

Maintaining continuity of nutrient intake after weaning. I. Review of pre-weaning strategies

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ABSTRACT: Weaning is a crucial phase of swine production marked by a multitude of biological and environmental stressors, which have a significant impact on immediate postweaning behavior and feed intake (FI). During this time, the piglet's gastrointestinal (GI) system is also undergoing extensive epithelial, immune, and nervous system development. In this review, our objective is to describe the different preweaning strategies that can be used to minimize nutrient intake disruption and improve FI in the immediate postweaning period. Reducing nutrient disruption postweaning can be accomplished through the implementation of management and nutritional strategies. Research consistently demonstrates that weaning older, more developmentally mature pigs helps prevent many of the adverse GI effects associated with weaning stress. Providing creep feed to pigs during lactation is another reliable strategy that has been shown to increase immediate postweaning FI by acclimating pigs to solid feed prior to weaning. Likewise, socialization by allowing pigs to mix before weaning improves social skills, minimizing mixing stress, and aggression-related injury immediately postweaning.

Supplemental milk replacer has also been shown to elicit a positive response in preweaning growth performance, which may help to reduce preweaning mortality. While socialization and milk replacer are acknowledged to ease the weaning transition, these strategies have not been widely adopted due to labor and application challenges. Additionally, the cost of milk replacer and logistics of retrofitting farrowing houses to accommodate litter socialization have limited adaptation. Further exploration of maternal nutrition strategies, particularly fetal imprinting, is needed to better understand the implications of perinatal learning. Other areas for future research include, combining environmental enrichment with feeding strategies, such as large destructible pellets or play feeders, as well as determining at what time point producers should start socializing pigs before weaning. While more research is needed to develop strategic preweaning management programs, many of the strategies presented in this review provide opportunities for producers to minimize nutrient intake disruption by preventing feed neophobia, reducing stress, and easing the wean pig transition.

Key words: feed intake, nutrient disruption, preweaning, pig

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INTRODUCTION

Weaning is a stressful event in a pig's life, marked by maternal and littermate separation, dietary and environmental changes, in addition to co-mingling and social hierarchy establishment (Moeser et al., 2007a). In the wild, pigs are gradually weaned around 12 weeks of age, whereas pigs reared in modern U.S. production systems are weaned between 2.5 and 4 weeks of age (Moeser et al., 2017), an outcome determined by lactation space, pig flow, and disease status. The period preweaning is characterized by exogenous and endogenous factors that act to limit immune activation until 2.5–4 weeks of age, at which time there is a reduction in maternal immunity and an increase in piglet lymphocyte development and Peyer's patches maturity (Moeser et al., 2017). During this time, the piglet's gastrointestinal (GI) system is also undergoing extensive epithelial, immune and nervous system development. This emphasizes the need for a sanitary environment to achieve long-term maturation of the immune system. However, this critical window of maturation is often interrupted by the weaning transition, which can have detrimental effects on gut health, nutrient utilization, and disease resistance (Moeser et al., 2017). Furthermore, the combination of stressors that occur at weaning has a significant impact on immediate postweaning behavior and feed intake (FI; Pluske, 2016).

It is well established that stress plays a pivotal role in intestinal barrier breakdown (Hart and Kamm, 2002; Kelly et al., 2015). Exploration of the gut-brain axis has revealed the impacts of stress on the biochemical signaling that occurs between the GI tract and central nervous system (Hart and Kamm, 2002), suggesting an interactive relationship between the microbiome, intestinal barrier, and enteric nervous and mucosal immune systems (Yu et al., 2012; Kelly et al., 2015). Stress stimuli activate the hypothalamic–pituitary–adrenal (HPA) axis, the body's central stress response mechanism. Activation of this pathway is characterized by increased corticotropin release factor (CRF) activity, mast cell (MC) degranulation, and increased gut permeability (Hart and Kamm, 2002). Continuous activation of this stress response system can have detrimental effects on the protective, metabolic, structural, and immune functions of the gut coinciding with persistent inflammation, decreased nutrient utilization, and poor growth performance (Hart and Kamm, 2002; Yu et al., 2012).

In addition to weaning stressors, genetic selection for large litter sizes has increased demands

on the sow to supply more nutrients, both in utero and during lactation, which has led to an increased proportion of light birth weight pigs (≤ 1 kg). Data collected from 965 litters indicated that this proportion increased from 7% to 23% of total pigs born as litter size increased from ≤ 11 to ≥ 16 pigs, with 17% of light birth weight pigs dying within the first 24 h after farrowing (Quiniou et al., 2002). In more recent years, Feldpausch et al. (2019) observed that 43% of total preweaning mortalities occurred amongst the light birth weight population. In addition, Craig et al. (2017) observed that in gilt progeny, pigs were weaned and marketed at lighter weights than sow progeny, with significantly increased mortality rates. Differences in gilt progeny birth weights and subsequent growth is attributed to developmental delays associated with decreased organ weights, restricted colostrum digestion, and lower serum IgG concentrations (Craig et al., 2019). These data indicate an opportunity for producers to implement nutritional and management programs prior to weaning to better prepare pigs for the changes in FI and growth rate postweaning. Therefore, the present review will focus on different preweaning strategies to minimize nutrient intake disruption and improve FI in the immediate (7 d) postweaning period.

PREWEANING STRATEGIES TO INCREASE FEED INTAKE AFTER WEANING

Maternal Nutrition

Lucas et al. (1991; derived from Davies and Norman, 2002) defined programming as the physiological “setting” by an early stimulus or insult at a “sensitive” period, resulting in long-term consequences for function. Fetal programming is the foundation for fetal growth and development and is influenced by maternal uterine conditions that are often categorized into nutritive and non-nutritive factors (Johnston et al., 2008). These conditions include uterine capacity, gestational stress from the environment, maternal under and over nutrition, and placental nutrient transport. These conditions impact postnatal growth and development, HPA activity, intestinal morphology, and offspring lifetime reproductive performance (Johnston et al., 2008; Ji et al., 2017). The final weeks leading to parturition are well documented as the most sensitive stage for fetal programming (Ji et al., 2017).

Nutritional strategies to influence uterine conditions have been suggested throughout the

literature. It is understood that vitamin and mineral nutrition, glucose transport, and growth hormone circulation play crucial roles in fetal growth and development (Johnston et al., 2008). Specifically, L-glutamine supplementation during gestation has demonstrated encouraging physiological and developmental benefits, ameliorating intrauterine growth retardation in gilt progeny (Wu et al., 2011) and increasing the average birth weight of multiparous sow progeny (Zhu et al., 2018). Dietary glutamine in lactating sow diets has also been shown to enhance glutamine concentrations in milk, increasing piglet growth and survival (Wu et al., 2011). While glutamine appears to have beneficial effects, limited research has prevented widespread adaptation. Glutamine is also not approved for feeding in all locations globally. Furthermore, Zhang et al. (2017) reviewed the effects of branched-chain amino acid (BCAA) supplementation in sow diets. Collectively, the data demonstrate that BCAAs stimulate mammary epithelial cell growth, increase the percentage of milk protein, and increases glutamine, glutamate, and aspartate concentrations in the milk. Among all BCAA, leucine plays a vital role in mTOR pathway activation, enhancing blastocyte development and embryo implantation, as well as fetal protein synthesis. Supplementing sow diets with BCAA remains promising, however, more research is needed in this area. Other interventions have reported that supplementing sow lactation diets with fatty acids (FA) influence the transfer of $n-3$ and $n-6$ polyunsaturated fatty acids (PUFA) from the sow milk to the piglet (Lauridsen, 2020). Uptake of these FA into the piglets enteric tissues may impact gut health and function, while also providing immune system support. In a review by Rosero et al. (2016), supplemental FA also showed a consistent improvement in litter growth. Piglet survival however was less consistent and was therefore not reported. The authors concluded maximum sow reproductive efficiency can be achieved by providing a minimum dietary intake of 10 g/d of α -linolenic acid and 125 g/d of linoleic acid. Additionally, many studies evaluating the effects of PUFA in sow diets have shown improved intestinal glucose absorption, FA concentrations, and tissue glycogen stores in piglets (Jarocka-Cyrta et al., 1998; Gabler et al., 2007; Boudry et al., 2009). Perinatal flavor learning is another interesting concept. Research shows that young animals can learn flavors from the maternal diet that appear in the amniotic fluid and mother's milk (Oostindjer et al., 2010). Prenatal exposure to flavors in addition to flavors in the maternal diet after birth have been shown to increase FI and BW

gain of piglets in the immediate postweaning period (Oostindjer et al., 2010; Blavi et al., 2016), and decrease time to initial FI (Oostindjer et al., 2011). Interestingly, when given a choice between feed with or without flavor after weaning, previous exposure did not affect flavor preference (Oostindjer et al., 2010; Figueroa et al., 2013); however, flavor learning did reduce aggressive tendencies following nursery placement (Fuentes et al., 2010; Oostindjer et al., 2010, 2011). This suggests that flavor learning in pigs works through a reduction of weaning stress rather than flavor preference, which may reduce feed neophobia at weaning.

While many of these strategies appear promising, few have gained industry-wide application as a result of limited research. Additionally, the economics of implementing these strategies on the farm is not well understood. Therefore, further research is needed in the area of sow nutrition to better understand its influence on fetal programming, as to develop more practical approaches to improving maternal uterine conditions and imprinting on subsequent offspring behavior and long-term growth performance.

Management Strategies

Cross fostering and split-suckling. Cross-fostering and split-suckling are management strategies widely used throughout the swine industry as a means to increase preweaning growth and survival. The process by which these strategies are carried out varies widely across production systems (Baxter et al., 2013); however, there is a consensus that age, birth order, litter size, and body weight (BW) play critical roles in the success of implementing these strategies.

Cross-fostering is the relocation of piglets from their biological mother to a foster sow in an attempt to equalize litter size and reduce mortality. It is well-recognized that fostering piglets is time-sensitive. Ideally, fostering should take place 12–24 h after birth which allows piglets sufficient colostrum intake from their birth sow, while also preventing the disruption of teat hierarchy establishment (Heim et al., 2012; Baxter et al., 2013). When there is a risk that sows colostrum production will not meet piglets needs (> 200 g), fostering should occur earlier (Alexopoulos et al., 2018). Observations at the time of milk let down throughout lactation suggest that the number of fights associated with suckling tend to be lower in biologically related litters compared to cross-fostered litters; however, this does not impact the number of successful nursing

episodes and the subsequent growth and survival of fostered pigs (Heim et al., 2012). Huting et al. (2017) utilized light and heavy birth weight pigs and assessed the impact of mixed- versus uniform-weight litters through cross-fostering. Not surprisingly, lightweight piglets reared in uniform litters had heavier weaning weights and fewer removals than those reared in mixed litters. Conversely, heavier birth weight piglets performed better and had fewer removals in mixed litters. Both of these responses are related to the piglet's ability to compete for a more productive anterior teat. These results are in agreement with Deen and Bilkei (2004) who observed greater mortality in low birth weight pigs reared with high birth weight littermates. More importantly, however, was the impact of litter size. Low birth weight pigs fostered into larger litters, regardless of littermate BW, missed more nursing episodes and had increased mortality compared to those fostered into smaller litters. Furthermore, piglets fostered into older litters had significantly reduced suckling activity compared to piglets fostered into younger litters (Pajžlar and Skok, 2019). Taken together, small piglets should be fostered into litters of other small pigs (Alexopoulos et al., 2018). When this is not feasible, litter size should be reduced by the removal of larger pigs. There is some data that suggest cross-fostering may also impact long-term growth and survival; however, the results are inconsistent and seem to be more closely related to piglet birth weight (Baxter et al., 2013; Huting et al., 2017). When done correctly, cross-fostering allows producers to equalize litter size, which should reduce teat competition and give piglets more opportunity to consume milk.

Limited research has been conducted to determine the best approach for split-suckling. Morton et al. (2019) conducted a study evaluating two split-suckling methods, temporarily removing either the heaviest six pigs in the litter or the first half of the piglets born. It was concluded that while both birth weight and order are important for preweaning growth and survival, the two interact differently. Birth weight was closely related to colostrum intake, compared to birth order which was observed to affect immunocrit levels. Furthermore, Donovan and Dritz (2000) demonstrated that while split-suckling decreased variation in ADG of pigs from birth to weaning, this response was only significant for pigs in large litters (≥ 9 pigs). These studies were conducted during the preweaning period, therefore the implications of split-suckling strategy on postweaning nutrient intake and performance is unknown; however, split-suckling creates more

opportunities for pigs to receive colostrum, which should provide greater immunity and promote healthy growth (Alexopoulos et al., 2018).

Intermittent suckling and socialization.

Intermittent suckling (IS) is a strategy that is long-established but not commonly used throughout the swine industry due to labor implications. Intermittent suckling is a form of gradual weaning where piglets are removed from the sow for a period of time each day. This simulates the progressive maternal separation that occurs during natural weaning. Turpin et al. (2016a,b; 2017) conducted three trials evaluating the effects of IS on postweaning behavior and performance. Litters exposed to IS 7 d prior to weaning had decreased preweaning mortality compared to conventionally weaned litters (Turpin et al., 2016a). Interestingly, 3 d after weaning IS groups had a negative average daily gain (ADG) in contrast to conventionally weaned groups; however, gain recovered and surpassed that of the conventionally weaned group by d 7. Turpin et al. (2016b) also observed that combining IS with a 35 d wean age improved the postweaning adaptation period, evident by increased FI and ADG through d 12 postweaning. No difference was observed when combining IS with a 28 d wean age relative to the control group. Lastly, IS with comingling non-littermate piglets before weaning, in combination with grouping familiar pigs together after weaning, improved performance in an additive manner, resulting in increased FI and decreased expression of manipulative behavior immediately postweaning (Turpin et al., 2017). This highlights the impact of familiarity on growth performance and the potential benefit of preweaning socialization on social skill development.

Hötzel et al. (2004) demonstrated that modern rearing systems have a significant impact on the development of piglet behavior. Compared to piglets reared in farrowing stalls, piglets reared in outdoor systems exhibit less social interaction with the sow and fewer nursing episodes, which appears to encourage earlier solid feed consumption during lactation and reduce manipulative social behaviors after weaning. Research conducted to mimic outdoor rearing systems by removing the barrier between two adjacent farrowing pens and allowing pigs to mix has shown a similar response in reducing agonistic behavior and lesion scores (North and Stewart, 2000; Hessel et al., 2006). Other studies have found that mixing pigs during lactation increases preweaning play behavior, reduces BW loss at weaning, and improves postweaning growth rates (North and Stewart, 2000;

Hessel et al., 2006; Salazar et al., 2018). D'Eath (2005) also observed that socialized pigs were able to more quickly form stable dominance hierarchies when faced with unfamiliar pigs compared to previously unsocialized pigs. These data demonstrate the importance of socialization prior to weaning as a strategy to minimize mixing stress and better prepare pigs for weaning. Despite these added benefits, early mixing strategies have not been widely adopted in practical operations. The logistics and cost of retrofitting farrowing houses to accommodate litter socialization, in addition to the potential disease spread when comingling litters have prevented application. However, as interest in this area increases, more research is needed to fully understand the effects of early mixing on postweaning FI and growth performance.

Wean age. Emerging evidence indicates that early life adversities lead to the early onset and greater severity of intestinal disorders (Gresse et al., 2017; Pohl et al., 2017). In humans, early-life stressors have been linked to irritable bowel syndrome and depression (Kelly et al., 2015). Moeser et al. (2007a) evaluated the effects of weaning age-induced stress on intestinal dysfunction in pigs 24 h postweaning. Compared to age-matched, unweaned littermates, pigs weaned at 19 d of age exhibited increased serum and peripheral CRF, a stress peptide hormone that is released in response to HPA axis stimuli. This neuroendocrine survival mechanism is responsible for bringing the body back to homeostasis after a stress event (Moeser et al., 2017). Additionally, HPA helps to regulate many body processes, including digestion and the immune system, thus playing a central role in gut health. This response was supported by using chamber analysis of jejunal tissue, which showed reduced tight junction integrity, increased intestinal permeability, and net ion transport, all of which suggest the role of CRF in intestinal permeability. In a follow-up trial, Moeser et al. (2007b) evaluated the effects of stress in delayed weaning. Compared to pigs weaned at d 19, pigs weaned at d 28 exhibited decreased CRF-receptor1 expression, an indicator of CRF concentrations. Furthermore, pigs weaned at d 28 displayed decreased tryptase activity, a marker of MC activation. Tryptase, along with pro-inflammatory compounds (serotonin/5-hydroxytryptamine and histamine) are released from MC in response to immune stimuli. Under normal conditions, these mediators are designed to increase intestinal secretion and inflammation to rid the body of invading pathogens (Yu et al., 2012). However, when pigs weaned at 16 d of age were subjected

to an *Escherichia coli* challenge, these immune responses were suppressed and exacerbated intestinal injury was observed (McLamb et al., 2013). This suggests stress-induced MC activation is different than pathogenic, and that stress compromises gut integrity, altering innate immune responses to subsequent health challenges. Interestingly, the *E. coli* challenge reduced growth rates in pigs weaned at 16 d, whereas growth was not affected in pigs weaned at 20 d of age; however, feed intake was similar between wean age groups. This data further demonstrates the importance of weaning an older, more biologically mature pig.

Further research investigating early weaning and its impact on gut integrity revealed that pigs weaned at 15 d of age developed chronic, relapsing diarrhea, with a more severe clinical response observed in females (Pohl et al., 2017). Others have shown that these clinical (Medland et al., 2016) and pathophysiological (Smith et al., 2010) responses can persist into later life, which supports the observations by Main et al. (2004) where they reported improved wean-to-finish performance as wean age increased from 12 to 21 d of age. Despite there being no difference in lifetime performance when analyzed on a common age, Faccin et al. (2020) observed that as wean age increased up to 25 d, belly nosing behavior, immediate postweaning body weight loss, and nursery removal rates were reduced. As a result, BW sold per pig weaned increased with weaning age, which is in support of the Main et al. (2004) study.

The immediate postweaning impacts of wean age have also been studied. van der Meulen et al. (2010) observed that increasing wean age from 4 to 7 wk of age improved postweaning FI and gain immediately after weaning. Furthermore, Pluske et al. (2003) reported GI underdevelopment in pigs weaned at either 2 wk of age or lighter body weight, regardless of age. Underdevelopment was marked by lighter GI organs and accessory organ weights, as well as lower specific maltase, glucoamylase, and pancreatic enzyme activity. Similarly, when pigs were divided into young (<32.4 wean age) versus old (>35.9 wean age) groups at a common wean date, higher mortality rates were observed in young (9.1%) compared to old pigs (5.0%; Huting et al., 2019). However, when divided into light versus heavy groups, no statistical differences were detected. Huting et al. (2019) also observed that increasing wean age and feeding allowance in the nursery benefited light weaned pigs compared to heavy weaned pigs. Regardless of BW though, Main et al. (2004) reported that feeding program

complexity in the nursery phase did not impact wean-to-finish performance.

These data suggest that weaning older, more developmentally mature pigs helps prevent many of the clinical, pathophysiological, and economic consequences associated with stress.

Nutrient Intake

Topsoil. Aside from a more natural weaning process, outdoor rearing systems offer more physical and social environmental interactions for young pigs (Lau et al., 2015). Specifically, early exposure to topsoil during lactation has been shown to accelerate gut microbiota maturation in weaning pigs (Vo et al., 2017). In modern indoor systems, piglets do not have access to topsoil, therefore reducing their microbial load exposure. This may be associated with immune deficiencies and poorer lifetime health.

Exposure to topsoil 4 d postfarrow until weaning resulted in lower weaning weights compared to litters that were not exposed to topsoil (Tsai et al., 2016). However, during the nursery period, pigs provided topsoil during lactation had increased FI and ADG. Subsequent FI during the grow-finish period was also increased with a tendency for a 4.6 kg heavier market weight. Furthermore, when challenged with lipopolysaccharide on d 56, pigs provided topsoil preweaning had an improved immune response, represented by increased plasma IL1 α concentration (Tsai et al., 2016). Vo et al. (2017) demonstrated that this response can be attributed to abundant *Prevotella* and short-chain fatty acid-producing taxa when pigs are exposed to soil early in life. Furthermore, because the soil contains plant-derived carbohydrates and fibers it is also believed that early transfer of these compounds in the colon can prepare the piglet GI tract for solid food, preventing reductions in postweaning FI and BW gain (Vo et al., 2017). Similar to outdoor rearing, these data suggest that exposure of naïve pigs to the soil during lactation may help to develop a more functional immune response, which may provide subsequent health and performance benefits. More research however is needed to better understand the microbial implications of topsoil exposure on the piglet GI tract. Likewise, fecal microbiota transplantation (FMT) has gained attention in regulating gut microbial colonization. Exogenous FMT has been shown to improve the growth performance, intestinal barrier function, and innate immune system of piglets (Hu et al., 2018), so as to potentially alleviate the damage of

weaning stress (Xiang et al., 2020). Furthermore, the transfer of feces from a healthy donor to a diseased recipient may offer the opportunity to alter the GI microbiota and reduce morbidity and mortality in health challenge herds (Niederwerder et al., 2018). While this strategy appears to have more relevance in human health, it does provide insight on specific bacteria or probiotics that may be used to create a more symbiotic microflora environment in the pig. Nevertheless, more research is needed to understand the interaction between the gut microbiota and the development of immune cells (Xiang et al., 2020).

Creep feeding. Offering creep feed preweaning is believed to ease the weaning transition by improving feed intake in the immediate postweaning period. At first introduction, familiarization of solid feed is an exploratory behavior; however, as pigs begin to mature, creep feed consumption is largely driven by nutrient demand (Pajor et al., 1991). It has also been suggested that piglets with insufficient milk intake or those with low BW will compensate by increasing solid feed consumption (Pajor et al., 1991; Fraser et al., 1994; Huting et al., 2017). Recent data by Middelkoop et al. (2019) are in agreement, demonstrating that piglets reared on restrict-fed sows and provided creep feed had increased creep FI and percentage of eaters at weaning compared to piglets reared on full-fed sows. English et al. (1980; derived from Pluske et al., 2018) suggest that piglets should consume, on average, 600 g of creep feed before weaning to better prepare them for solid feed. Consequently, Pluske et al. (2018) indicated that the level of creep feed intake needed to completely alleviate the postweaning growth check is not achievable considering wean age less than 28 days. Several others have reported relatively low creep FI up until the last week prior to weaning at 28 d of age (Pajor et al., 1991; Fraser et al., 1994; Bruininx et al., 2002), with FI having minimal effects on preweaning BW gain. These studies have also determined that creep feed consumption on an individual pig and within litter basis is highly variable.

While quantity and variability in total creep consumption are important considerations, the true value of creep feeding is found in the development of eaters, pigs that actually consume creep feed. Bruininx et al. (2002) observed that pigs designated as eaters had improved FI and ADG in the immediate postweaning period compared to non-eaters. Furthermore, eaters required less time from weaning to the initial consumption of dry feed. This was evident by the number of visits to the

feeder during which feed consumption was higher for eaters than non-eaters. The authors suggest that familiarity with solid feed at weaning may be the result of pigs focusing more on FI and less on exploratory behavior of the pen. In an attempt to understand the impact of feeding duration on the proportion of eaters, Sulabo et al. (2010b) reported 10% more pigs designated as eaters when increasing the duration in which creep feed was offered from 6 to 13 d. Likewise, creep feeder design plays an important role in maximizing the proportion of eaters, as well as managing creep feed wastage. Sulabo et al. (2010a) observed that although feeder type did not impact preweaning BW, piglets that received creep from a rotary feeder with hopper had reduced feed disappearance and increased number of eaters than those provided creep in a pan feeder or rotary feeder without hopper. Moreover, the number of times feeders were filled compared to a rotary feeder with no hopper and pan feeder was reduced to once every 12 h. This indicates that workers getting piglets up while filling feeders did not encourage pigs to consume more feed. Play feeders, or conventional rotary feeders with canvas cloth, braided cotton ropes, and PVC spiral tubes attached on the inside bottom of the feeder, have also been shown to elicit exploratory behavior, attracting more pigs to creep feed (Middelkoop et al., 2019). This response followed pigs through the immediate postweaning period where increased FI and growth were observed. The authors suggested that providing creep feed in play feeders prior to weaning may develop a positive association between solid feed and object play, stimulating greater feed consumption. In contrast, research has shown that the pellet size in the suckling period has no effect on the number of pigs designated as eaters. However, van den Brand et al. (2014) observed that feeding large pellets during lactation increased FI and BW gain after weaning. The authors attributed this response to greater pellet consumption in early lactation. Additionally, feeding a large pellet diameter has been reported to reduce preweaning mortality (Clark et al., 2015).

Research has also looked at increasing the diet complexity of creep feed to offer additional growth performance benefits. Results in the preweaning period indicate that increasing the diet complexity (Fraser et al., 1994) or energy density (Yan et al., 2011) of creep feed has little effect on BW gain prior to weaning. Conversely, Pajor et al. (2002) reported that pigs offered a complex diet consumed 50% more solid feed before weaning compared to pigs provided a simple diet. While this did not

impact BW at weaning, the authors did observe that pigs who had received more complex diets during lactation continued to eat more postweaning and exhibited reduced BW loss immediately after weaning. Furthermore, pigs fed high complexity creep feed had improved growth performance in the postweaning period (Fraser et al., 1994; Pajor et al., 2002; Yan et al., 2011) compared with those that had received a simple creep feed diet. Cabrera et al. (2013) noted that pigs who received glutamine supplementation in creep feed and throughout a 6-week nursery phase tended to have improved FG. This response was also observed in pigs that received either no creep or a controlling creep feed in the preweaning period and were later weaned onto a glutamine supplemented diet. Intestinal histology measures concluded that glutamine supplemented pigs had increased villous height and cell proliferation, similar to pigs who were weaned at a later age. Research evaluating flavored creep feed has demonstrated that adding flavor has no influence on total creep intake or the proportion of eaters (Sulabo et al., 2008); however, pigs exposed to flavored creep feed tended to have improved FI immediately postweaning and increased gain when fed complex starter diets supplemented with the same flavor.

Several factors should be considered when implementing a creep feeding program, including the duration of feeding, feeder design, pellet size, and diet complexity. It is expected that pigs may lose weight immediately postweaning; however, these data indicate that the growth check associated with weaning can be reduced by acclimating pigs to feed during the suckling period. Providing creep feed to nursing pigs weaned at older ages (> approximately 25 days) may also have the opportunity to improve weaning weights (Tokach et al., 2020). Taken collectively, providing creep feed for 2–3 days prior to weaning is often satisfactory to observe the benefits in postweaning performance (Tokach et al., 2020).

Water consumption and liquid milk replacer. Water access and intake of piglets in the first days after farrowing is often assumed to be of little relevance. Fraser et al. (1988) speculated that piglets who are not receiving enough milk from the sow may be at risk of dehydration. In agreement, the authors observed that litters of pigs with low growth during the first 4 d after farrowing used more water than faster gaining litters. This suggests that pigs may correct for low milk intake by compensating with increased water intake (Fraser et al., 1988). Other trials looking at water dispenser design have demonstrated that when water is visible in

either an open bowl or cup, compared to a nipple or push-lever dispenser, discovery time is significantly reduced (Phillips and Fraser, 1991). Furthermore, bite nipples can be modified to reduce discovery time by adding either a chain to the valve lever or floor-mounting the nipple at an upward angle so that it's eye level with the pig (Phillips and Fraser, 2001). This data provides insight into dispenser systems that may be more advantageous to provide nutrition supplements, such as milk replacer, to preweaned pigs.

van Oostrum et al. (2016) evaluated the effects of supplementing milk replacer before or after weaning. The authors observed that pigs provided milk replacer preweaning had improved FI during the first week postweaning compared to those supplemented with milk replacer after weaning. During the preweaning period, several studies have reported that pigs supplemented with milk replacer were heavier at weaning (Novotni-Dankó et al., 2015; de Greeff et al., 2016), with a more pronounced response observed in heavy birth weight pigs (Wolter et al., 2002). Furthermore, pigs that received milk replacer from birth to weaning had significantly reduced preweaning mortality (Novotni-Dankó et al., 2015). Nutrient-dense complex milk replacer has also elicited increased concentrations of metabolic fermentation products and expression of cell proliferation in the crypts along the piglet GI tract, which may explain the performance response (de Greeff et al., 2016). Alternatively, research in the last decade has demonstrated that bovine colostrum may be a beneficial substitute for milk replacer because of its high immunoglobulin levels (de Lange et al., 2010). Piglets supplemented with bovine colostrum had reduced *E. coli* colonization in the intestine, similar to the colonization seen in suckling litters (Sugiharto et al., 2015). Likewise, the ileal microbiota population of pigs offered bovine colostrum more closely resembled sow-reared piglets compared to those that received milk replacer (Poulsen et al., 2017). Despite these benefits, milk replacer is not widely used throughout the industry due to increased labor and hygiene challenges. Additionally, the added cost of milk replacer has prevented further application.

While current data on water supplementation for suckling pigs is limited, previous research has demonstrated the importance of preventing dehydration in piglets. This is particularly important as litter size increases and sows milk yield remains relatively constant. These data also demonstrate that providing milk replacer to pigs prior to weaning offers an additional source of nutrients that may

help improve weaning weights, decrease preweaning mortality, and increase FI postweaning.

Gaps in Knowledge

Reducing nutrient disruption postweaning can be accomplished through further exploration of multiple preweaning strategies that may be best implemented in combination to prevent feed neophobia, reduce stress, and improve the weaning transition. Areas where further research would be particularly beneficial include:

- **Maternal nutrition:** Gestation and lactation feeding programs to influence piglet growth and development (colostrum supply, BCAA, glutamine, and essential fatty acid concentrations).
- **Fetal imprinting:** Gestation and lactation feeding programs designed to reduce stress in the immediate postweaning period by providing pigs with familiar olfactory stimuli.
- **Sow management:** When sow management trials (i.e., split suckling, cross-fostering, etc.) are conducted, often piglets are not followed downstream into the nursery. Research instead focuses primarily on weaning weight. The question then becomes, does improving weaning weight, translate to improved postweaning performance?
- **Socialization:** In socialization studies, pigs are often not regrouped at weaning with pigs they had previously been socialized with before weaning. This suggests an opportunity to assess the effects of postweaning placement strategies in combination with preweaning socialization on latency to feed and potentially BW loss after weaning. At what time point should we start mixing pigs before weaning?
- **Environmental enrichment:** Combining enrichment with feeding strategies, such as large, destructible pellets or play feeders on feed consumption after weaning.
- **Creep feeding:** Providing lactation feed on farrowing stall mats prior to weaning as a strategy to familiarize pigs with solid feed.
- **Topsoil or other bacteria source:** Influence of bacteria exposure on the gut microbial population, piglet performance, and health.

CONCLUSION

Weaning is an important phase of swine production marked by some of the most profound stressors. It is during this time period that pigs exhibit low voluntary FI, much of which stems from

their physiological response to stress and the behavioral mechanisms that follow, therefore prevent weanling pigs from searching out and consuming feed. Several factors are known to influence nutrient intake after weaning including:

- **Wean age:** Weaning older, more developmentally mature pigs helps prevent many of the adverse effects of weaning associated stressors.
- **Cross-fostering and split-suckling:** While there is limited research on the effects of these management strategies immediately after weaning, it is understood that providing greater opportunities for pigs to nurse prior to weaning should improve nutrient intake and weaning BW, creating a more robust pig for the postweaning period.
- **Socialization:** Allowing pigs to mix prior to weaning improves social skills and encourages play behavior, minimizing mixing stress and injury from aggression immediately postweaning.
- **Creep feeding:** Providing creep feed to pigs during lactation encourages exploratory behavior and familiarizes pigs with solid feed before weaning, increasing immediate postweaning FI.
 - Water supplementation in combination with creep feed may help pigs learn the difference between hunger and thirst prior to weaning.
- **Milk supplementation:** Provides an additional source of nutrients that may help to reduce pre-weaning mortality, particularly in the lightweight pig population.

LIST OF ABBREVIATIONS

GI, gastrointestinal; HPA, hypothalamic pituitary adrenal; CRF, corticotropin release factor; MC, mast cell; BCAA, branched-chain amino acids; FA, fatty acids; PUFA, polyunsaturated fatty acids; BW, body weight; IS, intermittent suckling; ADG, average daily gain; FI, feed intake; FG, feed-to-gain ratio; FMT, fecal microbiota transplantation

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LITERATURE CITED

Alexopoulos, J. G., D. S. Lines, S. Hallett, and K. J. Plush. 2018. A review of success factors for piglet fostering in lactation. *Animals*. 8:38. doi:10.3390/ani8030038

- Baxter, E. M., K. M. D. Rutherford, R. B. D'Eath, G. Arnott, S. P. Turner, P. Sandøe, V.A. Moustsen, F. Thorup, S. A. Edwards, and A. B. Lawrence. 2013. The welfare implications of large litter size in the domestic pig II: management factors. *Anim. Welf.* 22:2019–238. doi:10.7120/09627286.22.2.219
- Blavi, L., D. Solà-Oriol, J. J. Mallo, and J. F. Pérez. 2016. Anethol, cinnamaldehyde, and eugenol inclusion in feed affects postweaning performance and feeding behavior of piglets. *J. Anim. Sci.* 94:5262–5271. doi:10.2527/jas.2016-0760
- Boudry, G., V. Douard, J. Mourot, J. P. Lallès, and I. Le Huërou-Luron. 2009. Linseed oil in the maternal diet during gestation and lactation modifies fatty acid composition, mucosal architecture, and mast cell regulation of the ileal barrier in piglets. *J. Nutr.* 139:1110–1117. doi:10.3945/jn.108.102640
- van den Brand, H., D. Wamsteeker, M. Oostindjer, L. C. M. van Enckevort, A. F. B. van der Poel, B. Kemp, and J. E. Bolhuis. 2014. Effects of pellet diameter during and after lactation on feed intake of piglets pre- and postweaning. *J. Anim. Sci.* 92:4145–4153. doi: 10.2527/jas2014-7408
- Bruininx, E. M. A. M., G. P. Binnendijk, C. M. C. van der Peet-Schwering, J. W. Schrama, L. A. den Hartog, H. Everts, and A. C. Beynen. 2002. Effect of creep feed consumption on individual feed intake characteristics and performance of group-housed weanling pigs. *J. Anim. Sci.* 80:1413–1418. doi:10.2527/2002.8061413x
- Cabrera, R. A., J. L. Usry, C. Arrellano, E. T. Nogueira, M. Kutschenko, A. J. Moeser, and J. Odle. 2013. Effects of creep feeding and supplemental glutamine or glutamine plus glutamate (Aminogut) on pre- and post-weaning growth performance and intestinal health of piglets. *J. Anim. Sci. Biotechnol.* 4:29. doi:10.1186/2049-1891-4-29
- Clark, A. B., J. A. De Jong, J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. C. Woodworth. 2015. Effects of creep feed pellet diameter on suckling and nursery pig performance. *Kansas Agric. Exp. Sta. Res. Rep.* 8:13. doi:10.4148/2378-5977.1118
- Craig, J. R., C. L. Collins, K. L. Bunter, J. J. Cottrell, F. R. Dunshea, and J. R. Pluske. 2017. Poorer lifetime performance of gilt progeny compared with sow progeny is largely due to weight differences at birth and reduced growth in the preweaning period, and is not improved by progeny segregation after weaning. *J. Anim. Sci.* 95:4904–4916. doi:10.2527/jas2017.1868.
- Craig, J. R., F. R. Dunshea, J. J. Cottrell, J. B. Furness, U. A. Wijesiriwardana, and J. R. Pluske. 2019. A comparison of the anatomical and gastrointestinal functional development between gilt and sow progeny around birth and weaning. *J. Anim. Sci.* 97:3809–3822. doi:10.1093/jas/skz217
- D'Eath, R. B. 2005. Socialising piglets before weaning improves social hierarchy formation when pigs are mixed post-weaning. *Appl. Anim. Behav. Sci.* 93:199–211. doi:10.1016/j.applanim.2004.11.019
- Davies, M. J., and R. J. Norman. 2002. Programming and reproductive functioning. *Trends Endocrinol. Metab.* 13:386–392. doi:10.1016/s1043-2760(02)00691-4
- Deen, M. G. H. and G. Bilkei. 2004. Cross fostering of low-birthweight piglets. *Livest. Prod. Sci.* 90:279–284. doi:10.1016/j.livprodsci.2004.02.012

- Donovan, T. S., and S. S. Dritz. 2000. Effect of split nursing on variation in pig growth from birth to weaning. *J. Am. Vet. Med. Assoc.* 217:79–81. doi:[10.2460/javma.2000.217.79](https://doi.org/10.2460/javma.2000.217.79)
- Faccin, J. E. G., F. Laskoski, L. F. Hernig, R. Kummer, G. F. R. Lima, U. A. D. Orlando, M. A. D. Gonçalves, A. P. G. Mellagi, R. R. Ulguim, and F. P. Bortolozzo. 2020. Impact of increasing weaning age on pig performance and belly nosing prevalence in a commercial multisite production system. *J. Anim. Sci.* 1–8. doi:[10.1093/jas/skaa031](https://doi.org/10.1093/jas/skaa031)
- Feldpausch, J. A., J. Jourquin, J. R. Bergstrom, J. L. Bargaen, C. D. Bokenkroger, D. L. Davis, J. M. Gonzalez, J. L. Nelssen, C. L. Puls, W. E. Trout, et al. 2019. Birth weight threshold for identifying piglets at risk for preweaning mortality. *Transl. Anim. Sci.* 3:633–640. doi:[10.1093/tas/txz076](https://doi.org/10.1093/tas/txz076)
- Figuroa, J., D. Solá-Oriol, X. Manteca, J. F. Pérez. 2013. Social learning of feeding behavior in pigs: effects of neophobia and familiarity with the demonstrator conspecific. *Appl. Anim. Behav. Sci.* 148:120–127. doi:[10.1016/j.applanim.2013.06.002](https://doi.org/10.1016/j.applanim.2013.06.002)
- Fraser, D., E. A. Pajor, and J. J. R. Feddes. 1994. The relationship between creep feeding behavior of piglets and adaptation to weaning: effect of diet quality. *Can. J. Anim. Sci.* 74:1–6. doi:[10.4141/cjas94-001](https://doi.org/10.4141/cjas94-001)
- Fraser, D., P. A. Phillips, B. K. Thompson, and W. B. Peeters. 1988. Use of water by piglets in the first days after birth. *Can. J. Anim. Sci.* 68:603–610. doi:[10.4141/cjas88-070](https://doi.org/10.4141/cjas88-070)
- Fuentes, M., J. Ota, M. L. Hevia, A. Quiles, and F. C. Fuentes. 2010. Effect of olfactory stimulation during suckling on agonistic behavior in weaned pigs. *J. Swine Health Prod.* 20:25–33. Available online at <http://www.aasv.org/shap.html>
- Gabler, N. K., J. D. Spencer, D. M. Webel, and M. E. Spurlock. 2007. In utero and postnatal exposure to long chain (n-3) PUFA enhances intestinal glucose absorption and energy stores in weanling pigs. *J. Nutr.* 137:2351–2358. doi:[10.1093/jn/137.11.2351](https://doi.org/10.1093/jn/137.11.2351)
- de Greeff, A., J. W. Resink, H. M. van Hees, L. Ruuls, G. J. Klaassen, S. M. Rouwers, and N. Stockhofe-Zurwieden. 2016. Supplementation of piglets with nutrient-dense complex milk replacer improves intestinal development and microbial fermentation. *J. Anim. Sci.* 94:1012–1019. doi:[10.2527/jas.2015-9481](https://doi.org/10.2527/jas.2015-9481)
- Gresse, R., F. Chaucheyras-Durand, M. A. Fleury, T. Van de Wiele, E. Forano, and S. Blanquet-Diot. 2017. Gut microbiota dysbiosis in postweaning piglets: understanding the keys to health. *Trends Microbiol.* 25:851–873. doi:[10.1016/j.tim.2017.05.004](https://doi.org/10.1016/j.tim.2017.05.004)
- Hart, A., and M. A. Kamm. 2002. Review article: mechanisms of initiation and perpetuation of gut inflammation by stress. *Aliment. Pharmacol. Ther.* 16:2017–2028. doi:[10.1046/j.0269-2813.2002.01359.x](https://doi.org/10.1046/j.0269-2813.2002.01359.x)
- Heim, G., A. P. G. Mellagi, T. Bierhals, L. P. de Souza, H. C. C. de Fries, P. Piuco, E. Seidel, M. L. Bernardi, I. Wentz, and F. P. Bortolozzo. 2012. Effects of cross-fostering within 24 h after birth on pre-weaning behavior, growth performance and survival rate of biological and adopted piglets. *Livest. Sci.* 150:121–127. doi:[10.1016/j.livsci.2012.08.011](https://doi.org/10.1016/j.livsci.2012.08.011)
- Hessel, E. F., K. Reiners, and H. F. A. van den Weghe. 2006. Socializing piglets before weaning: effects on behavior of lactating sows, pre- and post-weaning behavior and performance of piglets. *J. Anim. Sci.* 84: 2847–2855. doi:[10.2527/jas.2005-606](https://doi.org/10.2527/jas.2005-606)
- Hötzel, M. J., L. C. P. Machado, F. M. Wolf, and O. A. D. Costa. 2004. Behaviour of sows and piglets reared in intensive outdoor or indoor systems. *Appl. Anim. Behav. Sci.* 86:27–39. doi:[10.1016/j.applanim.2003.11.014](https://doi.org/10.1016/j.applanim.2003.11.014)
- Hu, L., S. Geng, Y. Li, S. Cheng, X. Fu, X. Yue, and X. Han. 2018. Exogenous fecal microbiota transplantation from local adult pigs to crossbred newborn piglets. *Front. Microbiol.* 8:2663. doi:[10.3389/fmicb.2017.02663](https://doi.org/10.3389/fmicb.2017.02663)
- Huting, A. M. S., K. Almond, I. Wellock, and I. Kyriazakis. 2017. What is good for small piglets might not be good for big piglets: the consequences of cross-fostering and creep feed provision on performance to slaughter. *J. Anim. Sci.* 95:4926–4944. doi:[10.2527/jas2017.1889](https://doi.org/10.2527/jas2017.1889)
- Huting, A. M. S., I. Wellock, S. Tuer, and I. Kyriazakis. 2019. Weaning age and post-weaning nursery feeding regime are important in improving the performance of lightweight pigs. *J. Anim. Sci.* 97:4834–4844. doi:[10.1093/jas/skz337](https://doi.org/10.1093/jas/skz337)
- Jarocka-Cyrta, E., N. Perin, M. Keelan, E. Wierzbicki, T. Wierzbicki, M. T. Clandinin, and A. B. R. Thomson. 1998. Early dietary experience influences ontogeny of intestine in response to dietary lipid changes in later life. *Am. J. Physiol.* 275:G250–G258. Doi:[10.1152/ajpgi.1998.275.2.G250](https://doi.org/10.1152/ajpgi.1998.275.2.G250)
- Ji, Y., Z. Wu, Z. Dai, X. Wang, J. Li, B. Wang, and G. Wu. 2017. Fetal and neonatal programming of postnatal growth and feed efficiency in swine. *J. Anim. Sci. Biotechnol.* 8:42. doi:[10.1186/s40104-017-0173-5](https://doi.org/10.1186/s40104-017-0173-5)
- Johnston, L., J. Shurson, and M. Whitney. 2008. Nutritional effects of fetal imprinting in swine. *Minnesota Nutr. Conf., Owatonna, Minnesota.*
- Kelly, J. R., P. J. Kennedy, J. F. Cryan, T. G. Dinan, G. Clarke, and N. P. Hyland. 2015. Breaking down the barriers: the gut microbiome, intestinal permeability and stress-related psychiatric disorders. *Front. Cell. Neurosci.* 9:392. doi:[10.3389/fncel.2015.00392](https://doi.org/10.3389/fncel.2015.00392)
- de Lange, C. F. M., J. Pluske, J. Gong, and C. M. Nyachoti. 2010. Strategic use of feed ingredients and feed additives to stimulate gut health and development in young pigs. *Livest. Sci.* 134:124–134. doi:[10.1016/livsci.2010.06.117](https://doi.org/10.1016/livsci.2010.06.117)
- Lau, Y. Y., J. R. Pluske, and P. A. Fleming. 2015. Does the environmental background (intensive v. outdoor systems) influence the behaviour of piglets at weaning? *Animal* 9:1361–1372. doi:[10.1017/S1751731115000531](https://doi.org/10.1017/S1751731115000531)
- Lauridsen, C. 2020. Effects of dietary fatty acids on gut health and function of pigs pre- and post-weaning. *J. Anim. Sci.* 98:1–12. doi:[10.1093/jas/skaa086](https://doi.org/10.1093/jas/skaa086)
- Lucas, A. 1991. Programming by early nutrition in man. In: G.R. Block and J. Whelan, editors. *The Childhood Environment and Adult Disease*. Hoboken, NJ: John Wiley & Sons, Inc.; p. 38–55.
- Main, R. G., S. S. Dritz, M. D. Tokach, R. D. Goodband, and J. L. Nelssen. 2004. Increasing weaning age improves pig performance in a multisite production system. *J. Anim. Sci.* 82:1499–1507. doi:[10.2527/2004.8251499x](https://doi.org/10.2527/2004.8251499x)
- McLamb, B. L., A. J. Gibson, E. L. Overman, C. Stahl, and A. J. Moeser. 2013. Early weaning stress in pigs impairs innate mucosal immune responses to enterotoxigenic *E. coli* challenge and exacerbates intestinal injury and clinical disease. *PLoS One* 8:e59838. doi:[10.1371/journal.pone.0059838](https://doi.org/10.1371/journal.pone.0059838)
- Medland, J. E., C. S. Pohl, L. L. Edwards, S. Frandsen, K. Bagley, Y. Li, and A. J. Moeser. 2016. Early life adversity in piglets induces long-term upregulation of the enteric

- cholinergic nervous system and heightened, sex-specific secretomotor neuron responses. *Neurogastroenterol. Motil.* 28:1317–1329. doi:[10.1111/nmo.12828](https://doi.org/10.1111/nmo.12828)
- van der Meulen, J., S. J. Koopmans, R. A. Dekker, and A. Hoogendoorn. 2010. Increasing weaning age of piglets from 4 to 7 weeks reduces stress, increases post-weaning feed intake but does not improve intestinal functionality. *Animal* 4:1653–1661. doi:[10.1017/S1751731110001011](https://doi.org/10.1017/S1751731110001011)
- Middelkoop, A., N. Costermans, B. Kemp, and J. E. Bolhuis. 2019. Feed intake of the sow and playful creep feeding of piglets influence piglet behavior and performance before and after weaning. *Nature*. 9:16140. doi:[10.1038/s41598-019-52530-w](https://doi.org/10.1038/s41598-019-52530-w)
- Moerer, A. J., C. V. Klok, K. A. Ryan, J. G. Wooten, D. Little, V. L. Cook, and A. T. Blikslager. 2007a. Stress signaling pathways activated by weaning mediate intestinal dysfunction in the pig. *Am. J. Physiol. Gastrointest. Liver Physiol.* 292:G173–G181. doi:[10.1152/ajpgi.00197.2006](https://doi.org/10.1152/ajpgi.00197.2006)
- Moerer, A. J., C. S. Pohl, and M. Rajput. 2017. Weaning stress and gastrointestinal barrier development: implications for lifelong gut health in pigs. *Anim. Nutr.* 3:313–321. doi:[10.1016/j.aninu.2017.06.003](https://doi.org/10.1016/j.aninu.2017.06.003)
- Moerer, A. J., K. A. Ryan, P. K. Nighot, and A. T. Blikslager. 2007b. Gastrointestinal dysfunction induced by early weaning is attenuated by delayed weaning and mast cell blockage in pigs. *Am. J. Physiol. Gastr. Liver Physiol.* 293:G413–G421. doi:[10.1152/ajpgi.00304.2006](https://doi.org/10.1152/ajpgi.00304.2006)
- Morton, J. M., A. J. Langemeier, T. J. Rathbun, and D. L. Davis. 2019. Immunocrit, colostrum intake, and preweaning body weight gain in piglets after split suckling based on birth weight or birth order. *Transl. Anim. Sci.* 3:1460–1465. doi:[10.1093/tas/txz131](https://doi.org/10.1093/tas/txz131)
- Niederwerder, M. C., L. A. Constance, R. R. Rowland, W. Abbas, S. C. Fernando, M.L. Potter, M. A. Sheahan, T. E. Burkey, R. A. Hesse, and A. G. Cino-Ozuna. 2018. Fecal microbiota transplantation is associated with reduced morbidity and mortality in Porcine Circovirus Associated Disease. *Front. Microbiol.* 9:1631. doi:[10.3389/fmicb.2018.01631](https://doi.org/10.3389/fmicb.2018.01631)
- North, L. and A. H. Stewart. (2000) The effect of mixing litters pre-weaning on the performance of piglets pre and post weaning. In: *Proceedings of the British Society of Animal Science 2000*; p. 135.
- Novotni-Dankó, G., P. Balogh, L. Huzsval, and Z. S. Györl. 2015. Effect of feeding liquid milk supplement on litter performance and on sow back-fat thickness change during the suckling period. *Arch. Anim. Breed.* 58:229–235. doi:[10.5194/aab-58-229-2015](https://doi.org/10.5194/aab-58-229-2015)
- Oostindjer, M., J. E. Bolhuis, H. van den Brand, E. Roura, and B. Kemp. 2010. Prenatal flavor exposure affects growth, health and behavior of newly weaned piglets. *Physiol. Behav.* 99:579–586. doi:[10.1016/j.physbeh.2010.01.031](https://doi.org/10.1016/j.physbeh.2010.01.031)
- Oostindjer, M., J. E. Bolhuis, K. Simon, H. van den Brand, and B. Kemp. 2011. Perinatal flavour learning and adaptation to being weaned: all the pig needs is smell. *PLoS One* 6:e25318. doi:[10.1371/journal.pone.0025318](https://doi.org/10.1371/journal.pone.0025318)
- van Oostrum, M., A. Lammers, and F. Molist. 2016. Providing artificial milk before and after weaning improves post-weaning piglet performance. *J. Anim. Sci.* 94:429–432. doi:[10.2527/jas2015-9732](https://doi.org/10.2527/jas2015-9732)
- Pajor, E. A., D. Fraser, and D. L. Kramer. 1991. Consumption of solid food by suckling pigs: individual variation and relation to weight gain. *Appl. Anim. Behav. Sci.* 32:139–155. doi:[10.1016/S0168-1591\(05\)80038-3](https://doi.org/10.1016/S0168-1591(05)80038-3)
- Pajor, E. A., D. M. Weary, C. Caceres, D. Fraser, and D. L. Kramer. 2002. Alternative housing for sows and litters. Part 3. Effects of piglet diet quality and sow-controlled housing on performance and behavior. *App. Anim. Behav. Sci.* 76:267–277. doi:[10.1016/S0168-1591\(02\)00010-2](https://doi.org/10.1016/S0168-1591(02)00010-2)
- Pajžlar, L., and J. Skok. 2019. Cross-fostering into smaller or older litter makes piglets integration difficult: suckling stability-based rationale. *Appl. Anim. Behav. Sci.* 220:104856. doi:[10.1016/j.applanim.2019.104856](https://doi.org/10.1016/j.applanim.2019.104856)
- Phillips, P. A., and D. Fraser. 1991. Discovery of selected water dispensers by newborn pigs. *Can. J. Anim. Sci.* 71:233–236. doi:[10.4141/cjas91-026](https://doi.org/10.4141/cjas91-026)
- Phillips, P. A., and D. Fraser. 2001. Technical note: modifying water nipples for newborn pigs. *Can. Biosystems Engineering.* 43:1–5. doi:
- Pluske, J. R. 2016. Invited review: aspects of gastrointestinal growth and maturation in the pre- and post-weaning periods of pigs. *J. Anim. Sci.* 94:399–411. doi: [10.2527/jas2015-9767](https://doi.org/10.2527/jas2015-9767)
- Pluske, J. R., D. J. Kerton, P. D. Cranwell, R. G. Campbell, B. P. Mullan, R. H. King, G. N. Power, S. G. Pierzynowski, B. Westrom, C. Rippe, et al. 2003. Age, sex, and weight at weaning influence organ weight and gastrointestinal development of weaning pigs. *Aust. J. Agric. Res.* 54:515–527. doi:[10.1071/AR02156](https://doi.org/10.1071/AR02156)
- Pluske, J. R., D. L. Turpin, and J. C. Kim. 2018. Gastrointestinal tract (gut) health in the young pig. *Anim. Nutr.* 4:187–196. doi:[10.1016/j.aninu.2017.12.004](https://doi.org/10.1016/j.aninu.2017.12.004)
- Pohl, C. S., J. E. Medland, E. Mackey, L. L. Edwards, K. D. Bagley, M. P. DeWilde, K. J. Williams, and A. J. Moerer. 2017. Early weaning stress induces chronic functional diarrhea, intestinal barrier defects, and increased mast cell activity in a porcine model of early life adversity. *Neurogastroenterol. Motil.* 29:e13118. doi:[10.1111/nom.13118](https://doi.org/10.1111/nom.13118)
- Poulsen, A. R., N. de Jonge, S. Sugiharto, J. L. Nielsen, C. Lauridsen, and N. Canibe. 2017. The microbial community of the gut differs between piglets fed sow milk, milk replacer or bovine colostrum. *Br. J. Nutr.* 117:964–978. doi:[10.1017/S0007114517000216](https://doi.org/10.1017/S0007114517000216)
- Quiniou, N., J. Dagorn, and D. Gaudré. 2002. Variation of piglets' birth weight and consequences on subsequent performance. *Livest. Prod. Sci.* 78:63–70. doi:[10.1016/S0301-6226\(02\)00181-1](https://doi.org/10.1016/S0301-6226(02)00181-1)
- Rosero, D. S., R. D. Boyd, J. Odle, and E. van Heugten. 2016. Optimizing dietary lipid use to improve essential fatty acid status and reproductive performance of the modern lactating sow: a review. *J. Anim. Sci. Biotechnol.* 7:34. doi:[10.1186/s40104-016-0092-x](https://doi.org/10.1186/s40104-016-0092-x)
- Salazar, L. C., H. Ko, C. Yang, L. Llonch, X. Manteca, I. Camerlink, P. Llonch. 2018. Early socialization as a strategy to increase piglets' social skills in intensive farming conditions. *Appl. Anim. Behav. Sci.* 206:25–31. doi:[10.1016/j.applanim.2018.05.033](https://doi.org/10.1016/j.applanim.2018.05.033)
- Smith, F., J. E. Clark, B. L. Overman, C. C. Tozel, J. H. Huang, J. E. Rivier, A. T. Blikslager, and A. J. Moerer. 2010. Early weaning stress impairs development of mucosal barrier function in the porcine intestine. *Am. J. Physiol. Gastrointest. Liver Physiol.* 298:G352–G363. doi:[10.1152/ajpgi.00081.2009](https://doi.org/10.1152/ajpgi.00081.2009)
- Sugiharto, S., A. R. Poulsen, N. Canibe, and C. Lauridsen. 2015. Effect of bovine colostrum feeding in comparison with milk replacer and natural feeding on the immune response and colonization of enterotoxigenic *Escherichia*

- coli* in the intestinal tissue of piglets. *Br. J. Nutr.* 113:923–934. doi:10.1017/S0007114514003201
- Sulabo, R. C., M. D. Tokach, J. M. DeRouchey, S. S. Dritz, R. D. Goodband, and J. L. Nelssen. 2010a. Effects of creep feeder design and feed accessibility on preweaning pig performance and the proportion of pigs consuming creep feed. *J. Swine Health Prod.* 18:174–181. doi:10.4148/2378-5977.7066
- Sulabo, R. C., M. D. Tokach, J. M. DeRouchey, C. D. Risley, J. L. Nelssen, S. S. Dritz, and R. D. Goodband. 2008. Influence of organoleptic properties of the feed and nursery diet complexity on preweaning and nursery performance. *Kansas Agric. Exp. Sta. Res. Rep.* 0:31–41. doi:10.4148/2378-5977.7004
- Sulabo, R. C., M. D. Tokach, S. S. Dritz, R. D. Goodband, J. M. DeRouchey, and J. L. Nelssen. 2010. Effects of varying creep feeding duration on the proportion of pigs consuming creep feed and neonatal pig performance. *J. Anim. Sci.* 88:3154–3162. doi:10.2527/jas.2009-2134
- Tokach, M. D., H. S. Cemin, R. C. Sulabo, and R. D. Goodband. 2020. Feeding the suckling pig: creep feeding. In: C. Farmer, editor. *The Suckling and Weaned Piglet*. The Netherlands: Wageningen Academics; p. 139–152.
- Tsai, T. C., H. J. Kim, M. A. Sales, X. Wang, G. F. Erf, E. B. Kegley, F. G. Carbonero, M. van der Merwe, R. K. Buddington, and C. V. Maxwell. 2016. Effect of topsoil exposure during lactation on subsequent performance and abundance of innate and adaptive immune cells in pigs. *J. Anim. Sci.* 94(Suppl. 2):84–85. (Abstr.) doi:10.2527/msasas2016-179
- Turpin, D. L., P. Langendijk, T. Chen, D. Lines, and J. R. Pluske. 2016a. Intermittent suckling causes a transient increase in cortisol that does not appear to compromise selected measures of piglet welfare and stress. *Animals.* 6:24. doi:10.3390/ani6030024
- Turpin, D. L., P. Langendijk, T. Chen, D. Lines, and J. R. Pluske. 2016b. Intermittent suckling in combination with an older weaning age improves growth, feed intake and aspects of gastrointestinal tract carbohydrate absorption in pigs after weaning. *Animals.* 6:66. doi:10.3390/ani6110066
- Turpin, D. L., P. Langendijk, K. Plush, and J. R. Pluske. 2017. Intermittent suckling with or without co-mingling of non-littermate piglets before weaning improves piglet performance in the immediate post-weaning period when compared with conventional weaning. *J. Anim. Sci. Biotechnol.* 8:14. doi:10.1186/s40104-017-0144-x
- Vo, N., T. C. Tsai, C. Maxwell, and F. Carbonero. 2017. Early exposure to agricultural soil accelerates the maturation of the early-life pig gut microbiota. *Anaerobe* 45:31–39. doi:10.1016/j.anaerobe.2017.02.022
- Wolter, B. F., M. Ellis, B. P. Corrigan, and J. M. DeDecker. 2002. The effect of birth weight and feeding of supplemental milk replacer to piglets during lactation on preweaning and postweaning growth performance and carcass characteristics. *J. Anim. Sci.* 80:301–308. doi:10.2527/2002.802301x
- Wu, G., F. W. Bazer, G. A. Johnson, D. A. Knabe, R. C. Burghardt, T. E. Spencer, X. L. Li, and J. J. Wang. 2011. Triennial growth symposium: important roles for L-glutamine in swine nutrition and production. *J. Anim. Sci.* 89:2017–2030. Doi:10.2527/jas.2010-3614
- Xiang, Q., X. Wu, Y. Pan, L. Wang, C. Cui, Y. Guo, L. Zhu, J. Peng, and H. Wei. 2020. Early-life intervention using fecal microbiota combined with probiotics promotes gut microbiota maturation, regulates immune system development, and alleviates weaning stress in piglets. *Int. J. Mol. Sci.* 21:503. doi:10.3390/ijms21020503
- Yan, L., H. D. Jang, and I. H. Kim. 2011. Effects of creep feed with varied energy density diets on litter performance. *Asian-Aust. J. Anim. Sci.* 24:1435–1439. doi:10.5713/ajas.2011.11116
- Yu, L. C., J. Wang, S. Wei, and Y. Ni. 2012. Host-microbial interaction and regulation of interstitial epithelial barrier function: from physiology to pathology. *World J. Gastrointest. Pathophysiol.* 3:27–43. doi: 10.4291/wjgp.v3.i1.27
- Zhang, S., X. Zeng, M. Ren, X. Mao, and S. Qiao. 2017. Novel metabolic and physiological functions of branched chain amino acids: a review. *J. Anim. Sci. Biotechnol.* 8:10. doi:10.1186/s40104-016-0139-z
- Zhu, Y., T. Li, S. Huang, W. Wang, Z. Dai, C. Feng, G. Wu, and J. Wang. 2018. Maternal L-glutamine supplementation during late gestation alleviates intrauterine growth restriction-induced intestinal dysfunction in piglets. *Amino Acids* 50:1289–1299. doi:10.1007/s00726-018-2608-5