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Effect of supplementing sows with *Solanum glaucophyllum*, a natural source of calcitriol, on farrowing performance, piglet survival and litter performance

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ABSTRACT. Survival of piglets until weaning is a major contributor to the rentability of pig production systems. Large litters are often associated with complications and prolongation of the farrowing duration causing piglet mortality. The vitamin D status of the pregnant female is known to play a role in parturition problems. The present experiment investigated the effect of *Solanum glaucophyllum* in the diet of sows on farrowing duration and progeny survival and growth. *Solanum glaucophyllum* was distributed in a feed supplement to gestating sows from one week before farrowing until weaning of the piglets. Control sows received the same feed supplement but without *S. glaucophyllum*. Sows at an earlier gestation stage and piglets did not receive *S. glaucophyllum*. From 108 farrowing events and litters, on average 14.3 total born and 12.7 liveborn piglets were observed. *Solanum glaucophyllum* had no positive effect on the farrowing duration (222 vs. 219 min for experimental vs. control sows, respectively), average piglet expulsion interval (17.2 vs. 17.3 min), piglet vitality at birth, piglets death during nursing (2.03 vs. 1.74 piglets/litter) and piglets average daily gains (both 274 g). The proportion of stillborn piglets was even higher in sows receiving *S. glaucophyllum* than in control ones. Nevertheless, further studies on hyperprolific sows having no access to direct sunlight and with diets clearly deficient in either vitamin D or calcium are needed to show whether *S. glaucophyllum* is effective in parturient sows or not.

Introduction

The number of piglets weaned per sow per year is a main determinant of the performance of breeding sows. Consequently, the genetic progress in pigs is connected with the success in breeding larger litter sizes. With increasing average litter size in the sow population, the economic weight of litter size diminishes and that of piglet survival at farrowing and during nursing increases (Quinton et al., 2006). At the same time, farrowing duration and expulsion interval between piglets may increase, which has been related to a greater occurrence of stillborn piglets (Udomchanya et al., 2019). However, means to shorten the duration of parturition do not always support piglet survival. For instance, the injection of oxytocin may, indeed, shorten the farrowing duration but this does not guarantee a concomitant reduction in the occurrence of stillborn piglets (Udomchanya et al., 2019). In order to increase survival rates of piglets before and after birth, empirical managerial improvements like the use of farrowing crates, optimal sow fitness at farrowing and the use of rescue desks are useful. These measures could be supported by supplementing the diet of the sows with ingredients that facilitate the farrowing process and support piglet vitality and growth.

Especially vitamin D_3 (cholecalciferol) supplementation is currently considered to be such a measure to facilitate parturition and support piglet survival. Accordingly, a reduced dietary cholecalciferol supplementation in gestating sows (800 IU/kg feed vs. 1400 IU/kg feed) resulted in a greater number of stillborn piglets (Lauridsen et al., 2010). Vitamin D deficiency was also associated with foetal asphyxia and low vitality of piglets at birth (Augustin et al., 2020), an indicator of neonatal survival (Baxter et al., 2008; Muns et al., 2016). Although the mechanisms for this effect are still not clear, there may be a direct influence of vitamin D on the uterine smooth muscle strength for efficient labour during parturition on the one hand (Ceglia and Harris, 2013), and an indirect effect of vitamin D by regulating the inflammation of the uterine smooth muscle on the other hand (Thota et al., 2014). Dietary and endogenous cholecalciferol undergoes hydroxylation in the liver to calcidiol (25-hydroxycholecalciferol; 25-OH-D_3), the major circulating form of vitamin D which, mostly depending on the circulating level of parathyroid hormone, subsequently undergoes a second hydroxylation in the kidneys to the biologically active hormone calcitriol (1,25-dihydroxycholecalciferol; 1,25-$(OH)_2$-D_3), the active form of vitamin D. Yet, one molecule of cholecalciferol does not systematically produce one molecule of calcidiol and ultimately one molecule of calcitriol, rendering the dietary supply of calcidiol more efficient than the equivalent dose of cholecalciferol (Lauridsen et al., 2010; Flohr et al., 2016). In addition, any condition inducing renal failure or lowering the circulating level of parathyroid hormone may reduce the conversion of calcidiol to calcitriol. In sows, the occurrence of mastitis-metritis-agalactia syndrome was associated with low blood calcidiol concentrations (Karst et al., 2019). Supplementing gestating and lactating sows with calcidiol consistently increased serum calcidiol level but effects on piglet survival and performance were inconsistent (Flohr et al., 2016; Upadhaya et al., 2021). Therefore, the direct supply of calcitriol is of interest because it bypasses the two hydroxylation steps. The oral supply of calcitriol was reported to increase blood calcium level and to reduce parathyroid hormone level without influencing blood calcidiol level in women (Zhang et al., 2012). Because calcitriol systematically raises blood calcium level bypassing the normal calcium homeostasis system, the supply of calcitriol increases the risk of hypercalcaemia. This was shown in rabbits orally supplied with 0.3 µg calcitriol/kg live weight per day in which foetal morbidity and mortality increased (McClain et al., 1980). Similar toxic effects were also observed in gestating sows accidentally fed a 200-fold overdosage of cholecalciferol (Palzer et al., 2006). Whether or not the supplementation of calcitriol, at a safe dosage in terms of avoiding the risk of hypercalcaemia, could facilitate the parturition process and piglet survival, and even improve piglet growth, has yet to be clarified.

Commercial pig diets are routinely supplemented with cholecalciferol. However, there are large discrepancies in recommended levels of its inclusion into pig diets. Currently, although the exact breeding sow's requirement remains undefined, much higher supplementation levels are recommended. These range from 800 IU (20 µg)/kg feed in the United States (NRC, 2012) to 1400 IU (35 µg)/kg feed (Lauridsen et al., 2010). However, levels greater than 2200 IU (55 µg)/kg feed are considered to bear risks for toxic effects on the long term (NRC, 2012).

Solanum glaucophyllum (waxy-leaf nightshade) is a plant native to South America. It has a high content of calcitriol glycosides and is even empirically known to produce hypercalcaemic toxicity in grazing cattle (Worker and Carrillo, 1967). At low dosage, the increase in blood calcium following the ingestion of *S. glaucophyllum* was suggested as a solution to prevent periparturient paresis in cows (Ishii et al., 2015) and to improve bone strength against breaking in broilers (Bachmann et al., 2013). An increased blood calcium level, but a concomitant reduced tibia strength were observed in growing pigs receiving a cholecalciferol dosage of 2000 IU (50 µg) per kg feed together with *S. glaucophyllum* at the level providing of about 1 µg calcitriol/kg live weight (Schlegel et al., 2017). Besides calcitriol, the presence of oestrogens and oestrogen binding receptors in *S. glaucophyllum* (Milanesi et al., 2001) may also modulate uterine contractions at parturition (Mueller et al., 2006).

The aim of the present study was to investigate whether the administration of a *S. glaucophyllum* preparation to sows fed moderate levels of vitamin D may facilitate the parturition process and support piglet survival and growth. The hypotheses tested in the present study were: 1. the supplementation with *S. glaucophyllum* accelerates the parturition process; 2. the supplementation with *S. glaucophyllum* improves piglet vitality and survival at birth and; 3. the supplementation with *S. glaucophyllum* improves piglets growth performance and survival during nursing.

Animals, materials and methods

The Swiss cantonal authorities for animal experimentation approved all animal-related activities carried out in the present experiment under the license ZH182/19. The experiment took place in the pig house of the research station AgroVet-Strickhof (Lindau, Switzerland) between October 2019 and June 2020.

Animals

The experiment involved 81 sows (*Sus domesticus*; Table 1) which were allocated to ten consecutive farrowing clusters in 3-week intervals. Each farrowing cluster consisted of 9 to 12 sows depending on the availability on the farm of sows in the respective reproduction stage. For each farrowing cluster, the sows were allocated in a randomised block design to either a control group or a *S. glaucophyllum* group (SG). Blocking was done considering sow type, parity number and cover boar (or at least cover boar breed if balancing for individual boar was not possible) so groups in total and within each farrowing cluster would be balanced for these traits (Table 1).

Table 1. Experimental sow type and cover boar breed as well as sow parity at farrowing of the sows in control and *Solanum glaucophyllum* (SG) groups, n

Group	Control	SG
Farrowing events	54	54
Sow type		
Landrace	39	39
Landrace × Swiss Large White	15	15
Cover boar breed		
Landrace	21	21
Duroc	33	33
Parity		
average	3.63	3.85
1st	12	8
2nd	8	7
3rd	5	9
4th	10	11
5th	7	8
6th	7	6
7th	4	2
8th	1	2
9th	0	1

In the last three farrowing clusters, 27 sows were used which had already been involved in the first, second or third farrowing clusters. During the second use, 16 of these 27 sows were attributed again to the same respective feeding group as in the first use whereas 11 sows were attributed to the other feeding group to be able to determine an eventual carry-over effect while still balancing feeding groups for the traits listed above. In total, 108 farrowing events and litters were observed.

Experimental feeding and animal management

During gestation period, sows received a commercial gestation feed in a meal form (feed 3267, Meliofeed AG, Herzogenbuchsee, Switzerland; Table 2) for approximately 107 days. This feed was composed of barley, wheat bran, wheat, barley flour, rapeseed meal, molasses, oat, sugar beet pulp, pomace, oat husks, animal fat, linseed, soybean meal and a mineral-vitamin premix. On Monday of the week preceding the anticipated parturition, the sows were transferred from group housing in the gestation unit (with outdoor access) to one of two neighbouring farrowing units. There, the sows were housed individually in 8.5 m^2 farrowing pens without farrowing crates and without outdoor access. The floor of each farrowing pen was covered to about 3/4 with solid concrete, and 1/4 was slatted. Bedding material consisted of sawdust. Until farrowing, chopped wheat straw was provided in addition to allow nesting behaviour. From entering the farrowing unit (i.e., already before farrowing) until weaning (5 weeks later on Monday again), all sows were offered three times a day a commercial lactation feed in a meal form (No. 3256, Meliofeed AG, Herzogenbuchsee, Switzerland; Table 2). This feed was composed of barley, wheat, soybean meal, wheat bran, animal fat, field peas, rapeseed meal, wheat starch, sugar beet pulp, linseed, molasses and a mineral-vitamin premix.

Table 2. Composition of the experimental feeds, as fed; in g/kg unless indicated otherwise

Purpose of feed	Gestation	Lactation	Top dressing[1]	Pre-starter
Analysed				
dry matter	902	907	925	908
organic matter	836	830	905	842
crude protein (6.25 × N)	140	186	79.9	175
ether extract	44.5	70.5	85.3	59.8
neutral detergent fibre	240	182	83.8	192
acid detergent fibre	144	115	77.6	105
Stated by producer				
lysine	6.0	11	3.8	12.5
methionine	2.3	3.4	1.8	4.4
Ca	7.9	8.3	0.9	5.1
P	5.5	6.8	4.7	4.9
vitamin D_3[2], IU/kg	1200	1200	-	2000
digestible energy, MJ/kg	12.0	14.0	14.8	14.5

[1] without *Solanum glaucophyllum* supplement; [2] cholecalciferol

The lactation feed was first restricted to 3–3.5 kg/sow per day before farrowing and then gradually increased to semi-*ad libitum* supply after farrowing and until weaning. Sows from the SG group received once daily 300 g of a top dressing (Meliofeed AG, Herzogenbuchsee, Switzerland; composed of dextrose, linseed and wheat bran; Table 2) including 600 mg of a complementary feed based on dried *S. glaucophyllum* (Panbonis 10, Herbonis, Augst, Switzerland). According to the producer's statement, this supplement contained 10 µg 1,25-calcitriol glycosides/g. Accordingly, with the top dressing approximately 6 µg/sow of calcitriol were supplied daily. The control group received the same amount of top dressing composed of the same main ingredients but no *S. glaucophyllum* supplementation.

To compensate large differences in litter size, cross fostering of piglets was practiced when possible. This was realised only within feeding groups and within 48 h after farrowing. Only 4% (62 out of 1410) of the liveborn piglets were cross fostered. A heated nest, separated from the area accessible to the sow, was available to the piglets at all times in the farrowing unit. Piglets from 7 days of life onwards had *ad libitum* access to a commercial pre-starter feed in crumble form (Glanzmann AG, Trullikon, Switzerland; Table 2). It was composed of oat flakes, barley, wheat bran, potato protein, dextrose, lactose, extruded linseed, whole milk powder, animal fat, cellulose, and a mineral-vitamin premix. Intake of the pre-starter was not recorded. Weaning of the piglets took place on Mondays at about 4 weeks of age.

Data collection

Individual live weight of the sows was recorded when entering the farrowing unit and at weaning. Individual feed consumption of the sows was recorded three times daily during the 5 weeks spent in the farrowing unit. Each farrowing pen was equipped with an infrared video camera that recorded the parturition process. The videos were then analysed by two trained technicians (one for five farrowing clusters). Total farrowing duration (time elapsed from the expulsion of the first piglet to the expulsion of the last piglet), expulsion intervals and piglet vitality scores were documented for each sow. For the latter, a scheme adapted from Baxter et al. (2008) was applied with scores: 0 – inert or stillborn, 1 – moving later than 15 s after birth, 2 – moving within 15 s after birth, and 3 – trying to stand within 15 s after birth. During the first five farrowing clusters, in addition, the position of the sow (standing, sitting, laying, changing laying side) during farrowing was documented. The decision about the necessity of oxytocin injection or assistance during farrowing was left to the appreciation routine of the experienced animal caretakers. Each was documented as binary data (0, 1) for each sow. The number of live and stillborn piglets was registered. Death causes of liveborn piglets during nursing were specified for each sow and classified as 'crushing', 'savaging', 'underdeveloped' or 'other causes'. Liveborn piglets were identified and weighed individually within approximately 12 h after birth and at weaning (4 weeks of age).

Laboratory analysis

Standard procedures (AOAC International, 1997) were followed to analyse the proximate contents of the feeds. Dry matter and ash contents were analysed by an automatic thermo-gravimetric device (model TGA-701, Leco, St. Joseph, MI; AOAC Official Method 942.05), and organic matter was calculated as non-ash dry matter. Crude protein was determined as 6.25 × nitrogen, with nitrogen assessed by a C/N analyser (model TruMac® CN, Leco, St. Joseph, MI; AOAC Official Method 968.06). Ether extract was determined with a Soxhlet extraction system (B-811, Büchi, Flawil, Switzerland; AOAC Official Method 963.15). Neutral and acid detergent fibre, corrected for ash content, were analysed on a Fibertec System M (Tecator, 1020 Hot Extraction, Foss, Hillerød, Denmark) according to Mertens (2002) and AOAC International (1997; Official Method 973.18), respectively. For neutral detergent fibre determination, 100 µl of α-amylase (Sigma-Aldrich, St. Louis, USA) was added.

Statistical analysis

All statistical analyses were performed with SAS 9.4 (SAS Institute, Cary, NC, USA). Pearson's correlation coefficients for selected criteria were calculated with the CORR procedure. The effect of the feeding group was tested with an analysis of variance. Sow or litter was considered as the experimental unit for all analyses except for piglet vitality, for which the piglet was the experimental unit. Continuous data (e.g. live weight) were analysed using the GLM procedure with the farrowing cluster as a random factor. Binary data (use of oxytocin and assistance during farrowing), categorical data (piglet vitality) and count data (e.g. litter size) were analysed with a generalised linear mixed model using the GLIMMIX procedure. In doing so, the binary distribution option was used for binary data while the negative binary distribution option was used for categorical and count data. The normality of the

residuals was tested with the UNIVARIATE procedure. Duration of farrowing and the average expulsion interval were log-transformed before statistical analysis. For data evaluation concerning piglet survival and daily weight gain during nursing cross-fostered piglets were considered as piglets from the nursing sow.

The effect of feeding group on litter weight and count of live- and stillborn piglets was corrected for litter size (included as a covariable). Further, the effect of feeding group on the number of piglets that died during nursing was corrected for the number of liveborn piglets. Finally, the effect of feeding group on average daily weight gain during nursing and live weight at weaning was corrected for litter size at weaning. The presence or absence of significant carry-over effect from the previous feeding treatment in the 27 sows that were used twice in the experiment was also tested. For this, the effect of the previous feeding group was added to the corresponding model. As this effect was never significant, these 27 sows were considered as new animals in the statistical evaluation when used for the second time. Only *P*-values from Type III sums of squares were considered for the analysis of variance. For all analyses, statistical significance was considered at $P < 0.05$. The tables present the least square means and standard errors of the mean.

Results and discussion

General results concerning the farrowing process and piglet survival

Gestation length was negatively correlated with piglet mortality during nursing (Table 3). Such a negative correlation was already reported by Rydhmer et al. (2008) and was attributed to the lighter average birth weight of the piglets in case of a shorter gestation (confirmed by the present results). Piglets with a lower live weight at birth are more prone to hypothermia shortly after birth (Baxter et al., 2008) because of a larger surface-area-to-volume ratio facilitating heat loss. This inclination to hypothermia is worsened by the longer latency of lighter piglets to reach a functional teat and start suckling (Baxter et al., 2008). The average expulsion interval was consistent with that of earlier studies both with and without farrowing crates (Oliviero et al., 2010; Mainau et al., 2010). This trait and the incidence of expulsion intervals longer than 60 min were positively correlated with the duration of farrowing as expected. Inversely, the share of time the sow spent standing or sitting instead of lying was negatively correlated with the duration of the farrowing process, which confirms observations by Mainau et al. (2010). Basically, the share of time sitting or standing (15% of the total farrowing time on average) as opposed to lying was in accordance with earlier results (Fraser et al., 1997). In agreement with previous studies (van Dijk et al., 2005; Oliviero et al., 2010), the duration of farrowing was positively correlated with the percentage of stillborn piglets. However, the percentage of stillborn piglets did not correlate with the average expulsion interval and the number of intervals longer than 60 min ($P = 0.177$ and $P = 0.732$, respectively). Yet, piglet vitality (an indicator of piglet survival; Baxter et al., 2008; Muns et al., 2016) was negatively correlated with the expulsion time registered for the same piglet ($R = -0.12$; $P < 0.001$; data not shown), which coincides with observations by Udomchanya et al. (2019). Average piglet live weight at birth positively correlated with the average expulsion interval. A similar trend was also observed for expulsion intervals longer than 60 min ($P = 0.065$). A heavier

Table 3. Pearson's correlation coefficients among farrowing characteristics (n=108) potentially related to farrowing duration and piglet survival

	Gestation length	Farrowing duration[1]	Average expulsion interval[1]	Expulsion intervals > 60min	Change of lateral side	Sitting or standing[2]	Litter size	Stillborn[3]	Died during nursing[4]
n	108	99	99	99	48	48	108	108	108
Farrowing duration[1]	0.031								
Average expulsion interval[1]	0.076	0.794***							
Expulsion intervals > 60 min	0.091	0.664***	0.670***						
Change of lateral side	-0.255	0.255	0.175	0.418**					
Sitting or standing[2]	-0.086	-0.401**	-0.185	-0.326*	-0.131				
Litter size	-0.043	0.218*	-0.323**	-0.047	0.239	-0.162			
Stillborn[3]	-0.006	0.218*	0.137	0.035	0.259	-0.206	0.242*		
Died during nursing[4]	-0.384***	0.194	-0.042	0.150	0.317*	-0.110	0.426***	-0.015	
Birth liveweight	0.225*	0.154	0.377***	0.186	-0.038	-0.184	-0.399***	0.192*	-0.432***

[1] log-transformed; [2] in percent of total farrowing duration; [3] in percent of litter size (dead and liveborn piglets); [4] in percent of liveborn piglets; *$P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

average live weight at birth was also correlated with better average survival rates during nursing. This means that the assumption that longer expulsion intervals are associated with greater piglet losses is not valid for heavier piglets.

No savaging was observed during this experiment. Deaths during nursing happened more often in larger litters, mainly due to crushing by the sow. The latter represented 40% of the piglet mortality causes during nursing (data not shown). Indeed, crushing is largely recognised as the main cause of mortality in liveborn piglets during nursing whether or not farrowing crates are used (Muns et al., 2016).

Effect of *Solanum glaucophyllum* on the parturition process

Both feeding groups displayed the same gestation length and the same litter size (Table 4). Litter size was fixed long before starting the experimental feeding. Therefore, the difference between groups for this characteristic would not have been the result of the feeding treatments anyway. Only very few sows required assistance or oxytocin injection during farrowing, and no significant difference was observed between groups for these traits. The average farrowing duration was not influenced by the supplementation with *S. glaucophyllum*. This refutes our first hypothesis. The share of time sitting or standing was also not influenced by the supplementation with *S. glaucophyllum*. Likewise, all other farrowing parameters recorded did not differ between feeding groups. Theoretically, supplementation of *S. glaucophyllum* should have been particularly efficient as, unlike cholecalciferol, it directly provided the active form of vitamin D, calcitriol. There could be several reasons for the lack of effect of the supplementation with *S. glaucophyllum.* As mentioned in the introduction, calcitriol in *S. glaucophyllum* is only present in the form of glycosides. This implies that calcitriol only becomes bioavailable after hydrolysis by either intestinal or microbial enzymes. Should this hydrolysis be limited by a poor enzymatic activity and/or take place further than the absorption site of calcitriol, then this would impair the bioavailability of calcitriol from *S. glaucophyllum.* The declared level of cholecalciferol in feed (1200 IU/kg) exceeded the current recommendations in the United States (NRC, 2012), but it was clearly below recommendations developed from scientific evidence (Lauridsen et al., 2010). So, this would not exclude an effect of *S. glaucophyllum.* Even in case the basic requirements would have been covered by the cholecalciferol in the lactation feed alone, an effect of a supranutritional nature could have been expected, as already reported on pork colour and pH (Wilborn et al., 2004). A reason for the inefficiency of the *S. glaucophyllum* could have been that the sows in the present experiment had access to an outdoor area in the gestation unit, which use was forced by mounting the automatic feeders outside the pig house. This exposure to UV light might have triggered endogenous cholecalciferol synthesis in the

Table 4. Characteristics of sows and litters and the farrowing process as measured in the control or *Solanum glaucophyllum* (SG) group

Item	n	Group		SEM	*P*-value
		control	SG		
Sow data					
sow liveweight on day 0, kg	108	293	300	6.0	0.370
gestation length, days	108	115	116	0.3	0.238
Farrowing data					
farrowing duration, min	99	222	219	1.1	0.917
average expulsion intervals, min	99	17.3	17.2	1.09	0.949
expulsion intervals > 60 min, n/farrowing	99	0.731	0.568	0.1782	0.286
standing or sitting position, % of total farrowing time	48	15.6	13.8	2.70	0.606
change of lateral side, n/farrowing	48	1.59	1.54	0.417	0.926
farrowing assistance realised, % of farrowing events	108	2.60	5.00	4.139	0.298
use of oxytocin, % of farrowing events	108	7.8	13.3	6.04	0.251
Piglet vitality at birth[1]	1145	1.87	1.78	0.061	0.260
Litter data					
total piglets born, n	108	14.5	14.1	0.54	0.602
liveborn piglets per litter, n	108	12.8	12.6	0.49	0.684
stillborn piglets per litter, n	108	0.832	1.30	0.210	0.046
litter weight, sum of liveborn piglets, kg	108	19.7	19.8	0.45	0.825

[1] adapted from Baxter et al. (2008): 0 – inert or stillborn, 1 – moving later than 15 s after birth, 2 – moving within 15 s after birth, 3 – trying to stand within 15 s after birth; SEM – standard error of the mean

skin of the sows, assisting to establish optimal circulating calcidiol concentrations in both control and SG groups and thus may have led to fully covered requirements or masked any supranutritional effects. Even though the outdoor access ended when the sows entered the farrowing unit, the exposure to sunlight could at least explain the lack of positive effect of the supplementation with calcitriol from *S. glaucophyllum* on farrowing characteristics, as farrowing followed soon after moving the sows to the farrowing unit. To discard this potential bias, a measure of the concentration of circulating calcidiol in sows would be recommended in a further experiment. An effect of the supplementation with *S. glaucophyllum* might have also been facilitated when using a diet deficient in calcium, as found in broilers (Bachmann et al., 2013), but this mineral was supplemented in sufficient amounts with the commercial mineral mix in the present study (NRC, 2012). At last, the dosage of *S. glaucophyllum* could have been insufficient to observe a significant effect on farrowing traits which are also influenced by many other factors.

The only trait for which *S. glaucophyllum* had a significant effect was the prevalence of stillborn piglets. There were 56% more stillborn piglets in the SG group than in the control one ($P < 0.05$), even though the overall proportion of stillborn piglets was within a normal range in both groups (Lauridsen et al., 2010) and the absolute number was low. This clearly refutes our second hypothesis about the improvement of piglet survival at birth by *S. glaucophyllum* supplementation and is an argument against the higher dosage suggested above. Also, a bias from the litter size (total born piglets) can be excluded as both groups were similar for this trait and litter size was included as a covariable in the statistical analysis. Therefore, the empirically positive correlation of litter size and proportion of stillborn piglets (Baxter et al., 2008) cannot be the explanation for the undesirable *S. glaucophyllum* effect. One aim of supplying calcitriol via with *S. glaucophyllum* was to support the strength of the uterine smooth muscle contractions (Ceglia and Harris, 2013) and thus to shorten the farrowing process. These contractions could have had an undesired side-effect as they might have facilitated an early rupture of the umbilical cord and subsequent piglet hypoxia at birth. Such a phenomenon has been observed before with oxytocin injections (Mota-Rojas et al., 2005). Piglet hypoxia was not directly measured in the present experiment. However, piglet vitality at birth is an indicator of the severity of hypoxia and did not differ between feeding groups. Despite the difference in the number of stillborn piglets, the visually assessed average vitality of all born piglets at birth (scoring 0 for inert or stillborn piglets and 1–3 for piglets observed moving after birth) was not inferior in the SG group, possibly because of the overall low proportion of stillborn piglets in regard to the total number of piglets born. Another explanation for the greater occurrence of stillborn piglets could be a slight fetotoxic effect of *S. glaucophyllum*. The SG sows in the present experiment received approximately 6 µg/day of calcitriol, which is equivalent to 0.02 µg/kg live weight per day for an average sow weight of 300 kg. This dosage is 15-fold lower than the reported teratogenic dosage for rabbits (McClain et al., 1980), 10-fold below the acceptable dosage for broilers (Bachmann et al., 2013) and about 20-fold below the acceptable dosage for growing pigs (Schlegel et al., 2017). Yet, it may be that the fetotoxicity of *S. glaucophyllum* (or at least of calcitriol) is greater in pigs than in rabbits or that other constituents of *S. glaucophyllum* were (slightly) detrimental with respect to intrauterine death. To our knowledge, this is the first time the effect of sow supplementation with calcitriol on farrowing and progeny performance is reported. However, a comparison with results from studies on sows supplemented with calcidiol is possible. Supplementing sows with about 283 µg calcidiol/sow per day instead of 283 µg cholecalciferol doubled serum calcidiol level in sows but had no effect on the number of stillborn or liveborn piglets (Flohr et al., 2016). Finally, as the whole plant *S. glaucophyllum* was fed, it cannot be excluded that compounds other than calcitriol with biological effectiveness and fetotoxic influence were also present. For instance, the oestrogens and oestrogen binding receptors present in this plant (Milanesi et al., 2001) could have interfered with the sow's own hormones at parturition (Mueller et al., 2006).

Effect of *Solanum glaucophyllum* during nursing

Both feeding groups exhibited very similar litter performances during nursing in the present experiment (Table 5). Supplementing sows with *S. glaucophyllum* had no statistically significant effect on piglet growth and survival during nursing. This refutes our third hypothesis. Flohr et al. (2016) replaced 50 µg cholecalciferol with 50 µg calcidiol/kg sow feed (approximately 283 µg/sow per day) which doubled serum calcidiol level in sows but showed no effect on weaning weight of piglets

Table 5. Sows and litter characteristics obtained during nursing and at weaning in control or *Solanum glaucophyllum* (SG) groups

Items	Group				
	n	control	SG	SEM	*P*-value
Sows					
liveweight at weaning, kg	108	249	257	5.3	0.301
individual daily feed intake day 0 to weaning, kg/day	108	5.20	5.00	0.092	0.123
Piglet deaths during nursing, n/litter					
total	108	2.03	1.74	0.214	0.281
crushed	108	0.884	0.755	0.1672	0.556
underdeveloped	108	0.311	0.421	0.1064	0.375
other causes (e.g., polyarthritis, diarrhoea)	108	0.834	0.512	0.1472	0.065
Piglets at weaning, n/litter					
weaned	108	10.5	10.7	0.45	0.773
Piglet weight development					
weight at birth (liveborn), kg	108	1.51	1.57	0.037	0.243
weight at weaning, kg	108	8.91	8.86	0.166	0.833
average daily weight gain during nursing, g	108	274	274	5.9	0.988

SEM – standard error of the mean

having an average birth weight of 1.4 kg. Different from that, Upadhaya et al. (2021) supplemented sows with 50 μg calcidiol/kg diet on top on the 2000 IU (50 μg) cholecalciferol/kg diet (approximately 343 μg calcidiol and 343 μg cholecalciferol/sow per day) and reported 2% increase in blood calcidiol in sows and 4% better average daily gains of the suckling piglets. However, in the latter study the average birth weight of the piglets was also much lower with 1 kg only than in the present experiment with 1.54 kg. In addition, weaning was practiced already at 3 and not at 4 weeks of age as practiced in the present experiment. Again, the exposure to daylight during gestation could have positively influenced the vitamin D status of all sows in the present experiment and rendered the calcitriol supply from *S. glaucophyllum* ineffective. The greater occurrence of stillborn piglets in the SG group (Table 4) was not compensated by a significant reduction in piglet deaths during nursing (Table 5) although the difference approached significance ($P = 0.065$) for the category 'other causes'. A more detailed analysis of this category of deaths (by conducting autopsies for instance) could be of interest in future studies.

Conclusions

Supplementing sows with a natural source of active vitamin D via a preparation of *Solanum glaucophyllum* at the end of gestation and during lactation has no positive effect on farrowing duration, piglet survival and subsequent growth. The effects could be different in hyperprolific sows with greater stillborn rates and longer farrowing duration or with animals having no access to direct sunlight or with diets clearly deficient in vitamin D or calcium.

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Conflict of interest

The Authors declare that there is no conflict of interest.

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