Animal 16 (2022) 100350

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Review: Improving the performance of neonatal piglets

C. Farmer [a,*], S.A. Edwards [b]

[a] Agriculture and Agri-Food Canada, Sherbrooke R & D Centre, 2000 College St., Sherbrooke, QC J1M 0C8, Canada
[b] Newcastle University, School of Natural and Environmental Sciences, Agriculture Building, Newcastle upon Tyne NE1 7RU, UK

ARTICLE INFO

Article history:
Received 14 April 2021
Revised 23 July 2021
Accepted 26 July 2021
Available online 10 November 2021

Keywords:
Gestation
Lactation
Management
Mortality
Sow

ABSTRACT

Newborn piglets have a high incidence of preweaning mortality that is not only associated with low birth weights but also with the presence of intra-uterine growth-restricted (**IUGR**) piglets. Such IUGR piglets are commonly seen in litters from hyperprolific sows as a result of insufficient placental transfer of nutrients. Nutritional strategies can be used prior to and during gestation to enhance foetal development and can also be implemented in the transition period to reduce the duration of farrowing and increase colostrum yield. Recent findings showed that the energy status of sows at the onset of farrowing is crucial to diminish stillbirth rate. Newborn piglets often fail to consume enough colostrum to promote thermostability and subsequent growth, and this is particularly problematic in very large litters when there are fewer available teats than the number of suckling piglets. One injection of 75 IU of oxytocin approximately 14 h after farrowing can prolong the colostral phase, hence increasing the supply of immunoglobulins to piglets. Nevertheless, assistance must be provided to piglets after birth in order to increase their chance of survival. Various approaches can be used, such as: (1) optimising the farrowing environment, (2) supervising farrowing and assisting newborn piglets, (3) using cross-fostering techniques, (4) providing nurse sows, and 5) providing artificial milk. Although research advances have been made in developing feeding and management strategies for sows that increase performance of their newborn piglets, much work still remains to be done to ensure that maximal outcomes are achieved.

Implications

The problem of high morbidity and mortality in neonatal piglets is still widespread and is exacerbated by increasing use of hyperprolific sow lines with their greater incidence of intra-uterine growth-restricted piglets. It has been shown that correct body condition of sows and targeted feed formulations can enhance piglet survival. Cross-fostering is a commonly used practice to equalise litter (and piglet) size, but it cannot ensure that there are enough teats available in very large litters. The use of nurse sows or artificial milk replacers are viable options but demand careful management and can be quite costly.

Introduction

The problem of high morbidity and mortality in neonatal piglets is one that has existed for a very long time. Approximately 15–20% of all piglets born will die either during the farrowing process or in early lactation and, despite improved management, this is still the case today largely due to the increased selection pressure to create hyperprolific sow lines (Baxter and Edwards, 2018). The two most important causes of death are stillborn piglets and crushing by the sow (Edwards and Baxter, 2015), but there are many predisposing physiological factors leading to these problems. Newborn piglets are most vulnerable due to their low body weight, especially relative to that of the sow, and to their lack of energy reserves. These problems can be associated with poor vitality, predisposing to starvation and hypothermia, which can be further exacerbated by conditions before, during or after birth. Ultimately, it is the vitality of individual piglets combined with the behaviour of their dam and the adequacy of the housing conditions that will determine survival rate. The various links between piglet vitality and preweaning mortality are illustrated in Fig. 1.

Many attempts have been made in the past years to develop best-adapted strategies during gestation, the transition period or early lactation in order to improve the survival and growth of neonatal piglets. Such strategies encompass nutritional, hormonal, behavioural and environmental components. The current review will succinctly describe the physiological limitations and challenges of newborn piglets that lead to increased mortality and the recent advances in nutritional and management strategies elaborated to assist the piglets in this most difficult period.

* Corresponding author.
E-mail address: chantal.farmer@canada.ca (C. Farmer).

https://doi.org/10.1016/j.animal.2021.100350
1751-7311/

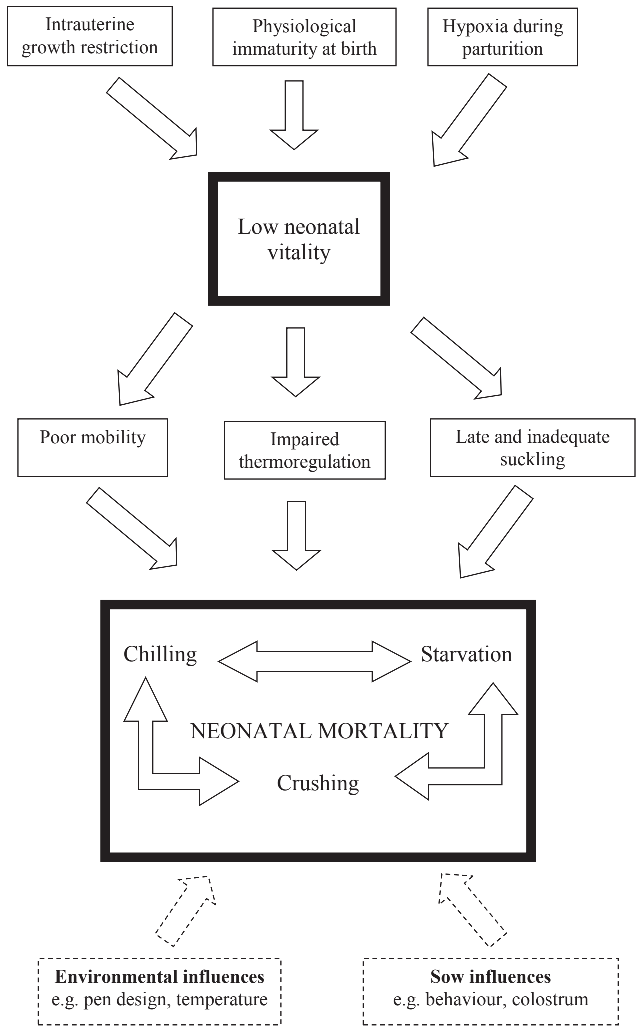

Fig. 1. The role of neonatal piglet vitality in preweaning mortality (adapted from Farmer and Edwards, 2020). The solid boxes represent characteristics of the neonatal piglet, while the broken line boxes indicate the additional external influences affecting risk of mortality.

Factors affecting vitality of neonatal piglets

Physiology of the intra-uterine growth-restricted piglet

It has long been established that low birth weight piglets have a greater incidence of mortality (Roehe and Kalm, 2000; Baxter et al., 2008; Pedersen et al., 2011) due to their poorer thermoregulatory ability and lower success in competing with littermates to achieve early and adequate colostrum intake (Edwards and Baxter, 2015). Indeed, piglets with a birth weight of <1 kg were reported to have 40% preweaning mortality, compared with 15% for piglets weighing 1.0–1.2 kg, and 7% when birth weight exceeded 1.6 kg (Roehe and Kalm, 2000). More recent work also reported an increased mortality rate from birth to slaughter in piglets weighing less than 0.95 kg (Díaz et al., 2017). Nevertheless, there are indications that factors other than birth weight are also important. For instance, certain body characteristics, such as a long thin shape (Baxter et al., 2008) reflected in a lower body mass index (Rootwelt et al., 2013), can predispose to mortality. This morphological trait is a characteristic of intra-uterine growth-restricted (**IUGR**) neonates of many species, including swine (Edwards et al., 2019), and is associated with a 'dolphin-like' head shape due to the brain-sparing response to foetal undernutrition (Amdi et al., 2013; Hales et al., 2013). Such IUGR piglets have poorer brain development as well as that of many organs including the heart, gastrointestinal tract and muscles, which hinders the intake and absorption of colostrum (Edwards et al., 2019). An association between the lower vitality of IUGR piglets and neural immaturity is suggested by the fact that the brain of low birth weight piglets is less myelinated and has less dendritic development than that of normal littermates (Dickerson et al., 1971).

Detailed information on the identification of IUGR piglets and the links between IUGR status, reduced vitality and lower colostrum intake was previously published (Edwards et al., 2019). It is important to mention that many of the neonatal characteristics associated with viability, such as IUGR status, birth weight, energy stores, and the ability to ingest adequate amounts of colostrum early on, are influenced by foetal development. It is now acknowledged that poor foetal growth is linked to a lesser ability of the placenta to transfer nutrients from the dam to the developing foetus (Leenhouwers et al., 2002; Van Rens et al., 2005). Hence, the size and vascularity of the placenta are most important for foetal development (Wu et al., 2004; Foxcroft et al., 2009) and an association between the incidence of IUGR in newborn piglets and a poorer quality of placenta was reported (Baxter et al., 2008). This is most prevalent in large litters because of uterine crowding that decreases the surface area available per foetus. While changes in the placental morphology can to some degree compensate for reduced uterine space, with this compensation being more pronounced in the Chinese Meishan than in European White breeds, limitations in placental transfer capacity ultimately restrict growth and development of smaller littermates (Miles and Vallet, 2021).

Interestingly, recent findings show that genetic selection could be used to decrease the prevalence of IUGR piglets. When using piglet head shape as a phenotypic criterion for IUGR, and expressing its occurrence as a sow trait (i.e. noting the incidence of IUGR piglets per litter), a heritability of 0.2 was reported (Matheson et al., 2018).

Stillbirth

Stillbirths generally account for 30–40% of all preweaning mortalities in piglets. The main cause of stillborn piglets is a lack of oxygen during the farrowing process; hence, later-born piglets and prolonged farrowings are major risk factors (Edwards and Baxter, 2015). There has been increased attention to the time course of farrowing as a result of recent reports of extreme durations in modern hyperprolific genotypes. Hales et al. (2015) noted that 29% of the 118 sows in their Danish study of free vs crated farrowing accommodation had farrowing durations exceeding 9 h, while only 33% completed farrowing in less than 5 h, which in previous studies had been considered the criterion for a prolonged farrowing (Oliviero et al., 2010). In 2005, Van Dijk et al. (2005) carried out a contemporary comparison of five different breeds in which they analysed both the total duration of farrowing (mean of 166 min) and the birth interval between individual piglets (mean of 15.7 min). They showed a significant effect of litter size on farrowing duration, and they also found that breed affected the total duration of the expulsive stage of farrowing, even after adjustment for differences in litter size. Meishan crossbred gilts had a shorter duration of the expulsive stage (130.4 min, SD = 89.4) and shorter birth intervals per piglet (14.2 min, SD = 23.0) than gilts or sows from European breeds. While not all breeds were present on the same farm, and thus other confounding factors may have been present, a significant difference in duration of the expulsive phase was shown between co-located Large White (135.9 min, SD = 73.0) and Dutch Landrace litters (245.8 min, SD = 107.2), with their crossbreds showing an intermediate mean (178.3 min, SD = 79.8). There was no effect of breed on individual birth intervals, but it was shown that increasing piglet birth weight in both the Meishan crossbred gilts and a commercial company damline resulted in increased individual birth intervals. It is thus to be expected that selection pressure for both increased litter size and increased piglet birth weight over recent years would impact adversely on the duration of farrowing. Such changes were demonstrated by Oliviero et al. (2019), who analysed the relationship between litter size and the duration of farrowing in 20 studies carried out from 1992 to 2018. They showed a change in the average duration of farrowing from slightly more than 2 h for 12 piglets in the earlier studies to more than 6 h for 19 piglets in the most recent studies. It is thus difficult to precisely delineate a normal from a prolonged parturition, since the commercial population of sows is of variable and continuously changing genetic composition and the detrimental effects of a longer farrowing for the piglet are of a graded rather than a threshold nature. Langendijk et al. (2018) demonstrated that the longer the foetus stayed in the uterus during the expulsive phase of farrowing, the higher was the risk of both stillbirth and postnatal mortality. As a result, various interventions designed to reduce farrowing duration have been investigated and their consequences for stillbirths, colostrum quality and intake, and mortality of liveborn piglets are discussed later in this review.

The incidence of stillbirths is linked not only to characteristics of the farrowing process but also to events taking place before farrowing, such as foetal development and placental quality (Baxter et al., 2008). It is more difficult for the IUGR piglets with a smaller and less efficient placenta to survive the farrowing process because of the respiratory challenges encountered. Indeed, Canario et al. (2014) noted that piglets of recent hyperprolific sow lines are more prone to be stillborn than those of older sow lines with smaller litter sizes. Furthermore, hypoxic stress, as measured by lactate concentrations in blood immediately after birth, was also greater in liveborn piglets that died before weaning compared to piglets that survived (Rootwelt et al., 2013), reflecting the detrimental consequences on neonatal physiology and piglet vigour.

Energy reserves

Piglets are most vulnerable at birth, largely due to their poor energy reserves. The carcass of newborn piglets contains only 1–2% fat (Elliot and Lodge, 1977), and liver and muscle glycogen are therefore important energy stores. Yet, these stores are depleted soon after birth with 51% of liver glycogen being used in the first 6 h (Boyd et al., 1978) and 42% of muscle glycogen being used in the first 12 h (Elliot and Lodge, 1977). Accordingly, Theil et al. (2011) reported that glycogen depots in newborn piglets can supply adequate amounts of energy for approximately 16 h. It is well known that piglets experience a thermoregulatory shock at birth because of the sudden 15–20 °C drop in their thermal environment. The inability of piglets to achieve thermostability at this time is due to their low provision of energy and to the fact that they are metabolically immature at birth (Herpin et al., 2002). Newborn piglets must therefore rely on external sources of heat for thermoregulation. The minimal critical temperature of neonatal piglets is 33–35 °C, and the ambient temperature in farrowing houses is generally quite lower than that. The energy need of piglets for heat production is supplied mainly by colostrum, which provides 75% of requirements at 24 °C (Herpin et al., 1994). However, piglets cannot ingest enough colostrum to rapidly reach an adequate body temperature, and this is partly due to their poor absorptive capacity (Gondret et al., 2020), making the use of supplementary heat essential for piglets.

Energy reserves present at birth will also affect the vitality of piglets. In a study looking at concentrations of glucose in blood and of glycogen in liver and skeletal muscles of newborn piglets, it was apparent that low-vitality piglets had lower muscle and liver glycogen at birth and failed to mobilise liver glycogen during the first 8 h postpartum. In consequence, it took 8 h for blood glucose concentrations to increase after birth in these low-vitality piglets compared with a rapid increase seen in normal piglets (Vanden Hole et al., 2019).

Nutritional strategies to improve foetal development

Nutritional events taking place even before ovulation in gilts and sows can influence the vitality of newborn piglets. In fact, events occurring as early as during the previous lactation can have an effect. Sows that lose too much weight during lactation will have less uniform piglet birth weights in their next litter (Wientjes et al., 2013). Hence, it is important to prevent excessive use of body reserves in lactating sows, and this is most important for primiparous sows. Prior to ovulation, oocyte quality can be improved by feeding more energy or more fermentable fibre (as sugar beet pulp) to sows (Ferguson et al., 2003 and 2007), while also lowering the occurrence of IUGR piglets. Supplying sow diets (71 and 63 control and treated sows, respectively) with dextrose and lactose (fermentable sources) during the last week of gestation and throughout lactation also increased mean liveborn piglet birth weight by 86 g in the next parity, likely through a greater secretion of insulin (Van den Brand et al., 2009).

Other nutritional approaches have aimed at enhancing the quality of placenta during gestation. Dietary supplementation with arginine, as a substrate for the synthesis of nitrous oxide and polyamines, was investigated with the goal of increasing placental blood supply. Feeding supplementary L-arginine to gilts (n = 26) starting on day 30 of gestation until farrowing increased total litter birth weight by 24% (Mateo et al., 2007), while treatment of gilts from days 14 to 28 of gestation (n = 10) led to a 32% greater total weight of viable foetuses on day 75 of pregnancy (Bérard and Bee, 2010). Nevertheless, a positive effect on birth weight has not always been observed (using 99 gilts and sows, Bass et al., 2017). Dietary supplementation with 1% L-glutamine, which acts as a precursor for arginine, from day 90 of pregnancy also led to greater mean piglet birth weights and decreased the number of IUGR piglets by 39% in the next parity (review by Wu et al., 2011). Furthermore, in their review, De Vos et al. (2014a) reported that feeding L-carnitine (used for energy metabolism) during gestation increased piglet birth weight by 2.7–7.9%, depending on the study.

Early nutritional studies aimed at increasing the nutrient supply available to the developing foetuses in order to increase birth weight. This was achieved by providing more feed to sows during late gestation when foetal growth is maximal. While some increase in piglet birth weight was observed (Yang et al., 2009; Ren et al., 2017), the response was not usually large. In the study by Che et al. (2019) using 118 sows, mean birth weight of piglets was only increased by 50 or 100 g with substantial increases in the dietary intakes of energy (33.8 vs 28.2 MJ/day of NE) or amino acids (20.6 vs 14.7 g/day of SID Lys), respectively, from day 90 of gestation onward. Certain studies on lipid supplementation of gestation diets, but not all, also showed an effect on piglet birth weight. For instance, feeding sows an extra 10% of energy in the first 60 days of pregnancy using palm oil or olive oil increased birth weight of their piglets (10.9 and 4.5% increases, respectively) relative to sows fed the extra energy as either sunflower or fish oil. The carcass content of piglets at birth was also affected, with piglets having more body fat when born from sows fed palm oil and less body fat when sows were fed olive oil (n = 24, Laws et al., 2007).

Sow feeding in gestation has also been used in an attempt to alter the energy stores of newborn piglets. When sows were fed 10% fat as of day 84 of gestation using soybean oil, coconut oil or medium chain triglycerides (**MCTs**), glycogen stores of their piglets at birth were increased by up to 20%. Hepatic glycogen in neonatal piglets was increased by using MCT or coconut oil, instead of soybean oil, in the diet of gestating sows and muscle glycogen content was also greater with MCT (Jean and Chiang, 1999). In contrast, feeding gestating sows a 6% fat diet using saturated fats, linseed or oats showed no effect on glycogen content in pigs at birth, but their carcasses contained most dry matter, protein and fat when sows were fed the diet containing linseed (Pastorelli et al., 2009). A more recent study also showed no effect on the content of glycogen in liver or muscle of newborn pigs when feeding a high-fibre diet (32–40% crude fibre) vs a 17% crude fibre diet to sows throughout gestation (Theil et al., 2011). However, in this study, the fibre source had an effect on body weight loss of fasted newborn piglets (n = 24), being 14% lower when sows were fed the pectin residue diet compared with the potato pulp, sugar beet pulp or control diets. Other studies showed no significant effect of high-fibre diets on colostrum yield when fed from day 26 of gestation onward (n = 9, Quesnel et al., 2009) or from day 106 onward (n = 15, Loisel et al., 2013); however, Loisel et al. (2013) reported that colostrum intake of piglets weighing less than 900 g at birth was approximately 60% greater when sows were fed a 23% compared with a 13% crude fibre diet.

It was demonstrated that feeding of the sow during gestation can affect the development of the foetal brain. Supplementing the late gestation diet with n-3 long chain polyunsaturated fatty acids, shown to affect brain weight and composition in newborn piglets, reduced the latency from birth to first standing (Adeleye et al., 2014) and first suckling (Rooke et al., 2001; Adeleye et al., 2014).

Despite the large body of research on nutritional interventions which indicate the potential to enhance piglet traits benefitting survival, it is apparent that many have not yet been widely adopted in commercial practice. An inconsistency in responses, with many studies also showing a lack of influence of maternal nutrition, can be attributed to differences in maternal genotype and management conditions, influencing both prolificacy and the ability to mobilise body reserves. This makes the extrapolation of small-scale research results to a diverse commercial population uncertain, and few interventions have been extensively evaluated in large-scale trials across different commercial conditions to confirm reliable cost-effective outcomes. It is therefore evident that the optimal feeding strategy to employ in different commercial circumstances in order to maximise foetal development and increase the vitality of newborn piglets still needs to be determined; hence, further research is warranted in this area.

Management practices in gestation to improve the performance of neonatal piglets

Factors other than nutrition may also be of importance for foetal development. One such factor is maternal stress. Studies looking at the effect of gestational stress in sows showed definite impacts on the physiological maturity of newborn piglets even though the effects on birth weight were variable (Kranendonk et al., 2006, Otten et al., 2007, Rutherford et al., 2009). These discrepancies on piglet birth weight may be linked to differences in the range of increases in maternal corticosteroid and catecholamine concentrations because of differing experimental models. The role of prenatal stress on the incidence of IUGR piglets needs to be further investigated but, considering that it could increase transplacental passage of maternal glucocorticoids to the foetus (Otten et al., 2008) and induce placental insufficiency (Zhao et al., 2020), its potential role is evident.

A common practice in the farrowing house is to induce farrowings in order to facilitate supervision and cross-fostering of piglets. Farrowing induction is achieved by using synthetic forms of prostaglandin F2alpha. When induction is done on days 113 or 114 of gestation, there is either a slight decrease (Devillers et al., 2007; Foisnet et al., 2011) or no effect (Otto et al., 2017; Boonraungrod et al., 2018) on colostrum yield. On the other hand, if induction is done on day 109 of gestation (n = 7), colostrum yield is 32% lower (Milon et al., 1983). It is therefore important not to induce farrowings earlier than one day before the expected farrowing date to avoid any negative impact on colostrum yield, as well as piglet maturity. Oxytocin (20 IU) or carbetocin (an oxytocin-like molecule, 0.6 μg/kg) were also injected after birth of the first piglet to reduce the duration of farrowing. Carbetocin had the greatest effect, with farrowing length decreasing from 228 to 151 min; however, colostrum yield was also decreased from 3.37 to 2.40 kg (Jiarpinitnun et al., 2019). Furthermore, such interventions must be used with care since inappropriate use of uterotonics can increase the need for farrowing assistance, foetal asphyxia and stillbirth (Muro et al., 2021).

Nutritional strategies in the transition period to improve the performance of neonatal piglets

The transition period in sows is generally considered as starting on day 108 of gestation and lasting until farrowing. This period is of particular physiological importance because it corresponds to the onset of lactogenesis and is associated with substantial hormonal and metabolite changes as well as altered nutrient utilization by the sow. It is also a period where nutrition could be used to favour the transfer of energy from the sow to the foetus and to improve the energy status of sows at parturition, hence reducing farrowing duration. Research has been undertaken to determine the best feeding strategy to use during this crucial period in order to improve energy stores and survivability of newborn piglets. As reported previously for studies carried out earlier in gestation, additional dietary energy provided to sows or changing the energy source during the transition period also altered the energy reserves of piglets at birth, but to a smaller extent. When the dietary energy source from day 109 of pregnancy onward was either corn oil or corn starch, replacing corn oil with corn starch had no effect on carcass fat. However, feeding corn starch increased both liver and muscle glycogen contents whereas feeding corn oil increased only glycogen in muscles (n = 20 piglets, Seerley et al., 1974). Supplementary feeding of MCT, soybean oil or starch as of day 100 of pregnancy did not affect carcass energy reserves of piglets at birth (n = 16–21 piglets, Newcomb et al., 1991). Providing 2.5 g/day of hydroxyl-methyl butyrate or 8% fat from various oil sources to sows as of day 108 of gestation had no effect on hepatic or muscle glycogen concentrations of their newborn piglets (n = 24 piglets, Theil et al., 2011). These last authors concluded that the currently used gestation diets supply enough glucose for glycogen synthesis not to be hindered.

As mentioned earlier, the risk of foetal hypoxia during parturition is greater in the currently used hyperprolific sow lines, which can have farrowings lasting for 9 h (Hales et al., 2015). An important cause of this prolonged parturition is insufficient maternal energy (Feyera et al., 2018). Indeed, recent data showed that the duration of farrowing and rate of stillbirth are greater when a sow has not eaten in the last 3.13 h before farrowing. It is therefore suggested to provide prepartal sows with three daily meals, so that circulating glucose concentrations are adequate at the onset of parturition (Feyera et al., 2018). A recent study compared various feeding levels (ranging from 1.8 to 5.0 kg/day) of a lactation diet during the transition period (Feyera et al., 2021). Feeding 4.1 kg/day proved to be ideal to achieve the shortest farrowings whereas feeding 3.0 kg/day was optimal to maximise colostrum yield. Considering that energy supply is most important to reduce farrowing length and protein supply is most needed for colostrogenesis, it was recommended to lower the lysine content of the diet to solve this discrepancy in amount fed. Increasing net energy intake from 28.2 to 33.8 MJ/day in late gestation (as of day 90) also reduced the duration of farrowing from 262 to 215 min (Che et al., 2019). Such a beneficial effect can also be observed when a readily available energy source (a sport-type supplement adapted for sows) is fed immediately before farrowing (van Kempen, 2007). Another avenue to speed up the farrowing process is to provide a transition diet rich in fibre in order to prolong energy uptake from hind-gut fermentation (Feyera et al., 2017). A further advantage of feeding a high-fibre diet prepartum is to decrease the incidence of constipation (Peltoniemi and Oliviero, 2015).

Lastly, transition feeding could be important for colostrum yield. Dietary conjugated linoleic acid (**CLA**) impacts the metabolism of mammary glands as well as milk production in dairy cows (Zheng et al., 2005). However, when 1.3% CLA was fed to nine sows from day 108 of gestation onward, colostrum yield tended to be reduced (Krogh et al., 2012). On the other hand, feeding 2.4 g/day of the leucine metabolite ß-hydroxy ß-methyl butyrate to eight sows, starting on day 108 of gestation, increased colostrum intake by piglets (512 vs 434 g; Flummer and Theil, 2012). When sows were given 4.5 kg (n = 22) of feed in three daily meals compared with one meal of 1.5 kg/day (n = 28), there was a tendency for colostrum yield to be greater (4.0 vs 3.5 kg; Decaluwé et al., 2014). These authors also showed that body condition had a greater impact than feeding level on colostrum yield. Sows of moderate body condition (17–23 mm backfat thickness) on day 108 of gestation produced more colostrum (4.0 vs 3.2 kg) than fat sows (>23 mm), and there was no interaction between feeding level and body condition (Decaluwé et al., 2014). This detrimental effect of fatness on colostrum yield and lactose content was suggested to be due to backfat changes occurring prior to the transition phase, which would impact aspects of physiological status such as insulin insensitivity and feed intake prior to farrowing. Another possibility could be the link between body condition and mammary development. Indeed, it was demonstrated that overly fat sows (>35 mm backfat) have impaired mammary development at the end of gestation (Head and Williams, 1991), and Farmer et al. (2016) also reported that lean gilts (<16 mm backfat) had less developed mammary glands (24.7% lower parenchymal tissue mass) on day 110 of gestation than gilts with 17–26 mm of backfat. It therefore seems that extremes in body condition need to be avoided.

Many immune-modulating agents have been fed to prepartal sows in an attempt to increase immunoglobulin concentrations in colostrum. A review of the effects of such dietary treatments over different periods in late-pregnant sows was published (Quesnel and Farmer, 2019). Feeding from 0.5 to 2.25% CLA to seven or eight sows in the last week before parturition increased immunoglobulin content of sow colostrum by 47.2% (Bontempo et al., 2004) or 30.7% (Corino et al., 2009). Dietary supplementation with shark-liver oil to 12 sows for the last 35 days of pregnancy more than doubled colostral immunoglobulin G (**IgG**) and increased by approximately 30% IgG concentrations in piglet blood (Mitre et al., 2005). This effect was likely due to its content of alkylglycerols and n-3 polyunsaturated fatty acids. Lastly, agents such as probiotics and prebiotics have received some attention. Dietary provision of living bacteria (*Lactobacillus* in fermented liquid feed), living cells (*Saccharomyces cerevisiae*), and the prebiotics mannan oligosaccharides or fructo oligosaccharides increased colostral IgG or immunoglobulin A (**IgA**) concentrations (see review by Quesnel and Farmer, 2019). Another study showed no effects of feeding prebiotics (n = 18) on colostral immunoglobulin content, but fat content and colostrum yield were increased by 21% and 24%, respectively (Hasan et al., 2018). A recent report showed that feeding 15 mg/kg body weight of ß-hydroxy ß-methyl butyrate to 107 sows (in three experiments) for the last 15 days of gestation increased concentrations of IgM and IgG in colostrum by approximately 10%, yet the effects on IgG were not consistent between trials (Davis et al., 2021).

Management practices in early lactation to improve the performance of neonatal piglets

As highlighted previously, low birth weight piglets are at great risk of high mortality and poor growth after birth. Special management strategies must therefore be used to assist these piglets, but this should also be based on the severity of the IUGR status of individual piglets (see review by Baxter et al., 2020). Various approaches can be used, such as: (1) optimising the farrowing environment, (2) farrowing supervision and assistance to piglets, (3) implementing cross-fostering techniques, (4) providing nurse sows, and (5) providing artificial milk.

Optimising the farrowing environment

Sows and newborn piglets have very different thermo-neutral zones and the farrowing environment must provide appropriate ambient temperatures for both the piglets and the sow. Housing must therefore be taken into consideration because the ability to maintain thermostability is affected by factors such as loose- or crate-housing and floor type (Pedersen et al. 2011; Malmkvist et al. 2012). Furthermore, the upper critical temperature of the hyperprolific sow is likely to be lower than that of older genotypes due to their greater metabolic load (Baxter et al., 2020). The use of cooling devices, such as water drip, snout cooling or floor cooling, may therefore be useful when sows are housed in crates and have limited possibility to perform behaviour to alleviate heat stress (Jeon et al., 2006; Perin et al., 2016; Cabezon et al. 2017). In contrast, the smaller IUGR piglets are more susceptible to hypothermia. Indeed, it was recently demonstrated that over the first 2 h after birth, IUGR piglets were approximately 1.3 °C cooler than normal piglets (Amdi et al., 2016). This makes it even more essential to entice newborn piglets to use a heated creep area within 24 h of birth. However, numerous attempts to achieve this via altered housing conditions have not been successful (Vasdal et al., 2010; Pedersen et al., 2013; Larsen and Pedersen, 2015) and other management procedures such as providing supplementary heat in localised areas at the time of parturition are therefore required. Providing additional heat either via a radiant heater behind the sow (Andersen and Pedersen, 2016) or using floor heating (Malmkvist et al., 2006; Pedersen et al., 2013) could help prevent hypothermia with no negative impact on colostrum ingestion. Floor type is also important because it affects heat loss. When using a device measuring heat loss via conduction, convection and radiation, solid concrete led to greater heat loss than many perforated floors (Christison and Farmer, 1983). Providing substrate, such as straw, in the periparturient period could therefore be beneficial both for the piglets (by providing insulation) and the sow (by allowing expression of nest-building behaviour). Furthermore, a positive link was found between providing sows a substrate allowing them to perform nest-building and the concentrations of IgG in serum of neonatal piglets (Yun et al., 2014).

Farrowing supervision and assistance to piglets

It has long been recognised that farrowing surveillance is beneficial in terms of piglet survival because it allows the stockperson to take actions such as drying of piglets and/or moving them to a heated area or to the udder soon after birth (Christison et al., 1997; Andersen et al., 2009; Vasdal et al., 2011; Rosvold et al., 2017; Vande Pol et al., 2020). The simple action of assisting piglets to find a teat as soon as possible after birth can decrease preweaning mortality from 11.7 to 6.2% (*n* = 22 sows, Andersen et al., 2009). The quantity of colostrum ingested by a piglet during the 24 h postpartum affects its ability to thermoregulate, grow and acquire passive immunity, with consequences that persist well beyond this period (Suárez-Trujillo et al., 2020). If a piglet shows no respiration by 15 seconds after birth, newborn care (i.e. removing the amniotic sac when present around the piglet and mucus from the snout, rubbing the piglet) can have a positive effect on its vitality (Revermann et al., 2018). More intensive protocols including piglet drying, clearing airways, feeding bovine colostrum and administering oxygen decreased preweaning mortalities by 8.1% (White et al. 1996). More invasive handling procedures, such as injecting glucose at birth or feeding colostrum by stomach tube, can be used to help IUGR piglets very early on (Amdi et al., 2017; Engelsmann et al., 2019). Energy supplementation to piglets must be done while the sow is still producing colostrum so that colostrum intake can be promoted; hence, it should be done in the first 12 h postpartum. Giving two doses in the first 24 h appears optimal (Muns et al., 2017), avoiding too great a volume in any one meal which might discourage teat-seeking. It was also observed that piglets should be warm for better results when providing the supplements (Engelsmann et al., 2019).

Of interest, acquiring a sufficient amount of energy seems more important for the survival of suckling piglets in the first 24 h postpartum than acquiring a sufficient amount of immunoglobulins (Muns et al., 2017). Indeed, supplements of MCT, which are particularly effective at supplying energy because of their rapid oxidation rate, have also been shown to reduce mortality to day 21 (from 58% to 25%) of very low birth weight (<1.0 kg) piglets (Declerck et al., 2016). In fact, the type of energy provided can affect piglet performance. Using 37 sows, Engelsmann et al. (2019) reported a 12% increase in body weight on day 21 for IUGR piglets injected with 300 mg of glucose compared with piglets tube-fed 20 mL of colostrum. When a protein-based energy product was fed to piglets from 73 sows, there was a statistically non-significant increase in preweaning survival between piglets fed the supplement and piglets non-supplemented but nursing their dam and also fed 120 mL of colostrum (Moreira et al., 2017).

Piglets acquire passive immunity through their dam's colostrum, but colostrum also contains other components, such as lymphocytes, that are essential for neonatal piglets to achieve proper immunocompetence. Bandrick et al. (2011) showed that newborn piglets cannot absorb such cells from a foster dam's colostrum; hence, adequate time must be spent with their biological dam for proper transfer of antigen-specific immune components. It is recommended that piglets spend around 12 h, and no less than 6 h, with their own mother. The technique of split-suckling can be used in early lactation to ensure that all piglets have adequate opportunity to ingest colostrum from their own mother by reducing competition for teat access. This consists in breaking up the litter and making two groups of piglets to allow those of smaller weight, hence weakest, to suckle first, during which time the heavier, hence strongest, piglets are put in a warm box or pen (Donovan and Dritz, 2000). Once the lighter piglets have been with their dam for approximately 90 min, they are swapped with the heavier group. This can be done alternately for a period of time and piglets from a whole litter are often then reunited at night.

Using cross-fostering techniques

Cross-fostering is used in large litters when the sow does not have enough teats for all live piglets. It involves moving certain piglets to another sow that has available teats. However, the problem persists when all sows in a batch have supernumerary piglets, which is common with hyperprolific sow lines. Cross-fostering can also be used to equalise size and vigour of piglets within a litter by interchanging appropriate piglets between sows. In order to be successful, cross-fostering must be done at the proper time. If it is done too early or too late (Price et al. 1994; Straw et al. 1998) or too repetitively during lactation (Straw et al. 1998; Robert and Martineau, 2001), it can be counterproductive because of disruption of the teat order and suckling behaviour. Furthermore, it was shown that teats which are not suckled for 3 days in early lactation will undergo irreversible involution, so one must ensure that there are enough functional teats present before cross-fostering additional piglets to a sow. Moreover, even though regression of unsuckled glands was found to be reversible during the first 24 h postpartum, milk production from those glands remained lower throughout lactation (Theil et al., 2005). It is known that cross-fostering can have a negative impact on long-term growth rate of fostered piglets (Stewart and Diekman, 1989) and may also negatively affect postweaning survival rate (Neal and Irvin, 1991). These last authors reported a 6.8% greater survival to day 42 in piglets that were not cross-fostered, when correcting for birth vigour. Stewart and Diekman (1989) noted that gilts reared by foster dams had poorer reproductive performance in their first parity, which is likely due to failure to ingest enough of their own dam's colostrum. This ties in with the lactocrine hypothesis described by Bartol et al. (2008), whereby colostrum and early milk would contain bioactive factors that are necessary for later development, such as that of uterine tissue (Bartol et al. 2008).

Providing nurse sows

An extreme fostering strategy, necessary when the total number of piglets born exceeds the number of available teats, is to provide nurse sows. This was reviewed in detail by Baxter et al. (2013). Basically, there are two possible protocols, namely, the one-step and the two-step strategies. In the one-step strategy, after weaning her own piglets (generally around 21 days of lactation), a sow is allowed to nurse surplus piglets for another 21–28 days. These piglets come from several litters and have suckled their own dam for 6–12 h. Such a technique prolongs the lactation of nurse sows by 3–4 weeks and gives a significant mismatch between the developmental stage of the new litter and the lactation curve of the sow so that milk quality and supply are not optimal for the piglets. In the two-step strategy, after weaning at around 21 days of lactation, the nurse sow is given a whole litter from an interim sow who was weaned after 5–7 days of lactation. This interim sow is then allowed to nurse supplementary newborn piglets that come from various litters being weaned at 6–12 h postpartum. This last strategy extends the duration of lactation in interim sows by 2–3 weeks and gives a closer time match with the developmental stage of the foster litter. The nurse sow strategies are undoubtedly quite complex so that results can be difficult to evaluate. Nonetheless, when carried out with care, there generally seems to be no increase in mortality of fostered piglets compared to unfostered piglets (Schmitt et al., 2019; Kobek-Kjeldager et al., 2020a) and in only some studies (Kobek-Kjeldager et al., 2020a*)* has a detrimental effect on growth rate during lactation been observed. On the other hand, there seems to be a greater incidence of carpal lesions in fostered piglets (Sørensen et al., 2016), possibly reflecting greater efforts to suckle. One must also take into consideration the welfare of the nurse sows, which experience an extended lactation and can be negatively affected by these strategies (Sørensen et al., 2016). Another problem is that of sows not readily accepting to nurse foreign piglets (Baxter et al., 2020; Kobek-Kjeldager et al., 2020a) and special methods may need to be used. These may aim at reducing the general responsiveness of the sow or reducing negative olfactory stimuli (via mixing piglets from both sows before proceeding with the adoption). Research still remains to be done in this area.

Providing artificial milk

Artificial rearing is sometimes used to help piglets that could not otherwise be reared by their own dams. This involves taking piglets away from their dam and housing them until weaning in special facilities with a heat lamp and where they are fed milk replacer (Baxter et al., 2013). Mortality due to crushing by the sow is obviously eliminated, yet this strategy is quite costly due to the specialised housing, the milk replacer and the milk delivery system. The piglet welfare should also be considered because newborn piglets are deprived of maternal contact. Such rearing is therefore only used in extreme situations. The milk delivery system is a very important feature of artificial rearing and, in addition to considerations of hygiene, will affect the incidence of stereotypies. When a cup system is used to feed the piglets, it precludes suckling and postnursing massage. There are fewer behavioural problems when a nipple drinker system or an artificial udder is used (Widowski et al., 2005). Many factors need to be considered for successful artificial nursing, such as piglet age, milk replacer formulation, type of enclosure (Cabrera et al., 2010; Rzezniczek et al., 2015), milk delivery system (Cabrera et al., 2010; De Vos et al., 2014b; Rzezniczek et al., 2015) and mixing or not of piglets at transfer (De Vos et al., 2014b; Rzezniczek et al., 2015).

Another strategy to provide enough milk for all piglets is to provide supplementary milk in the farrowing pen. While this can be done manually, it is becoming more common to install milk cups into which milk is automatically delivered through a pipeline system that is supplied from a tank where mixing of the milk supplement is generally done twice daily. There are various designs of milk cups, which can be filled either by piglets using a push-valve inside the cup, or which can be filled automatically at regular intervals or only when empty. Irrespective of the system used, the pipeline must be cleaned frequently to avoid bacterial growth inducing piglet diarrhoea. The first milk replacer generally contains milk powder as the main ingredient and a second, more grain-based, milk replacer can be used later in lactation to reduce cost and promote digestive maturation. The major drawback of this method is the cost for both installation and running of the system and the milk consumed. Nonetheless, providing more milk to piglets in large litters will have a beneficial effect on their performance. Early studies reported approximately 16% greater weaning weights of piglets (with a litter size of 12) when they were provided milk three times per day in a trough (Azain et al., 1996; Wolter et al., 2002). More recently a study looked at the impact of continuously providing milk replacer using milk cups (Kobek-Kjeldager et al., 2020b). In a project using 98 litters from 73 sows, feeding the milk replacer increased both survival (by approximately 15%) and weights (by approximately 11%) at weaning in piglets from large litters (17 piglets after cross-fostering on day 1). However, the variability in piglet weight within a litter tended to be greater with the milk replacer system. It is important to mention that, even with access to milk cups, these large litters had a greater mortality rate and lower weaning weights than litters of 14 piglets. Indeed, it was noted that milk replacer was rarely the major feed source of piglets (Kobek-Kjeldager et al., 2020b), which could be related to the different nutritional or sensory qualities of milk replacer when compared to sow milk. It is therefore apparent that providing milk replacer cannot totally solve the issue of underfed piglets in very large litters. However, such a system could be very advantageous for low birth weight piglets. When litters of either low birth weight (<1.25 kg) or mixed birth weight (<1.25 kg and 1.6–2.0 kg) piglets were created via cross-fostering within 24 h of birth and milk replacer was provided, the low birth weight litters drank 23.9% more milk replacer than mixed litters (Douglas et al., 2014). The low birth weight piglets in low birth weight litters also had a greater average daily gain compared with low birth weight piglets in mixed litters (0.25 vs 0.22 kg/day, respectively), corresponding to more than 500 g body weight difference at weaning.

Other management strategies

A main concern with hyperprolific sows is that the number of liveborn piglets in a litter should not exceed the number of functional teats available. Special management interventions, such as cross-fostering, must therefore be used when necessary and teat quality becomes particularly important. It was shown that a teat that is suckled in the first parity will produce more milk in the second parity. In fact, as early as from days 2 to 4 of lactation, the growth rate is greater for piglets suckling a previously used teat compared to those suckling a previously unused teat (Farmer et al., 2012). This suggests that colostrum yield might be greater when a teat was previously used, and that litter size should be adjusted so that all teats of first parity sows are utilised. Interestingly, if in parity one, a teat is suckled for the first 2 days after farrowing, the suckling stimulus is enough to ensure adequate milk yield of that teat in parity two (Farmer et al., 2017a). Hence, in primiparous sows with very large litters and poor body condition, it could be possible to remove some piglets as of day 3 of lactation to aid sow recovery without a negative impact on lactation performance in the next parity.

One way to increase the amount of colostrum ingested by piglets would be to prolong the colostral phase. Knowing that the composition of colostrum is affected by the status of tight junctions between mammary epithelial cells, a high dose of oxytocin was used in the late colostral phase to manipulate the tight junctions and increase the immunoglobulin content of early milk. When a supraphysiological dose (75 IU) of oxytocin was injected into sows towards the end of the colostrum phase (between 12 and 20 h after birth of the last piglet), IgG and IgA concentrations in milk collected 8 h after the injection were both increased, as well as concentrations of IGF-1 (Farmer et al., 2017b). This was explained by the greater Na:K ratio, indicating that the injection of oxytocin delayed the occurrence of tightening of mammary tight junctions, hence prolonging the colostral phase. However, the intervention was performed with only 10 sows per treatment so that further research on a larger number of animals is needed to determine its true potential in terms of piglet performance.

Conclusions

Neonatal piglets are very vulnerable to death due to many physiological handicaps, and these are exacerbated by the very high litter sizes of the currently used hyperprolific sow lines which increase the incidence of IUGR piglets. Nutritional and management strategies must therefore be developed to stimulate foetal growth and development, and to assist the newborn piglet in maintaining homeothermy and ingesting as much colostrum as possible. The challenges experienced by piglets born into litters of hyperprolific sows and the potential methods for their alleviation are summarised in Table 1. Even though there has been much research on both nutritional and management strategies for sows in late gestation and early lactation, it is apparent that many of the interventions demonstrated experimentally to yield beneficial outcomes have yet to receive widespread adoption in practice. The inconsistency in results arising from differences between genotypes and in the basal level of production and management, and the sparsity of large-scale validation trials demonstrating

Table 1
Challenges and potential interventions to improve piglet performance in litters from hyperprolific sows.

The Challenge	Possible solutions
Prolonged farrowing: piglet asphyxia, stillbirth and low vitality	• Correct sow body condition • 3x/day feeding before farrowing • Transition diet with increased fibre • Sow energy supplement at farrowing
Insufficient colostrum yield: inadequate energy and Ig provision for all piglets	• Increased fibre in gestation diet • Correct body condition at farrowing • Targeted dietary supplements: CLA, alkylglycerols, probiotics, prebiotics • No induction before full term • Oxytocin injection to prolong colostral phase
More low birth weight and IUGR piglets: inadequate piglet energy reserves for thermoregulation and vitality	• Genetic selection for piglet quality • Pre-ovulatory diets with increased energy or fermentable properties • Targeted dietary gestation supplements: arginine, glutamine, carnitine • Fat supplements in gestation: MCT, n-3 FA • Minimal stress in gestation
Low-vitality piglets at birth	• Localised supplementary heat • Supervised farrowing and assistance to suckle • Glucose injection • Colostrum or MCT dosing
Increased competition to obtain a teat and suckle	• Split suckling • Timely cross-fostering
Number of piglets exceeds total available teats	• Nurse sows • Artificial rearing • Supplementary milk
Insufficient milk to support good piglet growth	• Better quality teats: full utilisation in gilt litters • Supplementary milk

Abbreviations: CLA = conjugated linoleic acid; FAs = fatty acids; Ig = immunoglobulin; IUGR = intra-uterine growth-restricted, MCTs = medium chain triglycerides.

cost-effectiveness under commercial conditions have contributed to this outcome. Despite the advances made, further research endeavours in this area are therefore needed in developing specially adapted strategies to ensure maximum survival and growth of piglets from modern sow genotypes.

Ethics statement

This paper is a review of published information. No new ethical approval was required.

Data and model availability statement

No new data were generated in this paper.

Author ORCID

Chantal Farmer: https://orcid.org/0000-0001-8390-6163.
S.A. Edwards: https://orcid.org/0000-0002-8890-0112.

Author contribution

Chantal Farmer: Writing- original draft preparation, Writing – reviewing and editing. **Sandra A Edwards**: Writing- original draft preparation, Writing – reviewing and editing.

Declaration of interest

There is no conflict of interest involved with this paper.

Acknowledgements

None.

Financial support statement

This research received no specific grant from any funding agency, commercial or not-for-profit section.

Transparency Declaration

This article is part of a supplement entitled *Manipulating Pig Production XVIII: Proceedings of the Eighteenth Biennial Conference of the Australasian Pig Science Association (APSA)* supported by the Australasian Pig Science Association.

References

Adeleye, O.O., Brett, M., Blomfield, D., Guy, J.H., Edwards, S.A., 2014. The effect of algal biomass supplementation in maternal diets on piglet survival in two housing systems. Livestock Science 162, 193–200.
Amdi, C., Jensen, L.L., Oksbjerg, N., Hansen, C.F., 2017. Supplementing newborn intrauterine growth restricted piglets with a bolus of porcine colostrum raises rectal temperatures one degree Celsius. Journal of Animal Science 95, 2968–2976.
Amdi, C., Klarlund, M.V., Hales, J., Thymann, T., Hansen, C.F., 2016. Intrauterine growth-restricted piglets have similar gastric emptying rates but lower rectal temperatures and altered blood values when compared with normal-weight piglets at birth. Journal of Animal Science 94, 4583–4590.
Amdi, C., Krogh, U., Flummer, C., Oksbjerg, N., Hansen, C.F., Theil, P.K., 2013. Intrauterine growth restricted piglets defined by their head shape ingest insufficient amounts of colostrum. Journal of Animal Science 91, 5605–5613.
Andersen, H.L., Pedersen, L.J., 2016. Effect of radiant heat at the birth site in farrowing crates on hypothermia and behaviour in neonatal piglets. Animal 10, 128–134.
Andersen, I.L., Haukvik, I.A., Bøe, K.E., 2009. Drying and warming immediately after birth may reduce piglet mortality in loose-housed sows. Animal 3, 592–597.
Azain, M.J., Tomkins, T., Sowinski, J.S., Arentson, R.A., Jewell, D.E., 1996. Effect of supplemental pig milk replacer on litter performance: Seasonal variation in response. Journal of Animal Science 74, 2195–2202.
Bandrick, M., Pieters, M., Pijoan, C., Baidoo, S.K., Molitor, T.W., 2011. Effect of cross-fostering on transfer of maternal immunity to *Mycoplasma hyopneumoniae* to piglets. Veterinary Record 168, 100.
Bartol, F.F., Wiley, A.A., Bagnell, C.A., 2008. Epigenetic programming of porcine endometrial function and the lactocrine hypothesis. Reproduction in Domestic Animals 43, 273–279.
Bass, B.E., Bradley, C.L., Johnson, Z.B., Zier-Rush, C.E., Boyd, R.D., Usry, J.L., Maxwell, C.V., Frank, J.W., 2017. Influence of dietary L-arginine supplementation of sows during late pregnancy on piglet birth weight and sow and litter performance during lactation. Journal of Animal Science 95, 248–256.
Baxter, E.M., Edwards, S.A., 2018. Piglet mortality and morbidity: inevitable or unacceptable? In: Spinka, M. (Ed.), Advances in Pig Welfare. Elsevier, Duxford, UK, pp. 73–100.
Baxter, E.M., Jarvis, S., D'Eath, R.B., Ross, D.W., Robson, S.K., Farish, M., Nevison, I., Edwards, S.A., 2008. Investigating the behavioural and physiological indicators of neonatal survival in pigs. Theriogenology 69, 773–783.

Baxter, E.M., Rutherford, K.M.D., D'Eath, R.B., Arnott, G., Turner, S.P., Sandøe, 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. Animal Welfare 22, 219–238.
Baxter, E.M., Schmitt, O., Pedersen, L.J., 2020. Management of hyperprolific litters. In: Farmer, C. (Ed.), The suckling and weaned piglet. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 71–106.
Bérard, J., Bee, G., 2010. Effects of dietary L-arginine supplementation to gilts during early gestation on foetal survival, growth and myofiber formation. Animal 4, 1680–1687.
Bontempo, V., Sciannimanico, D., Pastorelli, G., Rossi, R., Rosi, F., Corino, C., 2004. Dietary conjugated linoleic acid positively affects immunologic variables in lactating sows and piglets. Journal of Nutrition 134, 817–824.
Boonraungrod, N., Sutthiya, N., Kumwan, P., Tossakui, P., Nuntapaitoon, M., Muns, R., Tummaruk, P., 2018. Control of parturition in swine using PGF2alpha in combination with carbetocin. Livestock Science 214, 1–8.
Boyd, R.D., Moser, B.D., Peo Jr, E.R., Cunningham, P.J., 1978. Effect of energy source prior to parturition and during lactation on tissue lipid, liver glycogen and plasma levels of some metabolites in the newborn pig. Journal of Animal Science 47, 874–882.
Cabezon, F.A., Schinckel, A.P., Smith, A.J., Marchant-Forde, J.N., Johnson, J.S., Stwalley, R.M., 2017. Initial evaluation of floor cooling on lactating sows under acute heat stress. The Professional Animal Scientist 33, 254–260.
Cabrera, R.A., Boyd, R.D., Jungst, S.B., Wilson, E.R., Johnston, M.E., Vignes, J.L., Odle, J., 2010. Impact of lactation length and piglet weaning weight on long-term growth and viability of progeny. Journal of Animal Science 88, 2265–2276.
Canario, L., Bidanel, J.-P., Rydhmer, L., 2014. Genetic trends in maternal and neonatal behaviors and their association with perinatal survival in French Large White swine. Frontiers in Genetics 5, 00410.
Che, L., Hu, L., Wu, C., Xu, Q., Zhou, Q., Peng, X., Fang, Z.F., Lin, Y., Xu, S.Y., Feng, B., Li, J., Tang, J., Zhang, R., Li, H., Theil, P.K., Wu, D., 2019. Effects of increased energy and amino acid intake in late gestation on reproductive performance, milk composition, metabolic, and redox status of sows. Journal of Animal Science 97, 2914–2926.
Christison, G.I., Farmer, C., 1983. Physical characteristics of perforated floors for young pigs. Canadian Agricultural Engineering 25, 75–80.
Christison, G.I., Wenger, I.I., Follensbee, M.E., 1997. Teat seeking success of newborn piglets after drying or warming. Canadian Journal of Animal Science 77, 317–319.
Corino, C., Pastorelli, G., Rosi, F., Bontempo, V., Rossi, R., 2009. Effect of dietary conjugated linoleic acid supplementation in sows on performance and immunoglobulin concentration in piglets. Journal of Animal Science 87, 2299–2305.
Davis, H.E., Jagger, S., Toplis, P., Miller, H.M., 2021. Feeding ß-hydroxy ß-methyl butyrate to sows in late gestation improves litter and piglet performance to weaning and colostrum immunoglobulin concentrations. Animal Feed Science and Technology 275, 114889.
Decaluwé, R., Maes, D., Cools, A., Wuyts, D., De Smet, S., Marescau, B., De Deyn, P.P., Janssens, G.P.J., 2014. Effect of peripartal feeding strategy on colostrum yield and composition in sows. Journal of Animal Science 92, 3557–3567.
Declerck, I., Dewulf, J., Decaluwé, R., Maes, D., 2016. Effects of energy supplementation to neonatal (very) low birth weight piglets on mortality, weaning weight, daily weight gain and colostrum intake. Livestock Science 183, 48–53.
Devillers, N., Farmer, C., Le Dividich, J., Prunier, A., 2007. Variability of colostrum yield and colostrum intake in swine. Animal 1, 1033–1041.
De Vos, M., Che, L., Huygelen, V., Willemen, S., Michiels, J., van Cruchten, S., van Ginneken, C., 2014a. Nutritional interventions to prevent and rear low-birthweight piglets. Journal of Animal Physiology and Animal Nutrition 98, 609–619.
De Vos, M., Huygelen, V., Willemen, S., Fransen, E., Casteleyn, C., Van Cruchten, S., Michiels, J., Van Ginneken, C., 2014b. Artificial rearing of piglets: effects on small intestinal morphology and digestion capacity. Livestock Science 159, 165–173.
Díaz, J.A.C., Boyle, L.A., Diana, A., Leonard, F.C., Moriarty, J.P., McElroy, M.C., McGettrick, S., Kelliher, D., Manzanilla, E.G., 2017. Early life indicators predict mortality, illness, reduced welfare and carcass characteristics in finisher pigs. Preventive Veterinary Medicine 146, 94–102.
Dickerson, J.W.T., Merat, A., Widdowson, E.M., 1971. Intrauterine growth retardation in the pig. III. The chemical structure of the brain. Biology of the Neonate 19, 354–362.
Donovan, T.S., Dritz, S.S., 2000. Effect of split nursing on variation in pig growth from birth to weaning. Journal of the American Veterinary Medical Association 217, 79–81.
Douglas, S.L., Edwards, S.A., Kyriazakis, I., 2014. Management strategies to improve the performance of low birth weight pigs to weaning and their long term consequences. Journal of Animal Science 92, 2280–2288.
Edwards, S.A., Baxter, E.M., 2015. Piglet mortality: causes and prevention. In: Farmer, C. (Ed.), The gestating and lactating sow. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 253–278.
Edwards, S.A., Matheson, S.M., Baxter, E.M., 2019. Genetic influences on intra-uterine growth retardation of piglet and management interventions for low birth weight piglets. In: Palomo Yagüe, A. (Ed.), Nutrition of hyperprolific sows. Novus International Inc, St-Louis, MO, USA, pp. 207–235.
Elliot, J.I., Lodge, G.A., 1977. Body composition and glycogen reserves in the neonatal pig during the first 96 hours postpartum. Canadian Journal of Animal Science 57, 141–150.
Engelsmann, M.N., Hansen, C.F., Nielsen, M.N., Kristensen, A.R., Amdi, C., 2019. Glucose injections at birth, warmth and placing at a nurse sow improve the growth of IUGR piglets. Animals 9, 519.
Farmer, C., Amezcua, M., Bruckmaier, R., Wellnitz, O., Friendship, R., 2017a. Does duration of teat use in first parity affect milk yield and mammary gene expression in second parity? Journal of Animal Science 95, 681–687.
Farmer, C., Duarte, C.R.A., Vignola, M., Palin, M.-F., 2016. Body condition of gilts at the end of gestation affects their mammary development. Journal of Animal Science 94, 1897–1905.
Farmer, C., Edwards, S.A., 2020. The neonatal pig: developmental influences on vitality. In: Farmer, C. (Ed.), The suckling and weaned piglet. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 9–39.
Farmer, C., Lessard, M., Knight, C.H., Quesnel, H., 2017b. Oxytocin injections in the postpartal period affect mammary tight junctions in sows. Journal of Animal Science 95, 3532–3539.
Farmer, C., Palin, M.-F., Theil, P.K., Sorensen, M.T., Devillers, N., 2012. Milk production in sows from a teat in second parity is influenced by whether it was suckled in first parity. Journal of Animal Science 90, 3743–3751.
Ferguson, E.M., Ashworth, C.J., Edwards, S.A., Hawkins, N., Hunter, M.G., 2003. Effect of different nutritional regimens before ovulation on plasma concentrations of metabolic and reproductive hormones and oocyte maturation in gilts. Reproduction 126, 61–71.
Ferguson, E.M., Slevin, J., Hunter, M.G., Edwards, S.A., Ashworth, C.J., 2007. Beneficial effects of a high fibre diet on oocyte maturity and embryo survival in gilts. Reproduction 133, 433–439.
Feyera, T., Højgaard, C.K., Vinther, J., Bruun, T.S., Theil, P.K., 2017. Dietary supplement rich in fiber fed to late gestating sows during transition reduces rate of stillborn piglets. Journal of Animal Science 95, 5430–5438.
Feyera, T., Pedersen, T.F., Krogh, U., Foldager, L., Theil, P.K., 2018. Impact of sow energy status during farrowing on farrowing kinetics, frequency of stillborn piglets, and farrowing assistance. Journal of Animal Science 96, 2320–2331.
Feyera, T., Skovmose, S.J.W., Nielsen, S.E., Vodolazska, D., Bruun, T.S., Theil, P.K., 2021. Optimal feed level during the transition period to achieve faster farrowing and high colostrum yield in sows. Journal of Animal Science 99, 1–11. https://doi.org/10.1093/jas/skab040.
Flummer, C., Theil, P.K., 2012. Effect of ß-hydroxy ß-methyl butyrate supplementation of sows in late gestation and lactation on sow production of colostrum and milk and piglet performance. Journal of Animal Science 90 (Suppl. 4), 372–374.
Foisnet, A., Farmer, C., David, C., Quesnel, H., 2011. Farrowing induction induced transient alterations in prolactin concentrations and colostrum composition in primiparous sows. Journal of Animal Science 89, 3048–3059.
Foxcroft, G.R., Dixon, W.T., Dyck, M.K., Novak, S., Harding, J.C.S., Almeida, F.C.R.L., 2009. Prenatal programming of postnatal development in the pig. Society of Reproduction and Fertility Supplement 66, 213–239.
Gondret, F., Lefaucheur, L., Perruchot, M.H., Farmer, C., Liaubet, L., Louveau, I., 2020. Lean and fat development in piglets. In: Farmer, C. (Ed.), The suckling and weaned piglet. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 41–69.
Hales, J., Moustsen, V.A., Devreese, A.M., Nielsen, M.B.F., Hansen, C.F., 2015. Comparable farrowing progress in confined and loose housed hyper-prolific sows. Livestock Science 171, 64–72.
Hales, J., Moustsen, V.A., Nielsen, M.B.F., Hansen, C.F., 2013. Individual physical characteristics of neonatal piglets affect preweaning survival of piglets born in a non-crated system. Journal of Animal Science 91, 4991–5003.
Hasan, S., Junnikkala, S., Peltoniemi, O., Paulin, L., Lyyski, A., Vuorenmaa, J., Oliviero, C., 2018. Dietary supplementation with yeast hydrolysate in pregnancy influences colostrum yield and gut microbiota of sows and piglets after birth. PLoS ONE 13, e0197586.
Head, R.H., Williams, I.H., 1991. Mammogenesis is influenced by pregnancy nutrition. In: Proceedings of the Third Biennial Conference of the Australasian Pig Science Association, 24-27 November 1991, Albury, NSW, Australia, p. 33.
Herpin, P., Damon, M., Le Dividich, J., 2002. Development of thermoregulation and neonatal survival in pigs. Livestock Production Science 78, 25–45.
Herpin, P., Le Dividich, J., Berthon, D., Hulin, J.C., 1994. Assessment of thermoregulatory and postprandial thermogenesis over the first 24 hours after birth in pigs. Experimental Physiology 79, 1011–1019.
Jean, K.-B., Chiang, S.-H., 1999. Increased survival of neonatal pigs by supplementing medium-chain triglycerides in late-gestating sow diets. Animal Feed Science and Technology 76, 241–250.
Jeon, J.H., Yeon, S.C., Choi, Y.H., Min, W., Kim, S., Kim, P.J., Chang, H.H., 2006. Effects of chilled drinking water on the performance of lactating sows and their litters during high ambient temperatures under farm conditions. Livestock Science 105, 86–93.
Jiarpinitnun, P., Loyawatananan, S., Sangratkanjanasin, P., Kompong, K., Nuntapaitoon, M., Muns, R., De Rensis, F., Tummaruk, P., 2019. Administration of carbetocin after the first piglet was born reduced farrowing duration but compromised colostrum intake in newborn piglets. Theriogenology 128, 23–30.
Kobek-Kjeldager, C., Moustsen, V.A., Theil, P.K., Pedersen, L.J., 2020a. Managing large litters: Selected measures of performance in 10 intermediate nurse sows and welfare of foster piglets. Applied Animal Behaviour Science 233, 105149.

Kobek-Kjeldager, C., Moustsen, V.A., Theil, P.K., Pedersen, L.J., 2020b. Effect of litter size, milk replacer and housing on production results of hyper-prolific sows. Animal 14, 924–1833.

Kranendonk, G., Hopster, H., Fillerup, M., Ekkel, E.D., Mulder, E.J., Wiegant, V.M., Taverne, M.A., 2006. Lower birth weight and attenuated adrenocortical response to ACTH in offspring from sows that orally received cortisol during gestation. Domestic Animal Endocrinology 30, 218–238.

Krogh, U., Flummer, C., Jensen, S.K., Theil, P.K., 2012. Colostrum and milk production of sows is affected by dietary conjugated linoleic acid. Journal of Animal Science 90, 366–368.

Langendijk, P., Fleuren, M., van Hees, H., van Kempen, T., 2018. The course of parturition affects piglet condition at birth and survival and growth through the nursery phase. Animals 8, 60. https://doi.org/10.3390/ani8050060.

Larsen, M.L.V., Pedersen, L.J., 2015. Does light attract piglets to the creep area? Animal 9, 1032–1037.

Laws, J., Laws, A., Lean, I.J., Dodds, P.F., Clarke, L., 2007. Growth and development of offspring following supplementation of sow diets with oil during early to mid gestation. Animal 1, 1482–1489.

Leenhouwers, J.I., Knol, E.F., deGroot, P.N., Vos, H., van der Lende, T., 2002. Fetal development in the pig in relation to genetic merit for piglet survival. Journal of Animal Science 80, 1759–1770.

Loisel, F., Farmer, C., Ramaekers, P., Quesnel, H., 2013. Effect of high fibre intake during late pregnancy on sow physiology, colostrum production and piglet performance. Journal of Animal Science 91, 5269–5279.

Malmkvist, J., Pedersen, L.J., Damgaard, B.M., Thodberg, K., Jørgensen, E., Labouriau, R., 2006. Does floor heating around parturition affect the vitality of piglets born to loose housed sows? Applied Animal Behaviour Science 99, 88–105.

Malmkvist, J., Pedersen, L.J., Kammersgaard, T.S., Jørgensen, E., 2012. Influence of thermal environment on sows around farrowing and during the lactation period. Journal of Animal Science 90, 3186–3199.

Mateo, R.D., Wu, G., Bazer, F.W., Park, J.C., Shinzato, I., Kim, S.W., 2007. Dietary L-arginine supplementation enhances the reproductive performance of gilts. Journal of Nutrition 137, 652–656.

Matheson, S.M., Walling, G.A., Edwards, S.A., 2018. Genetic selection against intrauterine growth retardation in piglets: a problem at the piglet level with a solution at the sow level. Genetics Selection Evolution 50, 46.

Miles, J.R., Vallet, J.L., 2021. Breed differences in placental development during late gestation between Chinese Meishan and White crossbred gilts in response to intrauterine crowding. Animal Reproduction Science 226, 106711.

Milon, A., Aumaitre, A., Le Dividich, J., Franz, J., Metzger, J.J., 1983. Influence of birth prematurity on colostrum composition and subsequent immunity of piglets. Annales de Recherche Vétérinaire 14, 533–540.

Mitre, R., Etienne, M., Martinais, S., Salmon, H., Allaume, P., Legrand, P., Legrand, A., 2005. Humoral defence improvement and haematopoiesis stimulation in sows and offspring by oral supply of shark-liver oil to mothers during gestation and lactation. British Journal of Nutrition 94, 753–762.

Moreira, L.P., Menegat, M.B., Barros, G.P., Bernardi, M.L., Wentz, I., Bortolozzo, F.P., 2017. Effects of colostrum, and protein and energy supplementation on survival and performance of low-birth-weight piglets. Livestock Science 202, 188–193.

Muns, R., Nuntapaitoon, M., Tummaruk, P., 2017. Effect of oral supplementation with different energy boosters in newborn piglets on pre-weaning mortality, growth and serological levels of IGF-I and IgG. Journal of Animal Science 95, 353–360.

Muro, B.B.D., Carnevale, R.F., Andretta, I., Leal, D.F., Monteiro, M.S., Poor, A.P., Almond, G.W., Garbossa, C.A.P., 2021. Effects of uterotonics on farrowing traits and piglet vitality: a systematic review and meta-analysis. Theriogenology 161, 151–160.

Neal, S.M., Irvin, K.H., 1991. The effects of cross-fostering pigs on survival and growth. Journal of Animal Science 69, 41–46.

Newcomb, M.D., Harmon, D.L., Nelssen, J.L., Thulin, A.J., Allee, G.L., 1991. Effect of energy source fed to sows during late gestation on neonatal blood metabolite homeostasis, energy stores and composition. Journal of Animal Science 69, 230–236.

Oliviero, C., Heinonen, M., Valros, A., Peltoniemi, O., 2010. Environmental and sow-related factors affecting the duration of farrowing. Animal Reproduction Science 119, 85–91.

Oliviero, C., Junnikkala, S., Peltoniemi, O., 2019. The challenge of large litters on the immune system of the sow and the piglets. Reproduction in Domestic Animals 54 (Suppl 3), 12–21.

Otten, W., Kanitz, E., Tuchscherer, M., Puppe, B., Nürnberg, G., 2007. Repeated administration of adrenocorticotropic hormone during gestation in gilts: effects on growth, behaviour, and immune responses of their piglets. Livestock Science 106, 261–270.

Otten, W., Kanitz, E., Tuchscherer, M., Brüssow, K.-P., Nürnberg, G., 2008. Repeated administrations of adrenocorticotropic hormone during late gestation in pigs: maternal cortisol response and effects on fetal HPA axis and brain neurotransmitter systems. Theriogenology 69, 312–322.

Otto, M.A., Machado, A.P., Moreira, L.P., Bernardi, M.L., Coutinho, M.L., Vaz Jr, I.S., Wentz, I., Bortolozzo, F.P., 2017. Colostrum yield and litter performance in multiparous sows subjected to farrowing induction. Reproduction in Domestic Animals 52, 749–755.

Pastorelli, G., Neil, M., Wigren, I., 2009. Body composition and muscle glycogen contents of piglets of sows fed diets differing in fatty acids profile and contents. Livestock Science 123, 329–334.

Pedersen, L.J., Berg, P., Jørgensen, G., Andersen, I.L., 2011. Neonatal piglet traits of importance for survival in crates and indoor pens. Journal of Animal Science 89, 1207–1218.

Pedersen, L.J., Malmkvist, J., Andersen, H.M.L., 2013. Housing of sows during farrowing: a review on pen design, welfare and productivity. In: Aland, A., Banhazi, T. (Eds.), Livestock housing: modern management to ensure optimal health and welfare of farm animals. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 285–297.

Peltoniemi, O.A.T., Oliviero, C., 2015. Housing, management and environment during farrowing and early lactation. In: Farmer, C. (Ed.), The gestating and lactating sow. Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 77–84.

Perin, J., Gaggini, T.S., Manica, S., Magnabosco, D., Bernardi, M.L., Wentz, I., Bortolozzo, F.P., 2016. Evaporative snout cooling system on the performance of lactating sows and their litters in a subtropical region. Ciência Rural 46, 342–347.

Price, E.O., Hutson, G.D., Price, M.I., Borgwardt, R., 1994. Fostering in swine as affected by age of offspring. Journal of Animal Science 72, 1697–1701.

Quesnel, H., Farmer, C., 2019. Review: nutritional and endocrine control of colostrogenesis in swine. Animal 13 (S1), s26–s34.

Quesnel, H., Meunier-Salaün, M.-C., Hamard, A., Guillemet, R., Etienne, M., Farmer, C., Dourmad, J.-Y., Père, M.-C., 2009. Dietary fiber for pregnant sows: influence on sow physiology and performance during lactation. Journal of Animal Science 87, 532–543.

Robert, S., Martineau, G.P., 2001. Effects of repeated cross-fosterings on preweaning behaviour and growth performance of piglets and on maternal behaviour of sows. Journal of Animal Science 79, 88–93.

Ren, P., Yang, X.J., Kim, J.S., Menon, D., Baidoo, S.K., 2017. Effect of different feeding levels during three short periods of gestation on sow and litter performance over two reproductive cycles. Animal Reproduction Science 177, 42–55.

Revermann, R., Winckler, C., Fuerst-Waltl, B., Leeb, C., Pfeiffer, C., 2018. Assessment of viability of newborn piglets using an adjusted APGAR score. Journal of Central European Agriculture 19, 829–833.

Roehe, R., Kalm, E., 2000. Estimation of genetic and environmental risk factors associated with pre-weaning mortality in piglets using generalized linear mixed models. Animal Science 70, 227–240.

Rooke, J.A., Sinclair, A.G., Edwards, S.A., 2001. Feeding tuna oil to the sow at different times during pregnancy has different effects on piglet long-chain polyunsaturated fatty acid composition at birth and subsequent growth. British Journal of Nutrition 86, 21–30.

Rootwelt, V., Reksen, O., Farstad, W., Framstad, T., 2013. Postpartum deaths: piglet, placental, and umbilical characteristics. Journal of Animal Science 91, 2647–2656.

Rosvold, E.M., Kielland, C., Ocepek, M., Framstad, T., Fredriksen, B., Andersen-Ranberg, I., Næss, G., Andersen, I.L., 2017. Management routines influencing piglet survival in loose-housed sow herds. Livestock Science 196, 1–6.

Rutherford, K.M., Robson, S.K., Donald, R.D., Jarvis, S., Sandercock, D.A., Scott, E.M., Nolan, A.M., Lawrence, A.B., 2009. Pre-natal stress amplifies the immediate behavioural responses to acute pain in piglets. Biology Letters 5, 452–454.

Rzezniczek, M., Gygax, L., Wechsler, B., Weber, R., 2015. Comparison of the behaviour of piglets raised in an artificial rearing system or reared by the sow. Applied Animal Behaviour Science 165, 57–65.

Schmitt, O., Baxter, E.M., Boyle, L.A., O'Driscoll, K., 2019. Nurse sow strategies in the domestic pig: II. Consequences for piglet growth, suckling behaviour and sow nursing behaviour. Animal 13, 590–599.

Seerley, R.W., Pace, T.A., Foley, C.W., Scarth, R.D., 1974. Effect of energy intake prior to parturition on milk lipids and survival rate, thermostability and carcass composition of piglets. Journal of Animal Science 38, 64–70.

Sørensen, 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.

Stewart, T.S., Diekman, M.A., 1989. Effect of birth and fraternal litter size and cross-fostering on growth and reproduction in swine. Journal of Animal Science 67, 635–640.

Straw, B.E., Dewey, C.E., Bürgi, E.J., 1998. Patterns of crossfostering and piglet mortality on commercial US and Canadian swine farms. Preventive Veterinary Medicine 33, 83–89.

Suárez-Trujillo, A., Senn, I.K., Teeple, K., Casey, T.M., Stewart, K.R., 2020. A standardized model to study effects of varying 24-h colostrum dose on postnatal growth and development. Translational Animal Science 4. https://doi.org/10.1093/tas/txaa212.

Theil, P.K., Cordero, G., Henckel, P., Puggaard, L., Oksbjerg, N., Sorensen, M.T., 2011. Effects of gestation and transition diets, piglet birth weight, and fasting time on depletion of glycogen pools in liver and 3 muscles of newborn piglets. Journal of Animal Science 89, 1805–1816.

Theil, P.K., Labouriau, R., Sejrsen, K., Thomsen, B., Sorensen, M.T., 2005. Expression of genes involved in regulation of cell turnover during milk stasis and lactation rescue in sow mammary tissue. Journal of Animal Science 83, 2349–2356.

Vande Pol, K.D., Tolosa, A.F., Shull, C.M., Brown, C.B., Alencar, S.A.S., Ellis, M., 2020. Effect of method of drying piglets at birth on rectal temperature over the first 24 h after birth. Translational Animal Science 4. https://doi.org/10.1093/tas/txaa183.

van den Brand, H., van Enckevort, L.C.M., van der Hoeven, E.M., Kemp, B., 2009. Effects of dextrose plus lactose in the sows diet on subsequent reproductive performance and within litter birth weight variation. Reproduction in Domestic Animals 44, 884–888.

Vanden Hole, C., Ayuso, M., Aerts, P., Prims, S., Van Cruchten, S., Van Ginneken, C., 2019. Glucose and glycogen levels in piglets that differ in birth weight and vitality. Heliyon 5, e02510.

Van Dijk, A.J., van Rens, B.T., van der Lende, T., Taverne, M.A.M., 2005. Factors effecting duration of the expulsive stage of parturition and piglet birth intervals in sows with uncomplicated, spontaneous farrowings. Theriogenology 64, 1573–1590.

van Kempen, T., 2007. Supplements to facilitate parturation and reduce perinatal mortality in pigs. In: Garnsworthy, P.C., Wiseman, J. (Eds.), Recent advance in animal nutrition. Nottingham University Press, Nottinghan, UK, pp. 317–330.

van Rens, B.T.T.M., de Koning, G., Bergsma, R., van der Lende, T., 2005. Preweaning piglet mortality in relation to placental efficiency. Journal of Animal Science 83, 144–151.

Vasdal, G., Glærum, M., Melišová, M., Bøe, K.E., Broom, D.M., Andersen, I.L., 2010. Increasing the piglets' use of the creep area – a battle against biology? Applied Animal Behaviour Science 125, 96–102.

Vasdal, G., Østensen, I., Melišová, M., Bozděchová, B., Illmann, G., Andersen, I.L., 2011. Management routines at the time of farrowing—effects on teat success and postnatal piglet mortality from loose housed sows. Livestock Science 136, 225–231.

White, K.R., Anderson, D.M., Bate, L.A., 1996. Increasing piglet survival through an improved farrowing management protocol. Canadian Journal of Animal Science 76, 491–495.

Widowski, T.M., Yuan, Y., Gardner, J.M., 2005. Effect of accommodating sucking and nosing on the behaviour of artificially reared piglets. Laboratory Animals 39, 240–250.

Wientjes, J.G.M., Soede, N.M., Knol, E.F., van den Brand, H., Kemp, B., 2013. Piglet birth weight and litter uniformity: effects of weaning-to-pregnancy interval and body condition changes in sows of different parities and crossbred lines. Journal of Animal Science 91, 2099–2107.

Wolter, B., Ellis, M., Corrigan, B., Dedecker, J., 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. Journal of Animal Science 80, 301–308.

Wu, G., Bazer, F.W., Cudd, T.A., Meininger, C.J., Spencer, T.E., 2004. Maternal nutrition and fetal development. Journal of Nutrition 134, 2169–2172.

Wu, G., Bazer, F.W., Johnson, G.A., Knabe, D.A., Burghardt, R.C., Spencer, T.E., Li, X.L., Wang, J.J., 2011. Important roles for L-glutamine in swine nutrition and production. Journal of Animal Science 89, 2017–2030.

Yang, Y.X., Heo, S., Jin, Z., Yun, J.H., Choi, J.Y., Yoon, S.Y., Park, M.S., Yang, B.K., Chae, B.J., 2009. Effects of lysine intake during late gestation and lactation on blood metabolites, hormones, milk composition and reproductive performance in primiparous and multiparous sows. Animal Reproduction Science 112, 199–214.

Yun, J., Swan, K.M., Vienola, K., Kim, Y.Y., Oliviero, C., Peltoniemi, O.A.T., Valros, A., 2014. Farrowing environment has an impact on sow metabolic status and piglet colostrum intake in early lactation. Livestock Science 163, 120–125.

Zhao, W., Liu, F., Bell, A.W., Le, H.H., Cottrel, J.J., Leury, B.J., Green, M.P., Dunshea, F.R., 2020. Controlled elevated temperatures during early–mid gestation cause placental insufficiency and implications for fetal growth in pregnant pigs. Scientific Reports 10, 20677.

Zheng, H.C., Liu, J.X., Yao, J.H., Yuan, Q., Ye, H.W., Ye, J.A., Wu, Y.M., 2005. Effects of dietary sources of vegetable oils on performance of high-yielding lactating cows and conjugated linoleic acids in milk. Journal of Dairy Science 88, 2037–2042.