alive	10.88	11.33	0.36	.318
Weaned ^b	9.21	10.79	0.41	.070
Mean BW of piglets (kg)				
Birth	1.50	1.52	0.05	.401
Weaned ^b	5.13	5.74	0.18	.003
Litter weight (kg)				
Birth	16.90	16.51	0.58	.453
Weaned ^b	50.31	56.79	1.53	<.001
Average daily gain (g/day)	158.41	192.30	6.20	<.001

Note: Differences were considered significant at $p \leq .05$, highly significant at $p \leq .01$, and as trending toward to significance at $.05 < p \leq .10$.

^aC and AH, the control diet and the AH-diet containing *Amaranthus hypochondriacus*.

^bPiglets were weaned on day 21 of lactation.

concentration of fat in colostrum was significantly reduced ($p < .05$). There was no difference between AH and the control groups with regard to the total solid content of colostrum or milk. Moreover, AH supplementation did not affect IgA and IgG levels in colostrum or milk (Table 5).

4 | DISCUSSION

In the present study, AH supplementation in the diet of gestating sows was associated with significantly decreased digestibility of DM and CP, and these decreases resulted in lesser backfat depth during gestation. However, AH supplementation in lactating sows did not significantly affect nutrient digestibility or milk composition. Furthermore, in lactating sows, AH supplementation significantly increased feed intake, and decreased backfat loss. Compared with the control group at day 21 of lactation, the AH group showed greater average daily gains in piglets, greater mean BW of piglets and greater litter weight; these improvements in piglet growth performance were likely due to the increased lactational feed intake associated with AH supplementation.

The results of this study show that sows fed AH had less backfat and a leaner body condition at parturition. Consistent with previous studies, a lower backfat and leaner body condition of sows at parturition following a pregnancy have a beneficial effect on feed intake during lactation (Danielsen & Vestergaard, 2001; Matte et al., 1994). However, the specific mechanism by which AH improves lactational feed intake is still unknown. It may be that the fibrous components of this highly nutritious GF source have unique properties (water-holding capacity, physical volume and chemical composition) that

TABLE 5 Effects of AH inclusion in gestation and lactation diets on colostrum and milk compositions of sows

Items	C ^a	AH ^a	SEM	p-value
No. of sows	10	10		
T 0				
IgG, mg/ml	47.9	48.4	1.51	.855
IgA, mg/ml	9.9	9.6	0.48	.656
T 24				
IgG, mg/ml	9.4	9.2	0.58	.874
IgA, mg/ml	4.6	4.5	0.27	.793
d 1				
Total solids, %	36.1	36.9	1.32	.543
Protein, %	21.3	21.8	1.11	.627
Fat, %	4.8	4.3	0.22	.046
Lactose, %	4.4	4.6	0.28	.652
d 7				
Total solids, %	29.4	28.4	1.08	.304
Protein, %	8.0	7.7	0.42	.529
Fat, %	8.0	7.7	0.42	.529
Lactose, %	7.6	7.6	0.37	.893
IgA, mg/ml	2.8	2.7	0.22	.322
d 21				
Total solids, %	29.0	29.6	1.40	.693
Protein, %	7.5	7.9	0.39	.346
Fat, %	7.5	7.9	0.39	.346
Lactose, %	7.8	7.7	0.32	.827
IgA, mg/ml	4.1	3.9	0.34	.728

Note: T0 and T24, onset of parturition and 24 hr after the onset of parturition; d 1, d 7 and d 21, the 1st, 7th and 21st day of lactation. Differences were considered significant at $p \leq .05$, highly significant at $p \leq .01$, and as trending towards significance at $.05 < p \leq .10$.

^aC and AH, the control diet and the AH-diet containing *Amaranthus hypochondriacus*.

promote an increase in the size and capacity of the digestive tract, allowing it to process more feed and resulting in high voluntary feed intake.

In order to ensure healthy fetal development and parturition, the feed intake of gestating sows is often severely restricted. However, in lactating sows, such restriction (even when all essential nutrients are supplied) can cause low voluntary feed intake, leading to more body fat mobilization and lower milk yield, especially in the early stages of lactation (Verstegen et al., 1985; Yoder et al., 2013). These studies highlight the importance of ensuring sufficient feed intake during lactation in order to prevent excessive levels of body fat mobilization to support milk production. Furthermore, a previous study that used piglet growth, as an indicator of milk production found that piglet growth, was affected by sows' lactational feed intake (Mallmann et al., 2019). It is well known that vigorous body fat mobilization during lactation negatively influences the subsequent reproductive performance of sows (Mallmann et al., 2019;

Weerathilake et al., 2019). In the present study, AH supplementation produced no significant change in the composition of colostrum or milk. Colostrum and milk are the major nutrient sources of suckling piglets. Both the quantity and quality of a sow's milk play a key role in the health and growth of her piglets. Therefore, AH supplementation during gestation and lactation increased the lactational feed intake of sows, which may have led to an increase in milk production, thus improving the growth performance of suckling piglets.

In summary, increasing the fibre content in the feed of gestating and lactating sows by supplementing their diets with AH resulted in increased lactational feed intake in sows and improved growth performance in suckling piglets. However, the interaction between diet composition and feed intake regulation in sows requires further study.

5 | CONCLUSIONS

Increasing the fibre content in the feed of gestating and lactating sows by supplementing their diets with AH resulted in increased lactational feed intake in sows and improved growth performance in suckling piglets. However, the mechanisms of these effects are still unclear, and further investigation is required to increase our understanding of the interactions between diet composition and feed intake regulation in sows.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

Jun Xia: Investigation; Project administration; Writing-original draft.

Linlin Chen: Data curation; Writing-original draft; Writing-review & editing. **Peng-Fei Huang:** Conceptualization; Formal analysis; Methodology; Resources; Validation; Writing-review & editing.

Qi Mou: Formal analysis; Investigation. **Ying Yang:** Data curation.

Jiaming Li: Data curation. **Minglang Xu:** Data curation. **Jianzhong Li:** Conceptualization; Validation. **Huansheng Yang:** Conceptualization; Methodology; Resources. **Yulong Yin:** Methodology; Resources.

ETHICAL STATEMENT

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to and the appropriate Ethical Review Committee approval has been received. The experimental protocol in this study was approved by the Animal Care and Use Committee of Hunan Normal University.

PEER REVIEW

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