Renewable Agriculture and Food Systems

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Research Paper

Cite this article: Quander-Stoll N, Holinger M, Früh B, Zollitsch W, Leiber F (2021). Comparison of different piglet diets in organic agriculture using milk powder, enriched lysine, conventional potato protein or high soybean cake content. *Renewable Agriculture and Food Systems* **36**, 245–254. https://doi.org/10.1017/S1742170520000253

Received: 10 March 2020
Revised: 25 May 2020
Accepted: 21 July 2020
First published online: 5 October 2020

Key words:
Amino acid supply; animal health; diet composition; growth rate; organic pig nutrition

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Comparison of different piglet diets in organic agriculture using milk powder, enriched lysine, conventional potato protein or high soybean cake content

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Abstract

Feeding monogastric livestock in organic agriculture is challenging due to several tradeoffs between animal welfare aspects, resource efficiency, as well as ecological and social sustainability. Organic standards may even increase such conflicts, as is currently the case with upcoming new regulations regarding restrictions of feed sources for organic pigs in Europe. In order to contribute data for balancing reasons to minimize tradeoffs, we compared four different piglet diets, each targeted to reach a high protein quality by either a high proportion of soybean cake (SOY), inclusion of milk powder (MILK), fermentatively produced lysine (LYS) or conventional potato protein (POT). All diets were designed to meet the nutritional requirements of piglets in the best possible way, however they all represented different conflicts with either organic regulations or sustainability goals. In each of five consecutive runs, respectively three litters were assigned to every dietary treatment, resulting in 15 litters per treatment in total. In each litter, seven focus animals were defined. The piglets were studied from birth until 58 days of age. They were weaned at day 46 and sold from the farm at day 58. Piglets were individually weighed at an average age of 3, 21, 43, 50 and 58 days with simultaneous assessment of body condition score (BCS) and prevalence of diarrhea. Feed intake (FI) was recorded litter wise weekly, starting from week three. Feed conversion ratio (FCR) was calculated for the period after weaning. Statistical analysis was executed using linear mixed effect models. Regarding FI, FCR and daily weight gains, no treatment effect was found. Only at day 21, BCS was lower for piglets receiving POT. Prevalence of diarrhea increased after weaning for all treatments. All four tested diets led to similar weight gains and feed conversion in the piglets. Animals fed diet POT recovered better from diarrhea compared to the other treatments. A high soybean cake content or lysine supplementation in the diet was disadvantageous with regard to the occurrence of diarrhea. LYS diet led to signs of threonine deficit, indicating that lysine addition alone may not solve the issue. The addition of milk powder provided no extra benefit. In recognition of the health benefits, the use of 5% potato protein, even if it is sourced from conventional production, must still be considered as a sustainable option for feeding organic piglets. The sustainability implications are discussed in the paper.

Introduction

Since more than 10 years, the goal of using 100% organic diets has been pursued for monogastric animals in European organic regulations, but the final implementation has been repeatedly delayed. This illustrates skepticism and concerns about the feasibility of diets consisting of 100% organic feedstuffs. As long as 5% conventional components are still permitted in diets for pigs, for example conventional potato protein is used depending on availability and region. Potato protein, which is a by-product of the potato starch industry, has an advantageous amino acid profile and thus improves the protein quality. However, it is not available in organic quality in sufficient quantities. According to Sundrum *et al.* (2006) and Schumacher *et al.* (2011) concerns are that an adequate supply with amino acids can no longer be guaranteed and animals may show a reduced health status and performance losses when 100% organic components will be prescribed. When the new EU regulation comes into force (January 1, 2021), conventional protein feed will only be permitted for piglets up to a live weight of 35 kg until December 31, 2025 (The Council of the European Union, 2018), and in Switzerland, according to the current guidelines for Organic Agriculture (Bio Suisse, 2020), 100% organic components will even be compulsory for piglets after the end of the transitional period (December 31, 2022).

The conditions for implementation of the 100%-rule may not be optimal: in Europe, the degree of self-sufficiency for organic protein feed is low, which leads to high nutrient imports (Früh *et al*., 2015). Although the proportion of self-produced soybeans is increasing in Europe, it is not enough for achieving a high self-supply. Due to the elimination of potato protein, the import of soybean products from overseas is expected to increase (Witten *et al*., 2014). This is in contradiction to a guiding principle of organic farming: the establishment of an almost complete nutrient cycle within an agricultural system and the use of predominantly regionally sourced components, which are preferably even produced on farm (Sundrum, 2001; Zollitsch, 2007; Smith *et al*., 2014). In purely plant-based organic diets, the protein content usually must be higher than in conventional diets to achieve an adequate supply with sulfur-containing amino acids, because according to European organic regulations the supplementation with free amino acids is not allowed (The Council of the European Union, 2007).

On the other hand, in order to produce meat, high quality feed protein is needed to ensure high nitrogen efficiency. The primary objective of diet formulation is to meet the nutritional requirements of the animals and thus ensure adequate growth performance and health. Provision of amino acids adequate to requirements in conventional systems shall ensure optimal nitrogen efficiency and lowest possible emissions. Thus, the ban of purified amino acids according to organic feeding standards may increase antagonisms between animal welfare, sustainability and feed efficiency. The allowance to organic pigs of eating roughage or having pasture access for well justified welfare and health reasons (Holinger *et al*., 2018) may even sharpen this problem, and with a prescription of 100% organic components the stated antagonisms are the more expected to rise. Therefore, it is of particular importance to develop diets that serve animal requirements, ecology, sustainability and organic standards in a best possible balance. Many examples of 100% organic feed rations show that it is generally possible to formulate diets without the use of non-organic feed components (Stalljohann, 2006; Baldinger *et al*., 2017; Schwediauer *et al*., 2018). However, concerning young animals, Witten *et al*. (2014) pointed out that a supply gap is likely to occur, due to the insufficient availability of high-quality protein components.

On the background of these multiple challenges, our aim was to assess several different options for the feeding of organic piglets. Bearing in mind the mentioned conflicts, which do not appear to be fully solvable, we considered four different diets, each of which implied one or several target conflicts or violations of standards, but was designed to fulfill nutrient requirements of piglets to the best possible degree. The aim was to assess their equivalence or failure to compete in health and weight development of piglets, in order to provide a basis for discussion of suitable organic diets, including a challenge toward the existing rules. As the basis for comparison, a current Swiss organic piglet diet was set, including 5% potato protein from conventional sources. This diet would violate regulations in due future but provide an appropriate amino acid profile. Furthermore, a diet was considered, where the potato protein was replaced mainly by soybean cake, which would increase import dependency of the system. In a third diet, milk powder was included, which should provide a high amino acid quality, but is in strong feed-food competition (Ertl *et al*., 2016). Finally, we designed a fourth diet using fermentatively produced lysine as an additive, to improve the amino acid supply, which is the usual option in conventional feed formulations, but again would violate the organic standards. Our aim was to compare these four approaches, and the null-hypothesis was that they would not differ with regard to health and growth of piglets.

Animals, materials and methods

Animals and experimental schedule

The experiment was carried out with approval by the responsible veterinary authority in Aarau, Switzerland (Approval No. AG 75701). The on-farm feeding experiment with piglets was performed on an organic pig farm in Switzerland between May 2017 and February 2018. Animals were housed and managed according to the Swiss Regulation for Organic Agriculture (Bio Suisse, 2020). Landrace × Large White crossbred sows were inseminated with semen from Duroc or Large White boars. Three days before farrowing, sows were transferred to single pens with a piglet nest. Pen size was 7.5 m^2 and the concrete floor was covered with straw. Three weeks after farrowing, sows and piglets were moved to a different single pen (7.5 m^2), including a larger nest for piglets and with access to a concrete outdoor run (6 m^2). According to the farrowing pattern, new experimental piglets were included every 6 weeks. Duration of the suckling period was 46 days, after which the sows were separated from the piglets, which remained in the pen. After weaning, the experiment continued until the piglets were sold to a fattening farm at 58 days of age.

In five consecutive runs, a total of 445 piglets were used. Every run comprised of 12 litters, each in a separate pen. The assignment of treatments to pens rotated in every run. This allowed assigning piglets from three litters to one out of four treatments each. At an age of 3 days (±2), litters were assigned randomly to one of the four treatments and piglets were marked with experimental ear tags. Per run, three litters received the same experimental diet. From each litter seven animals were selected as focal animals and examined for their growth performance, body condition (score) and occurrence of diarrhea. Selection of the focal piglets included in the experiment was carried out randomly but was balanced for numbers of female and male animals.

Piglets were weighed and iron injections were administered at the third day of life, and male piglets were surgically castrated at an age of 5 to 12 days under anesthesia and application of analgesic drugs. Subsequently, piglets were weighed individually again at 21 (±2), 43 (±2), 50 (±2) and 58 (±2) days of age (Kern IFB 30K5DMCH scale, sensitivity: 5 g; Swiss Waagen DC GmbH, Bertschikon, Switzerland). At the same time each animal was assessed for body condition score (BCS) corresponding to Doyle *et al*. (2015). The score ranked from 1 to 3 (1 = very compromised; 2 = moderately compromised; 3 = healthy). Of particular interest was the BCS after weaning to determine whether weaning problems had occurred which might have resulted in a decrease in body condition. Piglets with a BCS below two were defined as being under-conditioned (UC). At every assessment, each animal was also scored for diarrhea (0 = no diarrhea: formed feces; 1 = slight diarrhea: pasty feces; 2 = moderate diarrhea: liquid/pasty feces; 3 = severe diarrhea: liquid/watery feces) (Almeida *et al*., 2012). The occurrence of diarrhea was only assessed visually; no feces samples were analyzed and thus no pathogen detection was made. For the evaluation of feed intake (FI), two periods were considered separately: 25 days before and 12 days after weaning (from weaning to selling). Feed conversion ratio (FCR), i.e., ratio between average daily FI and average daily weight gain (ADG) was calculated for the second period only, when the piglets consumed no milk anymore.

Diets

Four basal piglet diets were prepared using common organic components (barley, oats, pea, soybean cake, rapeseed cake and faba bean). Different supplements were added to this basal diet, representing four different dietary treatments: The diet SOY as a purely vegetable ration without any other high-quality protein sources contained the highest proportion of soybean cake (13.4%). In the diet MILK, the use of 3% milk powder enabled a 21.6% reduction in soybean cake (compared to diet SOY). In the diet LYS, fermentatively produced lysine was added and thus the crude protein content reduced. The use of 0.24% 'VitaLys' enabled a soybean cake reduction of 29.1%. The used lysine preparation 'VitaLys' was fermentatively produced by GMO-free coryne bacteria. It was not purified and consisted of 58% pure lysine, 20% lysine-sulfate, 20% other amino acids and 2% water. Furthermore, diet LYS contained 5% sunflower cake instead of rapeseed cake. In diet POT, soybean cake was reduced and replaced with 5% conventional potato protein. All diets were adjusted for the same concentrations of lysine and methionine. This resulted in differences between the diets regarding their crude protein contents, which were slightly higher for SOY and MILK as compared to POT and LYS (Table 1).

Feed was offered to piglets starting from the third week of life. The feeders were refilled twice daily (morning and evening) to provide *ad libitum* feed supply. Feed leftovers were weighed back once a week to determine the weekly feed consumption on pen basis and thus the average daily FI per day and animal. For treatments SOY, MILK and LYS the sows' feed has also been optimized to 100% organic components (one diet for all sows). Sows of POT were given a common diet consisting of 95% organic feed components and 5% conventional potato protein.

Table 1. Composition of the four experimental diets for piglets

	SOY	MILK	LYS	POT
Components (g/100 g fresh matter as fed)[a]				
Barley	29	29.1	29.7	30
Oats	25	25	26	26
Soybean cake	13.4	10.5	9.5	5.6
Rapeseed cake	6	6	–	6
Sunflower seed cake	–	–	5	–
Peas	7.5	6.8	7.5	6.3
Faba bean	7	7	7	5
Wheat bran	2.4	2.9	5.1	3.8
Potato protein	–	–	–	4
VitaLys	–	–	0.24	–
Skimmed milk powder	–	3	–	–
Analyzed values (g/100 g dry matter)				
Crude protein	18.7	18.5	17.4	17.8
Ether extract	5.5	5.3	5.7	5.2
Crude fiber	5.2	5	5.8	6.1
Ash	7.8	7.5	7.1	7
Lysine	1.01	1	0.99	0.94
Methionine	0.23	0.25	0.21	0.25
Cystine	0.39	0.36	0.34	0.4
Met + Cys	0.62	0.61	0.55	0.65
Threonine	0.64	0.63	0.55	0.66
Calculated values[b] (g/100 g fresh matter as fed)				
MJ ME	13.1	13.2	13.1	13.2
SID Lysine	0.79	0.8	0.8	0.81
SID Methionine	0.22	0.23	0.2	0.25
SID Cystine	0.3	0.29	0.26	0.29
SID Met + Cys	0.52	0.52	0.47	0.54
SID Threonine	0.52	0.52	0.46	0.55

SID, standardized ileal digestible.
[a]Further components: cider vinegar, stone dust, premix, soybean oil, molasses, calcium carbonate, coal, sodium chloride, life yeast.
[b]Values as predicted by the feed mill.

Feed analysis

Samples of the four different diets were taken from each feed batch, which was delivered from the feed mill. In order to make the samples durable, samples were dried for 24 h at 60°C in a drying cabinet. Afterward samples were analyzed for nutrient contents according to VDLUFA (2007) at the Agricultural Research Institute Speyer, Germany. Dry matter was determined at 105° C. The crude protein content was determined by the DUMAS combustion method (4.1.2). Ether extracts were analyzed according to method A of 5.1.1. The crude fiber content was determined according to 6.1.1 and ash according to 8.1. The amino acids lysine, methionine, cysteine and threonine were analyzed following method 4.11.1 of VDLUFA (2007). The metabolizable energy content (MJ ME kg^{-1}) declared by the feed mill that produced the experimental piglet diets was used as an estimate.

Statistical analysis

The statistical analyses were conducted with software R, version 3.6.1 (R Core Team, 2017). (General) Linear mixed effects models were applied, considering diet, age/time of measurement and their interaction as fixed effects (Table 2). Nested random effects were used, which were measurement within animal within litter within run. Sow was considered as cross random effect and birth weight as covariable. Models for weight, ADG and BCS were calculated using the function 'lmer' from the 'lme4' package in R (Bates *et al.*, 2015). FI and FCR (kg FI kg^{-1} weight gain) were measured at the pen level, and statistical analysis was conducted using the function 'lm'. FI and FCR were analyzed separately for the periods before and after weaning. The model residuals were examined visually for deviations from normal distribution and homoskedasticity. The variable weight was log transformed to meet model assumptions (Table 2).

First, the full model including all fixed effects and interactions was compared to the zero model with the intercept only. Further steps were only carried out if this comparison resulted in a *P*-value of <0.05. Reduced models were calculated without the effect or interaction of interest. Comparing these reduced models

Table 2. Description of statistical models

Outcome variables	Transformation	Fixed effects	Nested random effects	Crossed random effects	Covariable
Body weight (kg)	Log	Diet, age	Measurement within piglet within litter within run	Sow	Birth weight
ADG (kg)	None	Diet, time of measurement	Piglet within litter within run	Sow	Birth weight
BCS	None	Diet, age	Measurement within piglet within litter within run	Sow	Birth weight
UC piglets (%)	binary, BCS < 2	Diet, age	Measurement within piglet within litter within run	Sow	Birth weight
Diarrhea (score 1–3)	Binary, diarrhea score > 0	Diet, age	Measurement within piglet within litter within run	Sow	Birth weight
Severe diarrhea (score > 2)	Binary, diarrhea score > 2	Diet, age	Measurement within piglet within litter within run	Sow	Birth weight

Table 3. Average daily feed intake and feed conversion ratio per animal

	SOY	MILK	LYS	POT	SEM	*P*-value
Before weaning (days 21–46)						
FI[1] (g day^{-1})	147	134	152	151	0.75	0.87
After weaning (days 47–58)						
FI[1] (g day^{-1})	557	603	676	597	1.32	0.47
FCR[2] (kg feed kg^{-1} weight gain)	1.89	1.78	2.16	1.84	0.06	0.31

During the first survey period (days 21–46) additional milk was consumed via the mother.
[1]FI, average daily feed intake per animal; [2]FCR, average feed conversion ratio.

with the full model using sum contrasts, yielded interpretable results for the main effects, even if there was a significant interaction. *P*-values for main effects and interactions were obtained by comparing reduced models to the full model in a parametric bootstrap approach with 1000 simulations, employing the function 'PBmodcomp' from the package 'pbkrtest' (Halekoh and Højsgaard, 2014). Afterward model estimates and confidence intervals were obtained with 1000 parametric bootstrap simulations for mixed models with the function 'bootMer' in 'lme4' (Bates *et al*., 2015). Model estimates were always calculated for the full model under consideration of all fixed effects and interactions (Forstmeier and Schielzeth, 2011).

The variables 'under-conditioned piglets' (BCS < 2) and the occurrence of diarrhea (in total and severe) were coded as binary variables and analyzed using the function 'glmer' ('lme4' package). In case of significant interactions between diet and age or a significant effect of diet, pairwise comparisons using the function 'emmeans' from the package 'emmeans' (Lenth *et al*., 2020) were conducted to determine which treatments differed at which time of measurement. Statistical differences were considered to be significant when $P < 0.05$. Only *P*-values <0.1 are reported.

Results

Feed intake

No difference was found for both time periods between the treatments in terms of FI (Table 3). Numerically, piglets of LYS consumed more feed after weaning. Setting the feed consumption in relation to the ADG, the best FCR (Table 3) was obtained for diet MILK with 1.78, then POT with 1.84, SOY with 1.89 and LYS scored the worst with 2.16, but without a statistically significant effect of treatment.

Growth performance and body condition score

The comparison of the four treatments showed no difference in the piglets' body weight (Fig. 1). Results showed an interaction between diet and piglets' age (Fig. 1). MILK and LYS showed a steeper increase in weight development. However, at the end of the experiment (58 days of age) all piglets reached similar weights. Furthermore, birth weight, which was considered as covariate in the model, had a positive effect on weight at later sampling dates.

Correspondingly, there were no treatment effects for ADG either. An effect of time of measurement and an interaction between diet and time of measurement was found (Fig. 2). The birth weight also had a positive effect. For the BCS an influence of diet, age and an interaction between diet and age was found. This is due to POT, which had a lower BCS than MILK at 21 (±2) days of age (Table 4). The BCS increased for POT from day 21 to 58, while it remained the same for the other treatments. In addition, a positive effect of birth weight was found ($P = 0.001$). The proportion of UC animals was affected by an interaction between diet and age and by diet. Birth weight was correlated with a lower proportion of UC piglets ($P = 0.04$).

https://doi.org/10.1017/S1742170520000253 Published online by Cambridge University Press

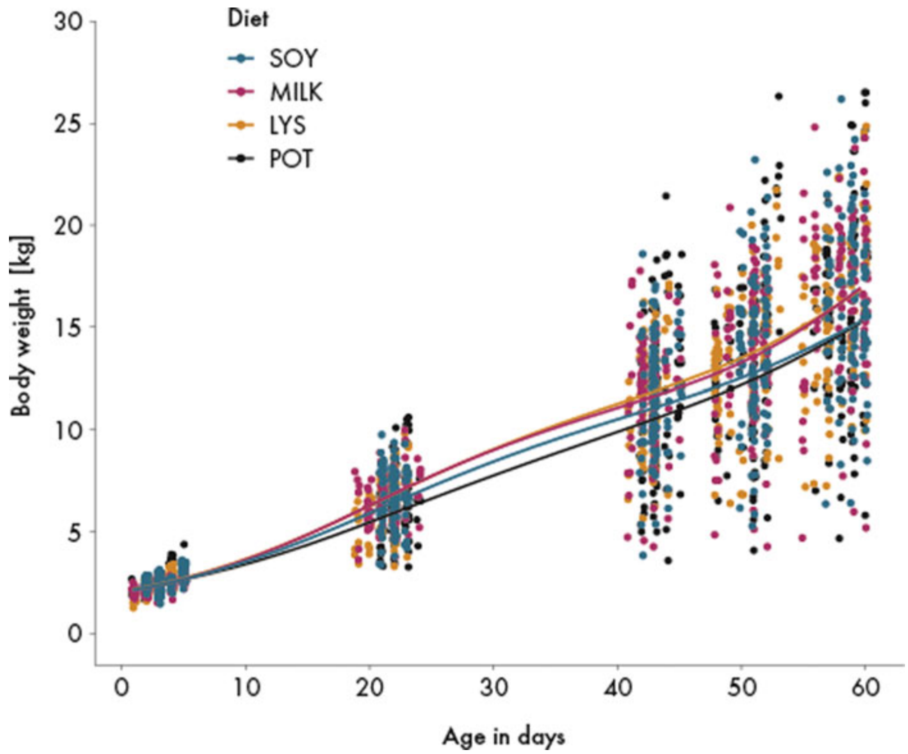

Fig. 1. Weight development of piglets fed organic diets supplemented with either conventional potato protein (POT), lysine (LYS), milk powder (MILK) or containing a high proportion of soybean cake (SOY). Lines represent model estimates. Diet $P = 0.97$, Age $P < 0.001$, Diet × Age $P < 0.001$.

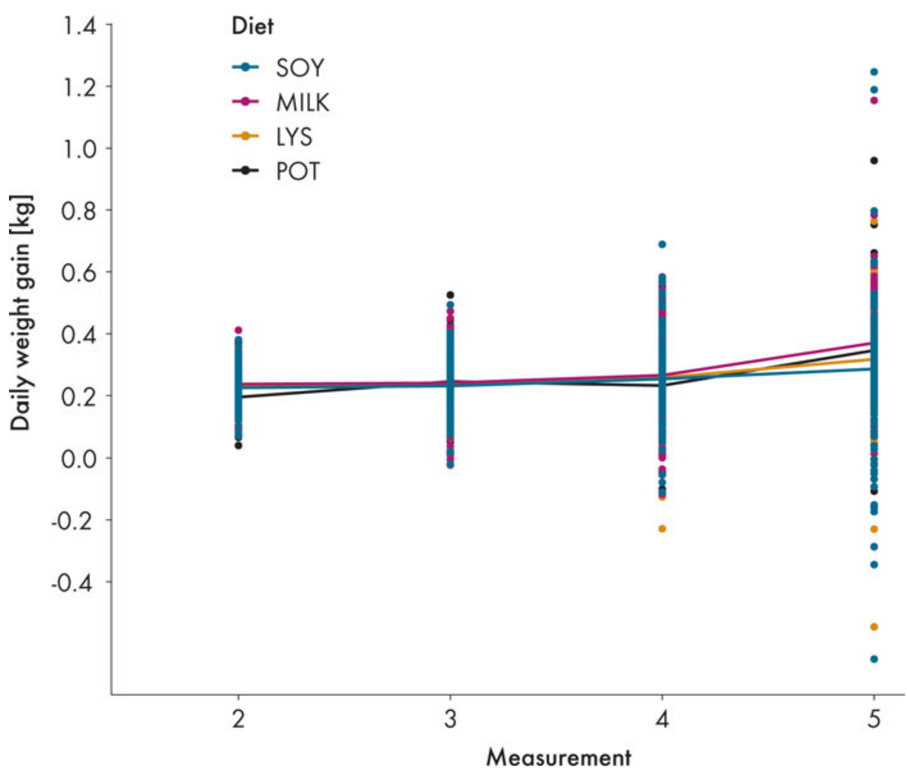

Fig. 2. Average daily weight gain of piglets fed organic diets supplemented with either conventional potato protein (POT), lysine (LYS), milk powder (MILK) or containing a high proportion of SOY. Lines represent model estimates. Diet $P = 0.28$, Time of measurement $P < 0.001$, Diet × Time of measurement $P = 0.002$.

Prevalence of diarrhea

The total prevalence of diarrhea increased sharply after weaning, so that 5 days post weaning 21.2–44.4% of the animals were affected and 15.1–28.9% suffered from severe diarrhea (Table 4). For total prevalence of diarrhea, no effect of diet, but an effect of age and an interaction of diet and age was found. At the last measurement (58 (±2) days of age), prevalence of diarrhea declined, but treatments SOY, MILK and LYS had a higher proportion of

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Table 4. Average body condition score and prevalence of diarrhea of piglets fed different diets

Item/days of life	Dietary treatments				*P*-values			
	SOY	MILK	LYS	POT	Diet	Age	Diet × Age	Birth weight
BCS[1] (average scores)					<0.05	0.05	<0.001	<0.001
3 (±2)	–	–	–	–				
21 (±2)	2.71[ab]	2.73[a]	2.6[ab]	2.53[b]				
43 (±2)	2.69	2.73	2.66	2.64				
50 (±2)	2.63	2.64	2.63	2.64				
58 (±2)	2.69	2.64	2.61	2.71				
UC[2] (in %)					<0.01	0.29	<0.001	<0.05
3 (±2)	0.00	0.00	0.00	0.00				
21 (±2)	1.43[ab]	0.51[a]	2.2[ab]	2.78[b]				
43 (±2)	1.43	1.26	1.37	2.27				
50 (±2)	1.43	1.77	1.37	1.26				
58 (±2)	0.48	1.77	1.65	1.01				
DT[3] (in %)					<0.1	<0.001	<0.001	0.81
3 (±2)	0.00	1.00	3.30	0.00				
21 (±2)	0.00	0.00	0.00	1.00				
43 (±2)	6.70	0.00	4.40	4.00				
50 (±2)	35.2	31.3	44.4	21.2				
58 (±2)	24.8[a]	24.2[a]	27.5[a]	4.00[b]				
DS[4] (in %)					<0.001	<0.001	<0.001	0.98
3 (±2)	0.00	0.00	0.00	0.00				
21 (±2)	0.00	0.00	0.00	1.00				
43 (±2)	5.70	0.00	4.40	1.00				
50 (±2)	28.6	22.2	28.9	15.1				
58 (±2)	17.1[a]	18.2[a]	17.6[a]	3.00[b]				

[1]BCS, body condition score.
[2]UC: proportion of under-conditioned piglets (BCS < 2).
[3]DT: proportion of diarrhea-affected animals (in total, severity 1–3).
[4]DS: proportion of piglets suffering from severe diarrhea.
[a–b]Numbers with different superscripts are significantly different between treatments at $P < 0.05$.

diarrhea-affected animals ($P < 0.001$) than POT. For severe diarrhea, an effect of diet, age and interaction of diet and age was found.

Discussion

With the aim of obtaining well-balanced piglet rations for organic farming, considering growth performance, health and nutrient efficiency, we tested four different diets, which were all designed in order to fulfill the nutritional requirements and be as close as possible compliant with the organic standards as by The Council of the European Union (2018). The aim was to use widely available organic feed components to achieve the lowest possible protein content at sufficient amino acid supply. Every diet suffered from different inadequacies according to organic production standards or ecological targets: for diet POT, a conventional component (potato protein) was used, which will be banned in the near future in the EU (The Council of the European Union, 2018). Diet LYS contained a lysine additive, which is currently not allowed according to organic regulations (The Council of the European Union, 2007); diet MILK contained organic milk powder, which is allowed, but problematic from a feed–food-competition perspective (Ertl *et al.*, 2016). Diet SOY consisted of plant-based components only, but the high proportion of soybean cake implies critical aspects concerning nitrogen imports, globalized land use, including socio-economic consequences in the regions of origin and transport distances, if it is not produced by the farm itself.

Compliance of the diets with sustainability targets and organic standards

Soybean cake is used in diets for pigs due to its advantageous amino acid profile (NRC, 2012). However, several studies (Meul *et al.*, 2012; Reckmann *et al.*, 2016; Saxe *et al.*, 2018) on the carbon footprint and other impact categories for soy-based pig diets emphasize the need to reduce the feeding of soybean products and rather use other protein components or isolated amino

https://doi.org/10.1017/S1742170520000253 Published online by Cambridge University Press

acids. Although a reduction of soybean imports would be desirable, soybean cake is one of the few components available in organic quality to enhance the amino acid profile and was used in our experiment because Swiss feed mills would offer a piglet diet in this composition if 100% organic feeding was introduced. Aiming at an appropriate amino acid supply, the protein content of diet SOY in the present study had to be higher than in all other formulations, which implied lower protein efficiency and higher nitrogen emissions (Dourmad and Jondreville, 2007).

The use of milk powder in diet MILK reduced soybean cake content by more than 20%. Milk powder is characterized by a good amino acid composition and high digestibility. It is an optimal feed component for piglets because it also improves the acceptance of the diet and promotes the development of the digestive tract (Le Huërou-Luron *et al.*, 2018). According to Stalljohann (2006), milk powder is essential to optimize piglet diets without potato protein and thus make 100% organic feeding possible. Many studies showed that the use of animal sourced proteins such as milk powder in piglet diets prevented behavioral disorders (manipulative, agonistic and abnormal behavior) and led to better performance (Araújo *et al.*, 2010; Bouzerzour *et al.*, 2012; Pluske *et al.*, 2018). However, since milk is a high value human food source, such a piglet diet would have negative impact with respect to feed–food-competition, which is undesirable (Schader *et al.*, 2015; Ertl *et al.*, 2016). Due to its high price, the use of organic milk powder also increases the feed costs.

By using fermentatively produced lysine in diet LYS, it was also possible to reduce the proportion of soybean cake and to achieve a lower dietary protein content. The use of fermentatively produced amino acids has numerous advantages and would be a good supplement to regional non-soy components. All amino acids can be produced by fermentation, except for methionine, for which no economically sufficient quantities are achieved (Kumar and Gomes, 2005; Leiber and Früh, 2014). Therefore the question arises as to whether supplementation of organic diets for monogastric livestock with isolated amino acids from fermentation should be permitted in the future in order to reduce the protein content and, subsequently, nitrogen emissions (Dourmad and Jondreville, 2007; Garcia-Launay *et al.*, 2014; Liu *et al.*, 2017). According to Philippe *et al.* (2011), per 10 g less protein per kg feed, the N excretions are reduced by about 10%. By adding isolated amino acids, the protein content can be lowered without compromising ADG or carcass quality. However, isolated amino acids, even if they are produced by fermentation, originate from a highly technological process, which is in conflict with the aim of naturalness of production (IFOAM, 2014).

The fourth experimental diet, POT, represented the common diet for piglets, which is currently dominating in European organic piglet production. Potato protein is an industrial by-product of potato starch production. It is highly digestible and contains comparably high proportions of essential, limiting amino acids such as lysine (Waglay *et al.*, 2013; Gorissen *et al.*, 2018). Potato protein allowed for almost 60% lower inclusion of soybean cake as compared to SOY. It currently has the greatest potential for optimizing diets, but it is of conventional origin and will be phased out in the near future (The Council of the European Union, 2018).

Physiological limitations of the different diets

The experimental investigation within a feeding trial should provide information about the physiological suitability of the diets tested. This was verified by performance parameters (ADG, FI and FCR) and health traits (BCS and diarrhea occurrence).

Although diet LYS was optimized by adding lysine and the crude protein content was reduced, other amino acids probably became limiting (Nyachoti *et al.*, 2006; Jayaraman *et al.*, 2015). This resulted in a deficiency of standardized ileal digestible (SID) sulfur-containing amino acids: 0.59 relative to lysine, instead of 0.64 and threonine: 0.58 relative to lysine, instead of 0.65 to 0.7, which is recommended for piglets between 7 and 25 kg (NRC, 2012; Zhang *et al.*, 2013; Jayaraman *et al.*, 2015). Methionine frequently is the second limiting amino acid for pigs and is essential for numerous processes in the body, including the maintenance and functionality of the small intestine. A deficiency in sulfur-containing amino acids can impair the growth performance and feed conversion of piglets (Fang *et al.*, 2010; Chen *et al.*, 2014). A threonine deficit can lead to higher FI and lower ADG (Hamard *et al.*, 2007; Fernández and Strathe, 2009). This could explain the higher FI and the poorest FCR for LYS (Table 3). It could indicate that threonine was used for building and maintaining the gastro-intestinal tract rather than for muscle protein synthesis (Schaart *et al.*, 2005; Law *et al.*, 2007; Wang *et al.*, 2010).

The FCR achieved by our experimental piglets was comparable to other studies, even if our ADG were rather below average in comparison (Baldinger *et al.*, 2014, 2015; Schwediauer *et al.*, 2018). The flat slope of the growth curve in the current experiment was likely due to a significant proportion of animals suffering from diarrhea (Table 4), which caused ADG to stagnate, although individual healthy animals had daily gains of 0.6–1.0 kg (data not shown).

In addition to body weight, the BCS is an important parameter for the external assessment of an animal in order to find slightly or severely emaciated animals and to take measures if necessary. A healthy piglet should have a BCS of 3.0 (Doyle *et al.*, 2015). The average BCS in our trial was about 2.7 in all treatments. Since a BCS of 3.0 is indicating good health (Doyle *et al.*, 2015), an average BCS of 2.7 conveys the impression that the animals were in a good body condition. However, the ADG stagnated due to the high incidence of diarrhea, so the question arises whether in this case the BCS was suitable as a diagnostic tool. The temporarily lower BCS in POT at an age of 21 (±2) days can be explained by the accidentally greater litter size of the sows (two piglets more). However, the proportion of UC piglets was below 3%, which can be considered to be low, as Wlcek *et al.* (2015) recommend less than 10% UC sows and less than 4% runts in piglets.

After weaning, animals in all treatments suffered from diarrhea, with SOY and LYS tending to have higher proportions of diseased animals. For the last survey, it was noticeable that animals of POT recovered faster from diarrhea than piglets in the other treatments. As no feces samples were analyzed and therefore no pathogen detection was available which could have explained the occurrence of diarrhea, it is difficult to determine the cause of diarrhea in the feed composition. Nevertheless, the diets should be discussed with regard to their composition and in connection with the occurrence of diarrhea.

Due to allergenic proteins in soybeans (Wu *et al.*, 2016; Zheng *et al.*, 2018), piglets can show a hypersensitivity to soy. There is little evidence for maximum inclusion rates of soybean cake, but Stoll (2004) and Lindermayer *et al.* (2010) recommend limiting the use of soybean cake for piglets to 10%, respectively 12%, a threshold, which was crossed with diet SOY. This may have contributed to the occurrence of tenacious diarrhea. In case of LYS, a

https://doi.org/10.1017/S1742170520000253 Published online by Cambridge University Press

relative threonine deficiency could be one cause of prolonged diarrhea (Law *et al.*, 2007), which underlines that adding lysine alone would offer no solution. For diet MILK, it was surprising that the proportion of diarrhea-affected animals was also quite high and that it lasted longer than in POT (Table 4). Various studies show that the type of protein source influences both the development of the digestive tract and its microflora (Bouzerzour *et al.*, 2012; Poulsen *et al.*, 2017). Animal protein sources such as milk powder in piglet diets are beneficial for intestinal development and health, especially after weaning (higher FI and feed conversion) (Vente-Spreeuwenberg *et al.*, 2004; Lange *et al.*, 2010; Le Huërou-Luron *et al.*, 2018). Our expectation was therefore a positive effect of milk powder. The amount of milk powder used may have been too small to have a positive effect in our feeding trial.

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Various strategies and feed components enable 100% organic feeding in piglets. Baldinger *et al.* (2014, 2015) showed good results with hydrothermally treated grass pea seeds and sainfoin seeds and Stalljohann (2006) with toasted field beans and heat-treated wheat flakes. Milk powder was always included in those diets. Our investigation on the one hand also showed that it is possible to optimize piglet diets without potato protein, but on the other hand, it revealed that all three tested alternatives tended to impair piglet health more than diet POT, and it brought along various challenges regarding the ecological targets and organic standards. Given that the use of milk powder or of higher soybean proportions influence the ecological footprint in undesired ways (Schader *et al.*, 2015; Ertl *et al.*, 2016), the two other diets, which do not comply with current or future organic standards (LYS and POT) remain to be relevant options.

Naturalness and animal welfare are crucial in organic farming, but different rearing systems for piglets must also be taken into consideration. One important option would be a prolonged suckling period. Sow's milk generally provides the best supply for piglets. According to Main *et al.* (2004), Bussemas and Weissmann (2008) and Faccin *et al.* (2019), piglets that are allowed to suckle longer show improved health, growth performance and productivity. If piglets are supplied with high quality protein through the sow milk, piglet feed with less external input can be used (Baldinger *et al.*, 2017). A greater variety in the choice of feed components would thus be an advantage of prolonged suckling and the introduction of 100% organic feeding would be easier to implement.

Conclusion

All four diets tested herein resulted in similar weight gains and feed conversion of the piglets. Piglets receiving a diet containing conventional potato protein coped better with diarrhea compared to the other treatments. Those containing high soybean cake contents or added lysine appeared to be more critical with regard to the occurrence of diarrhea. In general, the diet with lysine addition resulted in signs of threonine deficiency, indicating that only supplying the first limiting amino acid would not solve the problem. Each of four tested piglet diets either had shortcomings in ecological sustainability or did not comply with current or future organic standards, which demonstrates the dilemma of feeding monogastrics in organic agriculture. Acknowledging the health performance, the use of conventional potato protein needs to be considered as a particularly sustainable option, still.

Acknowledgements. The authors acknowledge Swiss Federal Office for Agriculture [Schweizer Bundesamt für Landwirtschaft (BLW)], contract number: 627000764; Bio Suisse; Peter Stoll, Agroscope and the involved feed mills.

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