https://doi.org/10.17221/209/2021-CJAS

# Effects of sweet potato vine silage supplementation on growth performance, nutrient digestibility, and intestinal health in finishing pigs

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**Citation:** Zhang J.J., Yue Z.Y., Sun Y.C., Wang Z.S., Zhang Y.M., Huang L.B., Tu J.M., Shi B.M., Shan A.S., Ma Q.Q. (2022): Effects of sweet potato vine silage supplementation on growth performance, nutrient digestibility, and intestinal health in finishing pigs. Czech J. Anim. Sci., 67: 218–227.

**Abstract:** We investigated the effects of sweet potato vine silage (SPVS) supplementation on the growth performance, apparent digestibility and gut health of finishing pigs. 180 Bali Black pigs (Berkshire × Licha Black, with body weight of 74.54 ± 3.32 kg) were assigned to three groups: basal diet (Ctrl), Ctrl supplemented with 2.5% SPVS (Lspvs) and 5.0% SPVS (Hspvs). Animals were slaughtered after nine weeks of feeding. The results indicated that dietary SPVS supplementation improved average daily food intake and average daily gain. However, SPVS treatment decreased the apparent digestibility. Activities of antioxidant enzymes including total superoxide dismutase, total antioxidant capacity, glutathione peroxidase and catalase in the intestines of the Lspvs group were markedly upregulated. Concentrations of IL-1β and IL-6 were decreased and secretory immunoglobulin A was increased in Lspvs group. A significant increase ($P < 0.05$) of ileum diamine oxidase in Lspvs group was observed. The ileum villus height/crypt depth in the Hspvs group was significantly reduced. The ratio of *Firmicutes* to *Bacteroidetes* in the caecum contents of pigs was reduced, and the abundance of *Lactobacillus* was significantly increased. Specifically, Hspvs treatment markedly reduced the abundances of *Proteobacteria*. Collectively, these results suggest that dietary supplementation with SPVS is capable of improving growth performance, immune function and intestinal health by promoting the balance of the intestinal microbiota.

**Keywords:** antioxidant activity; digestion; immunity; microbiota; swine

By-products of crops are a good alternative to substitute part of feed resources and improve livestock health. As a major food crop that is widely planted worldwide, sweet potato is rich in carotene, vitamin $B_1$, minerals, sugar and fibre. Sweet potato vine (SPV) is the stems and leaves of sweet potato and is rich in crude protein, fibre and water-soluble carbohydrates (Li et al. 2017).

However, the high water content of SPV leads to the decay and short storage period. Therefore,

Supported by grant from the National Key Research & Development Program of China (2018YFD0501202) and the National Natural Science Foundation of China (31772611).

https://doi.org/10.17221/209/2021-CJAS

fermentation is an efficient way to preserve the nutrients. During silage, *Lactobacillus* transforms water-soluble carbohydrates into an organic acid, resulting in the decrease of pH. Thus, this technique preserves the fresh forages with lower loss of nutrients that are even higher than in unfermented forages (Yin et al. 2021). For example, the stomach development was improved by maize silage (Mason et al. 2013) without appreciable decrease in digestibility (Zanfi and Spanghero 2012). Moreover, maize silage improved the welfare of growing-finishing pigs in environmentally friendly pens (Ocepek et al. 2020). Therefore, silage tends to be an effective storage method for feedstuffs to improve animal performance.

As a silage, sweet potato vine silage (SPVS) has been proved to improve milk yield and enhance the production response (Gakige et al. 2020). Because of its good pyrolysis selectivity, the highly palatable and digestible SPV is considered as a perfect feed. Besides lactating cows, SPV is a good alternative in non-ruminants. Data concerning the inclusion of SPVS in pig diet are scarce and insufficient in the literature. Hence, the objective of the experiment was to observe the influences of SPVS supplementation on the production performance, digestibility and gut health in crossbred pigs.

## MATERIAL AND METHODS

### Experimental design

A total of 180 Bali Black pigs (Berkshire × Licha Black pig) with body weight (BW) of 74.54 ± 3.32 kg were assigned to three dietary treatments during a 9-week feeding experiment. Each dietary treatment included six replicates, and each replicate had ten finishing pigs with half of these pigs being males and half females. Basal feed was used as the control (Ctrl). Treatments were set by adding SPVS to basal feed at levels of 2.5% (Lspvs) and 5% (Hspvs) on a dry matter (DM) basis. The fresh sweet potato vines with a moisture content of 70–75% were compacted and bundled, microbial additives were added, and then they were sealed in a plastic bag to create an anaerobic environment to make SPVS. SPVS was made by Shanxia Investment Company and used freshly. The chemical composition of SPVS is as follows: dry matter 32.24%; crude protein 1.95%; ether extract 0.86%; ash 3.45%; calcium 0.46%; total phosphorus 0.11%. All research procedures were agreed by the Institutional Animal Care and Use Committee of NEAU, and ethical rules followed the Animal Welfare Committee protocol [#NEAU-(2013)-9] at NEAU (Harbin, China). Pigs were provided by Shanxia Investment Company in Jiangxi Province, China.

### Diets

Experimental feed was formulated in the light of the nutrient requirements of pigs (NRC 2012) as shown in Table 1. All pigs were intensively reared in the temperature-controlled room at 23 ± 2 °C and 70% humidity. Each repeated pig was housed in a pen, and each pen had a water-saving drinker and feed tank. Feed and water were freely accessed. A one-week pre-experiment was conducted to test the supplemental dose of SPVS in diet. Finally, dietary supplementation with a maximum of 5% SPVS (on a dry matter basis) was confirmed to be adapted by animals.

### Growth performance

In a 9-week experiment, body weights (BW) and feed intakes of the animals were measured. Average daily gain (ADG), average daily food intake (ADFI), and feed conversion ratio (FCR) were analysed.

### Nutrient digestibility

About 200 g of fresh faecal samples were uniformly collected from each replicate on the last three days of the experiment, 10 ml of 10% sulfuric acid was added. The mixture was stored at –20 °C. After three days of continuous collection, the faecal samples of each replicate were mixed uniformly and dried in an oven at 65–70 °C. Each replicate was used as a unit to prepare samples for use. The digestibility of crude protein (CP), ether extract (EE), and crude fibre (CF) was tested by the endogenous indicator 4N-HCl method (Bergero et al. 2009).

### Sample collection

One pig per pen was slaughtered at the end of the trial after an overnight fasting. Segments (5 cm

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Table 1. Composition and nutrient levels of the diets (as-fed basis)

| Item | Ctrl | Lspvs | Hspvs |
|---|---|---|---|
| **Material ingredient** (%) | | | |
| Corn | 71.97 | 65.42 | 58.87 |
| Soybean meal | 14.35 | 13.04 | 11.74 |
| Wheat bran | 8.00 | 7.27 | 6.54 |
| Soybean oil | 2.00 | 1.82 | 1.64 |
| Dicalcium phosphate | 0.90 | 0.82 | 0.74 |
| Limestone | 0.90 | 0.82 | 0.74 |
| L-Lysine-HCL (78%) | 0.50 | 0.45 | 0.41 |
| L-Threonine | 0.1 | 0.09 | 0.08 |
| DL-Methionine | 0.05 | 0.05 | 0.04 |
| L-Tryptophan | 0.03 | 0.03 | 0.02 |
| Salt | 0.20 | 0.18 | 0.16 |
| Premix[a] | 1.00 | 0.91 | 0.82 |
| SPVS | 0.00 | 9.10 | 18.20 |
| Total | 100 | 100 | 100 |
| **Nutrient level** | | | |
| Metabolic energy (MJ/kg) | 13.2 | 12.1 | 10.9 |
| Crude protein (%) | 14.4 | 13.3 | 12.2 |
| Ether extract (%) | 5.1 | 4.8 | 4.4 |
| Crude fiber (%) | 2.5 | 2.8 | 3.2 |
| Calcium (%) | 0.5 | 0.5 | 0.4 |
| Total phosphorus (%) | 0.6 | 0.5 | 0.5 |
| Lysine (%) | 1 | 0.9 | 0.8 |
| Methionine (%) | 0.3 | 0.3 | 0.2 |
| Threonine (%) | 0.6 | 0.6 | 0.5 |
| Tryptophan (%) | 0.2 | 0.2 | 0.2 |

Ctrl = basal diet; Hspvs = Ctrl supplemented with 5.0% SPVS on a dry matter basis; Lspvs = Ctrl supplemented with 2.5% SPVS on a dry matter basis; SPVS = sweet potato vine silage

[a]The premix provided the following nutrients per kilogram of the complete diet: Vitamin A, 8 000 IU; Vitamin $D_3$, 2 000 IU; Vitamin E, 30 IU; Vitamin $K_3$, 1.5 mg; Vitamin $B_1$, 1.6 mg; Vitamin $B_6$, 1.5 mg; Vitamin $B_{12}$, 0.012mg; Niacin, 20 mg; Pantothenic acid, 15 mg; zinc (zinc oxide), 80 mg; iron (iron sulphate), 100 mg; copper (copper sulphate), 20 mg; manganese (manganese sulphate), 25 mg; iodine (potassium iodide), 0.3 mg; selenium (sodium selenite), 0.2 mg

in length) of the ileum and caecum were intercepted. A 2 cm ileum segment was cut and fixed in 10% formalin for intestinal HE staining to determine the intestinal morphology (Ma et al. 2020). The segments of the ileum were cut transversely and rinsed with saline solution. The samples of ileum tissue and caecum contents were frozen immediately. Ileum tissues were homogenized with a 10% intestinal tissue homogenate prepared with normal saline. The homogenized tissue was centrifuged at 3 500 rpm for 15 min and the supernatant was kept for analysis.

## Ileum antioxidation parameters

Part of the ileum tissue supernatant was used for protein concentration and antioxidant index determination. All antioxidant indicators were tested by commercial kits (A015-1-2, A001-1-2, A007-1-1, A005-1-2, Jiancheng Bioengineering Inc., Nanjing, China), including superoxide dismutase (T-SOD), total antioxidant capacity (T-AOC), glutathione peroxidase (GSH-PX) and catalase (CAT). All the specific tests strictly followed the detailed operating procedures on the kits, and an ultraviolet spectrophotometer (UV-2401, Shimadzu, Kyoto, Japan) was used to test absorbance.

## Assays of ileum pro-inflammatory cytokines and SIgA concentration

The contents of secretory immunoglobulin A (SIgA), IL-1β and IL-6, IL-8, IL-12 and TNF-α in the ileum tissue were determined by ELISA (Enzyme Linked Immunosorbent Assay) kits (H108-2, H002, H007-1-1, H008, H010, H052-1, Jiancheng Bioengineering Inc., Nanjing, China). The specific operation steps were carried out according to the protocols of the enzyme-linked immunoassay kit. Absorbance was measured by an ultraviolet spectrophotometer (UV-2401, Shimadzu, Kyoto, Japan).

## Ileum morphology

The intestinal segment fixed in 10% formalin was taken out, washed, transparent, waxed, paraffin embedded, trimmed, sliced, dewaxed, and stained with haematoxylin and eosin, dehydrated, and mounted. Ileum tissue sections having a typical field of view were selected and observed under a microscope (Eclipse Ci-L, Nikon, Tokyo, Japan). Villus height and crypt depth of six observations in each group were analyzed. The height of the

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villus is the distance between the villus top and the junction midpoint of the crypt villi at both ends, and the depth of the crypt is the distance between the midpoint of the junction of the crypt villi at both ends and the mucosal base.

### Assays of ileum diamine oxidase (DAO) and occludin-1 concentration

Part of the supernatant of ileum tissues was used for the determination of DAO and occludin-1. DAO activities in ileum tissues were measured using a DAO assay kit (A088-2-1, H369-1, Jiancheng Bioengineering Inc., Nanjing, China).

### Gut microbiota determination

The E.Z.N.A. ®Stool DNA Kit (Omega Bio-tek, Inc., Norcross, GA, USA) was employed to extract DNA. 16S rDNA sequencing was performed via the Illumina HiSeq platform by LC-Bio Technology Co., Ltd (Hangzhou, China) according to the manufacturer's instructions.

### Statistical analysis

Data on growth performance, digestibility, antioxidant capacity, pro-inflammatory cytokine, intestinal barriers and microbiota were expressed as means ± SEM. One-way ANOVA was used to evaluate the significance of differences between groups by SPSS Statistics v 21.0 (SPSS Inc., Chicago, IL, USA). Dunnett's test was used for multiple group comparisons. The significance was set at $P < 0.05$ and a trend was considered for $0.05 \leq P < 0.10$.

## RESULTS

### Growth performance

The initial BW did not differ across the treatments, with an average BW of 73.19 ± 1.26 kg (Table 2). Lspvs group showed positive effects on growth performance, with increased ADG, ADFI, and final BW ($P < 0.05$), and significantly reduced FCR ($P < 0.05$). However, Hspvs group decreased the ADFI ($P < 0.05$), and had a tendency to reduce ADG.

Table 2. Effects of sweet potato vine silage (SPVS) addition on performance in pigs

| Item | Ctrl | Lspvs | Hspvs | SEM | *P*-value |
|---|---|---|---|---|---|
| Initial BW (kg) | 73.25 | 74.38 | 71.93 | 3.009 | 0.621 |
| Final BW (kg) | 112.06$^{ab}$ | 116.28$^{a}$ | 109.24$^{b}$ | 4.362 | 0.018 |
| ADG (kg/day) | 0.59$^{a}$ | 0.64$^{b}$ | 0.57$^{a}$ | 0.036 | 0.012 |
| ADFI (kg/day) | 1.87$^{a}$ | 1.93$^{b}$ | 1.81$^{c}$ | 0.148 | 0.040 |
| FCR | 3.15$^{a}$ | 2.95$^{b}$ | 3.18$^{a}$ | 0.334 | 0.030 |

ADFI = average daily feed intake; ADG = average daily gain; BW = body weight; Ctrl = basal diet; FCR = feed conversion rate; Hspvs = Ctrl supplemented with 5.0% SPVS on a dry matter basis; Lspvs = Ctrl supplemented with 2.5% SPVS on a dry matter basis

$^{a–c}$Different superscripts in the same row indicate significant differences ($P < 0.05$)

### Apparent digestibility

The apparent digestibility of CP, EE and CF in feeds was significantly decreased with the increase of SPVS concentration ($P < 0.05$; Table 3). However, adding 2.5% SPVS to the diet had no significant effect on the digestibility of CF.

### Ileum antioxidant capacity

Effects of SPV silage supplementation on the antioxidant capacity of ileum are shown in Table 4. Results showed that Lspvs increased ($P < 0.05$) the activities of T-SOD, T-AOC, GSH-PX and CAT in the ileum compared to Ctrl group, but there was no significant difference between Ctrl and Hspvs. In addition, adding 5% SPVS to the diet presented only a tendency to increase the activity of GSH-PX in the ileum ($0.05 < P < 0.1$).

Table 3. Effects of sweet potato vine silage (SPVS) treatment on digestibility in pigs

| Item | Ctrl | Lspvs | Hspvs | SEM | *P*-value |
|---|---|---|---|---|---|
| Crude protein (%) | 83.76$^{a}$ | 81.55$^{b}$ | 79.25$^{c}$ | 0.199 | < 0.001 |
| Crude fat (%) | 87.88$^{a}$ | 85.38$^{b}$ | 83.40$^{c}$ | 0.024 | 0.047 |
| Crude fiber (%) | 16.97$^{a}$ | 16.52$^{a}$ | 13.39$^{b}$ | 0.021 | 0.026 |

Ctrl = basal diet; Hspvs = Ctrl supplemented with 5.0% SPVS on a dry matter basis; Lspvs = Ctrl supplemented with 2.5% SPVS on a dry matter basis

$^{a–c}$Different superscripts in the same row indicate significant differences ($P < 0.05$)

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Table 4. Effects of sweet potato vine silage (SPVS) supplementation on the antioxidant status of pigs

| Item | Ctrl | Lspvs | Hspvs | SEM | *P*-value |
|---|---|---|---|---|---|
| T-SOD (IU/mgprot) | 63.93[a] | 84.73[b] | 66.66[a] | 9.965 | < 0.001 |
| T-AOC (mM) | 1.73[a] | 2.18[b] | 1.72[a] | 0.297 | 0.023 |
| GSH-PX (IU/mgprot) | 60.12[a] | 74.80[b] | 64.99[a] | 7.907 | 0.011 |
| CAT (IU/mgprot) | 23.73[a] | 36.41[b] | 21.73[a] | 7.445 | 0.031 |

CAT = catalase; Ctrl = basal diet; GSH-PX = glutathione peroxidase; Hspvs = Ctrl supplemented with 5.0% SPVS on a dry matter basis; Lspvs = Ctrl supplemented with 2.5% SPVS on a dry matter basis; T-AOC = total antioxidant capacity; T-SOD = superoxide dismutase

[a,b]Different superscripts in the same row indicate significant differences ($P < 0.05$)

## Ileum pro-inflammatory cytokine

As shown in Table 5, Lspvs had lower concentrations of IL-1β, IL-6 compared with Ctrl and Hspvs groups ($P < 0.05$), and the content of IL-12 and TNF-α also tended to decrease. Supplementation with SPVS markedly enhanced the contents of SIgA ($P < 0.05$). However, Hspvs treatment had no impact on ileum pro-inflammatory cytokine compared with Ctrl.

## Ileum morphology and intestinal barrier

As shown in Table 6, Hspvs supplementation decreased the villus height, and both Lspvs and Hspvs

Table 5. Effects of sweet potato vine silage (SPVS) treatment on the inflammatory state in pigs

| Item | Ctrl | Lspvs | Hspvs | SEM | *P*-value |
|---|---|---|---|---|---|
| IL-1β (ng/l) | 50.04[a] | 32.84[b] | 51.99[a] | 13.151 | 0.011 |
| IL-6 (ng/l) | 87.70[a] | 62.36[b] | 84.75[a] | 16.171 | 0.032 |
| IL-8 (ng/l) | 103.54 | 116.62 | 114.31 | 26.442 | 0.791 |
| IL-12 (ng/l) | 71.38 | 64.62 | 91.46 | 11.709 | 0.650 |
| TNF-α (ng/l) | 57.00 | 51.79 | 49.50 | 16.809 | 0.754 |
| SIgA (ng/l) | 18.34[a] | 28.06[b] | 31.45[b] | 8.706 | 0.014 |

Ctrl = basal diet; Hspvs = Ctrl supplemented with 5.0% SPVS on a dry matter basis; Lspvs = Ctrl supplemented with 2.5% SPVS on a dry matter basis; SIgA = secretory immunoglobulin A; TNF-α = tumour necrosis factor α

[a,b]Different superscripts in the same row indicate significant differences ($P < 0.05$)

Table 6. Effects of sweet potato vine silage (SPVS) supplementation on the intestinal health of pigs

| Item | Ctrl | Lspvs | Hspvs | SEM | *P*-value |
|---|---|---|---|---|---|
| Villus height (μm) | 294.09[a] | 318.90[a] | 250.22[b] | 31.478 | 0.001 |
| Crypt depth (μm) | 131.53[a] | 154.65[b] | 162.23[b] | 15.045 | 0.004 |
| V/C | 2.24[a] | 2.07[a] | 1.55[b] | 0.323 | 0.030 |
| Occludin1 (ng/l) | 13.61 | 13.79 | 14.65 | 1.404 | 0.407 |
| DAO (IU/l) | 13.01[a] | 17.59[b] | 14.79[ab] | 3.725 | 0.046 |

Ctrl = basal diet; DAO = diamine oxidase; Hspvs = Ctrl supplemented with 5.0% SPVS on a dry matter basis; Lspvs = Ctrl supplemented with 2.5% SPVS on a dry matter basis

[a,b]Different superscripts in the same row indicate significant differences ($P < 0.05$)

increased the crypt depth. As a consequence, adding Hspvs reduced V/C, but adding Lspvs had no significant effect on V/C. Moreover, Lspvs treatment obviously promoted ($P < 0.05$) the activity of DAO, and there was no differences in occludin-1 between the three groups.

## Caecum contents microbiota

As shown in Figure 1A, SPVS supplementation obviously decreased and increased the concentrations of the *Firmicutes* and *Bacteroidetes*, respectively, and Hspvs group significantly decreased the abundances of the *Proteobacteria*. SPVS treatment markedly reduced the abundances of *Lactobacillus* while Lspvs group significantly decreased the abundances of the *Prevotella*, *Prevotellaceae*_UCG-003, *Prevotellaceae*_NK3B31_group and *Clostridium* (Figure 1B). SPVS supplementation obviously reduced the ratio of *Firmicutes* to *Bacteroidetes* (Table 7). The α-diversity of three treatments displayed no obvious discrepancy. The principal coordinate analysis (PCoA) showed that the clustering of microbiota composition of Ctrl and Lspvs treatments was more obvious than in Hspvs treatment (Figure 1C).

# DISCUSSION

This study demonstrated that SPVS was a valuable feedstuff for growing pigs. Through fermentation of SPV, by-products were fully utilized and nutrients were well preserved (Pereira et al.

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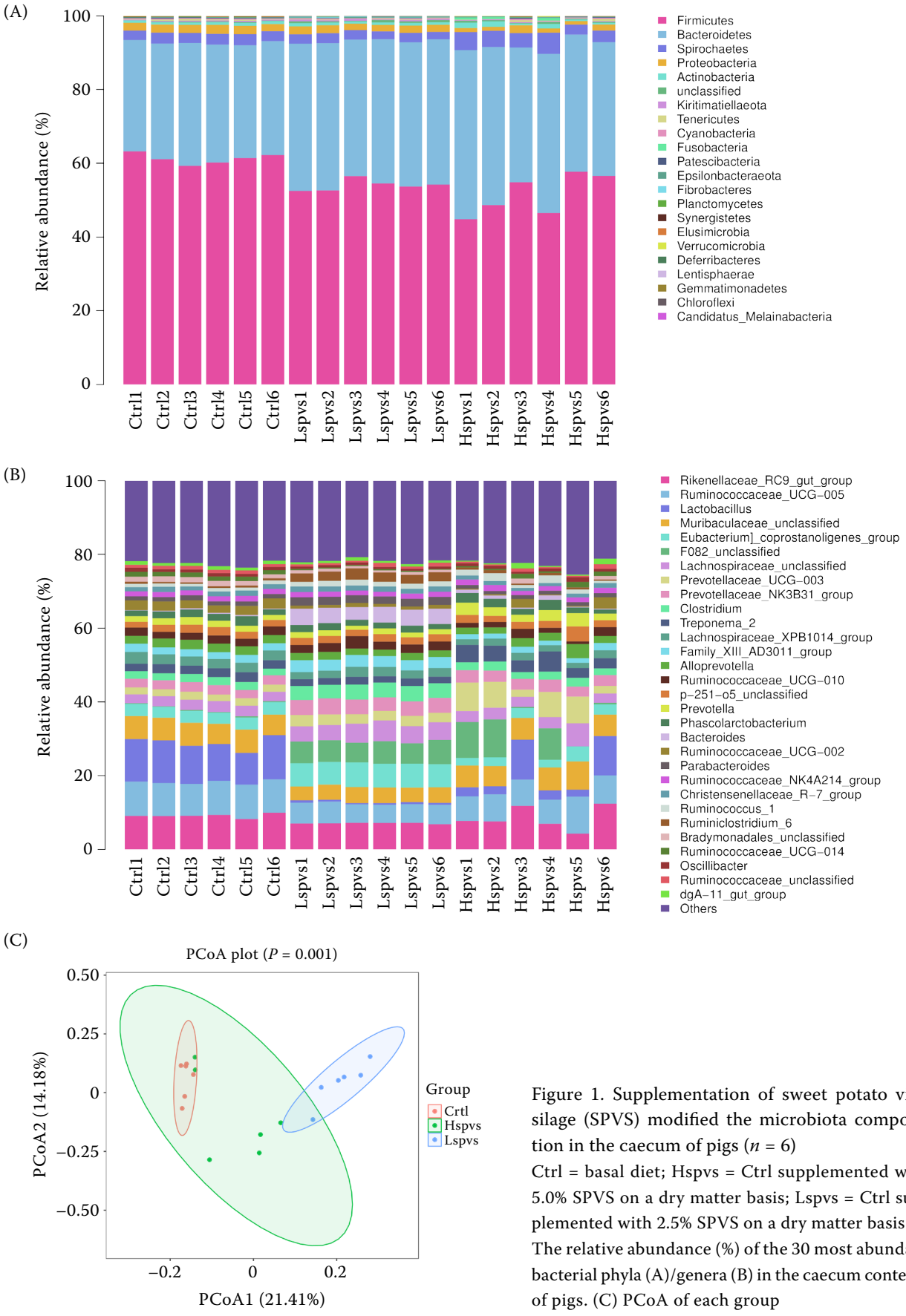


Figure 1. Supplementation of sweet potato vine silage (SPVS) modified the microbiota composition in the caecum of pigs ($n$ = 6)

Ctrl = basal diet; Hspvs = Ctrl supplemented with 5.0% SPVS on a dry matter basis; Lspvs = Ctrl supplemented with 2.5% SPVS on a dry matter basis

The relative abundance (%) of the 30 most abundant bacterial phyla (A)/genera (B) in the caecum contents of pigs. (C) PCoA of each group

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Table 7. Effects of sweet potato vine silage (SPVS) supplementation on the caecum microbiota of pigs

| Item | Ctrl | Lspvs | Hspvs | SEM | *P*-value |
|---|---|---|---|---|---|
| *Firmicutes*-to-*Bacteroidetes* ratio | 1.95[a] | 1.38[b] | 1.30[b] | 0.339 | < 0.001 |
| Shannon | 8.42 | 8.34 | 8.61 | 0.340 | 0.409 |
| Simpson | 0.991 | 0.992 | 0.995 | 0.019 | 0.408 |
| Chao1 | 1 147.66 | 1 096.04 | 1 168.24 | 103.39 | 0.515 |

Ctrl = basal diet; Hspvs = Ctrl supplemented with 5.0% SPVS on a dry matter basis; Lspvs = Ctrl supplemented with 2.5% SPVS on a dry matter basis

[a,b]Different superscripts in the same row indicate significant differences ($P < 0.05$)

2021). Dietary supplementation with SPVS is beneficial to the animal's nutrient absorption and intestinal health (Dang et al. 2017). These improvements may be attributed to the increase of bioactive molecules, such as short-chain fatty acids, which could be accumulated by the proliferation of lactic acid bacteria in silage (Alketife et al. 2017).

Dietary supplementation with silage has been proved to promote the pig production performance (Liu et al. 2017). In line with the mentioned researches, dietary SPVS supplementation increased ADG and ADFI. The reason may be that the animal's microbial ecology is modulated by fermentation (Jin et al. 2017). In addition, when the proportion of green feed in the diet is increased, the energy level of the overall diet will be reduced, and the animal will increase the feed intake to meet the energy requirements of the body. However, the high level of SPVS supplementation led to decreased ADFI, which was in accordance with previous studies showing the inhibitory effect of plant-based silage supplementation on ADG (Wallenbeck et al. 2014). SPVS in the diet is relatively high, which will increase the size of the diet and enhance the satiety of the pigs, which will lead to a decrease in dry matter intake. This suggests that the ability to consume and digest silage is limited, and too much silage cannot meet the animal's nutritional requirements.

The higher CF content in Hspvs, compared with the control, partly explained the reduction of apparent nutrient digestibility in pigs. This is consistent with previous reports on dietary supplementation of foliage and other fibre-rich feedstuffs in diets for growing pigs (Tejeda and Kim 2020). In diets rich in crude fibre, protein in the intestine will be combined or wrapped in the plant cell wall, and a high content of fibre accelerates the peristalsis of the intestinal tract and reduces the retention time, affecting the absorption and utilization of nutrients (Jorgensen et al. 2007).

Oxidative stress refers to a state in which the oxidation and antioxidants are imbalanced, and it is a negative effect produced by free radicals (Godfrey and Barker 2000). Previous study showed that the blood T-SOD level of gilts that were fed SPV is significantly higher while the serum concentration of MDA is lower (Zhang et al. 2019). SPV is rich in vitamin $B_1$, which is capable to increase the antioxidant level of animals (Traber and Atkinson 2007). Additionally, SPVS treatment increased the level of *Lactobacillus*, which has free radical scavenging activity in a dose dependent manner.

This study found that the addition of SPVS to the diet increased the depth of the ileal crypts. Fresh SPV is rich in xylose and uronic acid, the fermentation of which releases more acetic acid and butyric acid (Xu et al. 2019). SCFA receptors and transporters play an important role between intestinal bacterial metabolism and gut barrier function (Holota et al. 2019). After fermentation, starch gelatinization, cellulose and protein degradation lead to small molecular substances such as monosaccharides, disaccharides, oligosaccharides and amino acids. Fibre fermentation is correlated with the composition of monosaccharides (Jonathan et al. 2012), thereby resulting in different SCFA release in the gut. Dietary fibre could stimulate the growth and reproduction of microorganisms, and *Firmicutes* and *Bacteroidetes* are closely related to the production of butyrate and propionate (Bai et al. 2020), *Lactobacillus casei* could enrich SCFA-producing bacteria (Qu et al. 2018). Therefore, modification of microorganisms may cause the increase of SCFA. Butyrate maintains the integrity of the intestinal barrier (Kelly et al. 2015) via the regulation of tight junction protein expressions. Moreover, DAO is an indispensable substance for the proliferation of gastrointestinal mucosal cells. DAO activity in the intestinal mucosa is often used as a marker to test the maturity and integrity of the intestinal mucosa (Kazmierczak and Robertson 1992).

Butyrate can also induce apoptosis of intestinal cancer cells and promote the secretion of cellu-

https://doi.org/10.17221/209/2021-CJAS

lar immune factors IL-10 and IL-18 (Xiong et al. 2004). Pro-inflammatory factors induce pathological openings in the tight junction barrier of the gut and increase epithelial intestinal permeability (Al-Sadi et al. 2009). Studies have found that adding fructooligosaccharides to pig diets can enhance the expression of intestinal cellular immune factors, thereby improving intestinal inflammation (Carpenter and O'Neill 2007). Lspvs treatment can improve the inflammatory state of the intestinal mucosal epithelium, and can reduce the intestinal permeability by reducing the negative impact of pro-inflammatory cytokines.

A symbiotic relationship between the host and intestinal microbes maintains the intestinal homeostasis. Microbes in the caecum can use CF, fat, insoluble protein, and endogenous secretions that the small intestine cannot digest as fermentation substrates for digestion and absorption. The decomposition produces monosaccharides, volatile fatty acids and other organic acids. *Firmicutes* and *Bacteroidetes* are the dominant flora in the caecum, which are related to polysaccharide decomposition. *Firmicutes* play an important role in cellulose breakdown (Evans et al. 2011). *Bacteroidetes* have an important influence on the decomposition of carbohydrates and plant wall cell polysaccharides (Salyers et al. 1977). The ratio of *Firmicutes* to *Bacteroidetes* regulates energy metabolism (Ley et al. 2006), and increases in the intestinal tract of obese hosts (Ma et al. 2020). Here, the ratio of *Firmicutes* to *Bacteroides* was reduced, suggesting SPVS supplementation may improve lipid metabolism in pigs.

SPVS supplementation reduced the abundance of *Proteobacteria*, which are pathogenic bacteria that may damage the mucosal barrier and cause intestinal diseases. Moreover, SPVS supplementation enhanced the abundance of *Lactobacillus*, the colonization of which constitutes a protective barrier. The mucosal barrier formed by probiotics such as *Lactobacillus* could minimize the invasion of harmful microbes (Wang et al. 2007). In addition, *Lactobacillus reuteri* secretes reuterin that could effectively inhibit the proliferation of harmful microorganisms (Doleyres et al. 2005). Therefore, adding SPVS to the diet of finishing pigs will promote the growth and development of beneficial microorganisms and inhibit pathogenic bacteria to a certain extent, thereby improving the intestinal health. Dietary SPVS supplementation to fattening pigs improves the gut health via the colonization of beneficial microbes and inhibition of the reproduction of harmful bacteria.

## CONCLUSION

The beneficial effects of SPVS supplemented at an inclusion level of 2.5% of DM in feed were verified by the improvement of growth performance, enhancement of the immune function and promotion of the intestinal health of pigs. Notably, if SPVS were fed over 5.0% in DM, the excessive CF would burden the intestinal gut of the fattening pigs, thereby negatively affecting their normal growth and development. The findings from the study provide a reference for the application of SPVS in finishing pigs.

### Conflict of interest

The authors declare no conflict of interest.

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Received: December 26, 2021
Accepted: May 20, 2022
Published online: June 2, 2022