Preventive Veterinary Medicine 208 (2022) 105762

Contents lists available at ScienceDirect

Preventive Veterinary Medicine

journal homepage: www.elsevier.com/locate/prevetmed

A field trial on the effect of cross-fostering and weaning age on daily gain and disease resilience in weaned pigs

Cecilie Liv Nielsen *, Mogens Agerbo Krogh, Jan Tind Sørensen, Hanne Kongsted

Department of Animal and Veterinary Sciences, Aarhus University, Blichers Alle 20, DK-8830 Tjele, Denmark

ARTICLE INFO

Keywords:
Cross-fostering
Antibiotic treatment
Diarrhoea
Weaners
Weight gain
Weaning age

ABSTRACT

Alternative management strategies that can increase disease resilience and reduce antibiotics in weaned pigs are needed. Our objective was to compare the effect of two nursing strategies and weaning ages on weight gain, clinical health and antibiotic treatments in weaned pigs not provided with medical zinc oxide in feed. A 2×2 factorial trial was conducted in three Danish commercial herds. Nursing strategies tested were "cross-fostering allowed" (CF) vs. "cross-fostering not allowed" (non-CF). Weaning ages tested were four (24–29 days) vs. five weeks (31–35 days). Pigs were followed from weaning until 33–35 days post-weaning. Herd staff made decisions on and registered antibiotic treatment, removal of pigs to sick pens and mortality. Pigs were weighed at weaning (N = 3139) and on day 33–35 post-weaning (N = 2898). Clinical examinations were carried out on day 4, 7 and 33–35 post-weaning. The effect of nursing strategy and weaning age on weight gain, clinical health and antibiotic treatments was analysed by mixed linear and logistic models. We found that pigs weaned at five weeks of age gained 103.6 g more daily compared to pigs weaned at four weeks during the 33–35 days post-weaning (<0.001). Weaning age affected diarrhoea prevalence, but the effect differed between herds. For pigs weaned at five weeks compared to four weeks of age, the odds for diarrhoea one week post-weaning was 0.7 times lower in one herd whereas the odds for diarrhoea were 2.0 and 1.4 times higher in the two other herds, respectively ($P < 0.05$). In all herds, we found fewer runted (OR=0.28, $P < 0.001$) and thin (OR=0.23, $P < 0.001$) pigs 33–35 days post-weaning in pigs weaned at five weeks of age compared to four weeks. Furthermore, in all herds, CF pigs were more likely to be removed to a sick pen or to die. In total, 5.9%, 13.6% and 64.9% of the studied weaned pigs were treated with antibiotics in the three herds, respectively. Treatment prevalence did not associate to weaning age or nursing strategy and did not in all cases appear to be linked with diarrhoea prevalence. The results indicate that a higher weaning age and less cross-fostering to some extend increase disease resilience post-weaning but herd specific factors interacted with the effects. The prevalence of pigs treated with antibiotics were herd dependent and may relate more to management decisions than to disease level.

1. Introduction

Preventing diarrhoea in weaned pigs (weaners) is an essential step in reducing antibiotics used for food producing animals (Smits et al., 2021). In addition, the recent ban of medical zinc oxide used to prevent post-weaning diarrhoea in the EU calls for alternative preventive strategies (European Commision, 2017; Gresse et al., 2017). A recent review on non-antibiotic approaches to avoid diarrhoea and antibiotics in weaners found that the majority of studies focus on feed additives and vaccines, which calls for studies on management interventions (Wisener et al., 2021). Hence, investigations on alternative management strategies that can increase disease resilience in weaners are needed. Disease resilience is defined as the ability to maintain or restore performance and health when exposed to challenges (Albers et al., 1987).

Weaning of suckling piglets is a challenge with respect to both nutritional, psychological, and environmental stressors (Heo et al., 2013). In the EU, pigs can be weaned from the age of 21 days (European Commision, 2008). Weaning is done abruptly, by moving pigs to specialized weaner facilities (Robert et al., 1999). This contrasts to the semi-natural situation where weaning is gradual and pigs start to eat solid feed around four weeks of age with continued milk feeding until 9–14 weeks of age (Newberry and Woodgush, 1985; Petersen et al.,

* Corresponding author.
E-mail addresses: cecilie.liv@anivet.au.dk (C.L. Nielsen), mogens.krogh@anivet.au.dk (M.A. Krogh), jantind.sorensen@anivet.au.dk (J.T. Sørensen), hanne.kongsted@anivet.au.dk (H. Kongsted).

https://doi.org/10.1016/j.prevetmed.2022.105762
Received 7 July 2022; Received in revised form 16 August 2022; Accepted 18 September 2022
Available online 21 September 2022
0167-5877/

1989).

A number of studies investigated the effect of weaning age on average daily gain (ADG) post-weaning. Colson et al. (2006) compared weaning at 21 and 28 days of age with sow rearing until 40 days of age. Weaners showed a sharp decrease in ADG post-weaning compared to sow reared piglets but the intensity and duration of the decrease were highest in pigs weaned at 21 days of age. Likewise, Huting et al. (2019) showed a decreased ADG in pigs weaned at 31.8 days of age compared to 37.5 days from weaning and until 15 weeks post-weaning. Studies on the effect of weaning age on diarrhoea in weaners show contradicting results on whether an increased weaning age is a useful management strategy to reduce diarrhoea (Ball and Aherne, 1987; Partanen et al., 2007; Wellock et al., 2008a). Moreover, in a large observational study, a higher weaning age was associated with a lower antibiotic usage from birth to slaughter (Postma et al., 2016). However, the scientific evidence on the association between weaning age and antibiotic usage post-weaning is scarce. Some studies have investigated the effect of weaning age on the immune response and gastro-intestinal development in pigs. Pigs weaned later have an improved immune response (Blecha et al., 1983; Bonnette et al., 1990) and a more mature gastro-intestinal system (Pluske et al., 2003). In addition, pigs weaned later may be more familiar with solid feed as they have a longer period before weaning to establish a regular solid feed intake (Pluske et al., 1997). This may increase the feed intake post-weaning thereby reducing post-weaning anorexia and gastro-intestinal inflammation (Lalles et al., 2007; Wellock et al., 2008b). Therefore, it is likely that an increased weaning age may increase disease resilience post-weaning and reduce the need for antibiotic treatment.

Cross-fostering (movement of piglets from their birth sow to a foster sow) is a common management intervention in sow herds in several countries using hyper-prolific sows (Baxter et al., 2013; Sorensen et al., 2016). It is performed due to the number of live-born piglets outnumbering the number of functional teats (Rutherford et al., 2013). We previously reported that cross-fostered litters have an increased number of antibiotic treatments during the suckling period and tended to have more clinical disease at weaning compared to litters nursed by their own mother and only with siblings (Nielsen et al., 2022). In another study investigating potential long lasting effects of cross-fostering Calderon Diaz et al. (2017) found that cross-fostered piglets have a greater risk of pericarditis and heart condemnations at slaughter. Until now, no studies have investigated the effect of cross-fostering on clinical health and antibiotic treatments in weaners.

The primary objective of this field trial was to compare the effect of two different nursing strategies (cross-fostering allowed vs. cross-fostering not allowed after initial litter equalisation) and two different weaning ages (four vs. five weeks) on clinical health, weight gain and antibiotic treatments in weaners. Our main focus in relation to clinical health was on absence of diarrhoea.

2. Materials and methods

2.1. Housing and management in the herds

The study was conducted as a field trial in three Danish commercial conventional pig herds from January 2018 to June 2020. Only herds willing not to use medical zinc oxide in the trial groups, not to vaccinate weaners against *Escherichia coli* and *Lawsonia intracellularis* (less than 20% of Danish weaners are vaccinated against those) and not to use antibiotic batch treatments in the trial pens were eligible to be included. Herd recruitment was done by contacting pig herds located within one hour drive from our research facility. Interested herds were included. To include three herds, 209 herds were contacted by phone out of which 139 herds were reached. The recruitment process was described in detail earlier (Nielsen et al., 2022).

In the three herds, sows were housed crated in farrowing pens with a covered creep area for the piglets. Sows were vaccinated according to routine vaccination schemes as described in detail earlier (Nielsen et al., 2022). All piglets were tail docked, injected with iron and toltrazuril and male piglets were castrated on day 3–4 post-partum. In Herd 2 and 3, piglets were provided milk replacer and in all the herds, piglets were

Table 1
Herd characteristics. Selected production parameters and antibiotic usage in weaners one year prior to the trial are presented. Facilities, vaccination protocols and feeding regimens during the trial are presented as well. Part of the table is reprinted from Nielsen et al. (2022).

	Herd 1	Herd 2	Herd 3
Trial period	Jan 2019 - Jun 2019	Aug 2019 - Dec 2019	Dec 2020 - Jun 2021
SPF-status[1]	SPF +myc	SPF +myc, +PRRS2	SPF +myc, +PRRS1, +Ap2
Production parameters			
Herd size (sows)	1011	1308	664
Piglets weaned/ sow/ year	33.1	29.9	35.6
Antibiotic usage weaners			
ADD[2]/ 100 pigs/ day	8.94 & 11.70[3]	9.64	7.24
Facilities			
Pen sizes (m^2)	11.6–13.1	8.4	5.4 or 8.4
Washing	Soap	Soap	Soap
Disinfection	–	Virkon S/ hydrated lime	Chloride
Temperature (C°)			
Start of trial	24.0	26.0	23.1
End of trial	18.0	19.5	19.5
Floor type	Completely slatted plastic	Mix of solid concrete and slatted cast iron	Mix of solid and drained concrete and slatted cast iron
Controlled-environment creeps	No	Yes	Yes
Vaccinations			
Porcine Circovirus Type 2	14 days post-weaning	10 days post-weaning	7 days post-weaning
M. hyopneumoniae	14 days post-weaning	At weaning	7 days post-weaning
PRRS[4]	No (declared free)	At weaning	No
A. pleuropneumoniae type 2	No	No	21 days post-weaning
Feeding			
Mix 1 (% crude protein)	Factory made. Day 1–14 (20.1)	Homemade. Day 1–10 (20.0)	Homemade. 7–10 kg (17.6)
Mix 2 (% crude protein)	Homemade. Day 1–14 (20.5)	Homemade. Day 10–35 (18.1–18.9)	Homemade. 10–16 kg (17.5)
Mix 3 (% crude protein)	Homemade. From day 21 (18.8)	–	Factory made. From 16 kg (17.7)
Feed provision	Feed automates In troughs two times/ day	In troughs two-three times/ day (mix 1) Feed automates (mix 2)	Only feed automates
Acidified water	No	First week: malic acid	No

[1]SPF: Specific Pathogen Free – Danish voluntary health and surveillance programme for seven infectious diseases: Porcine reproductive and respiratory syndrome virus (PRRS), *M. hyopneumoniae (myc), A. pleuropneumonia (Ap), Toxin producing P. multocida, B. hyodysenteriae, Sarcoptes scrabei* and *Haematopinus suis*. SPF +myc means that the herd is declared free from all SPF diseases except *M. hyopneumoniae.*
[2]ADD: Animal Daily Doses calculated by the authorities from national surveillance data. The number reflects the percentage of pigs treated daily during the weaner stage. The numbers show that herds had an antibiotic usage comparable to the national average (see DANMAP reports for reference www.danmap.org).
[3]Data from two different locations.
[4]PRRS: Porcine reproductive and respiratory syndrome virus.

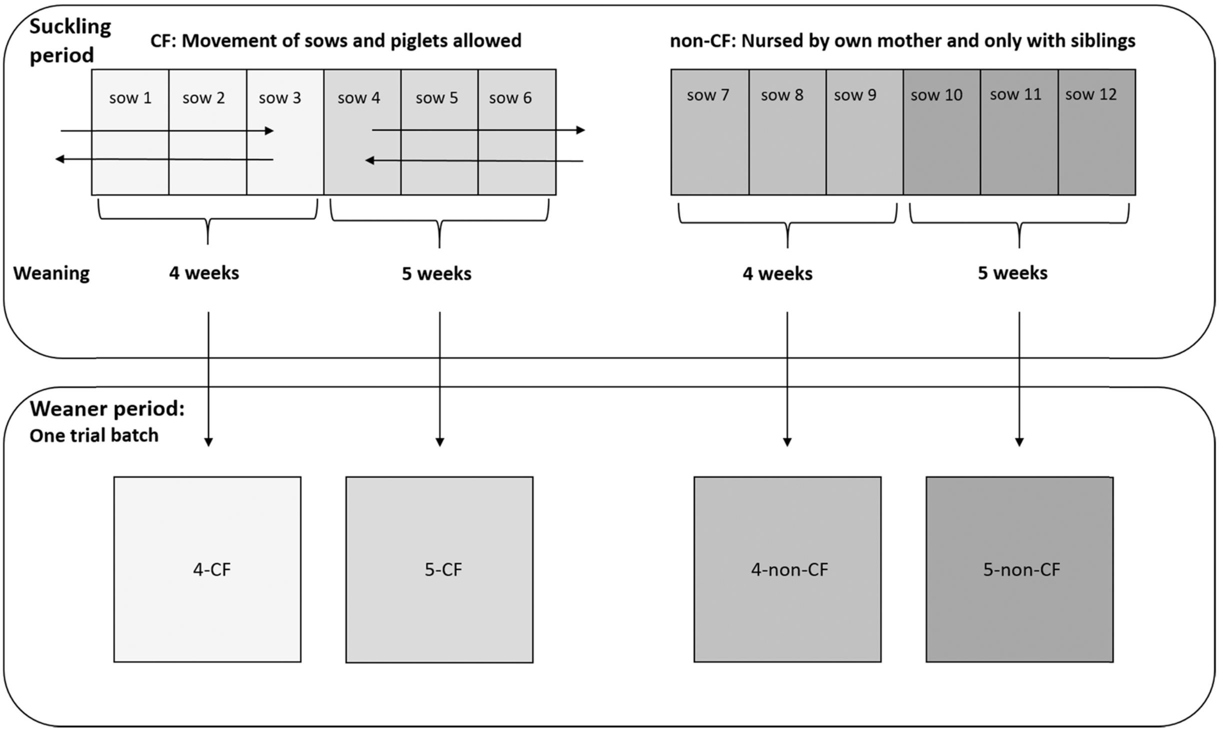

Fig. 1. Illustration of housing and pig movements in one trial batch during the suckling and weaner period for the four experimental groups. In CF litters, arrows indicate that sows and piglets are allowed to be moved to and from the litters during the suckling period.

offered creep feed from the age of one week until weaning.

Weaners were housed in sectioned stables with all-in all-out batch production. Details on facilities and management are given in Table 1. In Herd 1, the weaner stable used for the trial had been empty for three years prior to the trial.

2.2. Study design

The trial was a 2×2 factorial design with cross-fostering during the suckling period (cross-fostering allowed (CF) or cross-fostering not allowed (non-CF)) and weaning age (4 or 5 weeks) as factors. Thereby, four experimental groups were studied: CF pigs weaned at four weeks (4-CF), CF pigs weaned at five weeks (5-CF), non-CF pigs weaned at four weeks (4-non-CF) and non-CF pigs weaned at five weeks (5-non-CF). In CF litters, piglets were allowed to be taken out and put in and sows were allowed to be exchanged during the suckling period. In non-CF litters, piglets were nursed by their own mother and only with siblings during the suckling period and no movement was allowed after the initial litter equalisation.

In each trial batch, sows from two consecutive farrowing batches were included. This was done to enable simultaneous weaning of litters of both four and five weeks of age. Sows and their litters were allocated to one of the four experimental groups by systematic inclusion. Eight to twelve sows, which had farrowed during the past night, were included per trial batch (see Fig. 1). Nine trial batches were studied in each herd. In both CF and non-CF litters, a number of piglets equal to the sow's number of functional teats was ear tagged and included in the trial. Excessive piglets (the smallest and the biggest piglets in the litter) were moved to nurse sows and not followed in the trial. Farrowing pens under study were marked with a colour representing the experimental group assigned. At weaning, all piglets housed in these pens were considered part of the trial. Thus, in CF-litters, both piglets born in the pens and piglets moved to the pens during the suckling period were followed post-weaning in the trial. Piglets moved to the experimental pens in CF-litters were ear tagged before weaning and at weaning we registered whether a litter was nursed by the birth sow or a nurse sow. Detailed information regarding the inclusion and exclusion criteria for sows and piglets during the suckling period were reported previously (Nielsen et al., 2022).

All pigs in the same trial batch were weaned to the same weaner section to pens located within the same room (see Fig. 1). Each of the four experimental groups were weaned to one or two weaner pens depending on the size of the pens at hand. During the trial period, herd staff was allowed to separate pigs housed in one pen into two pens, in order to comply with legal requirements on stocking density. However, pigs from one experimental group were never mixed with other pigs. Herd staff was instructed to move pigs to sick pens if one or more of the following criteria were met: 1) runted (skinny pig with a relatively large head and a dull hair coat), 2) large hernia, 3) severe lameness, 4) bleeding ear-, tail- or flank lesion or 5) tail biting pigs. After being moved to sick pens, pigs were not followed further but registered as moved.

Antibiotic treatment was allowed during the whole trial period for diseased pigs. Herd staff was instructed to follow guidance from the farm veterinarian as usual. In addition, treatment of all pigs within a pen (from here: Pen level treatments) was allowed only if a minimum of three diarrhoeic droppings were seen in the pen.

Investigators and farmers were not blinded to interventions as the investigated management strategies are un-blinded by nature.

2.3. Data collection

Pigs were weighed on the day before weaning and again 33–35 days post-weaning. On day 4, 7 and 33–35 days post-weaning, presence of diarrhoea was evaluated both at individual- and pen level. At individual level, pigs were evaluated for 1) diarrhoea detected by digital rectal exploration, and 2) perianal staining, classified as wet faecal staining around and/or below anus. At digital rectal exploration, faeces adherent to the glove was evaluated visually and classified as diarrhoea if loose or watery in consistency as defined by Pedersen and Toft (2011). At pen level, the total number of diarrhoeic droppings in each pen was counted. One diarrhoeic dropping was defined as an individual faecal deposit with homogenous colour and consistency.

Table 2
Definitions of outcome variables and specification of analytical level in the models.

Outcomes	Definition	Level
Week 1 Diarrhoea	A pig with diarrhoea[1] and/or perianal staining[2] on day four and/or seven post-weaning.	Pig
Day 35 Diarrhoea	A pig with diarrhoea[1] and/or perianal staining[2] on the last examination (day 33–35 post-weaning).	Pig
Day 35 Runted	Dull hair coat and a large head compared to the size of the body.	Pig
Day 35 Thin	Hip and spine easily palpable.	Pig
Day 35 Umbilical outpouching	Swelling at the umbilicus.	Pig
Day 35 Joint swelling	Palpable swelling around a joint on one of the four legs.	Pig
Day 35 Tail lesion	Tail lesion and/or hyperaemia and swelling of tail.	Pig
Day 35 Ear lesions	Ear lesion of min. 1 cm^2.	Pig
Average daily gain	Average daily gain from weaning until 33–35 days post-weaning.	Pig
Removed	Pigs removed from the trial between weaning and the end of the trial. Pigs were either removed because they died or were moved to a sick pen.	Pig
Week 1 Droppings	Average of number of diarrhoeic droppings on day four and seven post-weaning.	Pen
Day 35 Droppings	Number of diarrhoeic droppings on the last examination (day 33-35 post-weaning).	Pen
Day 35 Sneezes	Number of sneezes during 5 minutes.	Pen
Antibiotic treatment	Total number of treated pigs divided by the average number of pigs in the pen during the trial period.	Pen

[1]Diarrhoea was defined as loose or watery faeces as defined by Pedersen and Toft (2011) and was evaluated by digital rectal exploration using a plastic glove.
[2]Perianal staining was defined as wet faecal staining around and/or below the anus.

Individual clinical examinations were made on day 33–35 post-weaning depending on the practical situation. We registered the following conditions: thin, runted, umbilical outpouching, joint swelling, tail lesion or ear lesion (see Table 2 for details). In addition, the number of sneezes on pen level was counted during a five minute period for each pen while standing right outside the pen observing the pigs. Trained and calibrated investigators performed all examinations and observations.

Herd staff recorded data on deaths, movements to sick pens and antibiotic treatment on an individual pig level from weaning and until day 33–35 post-weaning. In the analyses, an antibiotic treatment was defined as a treatment course of one or more days for the same indication.

2.4. Statistical analyses

The effect of nursing strategy (CF vs. non-CF) and weaning age (4 vs. 5 weeks) on diarrhoea, clinical disease, antibiotic treatment and removed pigs was analysed by mixed logistic regression models. The effect of nursing strategy (CF vs. non-CF) and weaning age (4 vs. 5 weeks) on diarrhoeic droppings, sneezes and ADG was analysed by mixed linear regression models. Definitions of outcomes and level of analysis (pig- or pen level) are specified in Table 2.

For the pen measurements, data was aggregated as the average between the two pens in cases where pigs from the same trial batch and experimental group were housed in two weaner pens.

All outcomes were analysed for the three herds in a single model with the exception of antibiotic treatments which was analysed separately for each herd as antibiotic treatment was highly correlated with herd.

Herd was included as a fixed effect in the models and batch was included as a random effect in the models to account for clustering within batches. Two-way interactions between weaning age, nursing strategy and herd were tested in all the full models one by one. Only significant interactions were kept in the models. Effects were considered significant at a 5% significance level. Model control was performed with Pearson residuals vs. fitted and normal Q-Q plots. Data analysis was performed in R version 3.6.1. (RCoreTeam, 2019).

Table 3
Descriptive data on number of weaner pens and pigs in the trial. Data are grouped for weaning ages (4 vs. 5 weeks), nursing strategies (CF: cross-fostering allowed vs. non-CF: no cross-fostering after initial litter equalisation) and herds (1–3).

Weaning age	4		5		Herd			Total
Nursing strategy	CF	non-CF	CF	non-CF	1	2	3	
Weaner pens[1]	27	26	26	27	36	36	34	106
Pigs								
Weaned[2]	819	729	835	756	1224	1308	607	3139
Removed								
Dead	18	7	13	8	2	25	19	46
Moved to sick pen	28	18	34	17	45	25	27	97
Unclassified[3]	30	25	24	19	17	53	28	98
Day 35 post-weaning	743	679	764	712	1160	1205	533	2898

[1]In the analysis, data analysed at pen level were aggregated for experimental groups belonging to the same trial batch in cases where pigs were separated into two weaner pens.
[2]Four pigs were excluded from the dataset prior to analysis because of an unlikely long period of 41–44 days from weaning and until the last examination.
[3]Pigs that were not present in the experimental pens at the last examination and not registered as either dead or moved to sick pen during the trial period.

2.5. Ethical permission

The trial did not require ethical permission according to University policy, since only common production strategies were used and no invasive procedures were performed.

3. Results

3.1. Descriptive statistics

In the trial, 3139 pigs were weaned and followed in the weaner section. Of these, 2898 pigs were followed until 33–35 days post-weaning and 241 pigs were removed from the trial. A total of 98 pigs were not in the weaner pen at the last examination but not registered as dead or moved to sick pens, thus designated “Unclassified”. Half of these pigs (N = 47) were not in the pens on day 4 post-weaning, thus they were either not weaned correctly or were moved to sick pens or dead very early. Of the 51 pigs examined on day 4, 43 of these were still in the pens at the examination on day 7 post-weaning. Unclassified pigs were more common in the group weaned at four weeks of age (3.6%) compared to five weeks (2.7%). Detailed information on the number of pigs in the trial is shown in Table 3.

The extend of cross fostering varied considerably between the three herds with approximately 60% of the CF litters cross-fostered in Herd 1 and 17% and 8% cross-fostered in Herd 2 and 3, respectively. Exact weaning ages, weaning weights, stocking density and trial period also differed between herds. Details on these elements are given in Table 4.

Table 4
Descriptive statistics on performed cross-fostering, weaning age and weight, stocking density and trial period in the three herds. Data were grouped for weaning ages (4 vs. 5 weeks) and nursing strategies (CF: cross-fostering allowed vs. non-CF: no cross-fostering after initial litter equalisation) for each of the three herds.

	Herd 1				Herd 2				Herd 3			
Weaning age	4		5		4		5		4		5	
Nursing strategy	CF	non-CF	CF	non-CF	CF	non-CF	CF	non-CF	CF	non-CF	CF	non-CF
Suckling period												
Performed cross-fostering (% litters)	63.0	–	53.8	–	14.8	–	18.5	–	8.3	–	7.1	–
Mean weaning age (days)	24	24	31	31	25	25	32	32	28	29	35	35
Mean weaning weight (kg)	5.9	6.3	7.6	7.4	6.8	6.9	9.3	9.0	8.1	8.2	9.9	9.9
Weaner section												
Mean stocking density (pigs/m^2)[1]	2.8	2.6	2.8	2.6	4.7	3.9	4.5	3.9	2.7	2.9	4.2	3.3
Mean trial period (days)	35	35	35	35	33	33	33	33	33	33	33	33

[1]Stocking density in the weaner section in week one post-weaning.

Table 5
Descriptive data on diarrhoea and diarrhoeic droppings in week one post-weaning and average daily gain (ADG) and antibiotic treatment during the trial. Data were grouped for weaning ages (4 vs. 5 weeks) and nursing strategies (CF: cross-fostering allowed vs. non-CF: no cross-fostering after initial litter equalisation) for each of the three herds.

	Herd 1				Herd 2				Herd 3			
Weaning age	4		5		4		5		4		5	
Nursing strategy	CF	non-CF	CF	non-CF	CF	non-CF	CF	non-CF	CF	non-CF	CF	non-CF
Week 1 Diarrhoea (%)	20.4	13.9	14.0	11.7	71.5	75.1	84.0	83.8	72.7	74.2	75.5	83.0
Week 1 Droppings (median (N))	4.0	1.5	1.0	2.0	4.0	5.0	8.5	6.0	5.5	4.3	8.0	6.0
ADG (mean (g))[1]	322	322	424	411	231	243	336	352	341	372	452	488
Antibiotic treatment (%)[2]	5.8	4.8	10.5	2.4	12.7	15.2	11.5	15.5	53.8	69.3	58.6	77.2

[1]Data from 36 pigs were not included in the ADG results as weight data was missing.
[2]Prevalence of pigs treated with antibiotics during the trial.

The ADG as well as the diarrhoea prevalence and the number of diarrhoeic droppings in pens in week one post-weaning varied across experimental groups and herds. In Herd 1, below 20% of the pigs had diarrhoea in week one post-weaning compared to more than three quarters in the two other herds. Details are given in Table 5. The ADG was numerically higher in Herd 3 and lowest in Herd 2 for both of the weaning ages. Across experimental groups, 5.9%, 13.6%, and 64.9% of the pigs were treated with antibiotics during the trial period in Herd 1, 2 and 3, respectively.

The herds used different treatment strategies. Herd 1 did not use pen level treatments during the whole trial period, whereas 4 pens (11% of pens in the trial) and 17 pens (50% of pens in the trial) were treated at pen level in Herd 2 and 3, respectively. All pen level treatments were applied within the first two weeks post-weaning and all of them, except one treatment against leg problems, were directed against diarrhoea. Individual antibiotic treatments were administered 90, 19 and 176 in Herd 1, 2 and 3, respectively. The majority of individual treatments were given within three weeks post-weaning. The main causes for individual treatments were diarrhoea and leg problems. Within Herd 1, 2 and 3, 28%, 58% and 69% of individual treatments, respectively, were provided against diarrhoea. In 49%, 42% and 14% cases of individual treatments in Herd 1, 2 and 3, treatments were provided against leg problems. In Herd 1, 11% of individual treatments were administered to treat infections caused by an outbreak of tail biting in one trial batch. In 13% of individual treatments in Herd 3 the cause of treatment was registered as “Small pig”.

The prevalence of clinical disease on pig level and the number of diarrhoeic droppings and sneezes at pen level at the end of the trial 33–35 days post-weaning are shown in Table 6.

Table 6
Prevalence of individual clinical disease and number of diarrhoeic droppings and sneezes on pen level at the end of the trial. Data were grouped for weaning ages (4 vs. 5 weeks), nursing strategies (CF: cross-fostering allowed vs. non-CF: no cross-fostering after initial litter equalisation) and herds (1–3).

Weaning age	4		5		Herd		
Nursing strategy	CF	non-CF	CF	non-CF	1	2	3
Day 35 Diarrhoea (%)	14.0	14.1	15.6	14.9	12.0	7.6	36.4
Day 35 Droppings (median (N))	2	2	2	1	1	1	4
Day 35 Thin (%)	8.3	5.6	1.7	1.8	2.1	6.6	4.1
Day 35 Runted (%)	5.1	4.0	1.3	1.4	4.0	2.1	2.6
Day 35 Umbilical hernia (%)	1.2	2.8	2.5	2.4	2.0	2.0	3.2
Day 35 Joint swelling (%)	3.2	3.2	4.3	3.2	3.0	3.7	4.3
Day 35 Tail lesions (%)	7.7	7.4	10.3	9.1	10.3	5.6	11.3
Day 35 Ear lesions (%)	39.0	28.9	45.4	37.6	53.7	32.6	15.9
Day 35 Sneezes[1] (median (N))	3	3	2	2	3	3	1

[1] Median number of sneezes per 5 min on pen level.

3.2. Analytical statistics

Weaning age affected ADG as well as the prevalence of runted and thin pigs and pigs with tail lesions. Pigs weaned at five weeks of age gained 103.6 g more per day compared to pigs weaned at four weeks ($P < 0.001$). Significant ADG model estimates are presented in Table 7 together with significant model estimates from diarrhoeic droppings and sneeze models. Model details are provided in Table S1.

The odds for being thin and runted 33–35 days post-weaning were 0.23 and 0.28 times smaller, respectively, for pigs weaned at five weeks of age compared to pigs weaned at four weeks ($P < 0.001$). In contrast, the odds for tail lesions were increased by 1.34 for pigs weaned at five weeks of age compared to four weeks ($P = 0.030$). Model results on clinical disease at pig level, antibiotic treatment and removal from trial are presented with significant odds ratios (OR) and *P*-values in Table 8. Details on estimates, OR, standard errors, exact *P*-values and batch variance are provided in Table S2.

Table 7
Parameter estimates (Est.) and *P*-values (P) for mixed linear regression models. The outcomes were: Number of diarrhoeic droppings in week one (Week 1 Droppings) and at the end of the trial (Day 35 Droppings) on pen level, number of sneezes during 5 min on pen level at the end of the trial and pig average daily gain from weaning and until the end of the trial. The effect of nursing strategy (CF: cross-fostering allowed vs. non-CF: no cross-fostering after initial litter equalisation), weaning age (4 vs. 5 weeks) and herd (Herd 1–3) was analysed in the models.

Models	Intercept	Nursing strategy		Weaning age		Herd			Nursing strategy x herd			Weaning age x herd		
		CF		5 weeks		Herd 2	Herd 3		CF x Herd 2	CF x Herd 3		5 weeks x Herd 2	5 weeks x Herd 3	
	Est.	Est.	P[2]	Est.	P	Est.	Est.	P	Est.	Est.	P	Est.	Est.	P
Week 1 Droppings	2.16		NS		NS	2.31	3.91	***			*not incl.*[3]	2.72	2.54	.
Day 35 Droppings	0.61		NS		NS	0.31	1.86	**			*not incl.*			*not incl.*
Day 35 Sneezes	4.77		NS		NS	0.39	-2.04	.			*not incl.*			*not incl.*
Average daily gain[1] (g)	313.78		NS	103.64	***	-67.93	66.44	***	-21.75	-40.70	***			*not incl.*

[1]36 pigs were not included in the ADG analysis as weight data was missing for those pigs.
[2]NS: not significant, * **P < 0.001, * *P < 0.01, *P < 0.05,. P < 0.10
[3]*Not included.* Only significant interactions were included in the models.

We found an interaction between weaning age and herd on Week 1 Diarrhoea. In Herd 1, the odds were 0.7 times smaller for diarrhoea for pigs weaned at five weeks of age compared to pigs weaned at four weeks (P = 0.024). Opposite, pigs weaned at five weeks of age had more diarrhoea than pigs weaned at four weeks of age in Herd 2 (OR=1.97) and 3 (OR=1.42) during week one post-weaning (P < 0.001) (see Table 8). We found a similar pattern with respect to pen droppings during week one, however only with a statistical tendency (P = 0.056).

We saw an effect of nursing strategy on the odds for being removed from the trial. Removed pigs include dead pigs, pigs moved to sick pens and unclassified pigs. CF pigs were more likely to be removed (OR=2.9) during the trial compared to non-CF pigs (P < 0.001) (see Table 8). In Herd 2 and 3, the ADG was 21.8 g and 40.7 g lower, respectively, in CF pigs compared to non-CF pigs whereas it was 7.6 g higher in Herd 1. In Herd 3, we saw an effect of nursing strategy on antibiotic treatment with fewer CF pigs treated with antibiotics (OR=0.39, P = 0.006). Moreover, we saw some interactions in the antibiotic treatment models. In Herd 1, significantly more CF pigs weaned at five weeks of age were treated with antibiotics compared to non-CF pigs weaned at four weeks. In Herd 3, CF pigs weaned at five weeks of age were treated less (OR=0.26) compared to non-CF pigs weaned at four weeks. Opposite non-CF pigs weaned at five weeks of age were treated more compared to non-CF pigs weaned at four weeks of age (OR=7.12).

We saw an interaction between nursing strategy and herd on Week 1 Diarrhoea. In Herd 1, the odds for diarrhoea in CF pigs was 1.4 times higher compared to non-CF pigs (P = 0.029). Contrary, CF pigs had less diarrhoea in Herd 2 (OR=0.89) and 3 (OR=0.75) in week one post-weaning (P = 0.026) (see Table 8).

We saw a difference between the herds on several of the outcomes. Compared to Herd 1, the ADG in Herd 2 and 3 was 67.9 g lower and 66.4 g higher, respectively (P < 0.001) (see Table 7). Moreover, we saw more thin pigs but fewer pigs with ear lesions at the end of the trial in Herd 2 and 3 compared to Herd 1. In Herd 2 and 3 more pigs were removed from the trial compared to Herd 1. We saw a large herd effect on pigs with diarrhoea in week one post-weaning with 19 times higher odds for diarrhoea in Herd 2 and 3 compared to Herd 1 (see Table 8). Likewise, there was 2.3 and 3.9 more diarrhoea droppings on pen level in week one post-weaning in Herd 2 and 3, respectively, compared to Herd 1 (see Table 7). In addition, we saw a herd effect on pigs with diarrhoea at the end of the trial with significantly less diarrhoea in Herd 2 (OR=0.71) and significantly more diarrhoea in Herd 3 (OR=5.58) compared to Herd 1 (P < 0.001).

4. Discussion

Our objective was to evaluate the effect of nursing and weaning age strategies on resilience in weaners, measured as clinical health, ADG and antibiotic treatments. We had in particular focus on the effect on diarrhoea, as this is the most common reason for antibiotic treatment in weaners.

We saw a large difference in the level of performed cross-fostering between the herds with a high level in Herd 1 and a very low level in Herd 3. Thus, the herds had different ways of applying the allowed cross-fostering strategy, which is likely to reflect the situation in practice. Moreover, we saw large differences in disease occurrence and antibiotic treatment intensities between herds. Thus, apart from differences in management strategies the herds also experienced different disease challenges and applied different treatment strategies. Thereby, the trial has the possibility to give an impression of how the investigated management strategies may perform under different conditions in different herds.

Overall, we saw that weaning age was associated with ADG, diarrhoea in week one post-weaning and with body condition five weeks post-weaning. We also found that nursing strategy had an effect on the risk of removal from the trial. In the following sections, we discuss possible explanations for these associations.

We found that the prevalence of diarrhoea during week one post-weaning was associated with weaning age. However, the direction of the association was herd dependent. In Herd 1, later weaning was protective for diarrhoea whereas in Herd 2 and 3, later weaning was associated with a higher prevalence of diarrhoea. Previous studies, investigating the effect of weaning between three and six weeks of age on diarrhoea occurrence post-weaning, show contradicting results. Ball and Aherne (1987) saw a higher diarrhoea score and diarrhoea incidence in pigs weaned at four weeks of age compared to three weeks (N = 128). Likewise, Wellock et al. (2008a) found a higher prevalence of diarrhoea post-weaning in pigs weaned at six weeks of age compared to four weeks (N = 104). However, weaning at six weeks of age was protective for diarrhoea when pigs were challenged with an enterotoxigenic *Escherichia coli* in the same experiment. Partanen et al. (2007) found no effect of weaning age (26 vs. 36 days of age) on the number of diarrhoea days or the diarrhoea severity post-weaning (N = 240), whereas Ming et al. (2021) found a decreased diarrhoea incidence post-weaning in pigs weaned at four weeks of age compared to three weeks (N = 96). Callesen et al. (2007) investigated the effect of weaning at 27 and 33 days of age on faecal score during the first two weeks post-weaning using four different diets. Pigs weaned on day 27 had equal fecal scores irrespective of diet. However, pigs weaned on day 33 had either higher, lower or equal fecal scores depending on their diet compared to pigs weaned at 27 days of age. Thus, the herd interaction we saw in the current trial, may be explained by differences in diet. All the mentioned previous studies were conducted in only one herd each, thus they do not seem to have an overall generalizability.

We found increased odds for being thin or runted five weeks post-

Table 8
Odds ratios (OR) and *P*-values (P) for mixed logistic models. The outcomes were diarrhoea in week one and at the end of the trial, other clinical measures at the end of the trial and antibiotic treatment and removal from trial during the trial period. Antibiotic treatment was analysed separately for the three herds whereas the other outcomes were analysed jointly in one model. The effect of nursing strategy (CF: cross-fostering allowed vs. non-CF: no cross-fostering after initial litter equalisation), weaning age (4 vs. 5 weeks) and herd (Herd 1–3) was analysed in the models.

Models[1]	Nursing strategy		Weaning age		Herd			Nursing strategy x weaning age		Nursing strategy x herd			Weaning age x herd		
	CF		5 weeks		Herd 2	Herd 3		CF x 5 weeks		CF x Herd 2	CF x Herd 3		5 weeks x Herd 2	5 weeks x Herd 3	
	OR	P[3]	OR	P	OR	OR	P	OR	P	OR	OR	P	OR	OR	P
Week 1 Diarrhoea	1.43[3]	*	0.69[4]	*	19.11	19.09	***		*not incl.*[5]	0.89	0.75	*	1.97	1.42	***
Day 35 Diarrhoea		NS		NS	0.71	5.58	***		*not incl.*			*not incl.*			*not incl.*
Day 35 Thin		NS	0.23	***	4.29	2.50	**		*not incl.*			*not incl.*			*not incl.*
Day 35 Runted		NS	0.28	***			NS		*not incl.*			*not incl.*			*not incl.*
Day 35 Umbilical hernia		NS		NS			NS		*not incl.*			*not incl.*			*not incl.*
Day 35 Tail lesions		NS	1.34	*			NS		*not incl.*			*not incl.*			*not incl.*
Day 35 Ear lesions		NS		NS	0.21	0.03	***		*not incl.*	2.09	2.01	***	1.36	4.50	***
Herd 1 Antibiotic treatment		NS	0.46	.	–	–	–	4.41[4]	**	–	–	–	–	–	–
Herd 2 Antibiotic treatment		NS		NS	–	–	–		*not incl.*	–	–	–	–	–	–
Herd 3 Antibiotic treatment	0.39	**	7.12	***	–	–	–	0.26	**	–	–	–	–	–	–
Removed[2]	2.9[7]	***		NS	3.0	4.9	***			1.12	1.12	*			*not incl.*

[1]Results from model on joint swelling is not presented as the model failed to converge.
[2]Removed from trial during trial period. Removed pigs either died, were moved to sick pen or were missing at examination for unknown reasons.
[3]NS: not significant, ***P < 0.001, **P < 0.01, *P < 0.05,. P < 0.10
[4]Likely explained by one outbreak of tail biting.
[5]*Not included.* Only significant interactions were included in the models.

weaning for pigs weaned at four weeks of age relative to pigs weaned at five weeks. Evaluation of poor body condition score is a clinical measure that indicates disease or discomfort over a longer period of time (Jackson and Cockcroft, 2005). This contrasts to the examinations for diarrhoea, which were only snapshots of perhaps brief clinical conditions. The lower risk of becoming thin or runted in pigs weaned at five weeks of age, suggests that pigs weaned later may be more disease resilient. Therefore, better suited for coping with stressors associated with weaning.

We saw an effect of nursing strategy on the number of removed pigs. The number of removed pigs were higher for CF pigs compared to non-CF pigs, which seems to indicate a reduced resilience in CF pigs compared to non-CF pigs. Calderon Diaz et al. (2017) documented long term negative health effects of cross-fostering with a higher risk of pericarditis and heart condemnations at slaughter. The effect of cross-fostering on diarrhoea, other clinical diseases, ADG and antibiotic treatments was inconsistent in the current trial. This may partly be explained by the low level of cross-fostering in our trial.

In relation to antibiotic treatment we saw herd specific associations. In Herd 1, one outbreak of tail biting caused a high number of treatments in CF pigs weaned at five weeks of age. In Herd 3, which was also the herd with most treatments, we saw some significant associations. In this herd, more pigs weaned at five weeks of age were treated compared to pigs weaned at four weeks. This is likely explained by the higher diarrhoea prevalence observed in those pigs. Likewise, in Herd 3, CF pigs were treated less. This may be explained by more CF pigs being removed during the trial.

Across herds, the ADG from weaning and until five weeks post-weaning was 104 g higher in pigs weaned at five weeks of age compared to pigs weaned at four weeks. Two other studies had similar results. Callesen et al. (2007) found that pigs weaned at 33 days of age had an increased ADG of 50 g compared to pigs weaned at 27 days of age during the first fourteen days post-weaning. Likewise, Leliveld et al. (2013) found an increased ADG of 74 g, an increased average daily feed intake and an increased feed conversion rate from weaning to 10 weeks of age for pigs weaned at five weeks of age compared to four weeks of age. However, at 10 weeks of age, Leliveld et al. (2013) found no difference in the body weight for pigs weaned at four and five weeks of age. This was supported by results from Partanen et al. (2007) who also did not find any difference in the body weight at 60 days of age in pigs weaned at 26 days of age compared to 36 days of age. In contradiction to these findings, Faccin et al. (2020) found a significant effect of weaning age on body weight on day 42 post-weaning with pigs weaned at 24.5 days of age weighing 5.5 kg more compared to pigs weaned at 18.5 days. In our trial, we did not weigh the pigs weaned at different ages at the same age. Therefore, in our case, we cannot draw conclusions on whether the increased ADG also would be reflected in an increased body weight at a certain age or not.

In the current study, we saw large herd differences on diarrhoea prevalence during week one post-weaning, from below 20% of pigs to more than 75% of pigs. Likewise, Morsing et al. (2022) found a diarrhoea prevalence within herds between 3.9% and 62.2% during the first seven days post-weaning in weaners not provided antibiotics and medical zinc oxide. Hence, herd prevalence of diarrhoea post-weaning seem very herd dependent. Moreover, it is important to notice that diarrhoea prevalence in herds not providing medical zinc oxide may be increased compared to herds receiving medical zinc oxide under the same management conditions as demonstrated by others (Keimer et al., 2022). One possible explanation for the lower diarrhoea prevalence in Herd 1 is that no weaners had been housed in the stable used for the trial for three years prior to the trial. Practical experiences from farmers and veterinarians show that leaving stables empty for longer periods decreases the pathogen load and thereby decrease the disease levels in animals later introduced to the stables. Moreover, the lower stocking density in Herd 1 may also explain the lower diarrhoea prevalence, as supported by results from Madec et al. (1998) indicating a positive effect of low stocking density on post-weaning digestive disorders. In Herd 2 and 3, pigs were supplemented with milk-replacer during the suckling period which has been associated with an increased feed intake post-weaning (Josa et al., 2015). An increased feed intake post-weaning is likely to increase the level of diarrhoea as shown by Madec et al. (1998). However, others showed that post-weaning anorexia causes intestinal inflammation and thereby increases the risk of diarrhoea (Madec et al., 1998; McCracken et al., 1999). Therefore, the association between feed intake and diarrhoea is complex and delicate. The factors above are all possible explanations for the differences seen in the diarrhoea prevalence between the herds but other factors like e.g. differences in quantity and type of diarrhoea causing pathogens may also play a role. Five weeks post-weaning, the diarrhoea prevalence was 12.0%, 7.6% and 36.4% in Herd 1, 2 and 3, respectively. There is no obvious explanation for these differences but different pathogen profiles may partly account for those differences. Anyway, the differences reflect the variable herd challenges between herds which you would also expect in real practical situations.

The prevalence of weaners treated with antibiotics was very different between the three herds with a high treatment prevalence in Herd 3 and a low treatment prevalence in Herd 1 and 2. We found no clear association between the number of antibiotic treatments and the diarrhoea prevalence within herds. Herd 2 and 3 had a comparable high diarrhoea prevalence in week one post-weaning but a large difference in the prevalence of pigs treated with antibiotics. This point towards antibiotic usage being highly dependent on the individual herd treatment strategies and not necessarily a valid indicator for the disease level in the herd. Previous research has shown that antibiotic usage is associated to farmer's perceptions and behaviors toward antibiotic usage (Coyne et al., 2014; Visschers et al., 2015). Furthermore, the distribution between single animal treatments and pen level treatments were very different between the three herds. The study design allowed pen level treatments if a minimum of three diarrhoea droppings were observed on the pen floor. Thus, some of the antibiotic treatments were provided to pigs not having diarrhoea. Therefore, antibiotic treatment is not always a good proxy for disease.

From our results it seems that differences in diarrhoea and treatment prevalence between the three herds also relate to some of the other investigated herd outcomes differences. The ADG was significantly different between the three herds. The ADG was lower in Herd 2 and higher in Herd 3 compared to Herd 1. Those differences may be explained by several factors. The diarrhoea prevalence was significantly higher in Herd 2 and 3, compared to Herd 1. This may influence the ADG negatively (Madec et al., 1998). However, Herd 3 had a high level of treatment and pigs in this herd were heavier at weaning. It is well documented that antibiotic treatment increases weight gain (Cromwell, 2002) and thus there could be a link between a higher usage of antibiotics and a higher ADG in Herd 3 compared to Herd 2. Pigs in Herd 3, however, also had a higher weaning weight and it was previously shown that weaning weight and ADG post-weaning is positively correlated (Leliveld et al., 2013). The odds for being thin in Herd 2 and 3 were higher compared to Herd 1. This corresponds well with the increased prevalence of diarrhoea in Herd 2 and 3, as diarrhoea decreases the ADG (Madec et al., 1998). The odds for being removed were higher in Herd 2 and 3 compared to Herd 1. This may also to some extend be explained by the higher prevalence of diarrhoea in those two herds.

5. Conclusions

In this study, we saw some indications that reduced cross-fostering in the nursing period and an increased weaning age may increase pig disease resilience post-weaning. Thus, in all three study herds we found that weaners nursed by their own mother and only with siblings during the nursing period were less likely to die and to be moved to sick pens. Moreover, we saw fever runted and thin pigs in pigs weaned later and pigs weaned later had an increased ADG from weaning and until five weeks post-weaning. However, the effect of later weaning on diarrhoea in week one post-weaning showed contradicting results across herds.

Our results suggest that management strategies using less cross fostering and later weaning may be useful in production herds as approaches to increase disease resilience in pigs post-weaning. Such approaches are highly needed to enable weaning of pigs without medical zinc oxide and only with a minimum of antibiotic treatments. However, a non cross-fostering strategy has some limitations in the current production system. Having a high number of live-born piglets and a limited nursing capacity in sows, applying such a practice is not straightforward. Thus, new breeding strategies or more efficient supplemental feeding strategies to enable raising of piglets by their own mother seems relevant. Furthermore, an increased weaning age will reduce herd productivity as the number of yearly farrowings per sow will be reduced. However, those limitations may be reconsidered to preserve sustainability of future pig production systems.

Funding

This work was funded by the Danish Veterinary and Food Administration as part of The Veterinary III Agreement.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.prevetmed.2022.105762.

References

Albers, G.A.A., Gray, G.D., Piper, L.R., Barker, J.S.F., Lejambre, L.F., Barger, I.A., 1987. The genetics of resistance and resilience to haemonchus-contortus infection in young merino sheep. Int. J. Parasit. 17, 1355–1363.
Ball, R.O., Aherne, F.X., 1987. Influence of dietary nutrient density, level of feed-intake and weaning age on young pigs. II. Apparent nutrient digestibility and incidence and severity of diarrhea. Can. J. Anim. Sci. 67, 1105–1115.
Baxter, E.M., Rutherford, K.M.D., D'Eath, R.B., Arnott, G., Turner, S.P., Sandoe, P., Moustsen, V.A., Thorup, F., Edwards, S.A., Lawrence, A.B., 2013. The welfare implications of large litter size in the domestic pig II: management factors. Anim. Welf. 22, 219–238.
Blecha, F., Pollmann, D.S., Nichols, D.A., 1983. Weaning pigs at an early age decreases cellular-immunity. J. Anim. Sci. 56, 396–400.
Bonnette, E.D., Kornegay, E.T., Lindemann, M.D., Notter, D.R., 1990. Influence of 2 supplemental vitamin-E levels and weaning age on performance, humaral antibody-production and serum cortisol-levels of pigs. J. Anim. Sci. 68, 1346–1353.
Calderon Diaz, J.A., Boyle, L.A., Diana, A., Leonard, F.C., Moriarty, J.P., McElroy, M.C., McGettrick, S., Kelliher, D., Garcia Manzanilla, E., 2017. Early life indicators predict mortality, illness, reduced welfare and carcass characteristics in finisher pigs. Prev. Vet. Med 146, 94–102.
Callesen, J., Halas, D., Thorup, F., Knudsen, K.E.B., Kim, J.C., Mullan, B.P., Hampson, D. J., Wilson, R.H., Pluske, J.R., 2007. The effects of weaning age, diet composition, and categorisation of creep feed intake by piglets on diarrhoea and performance after weaning. Livest. Sci. 108, 120–123.
Colson, V., Orgeur, P., Foury, A., Mormède, P., 2006. Consequences of weaning piglets at 21 and 28 days on growth, behaviour and hormonal responses. Appl. Anim. Behav. Sci. 98, 70–88.
Coyne, L.A., Pinchbeck, G.L., Williams, N.J., Smith, R.F., Dawson, S., Pearson, R.B., Latham, S.M., 2014. Understanding antimicrobial use and prescribing behaviours by pig veterinary surgeons and farmers: a qualitative study. Vet. Rec. 175, 593.
Cromwell, G.L., 2002. Why and how antibiotics are used in swine production. Anim. Biotechnol. 13, 7–27.
European Commision, 2008, Council Directive 2008/120/EC of 18 December 2008 laying down minimum standards for the protection of pigs.
European Commision, 2017, Comission Implementing Decision of 26.6.2017 concerning, in the framework of Article 35 of Directive 2001/82/EC of the European Parliament and of the Council, the marketing authorisations for veterianry medical products containing "zinc oxide" to be administered orally for food producing species.
Faccin, J.E.G., Tokach, M.D., Allerson, M.W., Woodworth, J.C., DeRouchey, J.M., Dritz, S.S., Bortolozzo, F.P., Goodband, R.D., 2020. Relationship between weaning age and antibiotic usage on pig growth performance and mortality. J. Anim. Sci. 98.
Gresse, R., Chaucheyras-Durand, F., Fleury, M.A., Van de Wiele, T., Forani, E., Blanquet-Diot, S., 2017. Gut microbiota dysbiosis in postweaning piglets: Understanding the keys to health. Trends Microbiol 25, 851–873.
Heo, J.M., Opapeju, F.O., Pluske, J.R., Kim, J.C., Hampson, D.J., Nyachoti, C.M., 2013. Gastrointestinal health and function in weaned pigs: a review of feeding strategies to control post-weaning diarrhoea without using in-feed antimicrobial compounds. J. Anim. Physiol. Anim. Nutr. 97, 207–237.

Huting, A.M.S., Wellock, I., Tuer, S., Kyriazakis, I., 2019. Weaning age and post-weaning nursery feeding regime are important in improving the performance of lightweight pigs. J. Anim. Sci. 97, 4834–4844.
Jackson, P., Cockcroft, P., 2005, Clinical examination of the pig.
Josa, L.B., Solà-Oriol, D., Pérez, J.F., 2015. Effect of supplementary feeding strategies during the suckling period to improve weanling performance. Dig. Physiol. Pigs.
Keimer, B., Hörstmann, M., Schlagheck, A., Asmussen, S., 2022. Effects of a synbiotic dietary concept on faecal consistency and growth performance compared to pharmacological dosages of zinc oxide in weaned piglets. Zero Zinc Summit, Cph.
Lalles, J.P., Bosi, P., Smidt, H., Stokes, C.R., 2007. Weaning - A challenge to gut physiologists. Livest. Sci. 108, 82–93.
Leliveld, L.M.C., Riemensperger, A.V., Gardiner, G.E., O'Doherty, J.V., Lynch, P.B., Lawlor, P.G., 2013. Effect of weaning age and postweaning feeding programme on the growth performance of pigs to 10 weeks of age. Livest. Sci. 157, 225–233.
Madec, F., Bridoux, N., Bounaix, S., Jestin, A., 1998. Measurement of digestive disorders in the piglet at weaning and related risk factors. Prev. Vet. Med. 35, 53–72.
McCracken, B.A., Spurlock, M.E., Roos, M.A., Zuckermann, F.A., Gaskins, H.R., 1999. Weaning Anorexia May Contribute to Local Inflammation in the Piglet Small Intestine. J. Nutr. 613–619.
Ming, D.X., Wang, W.H., Huang, C.Y., Wang, Z.J., Shi, C.Y., Ding, J., Liu, H., Wang, F.L., 2021. Effects of Weaning Age at 21 and 28 Days on Growth Performance, Intestinal Morphology and Redox Status in Piglets. Animals 11.
Morsing, M.K., Larsen, I., Pedersen, K.S., Weber, N.R., Nielsen, J.P., 2022. The prevalence of post-weaning diarrhoea and role of enterotoxigenic Escherichia coli in ten Danish nursery pig herds not using medicinal zinc oxide in the feed. publishing.
Newberry, R.C., Woodgush, D.G.M., 1985. The suckling behavior of domestic pigs in a semi-natural environment. Behaviour 95, 11–25.
Nielsen, C.L., Krogh, M.A., Sørensen, J.T., Kongsted, H., 2022. A field trial on the effect of cross-fostering on performance, clinical health and antibiotic usage during the suckling period of pigs. Prev. Vet. Med. 205 (2022), 105678.
Partanen, K., Siljander-Rasi, H., Pentikainen, J., Pelkonen, S., Fossi, M., 2007. Effects of weaning age and formic acid-based feed additives on pigs from weaning to slaughter. Arch. Anim. Nutr. 61, 336–356.
Pedersen, K.S., Toft, N., 2011. Intra- and inter-observer agreement when using a descriptive classification scale for clinical assessment of faecal consistency in growing pigs. Prev. Vet. Med. 98, 288–291.
Petersen, H.V., Vestergaard, K., Jensen, P., 1989. Integration of piglets into social-groups of free-ranging domestic pigs. Appl. Anim. Behav. Sci. 23, 223–236.
Pluske, J.R., Hampson, D.J., Williams, I.H., 1997. Factors influencing the structure and function of the small intestine in the weaned pig: a review. Livest. Prod. Sci. 51, 215–236.
Pluske, J.R., Kerton, D.J., Cranwell, P.D., Campbell, R.G., Mullan, B.P., King, R.H., Power, G.N., Pierzynowski, S.G., Westrom, B., Rippe, C., Peulen, O., Dunshea, F.R., 2003. Age, sex, and weight at weaning influence organ weight and gastrointestinal development of weanling pigs. Aust. J. Agric. Res. 54, 515–527.
Postma, M., Backhans, A., Collineau, L., Loesken, S., Sjolund, M., Belloc, C., Emanuelson, U., Beilage, E.G., Nielsen, E.O., Stark, K.D.C., Dewulf, J., Consortium, M., 2016. Evaluation of the relationship between the biosecurity status, production parameters, herd characteristics and antimicrobial usage in farrow-to-finish pig production in four EU countries. Porc. Health Manag. 2.
RCoreTeam, 2019. A language and environment for statistical computing. R. Found. Stat. Comput., Vienna, Austria.
Robert, S., Weary, D.M., Gonyou, H., 1999. Segregated Early Weaning and Welfare of Piglets. J. Appl. Anim. Welf. Sci. 2, 31–40.
Rutherford, K.M.D., Baxter, E.M., D'Eath, R.B., Turner, S.P., Arnott, G., Roehe, R., Ask, B., Sandoe, P., Moustsen, V.A., Thorup, F., Edwards, S.A., Berg, P., Lawrence, A. B., 2013. The welfare implications of large litter size in the domestic pig I: biological factors. Anim. Welf. 22, 199–218.
Smits, C.H.M., Li, D., Patience, J.F., den Hartog, L.A., 2021, Animal nutrition strategies and options to reduce the use of antimicrobials in animal production. Food and Agriculture Organization of the United Nations.
Sorensen, J.T., Rousing, T., Kudahl, A.B., Hansted, H.J., Pedersen, L.J., 2016. Do nurse sows and foster litters have impaired animal welfare? Results from a cross-sectional study in sow herds. Animal 10, 681–686.
Visschers, V.H.M., Backhans, A., Collineau, L., Iten, D., Loesken, S., Postma, M., Belloc, C., Dewulf, J., Emanuelson, U., Beilage, E.G., Siegrist, M., Sjolund, M., Stark, K.D.C., 2015. Perceptions of antimicrobial usage, antimicrobial resistance and policy measures to reduce antimicrobial usage in convenient samples of Belgian, French, German, Swedish and Swiss pig farmers. Prev. Vet. Med. 119, 10–20.
Wellock, I.J., Fortomaris, P.D., Houdijk, J.G.M., Kyriazakis, I., 2008a. Effects of dietary protein supply, weaning age and experimental enterotoxigenic Escherichia coli infection on newly weaned pigs: health. Animal 2, 834–842.
Wellock, I.J., Fortomaris, P.D., Houdijk, J.G.M., Kyriazakis, I., 2008b. Effects of dietary protein supply, weaning age and experimental enterotoxigenic Escherichia coli infection on newly weaned pigs: performance. Animal 2, 825–833.
Wisener, L.V., Sargeant, J.M., O'Sullivan, T.L., O'Connor, A.M., McEwen, S.A., Reist, M., Churchill, K.J., 2021. Non-antibiotic approaches for disease prevention and control in nursery pigs: a scoping review. Front. Vet. Sci. 8.