

**INVESTIGATING STRATEGIES TO OPTIMIZE FARROWING
PERFORMANCE AND PIGLET SURVIVAL**

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ABSTRACT

Sow litter sizes have been increasing over the years. Increasing litter sizes typically result in an increased duration of farrowing which can be detrimental to piglet survival due to the increased risk of *in-utero* asphyxiation. The cumulative effect of repeated contractions over extended time results in increased pressure on the umbilical cord. This causes an interruption of blood and oxygen to the piglet brain, increasing the risk of death. Although asphyxiation is the cause of the majority of stillbirths, piglets who are born alive can also suffer from *in-utero* asphyxiation. These piglets are considered to be of low vitality and are severely disadvantaged in regard to survival and growth. Different methods have been explored on ways to decrease farrowing duration, reduce stillbirths, and improve piglet survival, but the neonatal mortality rate is still rather high and is not decreasing. Therefore, new methods need to be investigated in the hopes of successfully decreasing the farrowing duration of sows.

The first project aimed to shorten the farrowing duration and improve piglet survival in farrowing crates via the provision of nesting material and enriched piglet mats. There have been several studies on the effects of nesting material in farrowing crates, but most of those studies use materials that will fall through the slatted floors and block the liquid manure systems. The current study implemented the use of jute as the nesting material and proposed a novel way to present the material, by attaching it to the side of the crate, to prevent it from falling through the slatted floors and disrupting the manure systems. The enriched piglet mats were made from a microfiber material to promote homeothermy and reduce heat loss, thus potentially positively impacting piglet growth and survival. Twenty sows were randomly assigned to 1 of 2 treatments: 1) farrowing crate with jute nesting material (Nest; n = 10; 3 pieces of jute, each 40.6 cm x 21.6 cm) and two enriched piglet mats made from an acrylic board (28.0 x 86.4 cm) covered with a microfiber material, or 2) farrowing crate without nesting material (Control; n = 10) and 1 standard rubber mat (28.0 x 86.4 cm) for piglets. Sows had access to the jute material from approximately d 113 of gestation until they finished farrowing, while piglets had access to the mats for the first 3 d of age. Sow saliva was collected to measure Immunoglobulin A (IgA) and cortisol to assess stress on d -1, 0, 1, and 2, relative to farrowing, and a final sample at weaning (d 16.9 \pm 0.18). Piglet plasma Immunoglobulin G (IgG) was collected from 4 piglets/litter at 48 h, 7 d, and weaning. Piglet skin temperature was measured from two piglets/litter using an infrared camera for 3 d after birth. Video

was continuously coded for observations of jute-directed and crate-directed interactions. Nest sows performed less crate-directed behavior than Control sows ($P = 0.02$), while both groups performed the same amount of total nesting behavior (the sum of crate-directed plus jute-directed behavior) ($P > 0.05$). Cortisol tended to be less in Nest sows ($P = 0.08$), but there was no difference in IgA concentrations ($P > 0.4$). Nest piglets tended to be heavier on d 7 ($P = 0.095$), had greater IgG concentrations ($P = 0.03$), and greater skin temperatures ($P = 0.02$). There were no differences in farrowing duration or number of stillbirths ($P > 0.7$).

The second study investigated the effects of a dietary supplement, 6.6% resistant starch (RS), on sow farrowing performance and piglet survival and vitality. Since RS has been shown to help stabilize blood glucose levels post-prandially, it was hypothesized that RS would decrease farrowing duration by improving the energy status of sows during farrowing. Forty-two sows were balanced for parity and randomly assigned to 1 of 2 treatments: standard lactation diet ($n = 21$) or diet containing RS ($n = 21$). Sow blood was analyzed for glucose concentrations at baseline, after 1 wk of being on their respective diets, and during farrowing. Blood glucose for RS sows increased between the beginning and end of farrowing while Control sow blood glucose decreased ($P = 0.04$). However, there were no other effects on sow blood glucose. Farrowing duration and number of stillbirths did not differ between treatments ($P > 0.05$). Piglet blood glucose concentrations for RS piglets tended to increase as the birth order increased, while blood glucose for the Control piglets tended to decrease. The other piglet vitality measures, assessed by blood lactate, pH, partial pressure of carbon dioxide (PCO_2), partial pressure of oxygen (PO_2), total carbon dioxide (TCO_2), bicarbonate (HCO_3), base excess (BE_{ecf}), and oxygen saturation (sO_2) did not differ between treatments ($P > 0.05$).

In conclusion, farrowing duration was not successfully decreased by the provision of jute nesting material attached to the side of the farrowing crate or by supplementation of RS. However, the jute nesting material and enriched piglet mats did positively impact sow welfare and piglet measures to an extent, although this did not translate into improved piglet survival. The resistant starch supplementation seemed to impact sow glucose during farrowing, but not enough to impact farrowing performance or piglet survival or vitality. These results could be because the nesting treatment was not robust enough to allow sows to fully express their nesting behavior needs in order to impact farrowing performance, while the RS supplementation may have been too low of

a dosage, not fed long enough, or a less effective type of RS. Novel ways to optimize sow farrowing performance and piglet survival are still needed.

CHAPTER ONE. LITERATURE REVIEW

1.1 Piglet Pre-weaning Mortality

Piglet pre-weaning mortality is one of the major contributors to reduced herd productivity in modern swine production (Muns et al., 2016). Decreasing piglet pre-weaning mortality is important to improve both animal welfare and industry productivity. There is a distinction between prenatal and postnatal piglet mortality. Prenatal mortality consists of mummies and stillbirths who were born dead and did not breathe upon delivery. Postnatal mortality consists only of the liveborn piglets. Approximately 10 to 20% of liveborn piglets are lost due to postnatal pre-weaning mortality, while between 5% and 10% are stillborn (Kilbride et al., 2010; Kirkden et al., 2013; Koketsu et al., 2006; Langendijk and Plush, 2019; Tuchscherer et al., 2000). Upwards of 50% of pre-weaning deaths occur within the first 3 days after birth making this an especially critical time (Tuchscherer et al., 2000). Low vitality is a major risk factor for postnatal pre-weaning mortality with approximately 14% of live-born piglets having low postnatal vitality (Mota-Rojas et al., 2012). These levels of pre-weaning mortality present a challenge to modern swine production and represent a welfare concern. Greater knowledge of the factors influencing pre-weaning mortality may help improve piglet welfare and reduce economic loss.

Prenatal piglet pre-weaning mortality is greatly influenced by the genetic selection of increasing litter size throughout recent decades (Muns et al., 2016b). In 2020, the average number of total piglets born per litter in the US was 14.99 (Pig Champ, 2020), while it was 12.78 in 2009 (Pig Champ, 2009). Currently, sows in the US wean, on average, 11.23 piglets per litter (NASS, 2021), while two decades ago they weaned, on average, 8.8 piglets per litter (NASS, 2000). Larger litter sizes have resulted in an increased farrowing duration which increases the risk of in-uterine asphyxiation, or oxygen deprivation. Extensive asphyxiation results in death in-utero. There are infectious causes of stillbirths as well, but the cumulative duration of farrowing has been shown to be the predominant cause of stillbirth (Langendijk and Plush, 2019).

Postnatal piglet pre-weaning mortality is a complex and multifaceted issue with many contributing factors. It is the outcome of complex interactions between the sow, the piglet, and the environment. Crushing by the sow is the predominate cause of pre-weaning mortality, but crushing is usually preceded by several other factors, predominantly chilling and starvation (Muns et al.,

2016). There are a variety of factors that make the piglet more susceptible to chilling due to the direct impact of their thermoregulatory capacity. Newborn piglets lack thermoregulatory processes that other animals have, such as brown adipose tissue, and therefore have to rely on the metabolic processes they do have: mobilization of free fatty acids, shivering, and modest gluconeogenesis using the liver's glycogen reserve. These are limited, however, by a number of factors, including the piglet's body temperature and energy status and intake (Berthon et al., 1994). Most mammals possess brown adipose tissue, which is rich in mitochondria and generates heat to maintain body temperature during cold exposure, but piglets lack this. Low piglet birth weight is an important factor for survival with small piglets being less able to maintain a sufficient body temperature than larger piglets (Theil et al., 2012). Cold piglets spend more time close to the sow, an obvious but not preferred heat source, which increases their risk of crushing.

It has been shown that one of the main causes of piglet loss is inadequate colostrum intake within the first day of life and this can result in starvation which is a major cause of postnatal death (Devillers et al, 2007; Dyck and Swiersta, 1987). Colostrum is the first milk secreted by the mammary gland of the sow and provides the newborn piglet with energy for growth and thermoregulation (Quesnel et al., 2012). Colostrum is characterized by high concentrations of maternal antibodies, or immunoglobulins (Ig), and provides passive immunity needed for protection against pathogens (Quesnel et al., 2012). This is essential since the piglet immune system is immature and undeveloped upon birth. Colostrum production ends between 24 and 30 hours post-partum in most sows, so immediate colostrum consumption after birth is vital for the piglet (Quesnel et al., 2012). Inadequate colostrum intake, due to a variety of reasons, results in an increased risk of mortality. Inadequate colostrum intake can be due to poor colostrum production by the sow or from reduced intake due to piglet factors. Competition between littermates to suckle can increase the risk of starvation from reduced colostrum intake, and therefore result in chilling and ultimately crushing (Milligan et al., 2001). Undernourished and cold piglets spend more time in close proximity to the sow, thus are more likely to be crushed. Colostrum yield can be impacted by the sow's water intake, environment, stress, hormone status, and many other factors, thus reducing piglet colostrum intake (Devillers et al., 2007).

Low vitality piglets are predisposed to difficulties in postnatal life making them more susceptible to postnatal pre-weaning mortality. These difficulties include teat competition, the ability to adequately thermoregulate, and the ability to find and suckle a functional teat (Oliviero,

2013). Piglet vitality is the ability of a piglet to survive at birth until weaning, and refers to the strength, liveliness, and vigor that the piglet exhibits postnatally (Farmer and Edwards, 2020; Merks et al., 2012). Low vitality piglets typically have lower viability and subsequently are less likely to adapt to post-uterine life and survive to weaning (Farmer and Edwards, 2020). The interactions between starvation, chilling, and crushing can be initiated by poor vitality.

Although researchers have evidenced instances of successfully lowering the stillbirth and pre-weaning mortality rates, little progress has been made in recent years to decrease pre-weaning mortality as a whole (Baxter and Edwards, 2013). Most of these attempts have been directed at the farrowing environment and husbandry practices. Nutritional interventions have been attempted to increase piglet vitality and therefore increase piglet pre-weaning survival. Rooke et al. (2001) demonstrated the positive effects of feeding salmon oil to sows during gestation on pre-weaning mortality of piglets, where pre-weaning mortality decreased in sows fed salmon oil, a source of long-chain polyunsaturated n-3 fatty acids, from 11.7% to 10.2%. The effect of positive handling of sows during gestation on pre-weaning mortality has been investigated (De Meyer et al., 2020). While pre-weaning survival was improved by positive handling, there was no effect on the number of stillborn piglets. Human assistance of piglets (attending farrowings, drying, cross-fostering, moving piglets to a nurse sow, suckling assistance, etc.) has been found to help improve pre-weaning survival. Without that assistance, however, the upper limit of piglets that the sow is capable of raising until weaning is much lower than the total number of piglets born (Oliviero, 2013). Oliviero et al., (2008) demonstrated that allowing sows to perform natural behaviors such as nest building with suitable substrate prior to farrowing can be a tactic to increase piglet survival by reducing the number of stillborn piglets.

Piglet pre-weaning mortality, both prenatal and postnatal, can occur due to several causes of death and many factors need to be considered to minimize it. Out of the many factors resulting in pre-weaning mortality, stillbirths and crushing are the two largest identified causes (Farmer and Edwards, 2013). Low vitality piglets are at an increased risk of pre-weaning mortality and should be given extra attention and care. In conclusion, pre-weaning mortality accounts for significant economic loss and poses a major welfare concern.

1.2 Animal Welfare

Animal welfare is defined as how well an animal copes with its environment (Broom, 1986). There are various philosophies about animal welfare, but two foundational theories are the basis of modern animal welfare. The first is The Five Freedoms from the ‘Brambell Report’ (Brambell, 1965). The British government’s Farm Animal Welfare Advisory Committee was developed to establish the foundational standards of animal welfare. The Five Freedoms proposed that animals are entitled to are as follows: (1) freedom from hunger and thirst, (2) freedom from discomfort, (3) freedom from pain, injury, and disease, (4) freedom to express normal behavior, and (5) freedom from fear and distress (Brambell, 1965). The second foundational framework for assessing animal welfare is the three circles concept (Fraser, 1997). The three categories Fraser proposes that should be focused on for assessing welfare are: “(1) that animals should lead natural lives through the development and use of their natural adaptations and capabilities, (2) that animals should feel well by being free from prolonged and intense fear, pain, and other negative states, and by experiencing normal pleasures, and (3) that animals should function well.” Animal welfare research investigates these categories individually or will overlap two or more of these categories. These two philosophies have shaped modern animal welfare as we know it today.

1.2.1 Sow and Piglet Welfare

In the swine industry, the farrowing period is a “welfare hot spot” for both sows and piglets. During the farrowing and lactation period, the sow and her piglets are at two very different stages of life and have different welfare needs. A major contrast in welfare requirements for sows and piglets occurs due to different ambient temperature requirements. Newborn piglets prefer a higher ambient temperature of 34°C while sows require a lower ambient temperature from 18°C to 20°C (Silva et al., 2009). In the environment in which we have them, piglets are susceptible to cold stress while sows are susceptible to heat stress. This is because piglets have a large surface area to body weight ratio, low reserves of energy, and poor thermoregulation capabilities at birth (English and Morrison, 1984). Low ambient temperatures can cause hypothermia in piglets which can lead to starvation and crushing, resulting in death (Muns et al., 2016). High ambient temperatures can have a negative impact on sow’s milk production, feed intake, body condition, reproductive abilities (long weaning to estrus intervals, decreased litter sizes), farrowing performance (longer

farrowing duration and increased stillbirths), and offspring performance (lighter weight piglets at weaning) (Muns et al., 2016; Nardone et al., 2006; Prunier et al., 1997). Farms attempt to combat this by keeping the farrowing house warm and supplying a supplementary heat source for the piglets upon birth to make sure the piglet can stay warm and have enough strength and energy to nurse to receive the nutrients it needs for growth and survival. Efforts to provide newborn piglets with a warm environment to prevent cold stress may cause sows to experience heat stress. This is just one welfare challenge sows and piglets face during the farrowing and lactation period.

In addition to high ambient temperatures, there are other determinants of sow welfare during farrowing and lactation that raise concern. One of these is the incidence of pain and injury, which is important since pain is an essential aspect of the welfare of animals. Due to housing elements such as flooring and physical restriction, locomotion disorders and skin lesions can arise. The impact of flooring and the lack of physical movement contribute to sow lameness and locomotion disorders. Poor traction and slip resistance, and hard flooring, may induce skin lesions that result in lameness (Barnett et al., 2001). Lameness can influence many different aspects of sow health by causing pain, which causes stress, and in turn makes the sow more susceptible to other illnesses (Heinonen et al., 2013). Exercise has a positive impact on health by increasing muscle mass, increasing bone strength, and strengthening the immune system (Marchant and Broom, 1996; Marchant et al., 1997; Golub and Gershwin, 1985). Since sows are typically housed in physically restrictive environments, their physical activity declines. During lactation, locomotion problems are a major cause of death or culling, with a culling rate of 15.2% due to lameness in US swine herds (Schenck et al., 2010; Barnett et al., 2001). This is important because mortality is an indicator of poor welfare. Conditions that may be responsible for locomotor problems include osteochondrosis, osteoarthritis, leg weakness, foot rot, foot and leg injuries, and fractures (Schenck et al., 2010).

Another welfare concern for the sow is the restriction of natural behavior in farrowing crates. Sow confinement is a major welfare concern during the farrowing and lactation period. Sows have specific behavioral motivations, and the restrictive farrowing environments cause frustration due to the inability to perform certain behaviors (Melisova et al., 2014). This restriction and inability to perform species-specific behaviors decreases sow welfare (Melisova et al., 2014).

1.2.2 Sow Confinement

The commercial swine industry houses sows in individual crates during farrowing and lactation. The farrowing crate was first introduced in the 1960's with the main goal being to decrease piglet pre-weaning mortality by decreasing crushing through limiting sow posture and movement (Robertson et al., 1960). Farrowing crates also have been widely adopted due to easier sow management and superior ability to provide a clean and disinfected environment for the newborn piglets. Although piglet pre-weaning mortality is an important welfare concern to address, farrowing crates also pose their own welfare issues due to being behaviorally and physically restrictive. Although there is growing global societal concern calling to abolish farrowing crates, 94% of sows in the United States are housed in farrowing crates (USDA, 2012).

There are certain biological needs around farrowing and farrowing crates can have a negative impact on those needs. Farrowing crates are typically small and barren crates that do not allow for much movement or species-specific behavior. This can lead to physiological and psychological stress. It can be stressful for the sow to be confined during farrowing and through lactation, compromising their welfare (Jarvis et al., 2006). One reason for this is the limitation of performing natural behaviors. One natural behavior that sows are motivated to perform prior to farrowing is nest-building, which they cannot perform in farrowing crates due to the lack of sufficient space and substrate availability. Sows have an innate drive to build nests prior to farrowing. This innate motivation to nest build is still present in domesticated and confined sows (Wischner et al., 2009), but the motivation is thwarted due to the small, restrictive, barren environments in the modern production system. Farrowing crates inhibit sows' expression of nesting behaviors which is not only a welfare concern for the sow, but for their offspring as well. It has been shown that increased stress in the sow before and during parturition can lead to increased piglet mortality and morbidity (Baxter et al., 2018). The inability to perform species-specific behaviors can influence the number of piglets born alive, vitality of the piglets, and maternal care capabilities of the sow (Baxter et al., 2018). This physical and behavioral restriction in farrowing crates has been shown to increase stress hormone responses and negative or abnormal behaviors in sows, indicating diminished welfare (Baxter et al., 2011). Since farrowing crates are a commonly used farrowing housing system in the United States, solutions to increase sow welfare and subsequently, piglet welfare, are needed.

1.2.3 Swine Stress

There are various sources of stress for pigs on commercial farms including processing of piglets, weaning, mixing, restraint, transportation, ambient temperature variations, and environmental stressors. This is a concern because stress can have undesirable consequences on the pig's welfare and general productivity. One of the widely accepted definitions of stress is "the biological response elicited when an individual perceives a threat to its homeostasis" (Moberg, 2000). Endocrine responses in animals such as rises in glucocorticoids and catecholamines are considered to be stress responses. Cortisol in particular is a commonly used marker of when an animal is experiencing stress and can be measured in blood, saliva, and feces. Cortisol is produced by activation of the hypothalamic-pituitary-adrenal (HPA) axis. The hypothalamus detects the stressful stimulus and releases corticotropin-releasing factor. This causes adrenocorticotrophic hormone to be released by the anterior pituitary gland, which acts on the adrenal cortex to produce glucocorticoids such as cortisol (Martinez-Miro et al., 2016).

Sows can experience stress due to confinement and restriction of nest-building before farrowing. It's been demonstrated that sows housed in pens, which have more space and substrate to nest-build, have lower cortisol levels than sows housed in crates (Jarvis et al., 1997a; Jarvis et al., 2002). This indicates that the inability to properly nest-build can be stressful for sows. Although cortisol concentrations do naturally increase with farrowing, because the HPA axis is activated during parturition, an environment without substrate can further stimulate it (Yun et al., 2015). In addition to cortisol being increased prior to farrowing due to lack of space and substrate, it's also been shown to increase during early lactation for sows housed in crates versus pens (Oliviero et al., 2008). One explanation for this could be that the farrowing process was more stressful for the crated sows since they had a longer farrowing duration compared to the penned sows. This could also be because sows housed in crates have a more difficult time evading piglet calls for nursing due to the physical constraints of the crate (Oliviero et al., 2008).

Immunoglobulin A (IgA) is another beneficial, yet novel, biomarker of stress in pigs. It is of growing interest because it can be measured non-invasively in saliva and can be supplemental to other stress biomarkers (Staley et al., 2018). Although IgA reflects the functional status of the mucosal immune system, its concentrations can also be influenced by physical and psychological stress (Staley et al., 2018). Physiological signaling molecules such as glucocorticoids and cytokines can bind receptors on B cells, which are IgA-secreting plasma cells. This influences IgA

production and secretion. Physiological signaling molecules can also bind receptors on mucosal epithelial cells, which influences polymeric immunoglobulin receptor (pIgR) production. Increased pIgR expression is typically associated with higher secretory IgA concentrations (Staley et al., 2018).

Salivary IgA fluctuations have been observed in pigs due to the result of a 20 minute restraint test (Muneta et al., 2010). Salivary IgA concentrations increased during the test then decreased back to baseline values 10 minutes after the restraint test had ended. In addition, the removal of a stress has been shown to decrease salivary IgA concentrations. Sows were either permanently crated after farrowing until weaning or temporarily crated for 3 days after farrowing. Sows from the temporary crated group had lower IgA concentrations 24 hours after opening of the crate, indicating that confinement was stressful for the sow (Goumon et al., 2018).

Due to the diverse causes that can influence stress in the pig, it has recommended to have a panel of multiple biomarkers to use for its assessment. The magnitude of negative effects on pig welfare can vary based on many factors such as stress duration and intensity, early life experiences, age, and genetics (Martinez-Miro et al., 2016).

1.3 Farrowing Process and Duration

1.3.1 Hormonal Mechanisms in the Farrowing Process

Farrowing, or parturition, involves the complex actions of several hormones. The beginning of parturition starts with a slow increase in estrogen (Ellendorff et al., 1979). Estrogen release by the ovaries is stimulated by the release of gonadotropin releasing hormone (GnRH) from the hypothalamus, which acts on the pituitary gland and produces follicle stimulating hormone (FSH). An increase in estrogen occurs when FSH acts on the ovaries. This increase in estrogen elevates prostaglandin $F_{2\alpha}$ levels with a simultaneous decrease in progesterone, thus causing a shift in progesterone dominance to estrogen dominance. Progesterone at this point in the pregnancy is secreted by the placenta, while it was secreted by the CL in early pregnancy. The increase in prostaglandin $F_{2\alpha}$ is initiated by placental corticotropin releasing hormone and causes the corpora lutea (CL) to regress. The CL is essential in maintaining pregnancy, therefore when it regresses parturition is ready to begin. A rapid fetal cortisol surge begins after the decrease of progesterone a couple days before farrowing and helps to initiate parturition (First and Bosc, 1979). The fetal

cortisol is carried via blood to the placenta and stimulates myometrial prostaglandins which play a role in uterine contractions (First and Bosc, 1979). During the 48 hours prior to parturition there are several dramatic changes happening very closely together. The first of these is the sharp rise in relaxin from the CL about 14 hours prior to parturition (Dziuk, 1979). Around that same time, prolactin increases and estrogen peaks. The pituitary gland produces prolactin and one of its key regulators during pregnancy is estrogen. Following the fall of relaxin, corticosteroids from the adrenal gland peak during expulsion. Oxytocin, which is produced in the pituitary gland, increases a few hours prior to parturition and depends on the decrease in progesterone. The increase in oxytocin promotes uterine contractions for piglet expulsion. This also results in a continuous let-down of colostrum (Castren et al., 1993). Oxytocin levels during parturition are pulsatile and fetal expulsion results in positive feedback to release more oxytocin (Gilbert et al., 1994). Once farrowing is completed, oxytocin levels are reduced and colostrum changes from a continuous supply to a phasic release (Baxter et al., 2018).

1.3.2 Behavior/Nest-building

An important behavioral trait before the onset of farrowing is nest-building. Nest-building is unique to members of the family *Suidae*, including the pig (*Sus scrofa*) and is performed mainly to provide the sow with comfort, and the offspring with comfort and shelter from the elements and predators (Lent, 1974; Wischner et al., 2009). This behavior occurs in Wild Boar sows as well as domesticated sows. Approximately 2 to 3 days before farrowing, Wild Boar sows will travel many kilometers to seek out a nesting site, which is typically isolated and enclosed. Sows will start to build the nest approximately 24 hours before farrowing, with the most intense activity occurring 12 to 6 hours prior to farrowing (Jensen, 1989). The nest-building process can generally be classified into two distinct and consecutive phases: first is the preparatory phase, an initial increase in activity where the sow roots and paws at the ground and digs a shallow hole. Second is the material-oriented phase, where the sow collects, carries, and arranges nesting material in the nest (Jensen, 1993). Construction of a nest in the wild takes 5 to 10 hours normally (Jensen, 1993).

Although sows in captivity do not have a need for protection against the elements and predators like they do in the wild, they still show nest-building behavioral patterns similar to that of wild pigs (Wischner et al., 2009). Modern production housing prevents much of the nest-building behavior due to the concrete, plastic, or metal floors, and barren and physically restrictive

environment, although rooting and pawing is shown by sows on concrete floors (Wischner et al., 2009). The motivation to gather nesting material with the mouth is shown by rooting and mouthing waterers, feeders, and railings (Lawrence et al., 1994).

Because sows are naturally motivated to nest-build, psychological distress can occur when this motivation is thwarted, and welfare is consequently impaired. Behavioral restriction can result in indicators of stress or frustration, shown by oral or nasal stereotypies, such as bar-biting (Jensen, 1988). This has also been shown by elevations in hypothalamic-pituitary-adrenal (HPA) activity in the sow, indicated by increased plasma cortisol levels (Jarvis et al., 2001). Furthermore, increased posture changes prior to farrowing are another indicator of increased stress and restlessness (Yun et al., 2019). Jarvis et al. (2001) found an increase in the frequency of posture changes in gilts that were housed in crates versus pens and were not provided with nesting substrate, suggesting that those sows without proper space or substrate were more stressed. The same study also found that gilts in barren crates increased the proportion of time spent sitting, which can represent motivational conflict (Jarvis et al., 1997a). The lack of feedback from external stimuli (nesting substrate) can lead to more fragmented and frustrated nest-building behavior, since external stimuli is crucial to successfully performing this behavior (Damm et al., 2000). Restriction of nest-building motivation can have detrimental effects on farrowing and lactation by resulting in a decrease in maternal hormones and subsequent negative effects on her provision of maternal care. Restriction of nest-building behavior can elicit a decrease in circulating plasma oxytocin concentrations, caused by an increase in endogenous opioid receptor density, and suppression of endogenous oxytocin concentrations could negatively affect sow lactation performance (Yun et al., 2013). Yun et al. (2014) found that sows provided with abundant nesting material had an increase in plasma oxytocin concentrations, compared to those sows provided with little or no nesting material. Sows without suitable nest-building material may have reduced maternal behavior since oxytocin is vital in regulating maternal behavior such as milk production and ejection and sow carefulness behavior (Ross and Young, 2009; Uvnas-Moberg et al., 2001). Work by Thodberg et al. (1999) also found that sows given a nest-building substrate had positive outcomes in their maternal behavior, shown by decreased number of posture changes once farrowing began. This is important because increased posture changes during farrowing increases the risk of piglet crushing. Nursing is another maternal behavior that can be affected when nest-building behavior is prevented. Sows without nesting substrate showed a tendency to terminate more sucklings than sows with

nesting substrate (Herskin et al., 1999). These sows also had shorter durations of suckling which could be due to their lack of willingness to nurse. Milk transfer from the sow to her piglets is vital in promoting growth and survival.

Internal and external stimuli are important for the chain of nest-building events to occur (Wischner et al., 2009). In addition to being influenced by external stimuli such as nesting substrate, nesting behavior is also influenced by internal stimuli such as hormones (Wischner et al., 2009). The start of nest-building is triggered by a rise in prolactin levels secreted from the pituitary gland, which occurs after a decline in progesterone and an increase in prostaglandin $F_{2\alpha}$ (Algers and Uvnas-Moberg, 2007). The first phase of nest-building is more strongly correlated with internal stimuli than the second phase, which largely depends on external stimuli and environmental feedback (Wischner et al., 2009). Specific nest-building behaviors have been found to correlate with levels of specific hormones. For example, the time spent carrying and depositing straw correlates with prolactin and progesterone, and negatively correlates with somatostatin concentrations (Algers and Uvnas-Moberg, 2007). It has been shown there is a negative correlation between plasma oxytocin concentrations and nosing and arranging nest materials (Damm et al., 2002). The commencement of nest-building is strongly correlated with the rise in oxytocin levels a few hours prior to parturition (Castren et al., 1993). Nest-building ends at approximately 4 hours before the start of parturition, whereas oxytocin levels elevate significantly about 6 hours before the start of parturition (Castren et al., 1993). The behavioral patterns in the sow before and during nest-building typically reflect the endocrine changes occurring during this time.

Although sows do not need a nest for shelter and protection in captivity, the innate motivation to perform nest-building behavior is still present, highlighting its importance. Domestic sows have been shown to be able to build nests identical to those of Wild Boar sows, demonstrating little change between domestic sows and their wild counterparts (Wischner et al., 2009).

1.3.2.1 Substrate and Space Availability

In modern pig production, most external stimuli are excluded so much of the nest-building behavior is prevented. With that being said, the internal stimuli are still present, and many motor elements of the behavioral pattern are as well (Wischner et al., 2009). Even in the absence of external stimuli nest-building behavior is shown to a certain extent, although it is typically in a smaller variation and in more fragmented phases (Wischner et al., 2009). With the lack of substrate

availability in most intensive housing systems, sows may bite and root at the floor, waterers, feeders, and rails, and stereotypic behaviors may be observed (Wischner et al., 2009). Sows housed with straw in pens have been shown to perform more nest-building behavior than sows housed without straw in pens (Burne et al., 2000). A substrate-deprived environment has been shown to significantly reduce the second phase (the external phase) of nest-building (Jensen, 1993). The availability of nesting substrate has also been shown to decrease the amount of nest-building during farrowing, which is a positive factor. Sows typically commence nest-building behavior when they are satisfied, and there are risks associated with nest-building behavior being performed into the farrowing process, including increased piglet crushing due to the increased activity and posture changes (Thodberg et al., 1999). Burne et al. (2000) demonstrated that nest-building behavior is initiated by hormones, such as prolactin and prostaglandin F2 α , and persists by the provision of nesting substrate. Gilts who were injected with prostaglandin F2 α , one of the hormones that initiates nest-building behavior, and provided straw had a higher frequency of pawing and rooting than those without straw. The ability of sows to get external feedback from the nesting substrate is restricted in barren environments since external stimuli are important in modulating this behavior.

In addition to the importance of external stimuli and the feedback from nesting substrate, adequate space is also important to satisfy the sow's nest-building needs. It has been shown that sows in pens performed more elaborate nest-building behavior compared to the sows in smaller, more restrictive farrowing crates (Thodberg et al., 2002). Cronin et al., (1994) found that sows in pens performed more "nesting-like" behavior than sows housed in crates. Damm et al., (2002) demonstrated that nest-building behavior may be thwarted in crates compared to pens evidenced by gilts in crates increasing their sitting behavior prepartum. It has been hypothesized that increased sitting may be related to the sow's inability to perform nest-building behavior, regardless of their motivation to do so (Damm et al., 2002). Providing sows with space and substrate decrease some of the negative effects of confinement, but do not eliminate them entirely (Wischner et al., 2009).

1.3.3 Farrowing Duration

Hyperprolific sows, or sows that have a higher number of piglets born, typically have a longer than average duration of farrowing due to their large litter sizes (Bjorkman et al., 2017).

Sows with litter sizes of 14 or more piglets are often referred to as hyperprolific, although the numbers are changing and litter sizes are increasing over the years (Baxter et al., 2013). According to the National Agricultural Statistics Service (NASS), the average weaned litter size per sow in the US in May 2021 was 11.16 piglets/litter. The duration of farrowing can vary but previous studies have calculated that the average duration of farrowing is 156 to 262 minutes (Oliviero et al., 2010; van Dijk et al., 2005). The duration of farrowing plays a major role in piglet survival, and the viability and vitality of piglets postnatally (van Dijk et al., 2005). It plays a role not only in piglet survival and welfare, but sow welfare as well. The birth process is a stressful and most likely painful event for the sow and prolonging this prolongs the pain and stress the sow experiences (van Rens and van der Lende, 2004).

There are several consequences to the sow and piglet due to a long duration of farrowing. One of these sow consequences is decreased fertility in sows. Sows that had a longer duration of farrowing were more likely to require repeat breedings due to a failed first insemination after weaning (Oliviero et al., 2013). This is likely due to a disruption of oxytocin activity from long farrowing durations, and this disruption can be extended to insemination. Oxytocin is necessary for the transport of oocytes and sperm cells, so a decrease of oxytocin could explain the higher rate of repeat breedings (Oliviero et al., 2013). The risk of in-utero asphyxia is an important piglet consequence from a long duration of farrowing. Piglets that experience in-utero asphyxia risk being stillborn or being born with low postnatal vitality. Low vitality piglets are significantly disadvantaged after birth with regards to general growth and survival, colostrum intake, and behavioral progression, such as ability to quickly reach the udder and suckle and general movement capabilities (Langendijk and Plush, 2019). A long farrowing duration has been shown to increase the risk of stillbirths by reduced oxygenation and blood supply to the brain (Langendijk and Plush, 2019). Another way that a longer farrowing duration can be detrimental to piglet survival is by decreasing the sow's colostrum yield, which is important due to the relationship between colostrum intake and piglet survival (Hasan et al., 2019). Longer farrowing durations can inhibit normal hormonal progression. During longer farrowing durations, opioids can inhibit oxytocin and prolactin secretion which reduces the colostrum yield (Jarvis et al., 1997b). Sows with a longer duration of farrowing can also experience a delayed decrease in progesterone concentrations, and consequently a delayed increase in prolactin (Foisnet et al., 2010). This too can reduce the colostrum yield.

There are various sow characteristics that impact the farrowing duration. Van Dijk et al., (2005) found that breed is an important factor affecting the farrowing duration, with Meishan crossbred gilts having a shorter farrowing duration compared to gilts or sows from European breeds. Gestation length and savaging behavior independently impacted the duration of farrowing. A longer gestation length resulted in a shorter duration of farrowing, and aggressive sows who showed savaging behavior resulted in a longer duration of farrowing as well (van Rens and van der Lende, 2004). Savagers often were more restless during farrowing which could have caused a longer duration of farrowing (van Rens and van der Lende, 2004). The environment can also have an impact on the duration of farrowing with sows in crates having a longer duration, 311 versus 218 minutes, than sows housed in pens (Oliviero et al., 2008). The authors attributed this to the crated sows having lower oxytocin concentrations than the penned sows. Thodberg et al. (1999) also demonstrated that environment can have an impact on farrowing duration by finding that environmental enrichment, straw in this case, resulted in a shorter duration of the first part of farrowing (birth of first to third piglet), likely due to the sow's ability to nest-build (Thodberg et al., 1999). Hormonal mechanisms can also be related to a longer duration of farrowing. Langendijk and Plush (2019) observed that a longer duration of farrowing can be related to reduced oxytocin secretion. A long duration of farrowing is a risk for many reasons, and methods should be implemented to decrease it.

1.3.4 Sow Energy Needs

Farrowing is an energy demanding process, especially in sows selected for large litter sizes, therefore dietary energy sources are vital in assuring a successful farrowing process. Carbohydrates make up 60-70% of the total energy uptake in the pig diet (Bach Knudsen et al., 2013). However, a large percentage of sows suffer from low-energy status at the onset of farrowing, which is associated with nest building, uterine contractions, and colostrum production (Feyera et al., 2018; Nielsen et al., 2021). Most of the dietary energy sows use comes from glucose, which results from absorption of carbohydrates in the GI tract during the first 4 to 6 hours postprandially (Serena et al., 2009). Feyera et al., (2018) demonstrated that sows that initiated farrowing within 3 hours of their last meal had a shorter farrowing duration and minimal need for farrowing assistance, indicating the importance of glucose during the farrowing process. These sows were not exposed to low blood plasma glucose at the onset of farrowing. Glucose is also vital to the

farrowing process because glucose is one of the key energy metabolites used by the uterus during farrowing (Feyera et al., 2018). Nielsen et al. (2021) demonstrated the importance of glucose at the onset of farrowing by applying intravenous infusion of glucose to sows before farrowing. The glucose infusions decreased the stillbirth rate and improved energy status of the sow. During farrowing glucose is necessary for colostrum production because it is used as a precursor for colostrum lactose and fat synthesis within the mammary gland (Feyera et al., 2019).

The nest-building process immediately prior to farrowing also requires energy due to the increased physical activity, thus contributing to the sow's decrease in energy supply at farrowing. Increased locomotor activity during nest-building causes the energy to be oxidized and carbon dioxide (CO₂) released. Because heat production is almost doubled when sows are in standing posture rather than lying, increased physical activity during nest-building has a considerable effect on the energy status of the sow at the onset of farrowing (Nielsen et al., 2021). Sufficient sow energy is also important to meet piglet energy demands. Piglets have a very high energy requirement due to their high physical activity and high need for thermoregulation (Theil et al., 2014). Strategies to improve energy transfer from sow to piglet can help increase piglet energy status, thus increasing piglet survival. A sufficient supply of energy is important to achieve a successful farrowing with little or no complications and acknowledging the importance of energy during this time is key in implementing strategies to meet the sow's energy needs and shorten the duration of farrowing.

1.3.4.1 Dietary Fiber and Resistant Starch

The term dietary fiber has several definitions. The Codex Alimentarius Commission agreed on a physiological definition of dietary fiber as “carbohydrate polymers with 10 or more monomeric units, which are not hydrolyzed by the endogenous enzymes in the small intestine of humans” (Codex Alimentarius Commission, 2008). In animal nutrition, fiber has classically been analyzed using the crude fiber method, although it has been increasingly difficult to analyze all the dietary fiber components using just one method (Bach Knudsen, 2014). Dietary fiber analysis was further broken down into polysaccharides, non-starch polysaccharides (NSP), and non-cellulosic polysaccharides (NCP), which can be further broken down into soluble and insoluble fiber. More recently, the human model typically has adapted total dietary fiber (TDF), which includes oligosaccharides, fructans, resistant starch (RS), soluble-NCP (S-NCP), insoluble-NCP (I-NCP),

cellulose, and klason lignin. Since the different analytical methods used to determine dietary fiber amounts in feedstuffs vary widely, the values reported in the literature also vary greatly (Bach Knudsen, 2014). For example, sugar beet pulp, a feedstuff high in fiber, only has 20.7% crude fiber, but 50.3% neutral detergent fiber (NDF) and 73.7% fiber, which is the sum of S-NCP, I-NCP, cellulose, and klason lignin (Bach Knudsen, 2014). Different fiber sources can be blends of the various fiber categories. For example, RS can be categorized as soluble fiber, water-soluble carbohydrates, non-structural carbohydrates, and TDF (NRC, 2012). One definition of fiber includes what is classically considered as dietary fiber: non-starch polysaccharides (NSP), and lignin, as well as carbohydrate components with similar physiological and nutritional properties such as non-digestible oligosaccharides and RS (Bach Knudsen, 2014). Different fiber molecules have an impact on where they are digested and how they impact the physiology and microbiome of the digestive tract.

Recently, dietary fiber has been a focus of research in pig diets. Dietary fiber usually contributes to small amounts in pig diets, which are typically corn and soybean meal-based (Li et al., 2021). However, there is growing evidence on the beneficial effects of feeding pigs with diets higher in fiber. Feeding a high fiber diet, which contains both soluble and insoluble fiber, to sows in late gestation has been shown to reduce stillbirth rate (Feyera et al., 2017). Feyera et al., (2017) hypothesized that this could be due to a reduced duration of farrowing. There are multiple hypotheses of why dietary fiber influences sow farrowing duration. The first is that fiber reduces constipation and constipation results in a longer farrowing duration by physically blocking the birth canal, inhibiting the rapid passage of piglets during farrowing (Oliviero et al., 2009). Another hypothesis references increased post-prandial energy uptake in the form of volatile fatty acids (VFA) from the hindgut of the GI tract in sows fed high dietary fiber (Serena et al., 2007). This can stabilize blood glucose levels for longer than a diet with low levels of dietary fiber (de Leeuw et al., 2004). In addition to reproductive processes being affected by dietary fiber, production measures have been shown to benefit from dietary fiber fed to sows as well. Reese et al., (2008) showed an increase in litter size in response to high dietary fiber fed over multiple reproductive cycles. Insoluble fiber has been shown to increase sow colostrum production and piglet colostrum intake, which is associated with pre-weaning mortality (Langendijk and Plush, 2019; Loisel et al., 2013; Theil et al., 2014). Although the inclusion of dietary fiber in sow diets have shown positive effects on welfare and productivity, the response may depend on the fiber source and type. In

contrast, Holt et al. (2006) found no effect on number of stillbirths. Holt et al. (2006) used soybean hulls that contain mostly soluble fiber and a high amount of neutral detergent fiber. The effects of dietary fiber remain controversial and future research is needed to elucidate results.

While resistant starch is a type of fiber, it is different than typical fibers. Resistant starch is defined as the starch that is resistant to digestion in the small intestine and passes to the large intestine where it is broken down (Higgins, 2004). Resistant starch is the most fermentable type of fiber, and the large intestine is where resistant starch is a candidate for fermentation. This fermentation thereby increases short-chain fatty acid (SCFA) production, which is beneficial because SCFA can be used as energy as well as assist in stabilizing blood glucose levels after feeding (de Leeuw et al., 2004; Higgins, 2004). Research on the effects of resistant starch in swine is very limited and variable, especially in sows around the time of farrowing, although there have been some useful results. Similarly to dietary fiber reducing the stillbirth rate, Huang et al. (2020) also found a reduction in stillbirth rate with the inclusion of resistant starch in the gestation diet. Resistant starch has been found to alleviate the stress of sows in mid-late gestation as well as decrease their aggression, increase their postprandial satiety, thus reducing abnormal, or stereotypic, behaviors during gestation (Huang et al., 2020; Sapkota et al., 2016). Feeding resistant starch to sows during lactation has been shown to increase milk total solid content and fat, which can improve nutrient supply to their offspring and promote greater postnatal piglet growth (Yan et al., 2017). In conclusion, it is possible to increase welfare and productivity by nutritional means, but more research is needed to clarify these results.

1.3.5 Asphyxiation

Stillbirths account for a significant proportion of pre-weaning mortality. A stillborn piglet refers to a fetus that dies *in utero* prior to or during farrowing and has never taken a breath upon birth (Gugjoo et al., 2012; Noblett et al., 2021). Stillbirths are generally classified into one of two types: Type 1 stillbirths include piglets that die prior to farrowing (pre-partum) and their deaths are generally associated with infectious causes; Type 2 stillbirths include piglets that die during farrowing (intra-partum) and are generally associated with non-infectious causes (Gugjoo et al., 2012). In-utero asphyxiation is a major cause of Type 2 stillbirths; however, asphyxiation can also plague live-born piglets as well.

Asphyxia, or oxygen deprivation, occurs at a moderate degree during parturition and is normal, however, piglets suffer from a greater degree of asphyxiation at times due to a long cumulative duration of farrowing. This is due to cumulative uterine contractions compressing the placenta during Stage II of parturition (expulsion of piglets), resulting in reduced blood and oxygen supply from the placenta to the fetus (Langendijk and Plush, 2019). These repeated obstructions of blood flow can result in anaerobic metabolism, followed by increasing fetal blood lactate levels and decreasing fetal blood pH. Piglets that experience a long farrowing are more likely to be stillborn or suffer from low vitality upon birth since they are experiencing more contractions during farrowing, thus oxygen delivery to the brain is being repeatedly impaired. Approximately 5 to 10% of piglets are stillborn with asphyxiation being the primary cause of this, while 15 to 20% of piglets born alive will have suffered from asphyxiation (Langendijk and Plush, 2019). Piglets born later in the litter have a greater risk of suffering asphyxiation and of being stillborn as they experience more uterine contractions as the farrowing process progresses (Langendijk and Plush, 2019). One common indicator of asphyxiation is meconium staining (Mota-Rojas et al., 2012). Meconium is a viscous, yellow substance present in the fetal intestines consisting of a mixture of gastrointestinal secretions, bile, pancreatic juice, mucus, cellular detritus, amniotic fluid, vernix caseosa, lanugo, and blood. During asphyxia, intestinal peristalsis increases resulting in relaxation of the anal sphincter and the expulsion of meconium into the amniotic fluid (Mota-Rojas et al., 2012). This results in a yellow-colored staining of the amniotic fluid and the fetal skin.

Low post-natal vitality due to asphyxiation can have several adverse consequences on the piglet. Low vitality piglets have less strength and vigor, are less capable of adapting to extra-uterine life, and face more postnatal challenges such as growth, behavioral functioning, and survival (Herpin et al., 1996). Vitality scores have been used to assess degree of asphyxiation, where an inverse relationship between the degree of asphyxia and vitality score has been demonstrated (Herpin et al., 1996). Vitality scores typically include measures regarding thermoregulation, behavioral assessments, and blood measurements at birth or shortly after. Asphyxiation increased the amount of time it took the piglet to successfully feed as well as decreased the volume of the colostrum intake, which can lead to diminished growth (Langendijk et al., 2018). The decreased colostrum intake could be due to piglets who have suffered from asphyxiation taking twice as long to reach and suckle the udder for the first time than those who did not experience asphyxiation (Orozco-Gregorio et al., 2008). Asphyxiated piglets also struggle

with temperature homeostasis, with heavily asphyxiated piglets having lower rectal temperatures than those suffering from little to no asphyxiation (Orozco-Gregorio et al., 2008). Temperature homeostasis in the newborn piglet is vital since piglets are at a major risk of hypothermia. Karna, et al. (1986) showed that blood flow is reduced to the small and large intestines during asphyxiation, which has been shown to result in intestinal lesions at 12 hours of age. This gastro-intestinal damage can have negative consequences on milk and colostrum absorption. Average daily gain (ADG) was reduced at weaning and at 10 weeks of age in heavily asphyxiated piglets, demonstrating that the consequences of asphyxiation can impact piglet performance past the perinatal period (Langedijk et al., 2018). Asphyxiation during farrowing triggers a cascade of internal events that lead to alterations in cellular function and reduces the survival of piglets.

1.3.6 Other Causes of Stillbirths

Apart from *in-utero* asphyxiation, there are several other factors that increase the risk of stillbirth, both infectious and non-infectious. Non-infectious agents cause about 70% of stillbirths, while the remaining 30% are caused by infectious factors (Vanroose et al., 2000).

One stillbirth risk is meconium aspiration syndrome (MAS) (Mota-Rojas et al., 2012). Meconium staining can be an indicator of asphyxia but can also be one of the factors leading up to stillbirth via MAS (Mota-Rojas et al., 2012; Vanderhaeghe et al., 2010a; Vanderhaeghe et al., 2010b). This occurs when the fetus aspirates the amniotic meconium-contaminated fluid into the lungs and severely obstructs the airway, resulting in perinatal death (Mota-Rojas et al., 2012). Meconium has been readily found in the oropharynx, trachea, and bronchi of stillborn piglets that suffered from MAS (Mota-Rojas et al., 2006).

Another factor related to increased stillbirth risk is total litter size, with there being a positive association between litter size and stillbirth rate. The major reason for this is likely that large litters experience a longer farrowing duration, thus an increased risk of asphyxiation (Gugjoo et al., 2012; Vanderhaeghe et al., 2010b). There is also an association between stillborn piglets and increased birth intervals, shown by Vallet et al. (2010) who concluded that birth intervals greater than 1 h are associated with an increase in stillbirths, and that the last piglet in the litter has an increased risk of stillbirth. Stillborn piglets are typically born after a longer birth interval than their live-born littermates (Van Dijk et al., 2005).

Specific sow characteristics can help identify which sows may be at risk for having stillborns. Hemoglobin (Hb) concentrations are used to determine if sows are anemic, and anemic sows have been found to be at greater risk of stillbirth. This has been demonstrated by Bhattarai et al. (2019) showing that the probability of stillbirths was negatively associated with sow Hb concentrations and by Noblett et al. (2021) reporting that the number of stillborn piglets was greater in anemic sows than nonanemic sows. The precise mechanism behind this has not been elucidated yet, although iron deficiency may contribute to diminished uterine contractions during farrowing (Noblett et al., 2021). Low Hb concentrations during late gestation could be partly due to the transfer of iron from the dam to the fetuses (Noblett et al., 2021). Higher parity sows were more likely to deliver stillborns, possibly due to poor calcium homeostasis, low iron levels, or poor oxytocin secretion in older parities (Vanderhaeghe et al., 2010a). Poor uterine muscle tone or anemia in older sows may also lead to a less efficient and prolonged farrowing process (Canario et al., 2006; Normand et al., 2012; Vanderhaeghe et al., 2010a; Vanderhaeghe et al., 2010b). Although an increasing number of stillborns have been reported with increasing parity, there is an exception for gilts, which can have high number of stillborns potentially due to a narrow birth canal (Gugjoo et al., 2012). In addition, poor body condition at farrowing (>16 mm back fat) is a risk factor for stillbirths presumably because a poor body condition may limit energy available for uterine contractions during farrowing (Vanderhaeghe et al., 2010a; Vanderhaeghe et al., 2010b). Vanderhaeghe et al. (2010b) found that sows with two or more stillbirths at previous farrowing had an increased risk for stillbirth during the next farrowing, demonstrating the potential to identify problem sows before they give birth again.

Stillborn piglets can also be caused by infections. Infectious causes can be characterized based on whether the infectious agent causes systemic effects by septicemias, viremias, or toxemias on the sow, or infectious agents that attack the fetus and/or placenta directly (Christianson, 1992). Porcine reproductive and respiratory syndrome virus (PRRS) is a highly infectious reproductive disease that falls into both categories (Christianson, 1992). The virus crosses the placental barrier late in pregnancy and spreads rapidly within the uterus resulting in stillbirth rates up to 40% (Gugjoo et al., 2012). Porcine parvovirus is an example of the latter category and is considered ubiquitous on most North American swine farms (Christianson, 1992). Infection occurs by direct transmission or indirectly through environmental contamination (Christianson, 1992). Leptospirosis, a zoonotic disease, is another example of the latter category.

It infects pigs through breaks in skin, mucous membranes, and conjunctiva (Christianson, 1992). It is characterized by a high incidence of stillbirths and of weak piglets dying soon after birth (Gugjoo et al., 2012). Another infectious cause in the second category, encephalomyocarditis virus, is believed to be transplacental and includes stillbirths as a clinical sign.

Farrowing a large litter without stillborn piglets is key in ensuring low pre-weaning mortality and high productivity with each piglet lost at birth being an economic loss. A high stillbirth rate is typically a multifactorial problem so individual analysis of each of these factors on the risk of stillbirth is challenging.

1.4 Piglet Vitality Measures

When asphyxiation occurs and compromises oxygen supply, a number of physiological abnormalities occur. Those abnormalities can be evaluated to assess neonatal vitality and survival. There is no universal agreement for what signifies asphyxiation, but there are several indicators that are commonly assessed. These include measures of thermoregulation, behavioral assessments, and physiological parameters. The most commonly used indicators of high vitality in piglets are a decreased time interval between birth and first breath, decreased latency to standing, quicker teat contact, and ability to suckle, as well as increased rectal temperature after birth and growth and survival within the first week after birth (Alonso-Spilsbury et al., 2005). Apart from the individual measures of vitality, there have been multiple attempts to score vitality. One of these, the Apgar (appearance-pulse-grimace-activity-respiration) score, which is widely used in human perinatology, was adapted to newborn piglets (Mota-Rojas et al., 2012). The Apgar score uses five clinical variables: respiration rate, heart rate, muscle tone, attempts to stand, and skin color. Another scoring system was developed by Mota-Rojas et al. (2012). This score uses a 10-point scale and neonates with scores lower than 6 have lower survival rates and are considered low vitality (Mota-Rojas et al., 2012). This score measures lower vitality within one minute after birth based on the following variables: increased heart rate, increased latency to breathing, pale or cyanotic color of the skin on the snout (preferred color is pink), increased latency to standing, and presence of meconium staining. These predisposing factors ultimately determine the piglet's survival prospects. The survival and normal growth and development of the newborn piglet are ultimate indicators of vitality and attention should be focused on piglet vitality and how it can be improved.

1.4.1 Thermoregulation

Asphyxiation lowers the ability to maintain body temperature and results in piglets being especially prone to hypothermia, one of the leading causes of pre-weaning mortality (Alonso-Spilsbury et al., 2005; Herpin et al., 1996; Muns et al., 2016b). After birth, piglets leave the highly temperature controlled uterine environment and are suddenly exposed to cold environmental temperatures and experience a 15 to 20°C drop in their ambient temperature. Because of this, temperature regulation becomes crucial for survival and depends on adaptation to the new environment via thermoregulation, the primary physiological mechanism for temperature conservation (Santiago et al., 2019). Piglets are susceptible to hypothermia due to their poor insulation, poor ability to thermoregulate, low amounts of mobile lipids and glycogen reserves, and lack of brown adipose tissue (Herpin et al., 2002). Brown adipose tissue is mitochondria-rich fat tissue that typically can be metabolized to generate heat and balance body temperature, but this is not possible in newborn piglets due to their lack of it (Berthon et al., 1994). Because of the piglet's small size, they have a proportionally larger body surface and therefore are more susceptible to heat loss compared to larger animals (Kammersgaard et al., 2011). Since lipid storage cannot be used as metabolic fuel, shivering thermogenesis is the piglet's primary method of thermoregulation (Alonso-Spilsbury et al., 2005). Hypothermia makes the piglets susceptible to starvation and crushing, thus contributing to pre-weaning mortality (Herpin et al., 2002).

The ability of a piglet to thermoregulate can be used as a measure of vitality and indicate chances of survival. Studies have shown that piglets suffering from asphyxiation have lower rectal temperatures 1 hour after birth (Alonso-Spilsbury et al., 2005). In a study by Herpin et al. (1996), high vitality piglets exhibited a higher rectal temperature at 24 hours after birth. It was proposed that the rectal temperature at 24 hours after birth was mainly dependent on the time taken to reach the udder, demonstrating the importance of a rapid colostrum intake to supply energy. Herpin et al. (1996) also showed that the piglets with lower rectal temperature ($36.5^{\circ}\text{C} \pm 0.8$) 24 hours after birth were more likely to die before 10 days of age. This demonstrates that high vitality piglets are better able to adapt to extrauterine life because they find the udder more rapidly and are able to sufficiently maintain homeothermia. Similarly, Tuchscherer et al. (2000) found that piglets who died within the first 10 days of life had significantly lower rectal temperatures 1 hour after birth. Low vitality scores typically translate into diminished thermoregulation for the newborn piglet.

1.4.2 Piglet Behavior

Certain behavior assessments can be used to identify low vitality piglets, although there is no universal behavioral test that has been developed. Low vitality significantly increases the amount of time required for a newborn pig to find the teat and begin suckling colostrum for the first time (Mota-Rojas et al., 2012). Latency to first udder contact was two times more in piglets who experienced asphyxiation compared to those who did not, and longer latency times were seen in piglets with lower vitality scores (Trujillo-Ortega et al., 2007). Latency to breathing and standing is also measured to assess vitality in newborn piglets. Latency to breathing is placed in one of three categories – more than 1 minute, between 16 seconds and 1 minute, and less than 15 seconds (Trujillo-Ortega et al., 2007). Piglets with high vitality scores take their first breath within 15 seconds after birth. Latency to standing was measured as the interval between birth and the first time the newborn stands on all four legs. It has been classified as more than 5 minutes, between 1 minute and 5 minutes, and less than 1 minute (Mota-Rojas et al., 2012). Piglets with high vitality scores stand in less than 1 minute after birth. Latency to first udder contact and latency to stand are both assumed to reflect impaired neurological functions in the neonates (Mota-Rojas et al., 2012). Low vitality piglets who take longer to reach the udder experience delayed feeding which impairs their ability to maintain body temperature and can result in reduced growth rates and survival (Alonso-Spilsbury et al., 2005). Piglets with reduced vitality also have less aggressive suckling behavior which results in reduced colostrum intake, impacting their ability to thermoregulate, grow, and survive. Highly viable piglets have been shown to reach the udder and suckle more rapidly and consequently have a higher rectal temperature at 24 hours after birth compared to low vitality piglets (Herpin et al., 1996). Herpin et al. (1996) reported that highly asphyxiated piglets reached the udder 31 minutes after the control piglets who did not experience asphyxiation and thus were delayed in receiving colostrum for thermoregulation and survival.

Muns et al. (2013) developed a behavioral scoring method where piglets were evaluated for four parameters: movement capacity, udder stimulation, number of completed circles around the enclosure, and “screaming”. The piglets were placed in a small circular area and these parameters were measured within 3 hours after birth with each test being 30 seconds long. Piglets scored high for movement capacity if they were able to turn their body at least 90° from its initial orientation within 15 seconds. Piglets scored high for udder stimulation if they showed head movements mimicking udder stimulation movements. Piglets scored high for number of completed

circles around the enclosure if they were able to walk along the limits of the enclosure at least twice. Piglets scored high for screaming if they screamed during the test time. Results indicated that the screaming parameter did not increase piglet chance of survival or influence its growth. The udder stimulation parameter showed the best correlation to body weight gain and survival of the piglet. This may be because the piglet may have a better capacity of reaching the udder and obtaining colostrum and milk when nursing, thus promoting growth and survival. Low vitality increases latencies to reach critical landmark behaviors such as movement capacity and udder stimulation, which has been shown to be related to risk of mortality (Farmer and Edwards, 2020).

1.4.3 Blood Parameters

Although there are no universal physiological cut off values to identify asphyxiation, asphyxiation is typically related to an elevated $p\text{CO}_2$, decreased pH, elevated lactate concentration, and elevated glucose concentrations (Herpin et al., 1996; Mota-Rojas et al., 2012). According to Mota-Rojas et al. (2012), neonatal survival is notably diminished when lactate rises above 90 mg/dL, pH decreases below 7.0, bicarbonate decreases below 10 mmol/L, or the $p\text{CO}_2$ increases above 110 mm/Hg. Blood calcium is also an indicator of neonatal stress when used in combination with the other blood parameters mentioned because an imbalance of calcium in muscle causes trembling and is related to neonatal mortality (Mota-Rojas et al., 2012). Normally, plasma calcium levels decrease during delivery, but parathyroid hormone will increase in response to this and mobilize calcium from the bone to stabilize the calcium levels. In asphyxiated individuals, there is a decreased parathyroid hormone response resulting in an imbalance of calcium (Thakur et al., 2018). Trujillo-Ortega et al. (2007) demonstrated that stillbirths were associated with blood pH levels of less than 6.90 and that glucose concentrations were more than two times higher in piglets who were stillborn. Increased blood glucose levels during asphyxiation could be caused by the release of catecholamines and associated liver glycogenolysis (Herpin et al., 1996). Lactate and $p\text{CO}_2$ levels have been shown to be positively associated with latency to first udder contact, one of the behavioral measures to assess vitality (Herpin et al., 1996; Trujillo-Ortega et al., 2007). Time taken to reach the udder was also associated with decreasing blood pH (Herpin et al., 1996). Rectal temperature at 24 hours after birth has been shown to increase with blood pH and decreasing blood $p\text{CO}_2$ and lactate (Herpin et al., 1996). Blood parameters in conjunction with behavior are valuable assets in assessing perinatal asphyxiation.

1.4.4 Immune Functioning

There is a gap in the literature on how to identify low vitality piglets based on their immune function, but research has demonstrated some ways to measure and predict piglet performance and survival based on immune system measurements. The intake of sow colostrum and consequently passive transfer of immunity by the newborn piglet is crucial for survival because the porcine immune system is not fully developed at birth and the epitheliochorial nature of the placenta in pigs does not allow for the passage of maternal antibodies to the fetus in-utero (Tuchscherer et al., 2000). Epitheliochorial placentas have the most morphological barriers out of all types of placentas due to the six layers of tissue elements that intervene between maternal and fetal blood streams. This prevents intra-uterine passage of maternal antibodies to the fetus (Borghesi et al., 2014). Therefore, piglets are born without sufficient immunoglobulins (Ig) and their immune system develops as they age (Farmer and Edwards, 2020). Alpha₂-macroglobulins are nonspecific serum proteins that are important to the defense of the organism by inactivating proteinases created by invading pathogens and parasites (Tuscherer et al., 2000). Tuchscherer et al. (2000) found that piglets who died within 10 days after birth had lower concentrations of α_2 -macroglobulin. Similarly, lower concentrations of α_2 -macroglobulins were found for stillborn and weak piglets in a study by Svendsen et al. (1986).

The importance of colostrum intake in neonatal survival has resulted in Ig being measured to calculate piglet performance and survival. Piglets are born with low concentrations of Ig and receive the majority of their stores of Ig from the sow's colostrum (Vallet et al., 2015). Colostrum is needed for growth and survival, as demonstrated in previous sections, and a measurement of Ig can provide an assessment of the amount of colostrum obtained by the piglet and subsequently their performance. Vallet et al. (2015) reported that Ig influences growth rate with low Ig concentrations resulting in reduced growth. De Passile et al. (1988) observed an association between the time taken for the piglet to successfully suckle the sow and immunoglobulin G (IgG) levels at 12 hours of age, with piglets who started to nurse sooner having higher IgG levels. As referenced in previous sections, low vitality piglets take longer to reach the udder and suckle and typically have a lower colostrum intake, thus likely have lower Ig concentrations. This decreases the piglet's passive immune protection as well as the development of their active immunity and puts them at risk for reduced growth, morbidity, and mortality (Rooke et al., 2003).

1.5 Conclusion

Given that pre-weaning mortality is still a prevalent issue in the swine industry, new strategies need to be implemented to reduce it, thus increasing piglet welfare, and decreasing economic loss. A common cause of pre-weaning mortality is a long cumulative duration of farrowing, but this could be mitigated by management strategies. The common farrowing housing for sows, farrowing crates, were implemented to decrease piglet pre-weaning mortality. However, their effectiveness has been questioned since these restrictive systems can prevent expression of natural mothering behavior such as nest-building. When sows are allowed to perform nest-building behavior, they have been shown to have decreased farrowing durations, affecting piglet survival. Another hypothesis of why a long farrowing duration occurs in sows is due to low energy. Because of this, using a supplement, such as resistant starch, to prolong sow energy during farrowing could be beneficial. However, the research on feeding resistant starch to swine is lacking, so new science determining its potential benefits is needed. Since fiber has been shown to have a positive effect on sow farrowing process, it's possible that resistant starch can too. Long farrowing durations can reduce piglet postnatal vitality, which interferes with their ability to sufficiently grow and survive. Therefore, the objective of this research was to determine if management strategies around farrowing such as the provision of nesting material in farrowing crates and feeding resistant starch to sows would increase piglet survival and decrease low vitality piglets.

1.6 Tables and Figures

Table 1.1. Summarized effects of fiber on sow reproductive performance and piglet performance.

Fiber source	Effect	Reference
Combined 24% sugar beet pellets, 24% soybean hulls	Reduced the proportion of stillborn piglets from 8.8 to 6.6%; Reduced mortality of total born piglets from 22.3 to 19.9%	Feyera et al., 2017
Combined 8% soybean hulls, 8% wheat bran, 8% sunflower meal, 8% sugar beet pulp	Increased colostrum intake of low birth weight (< 900 g) piglets; Decreased preweaning mortality from 14.7 to 6.2%	Loisel et al., 2013
Combined 19.5% sugar beet pulp, 9.75% soybean hulls, 9.75% sunflower meal, 9.75% wheat bran	Piglets had a higher ADG during week 1 (220 kg/d vs. 194 kg/d)	Quesnel et al., 2009
40% soybean hulls	No effect on number of stillbirths	Holt et al., 2006
5% resistant starch	Reduced the number of stillbirths from 2 to 0.9	Huang et al., 2020
Individually tested 15% wheat aleurone, 30% wheat aleurone	15% wheat aleurone reduced number of stillbirths from 2 to 1.1	Deng et al., 2021
Individually tested 24% wheat bran, 42% wheat bran	24% wheat bran increased piglets alive by 0.9 during the second reproductive cycle	Che et al., 2011
Combined 43.3% wheat bran and 53.3% corn cobs versus combined 41.48% oats, 53.2% oat hulls	No effect on number of piglets born alive	Matte et al., 1994
13.35% ground wheat straw	Litter birth weights were 0.87 kg heavier; Weaning weights were 3.59 kg heavier	Veum et al., 2008
50% alfalfa	Piglet survival rate over three reproductive cycles increased by 8%	Pollmann et al., 1980
46% alfalfa-orchardgrass hay	No effect on number of liveborn piglets	Holzgraefe et al., 1986
3% fiber mixture (50% guar gum and 50% cellulose)	Increased number of liveborn piglets by 1.18	Wu et al., 2020
Individually tested 0.2-0.8% guar gum, 0.8-3.5% cellulose	No effect on stillbirth rate or farrowing duration	Zhuo et al., 2020
2.1% konjac flour	Tended to increase litter weights at weaning by 3.95 kg; No effect on the number of stillbirths or piglets born alive	Sun et al., 2014

CHAPTER TWO. INVESTIGATING THE EFFECTS OF JUTE NESTING MATERIAL AND ENRICHED PIGLET MATS ON SOW WELFARE AND PIGLET SURVIVAL

2.1 Abstract

Domesticated sows are highly motivated to perform nesting behavior prior to farrowing. However, due to the potential for clogging slurry systems, large amounts of nesting material are not practical to use in most production systems. Nesting material is also used to provide the piglets with protection from the cold. Therefore, the study objectives were to assess an alternative nesting material provided prior to farrowing on sow welfare and piglet survival, and to investigate the effect of the entire nesting environment on piglet survival and growth performance. We hypothesized that the provision of jute nesting material would decrease sow stress and decrease farrowing duration, and that the provision of piglet nesting mats would allow piglets to remain euthermic and improve survival and growth. Twenty sows were randomly assigned to 1 of 2 treatments: farrowing crate with jute nesting material (Nest; $n = 10$; 3 pieces of jute, each 40.6 x 21.6 cm) and two enriched piglet mats made from an acrylic board (28.0 x 86.4 cm) covered with a microfiber material, or the farrowing crate without nesting material (Control; $n = 10$) and 1 standard plastic mat (28.0 x 86.4 cm) for piglets. Three jute pieces were attached to the front of the crate to prevent substrate from falling through the slatted floors. Saliva samples were collected, as a non-invasive way to measure cortisol and immunoglobulin A (**IgA**) to assess stress, on d -1, 0, 1, and 2 relative to farrowing, and a final sample was collected at weaning ($d\ 16.9 \pm 0.18$). Piglet blood plasma was collected from 4 piglets/litter to measure immunoglobulin G (**IgG**) at 48 h, d 7, and weaning. Piglet skin temperature was measured from two piglets/litter using an infrared camera for 3 d after birth at 0800, 1200, 1600, and 2000. One piglet was randomly chosen from each side of the crate (heat lamp side and non-heat lamp side) to measure skin temperature. Video was continuously coded for observations of jute-directed and crate-directed interactions. Data were analyzed as a mixed model analysis of variance in SAS 9.4. Nest sows performed less crate-directed behavior than Control sows ($P = 0.02$). Cortisol tended to be less in Nest sows ($P = 0.08$), but there was no difference in IgA concentrations ($P > 0.40$). Nest piglets tended to be heavier on d 7 ($P < 0.10$), had greater IgG concentrations ($P = 0.03$), and greater skin temperatures ($P = 0.02$). There were no differences in farrowing duration or number of stillbirths ($P > 0.70$). The jute

material and piglet nests positively impacted sow welfare and piglet measures but did not translate into improved piglet survival.

2.2 Introduction

It is well known that prepartum sows have an innate motivation to perform nest-building behavior such as foraging, rooting, pawing, and gathering before farrowing (Wischner et al., 2009). However, nest-building behavior is restricted in commercially-housed sows due to lack of space, nesting material, or both. It has been demonstrated that when the sow is able to perform nest-building behaviors, the farrowing process, sow welfare, and piglet survival and growth will be positively impacted (Yun and Valros, 2015). Multiple studies have shown that farrowing duration can be decreased when sows are able to express their nest-building behavior (Cronin et al., 1993; Oliviero et al., 2008; Rosvold and Andersen, 2019; Thodberg et al., 1999). This is an important finding since a prolonged farrowing duration increases the risk of piglet mortality during birth (Langendijk and Plush, 2019). Studies have also shown that the presence of nest-building materials can result in decreased stillborn piglets (Rosvold and Andersen, 2019; Westin et al., 2015).

It has been proposed that nest-building behavior can impact colostrum production by impacting oxytocin and prolactin concentrations in sows (Yun et al., 2014). Oxytocin is involved in initiation and maintenance of milk production in lactating sows and restriction of nest-building behavior can decrease circulating plasma oxytocin, negatively affecting early lactation performance (Oliviero et al., 2008; Yun et al., 2014). Prolactin is also necessary for colostrum production and provision of nesting materials has been shown to increase prolactin concentrations in the sow (Yun et al., 2013). Colostrum plays a crucial role in the transfer of passive immunity from sow to offspring in the first few days of life. Piglets are born without sufficient immunoglobulins and receive the majority from the sow's colostrum. A measure of immunoglobulin, specifically immunoglobulin G (IgG), can provide an assessment of the amount of colostrum obtained by the piglet (Vallet et al., 2015). This indicates that the ability to perform nest-building behavior could contribute to better colostrum intake by neonatal piglets, measured by IgG, thus improving their survival and performance.

Another problem that arises with nesting behavior in the farrowing crate is the presence of the liquid manure systems below. Most manure systems are not capable of handling typical nesting material, like straw, that will fall through the slats and block the slurry system. One purpose of

nest-building is to provide the offspring with shelter from predators and the cold. Neonatal piglets are not at risk of predators in modern production systems, but they are still at risk of hypothermia. Because of this, we aimed to see if providing sows with nesting material and piglets with an alternative mat material, to mimic a nest, versus the standard plastic mat, would impact piglet survival and growth. Therefore, there were two objectives of this study: 1) to investigate an alternative way of presenting nesting substrate to sows in farrowing crates and its effect on sow welfare and farrowing process, and 2) to investigate the effect of the entire nesting environment on piglet survival and growth performance.

2.3 Materials and Methods

All procedures involving animal use were approved by the Purdue University Animal Care and Use Committee (protocol #2010002080) and animal care and use standards were based upon the Guide for the Care and Use of Agricultural Animals in Research and Teaching (Federation of Animal Science Societies, 2020). The experiment took place in the farrowing facilities at the Purdue University Animal Science Research and Education Center (ASREC, West Lafayette, IN).

A total of 20 maternal line York x Landrace sows (parity range 2 to 8, parity average 4.0 ± 1.62) were used in the study. On approximately d 113 of gestation sows were randomly allocated to 1 of 2 treatment groups: 1) Nest ($n = 10$), or 2) Control ($n = 10$), and moved from gestation pens into farrowing crates. Each farrowing crate was equipped with a feeder and nipple drinker for the sows, and a single heat lamp and nipple drinker for the piglets. Nest crates contained 3 pieces of jute (each 40.6 x 21.6 cm, 22.2 g) attached at a singular spot on one of the side bars of the crate near the feeder. Jute was replaced as needed. Treatment crates also contained two enriched piglet mats made from an acrylic board (86.4 cm x 27.9 cm; Meyer Plastics Inc, Indianapolis, IN) covered with a microfiber material (86.4 cm x 27.9 cm; Carlisle Sanitary Maintenance Products, USA). Control crates contained a single plastic mat for the piglets. The Nest piglet mats were removed 3 d after birth, after the critical period for survival had ended (Dyck and Swierstra, 1987). Sows were fed a standard lactation diet (Table 2.1 and 2.2) at 2.7 kg/day twice daily in evenly divided meals from d 113 until farrowing. Post-farrowing sows were fed the lactation diets ad libitum until weaning. Sows and piglets received water from nipple drinkers ad libitum.

Video cameras (KPC-N502NUB, KT&C, Fairfield, NJ) were placed above the back end of the farrowing crates (2 cameras/sow) and sows were continuously video recorded from d 114

of gestation until d 3 of lactation using management software (GeoVision Network Video Recorder, Taipei, Taiwan). Video was analyzed for behavior using GeoVision Remote Viewlog (Taipei, Taiwan). A subset of sows, due to missing video files and poor visibility, $n = 6$ for Nest and $n = 5$ for Control were coded for behavior. Video was continuously coded for 12 h before birth for observations of jute and crate-directed behavior. In addition, farrowing duration was calculated from the video recordings.

Saliva samples were collected from sows (1 per animal per day), as a non-invasive way to measure cortisol and Immunoglobulin A (IgA) to assess stress on d -1, 0, 1, and 2 relative to farrowing, and a final sample collected at weaning, by allowing the pig to chew on 1 cotton swab (Salivette synthetic swab, Sarstedt, Numbrecht, Germany) until it was thoroughly moistened. Cotton swabs were attached to the end of forceps and placed in the sows' mouths so they could chew on them. Samples were collected without entering the crates. Samples were always collected at the same time (around 1200 h) to avoid any confounding effect of circadian rhythm. Saliva was extracted from the swabs by centrifugation at $1500 \times g$ for 10 min. Samples were aliquoted and stored at -20°C until required for assay. Cortisol concentrations were determined using a commercially available ELISA kit (Salivary Cortisol ELISA Kit, Salimetrics, State College, PA). Immunoglobulin A concentrations were determined using a commercially available ELISA kit (Pig IgA ELISA Kit, Bethyl Laboratories, Inc., TX).

Piglet blood plasma (2 mL) was collected from the jugular in vacutainer tubes (Monoject Coated EDTA tubes, Covidien, Mansfield, MA) using 21g x 2.54 cm needles (Vacuette® needles, Greiner Bio-One, Austria) from 4 piglets/litter (2 small piglets, 2 median sized piglets, balanced by sex) to measure IgG at 48 h, d 7, and weaning. Plasma was extracted by centrifugation at $1500 \times g$ for 15 min. Samples were aliquoted and stored at -20°C until analysis. Piglet immunoglobulin G (IgG) was determined using a commercially available ELISA kit (Pig IgG ELISA Kit, Bethyl Laboratories, Inc., TX). All piglets were weighed at d 0, 3, 7, and weaning. Piglet skin temperatures were measured using an infrared camera (FLIR Model T440, emissivity = 0.98; accuracy = $\pm 2\%$; FLIR Systems, Inc., USA) 4 times/d (0800, 1200, 1600, 2000 h) for 3 d after birth. We randomly chose a piglet not directly under the heat lamp and took a skin temperature measurement at the hock. This location was chosen because when animals are cold stressed, peripheral vasoconstriction occurs, therefore this area would be more sensitive to temperature change (Villanueva-Garcia et al., 2020). This area was also selected to minimize any influence from the

radiant heat from the heat lamp. One piglet was chosen to be analyzed from each side of the crate (heat lamp side and non-heat lamp side). Photos were analyzed with commercial software (FLIR Tools software, version 6.4). Some data were missing due to either all the piglets being at only one location (heat lamp or non-heat lamp side) of the crate at the time of data collection or because no piglets had a visible hock area in the photo. The total sample size for piglet skin temperature analysis was 93 piglets ($n = 50$ Control and 43 Nest). Piglet mat usage was evaluated by video recordings. Every 20 min during the daytime (0800 to 1800 h) during the first 3 d of life, the percent of piglets on both the enriched mats and the plastic mats was recorded for each crate. This was analyzed for percentage of piglets on mats for d 1, d 2, d 3, and total percentage over all 3 d.

All data except non-normal behavioral data were analyzed using a mixed model analysis of variance (PROC Mixed, SAS 9.4, Cary, NC), with crate as the experimental unit. The statistical model consisted of fixed effects of treatment (Nest and Control) and day. Parity was used as a random effect. Interactions were explored and included in the model when necessary to account for their effects. No sex differences were observed with any analyses, so it was removed from the final model. Weaning age was used as a covariate for piglet and litter weaning weight data. Repeated measures analysis was included for multiple measures over time (sow cortisol, sow IgA, piglet weights, and piglet IgG). Tukey-Kramer adjustment was made for multiple comparisons. Jute-directed and crate-directed behavior were not normal and were transformed and analyzed using the Wilcoxon-Mann-Whitney test. There was no significant interaction between treatment and time for piglet skin temperature data, so all four temperatures for a single day were averaged and time was removed from the model. Significance is denoted by $P \leq 0.05$ and trends by $0.05 \leq P < 0.10$. Data are presented as means \pm SE.

2.4 Results

The average weaning age for piglets was 16.9 ± 0.45 d. The number of piglets born alive, number of stillbirths, and number of piglets crushed, were 13.9 ± 1.1 , 0.4 ± 0.26 , and 1.3 ± 0.47 , respectively, and did not differ between treatments ($P > 0.2$; Table 2.4). The preweaning survival rate for Control and Nest sows was 94.4% and 92.9%, respectively ($P > 0.5$). Nest piglets tended to weigh more on d 7 when compared to Control piglets ($P < 0.1$; Table 2.3), but there were no other differences in piglet weights ($P > 0.3$; Table 2.3). Farrowing duration ranged from 94.8 to 386.5 min and averaged 227.1 ± 26.52 min and was not different between treatments ($P > 0.7$).

The stillbirth rates for control and nest sows were 2.6% and 1.7% respectively ($P > 0.7$). Sixteen of the 20 sows did not have any stillbirths. There was a treatment effect with Nest piglets having greater IgG concentrations overall compared to Control (Table 2.3). There was also a day effect, with IgG concentrations decreased as piglet age increased (Figure 2).

There were no interactive effects of treatment by time relative to farrowing on cortisol concentrations, however there was an effect of day, with cortisol concentrations on d 0 being greater than d -1 (Table 2.5). Overall cortisol concentrations tended to be greater in control sows compared to Nest sows (Table 2.5).

There were no interactive effects of treatment by d of age on piglet IgG concentrations; however, there was a treatment effect with Nest piglets having an overall greater IgG concentration compared to Control piglets ($P = 0.03$; Figure 2.1). There was an effect of d on piglet IgG concentrations with IgG concentrations decreasing as d of age increased (Figure 2.1).

Overall piglet skin temperatures were greater in Nest piglets compared to Control piglets (Figure 2.2). There was an interactive effect of treatment by day of age with Nest piglet's skin temperature on d 3 being greater than both Nest piglets on d 1 and control piglets on d 2 (Figure 2.2).

Nest sows spent an average of 30.7 ± 27.71 min interacting with the jute during the 12 h prior to farrowing and spent 40.4% of their total nesting behavior (the sum of jute-directed plus crate-directed behavior) interacting with the jute. Total time spent performing jute-directed behavior during the 12 h pre-partum ranged from 5.2 min to 90.4 min. Nest sows spent less time performing crate-directed behavior compared to control sows, 35.9 ± 9.44 min vs. 100.6 ± 21.78 min, respectively ($P < 0.02$). There was no difference in total time spent performing nesting behavior when crate-directed behavior was combined with jute-directed behavior, with Nest sows spending 66.6 ± 18.66 min and Control sows spending 100.6 ± 21.78 min on total nesting behavior ($P > 0.1$). Time spent in crate-directed behavior ranged from 10.0 min to 157.5 min.

2.5 Discussion

Pre-partum sows are highly motivated to perform nest-building behavior, regardless of their environment (Wischner et al., 2009). It has been demonstrated that allowing sows to have access to nesting material prior to farrowing can be advantageous in increasing sow welfare and piglet survival (Wischner et al., 2009). However, novel materials and ways to present those

materials are needed to avoid slurry system blockage on commercial farms. Nesting material can also improve piglet growth and survival by improving thermoregulatory capacity (Algers and Jensen, 1990). Because the newborn piglet is poorly insulated, an enriched nest area for the piglets could help prevent cold stress and promote homeothermy.

Straw and wood shavings have been shown to be the most effective and biologically relevant nesting substrate to promote nest-building behavior and reduce farrowing duration (Thodberg et al., 1999; Wischner et al., 2009). However, these substrates pose a risk of blocking the manure systems below the slatted floors and thus are not used in commercial systems. Therefore, the current study investigated a novel material and how to deliver that material in farrowing crates in hopes that it would be prevented from falling beneath the slatted floors. There have been several studies that explored the results of providing novel materials that would avoid falling into the slurry system. Bolhuis et al. (2018) provided straw balls and jute sacks to sows, both of which were unable to fall through the slatted floors. The materials showed beneficial effects on behavior during farrowing, although farrowing performance was not studied. In addition, Plush et al. (2021) provided hessian sacks to sows leading up to farrowing and found that the hessian sacks stimulated nesting behavior similar to that of sows provided with straw. However, the hessian sacks were not successful in impacting farrowing performance compared with the straw.

It has been demonstrated that sows without access to nesting material prior to farrowing have a prolonged farrowing duration and increased rate of stillborn piglets (Cronin et al., 1993; Thodberg et al., 1999; Oliviero et al., 2008; Rosvold and Andersen, 2019). However, there are also reports of nesting material not exerting an effect on farrowing duration (Edwards and Furniss, 1988; Bolhuis et al., 2018; Edwards et al., 2019). In the current study, sows provided with jute nesting material had a numerically shorter farrowing duration by 15 minutes, although the decrease was not statistically significant. The current study also did not find any difference in number of stillborn piglets, although both of these results could be due to the small sample size of only 10 sows per group. Other studies had larger sample sizes. Cronin et al. (1993), for example, found an effect on farrowing duration with 174 sows. One of the reasons nesting material can possibly influence farrowing duration is by impacting oxytocin concentrations. Inhibiting nesting behavior has been shown to decrease oxytocin concentrations, with oxytocin being a known modulator of uterine contractions (Taverne et al., 1979; Yun et al., 2013). This was demonstrated by Oliviero et al. (2008) who found that sows with a longer duration of farrowing had lower post-expulsion

oxytocin concentration. Interference with oxytocin release can cause intense straining (Nowland et al., 2019) and interruption of blood flow to the piglets, thus increasing the risk of perinatal mortality (Langendijk and Plush, 2019). Another reason nesting material can impact farrowing duration is due to a reduction in stress. It is possible that the absence of nesting material and thus the inability to properly perform nesting behavior is stressful for the sow, which has been indicated by increased cortisol concentrations (Lawrence et al., 1994; Jarvis et al., 2001) and increased heart rate (Damm et al., 2003). Stress can prolong the course of parturition and increase piglet mortality (Chaloupkova et al., 2011).

There was a tendency for Nest sows to have lower salivary cortisol concentrations overall when compared to control sows in the current study, although there were no differences in IgA concentrations. Immunoglobulin A has been shown to be an indicator of stress in pigs (Staley et al., 2018). Escribano et al. (2015) found an increase in salivary IgA in pigs during an isolation test, while Muneta et al. (2010) found increases during a restraint test. In the Muneta et al. (2010) study, cortisol was also measured, and they found that while IgA levels returned to pre-stress levels soon after removal of the stress, cortisol levels were still increased after removal. The initial confinement of the sows into farrowing crates could have been a stressful event and could lead to increased stress biomarkers. However, if IgA levels were only acutely increased, they could have returned to pre-confinement levels after the sows grew accustomed to the farrowing crates, while the cortisol levels stayed elevated as confinement continued. Parturition itself is also a stressor to pigs and the hypothalamic-pituitary-adrenal axis is stimulated for all sows during farrowing regardless of the farrowing environment (Jarvis et al., 1997). This is consistent with the current study with cortisol concentrations increasing on the day of farrowing compared with one day prior to farrowing. Although cortisol concentrations do increase with farrowing, an environment without substrate can further stimulate it, which could be why we saw greater cortisol concentrations for the control sows (Yun et al., 2015).

Sows housed without jute nesting material performed more crate-directed behavior compared to sows with jute. Although we did not differentiate between nesting behavior directed at the crate, such as nosing and pawing, and stereotypies, such as bar-biting, the increase in crate-directed behavior could have been due to increased frustration and stress, shown by the increase in cortisol concentrations. Cronin et al. (1993) found that sows in crates provided with nesting material performed less bar-biting compared to sows in crates without nesting material. Bar-biting

is considered to be a stereotypy that occurs during times of stress and frustration (Yun et al., 2015). The increase in crate-directed behavior observed in the current study is also in agreement with several other studies who reported an increase in amounts of floor and fixture-directed behavior in the absence of substrate (Lammers and de Lange, 1986; Heckt et al., 1988; Lawrence et al., 1994; Bolhuis et al., 2018; Edwards et al., 2019). Greater crate-directed behavior could be a result of sows becoming frustrated when they cannot properly perform nest-building behavior and direct the behavior to other structures of the crate (Swan et al., 2018). Although there was a difference in the amount of crate-directed behavior between the two groups, it is necessary to mention the limitations of the small sample size for the behavior analysis. Due to missing video files and poor visibility, we only had a sample size of 11 sows total for the behavior analysis – 5 Control sows and 6 Nest sows, and as such, results should be interpreted with caution.

Piglets born to Nest sows had an overall greater concentration of IgG compared to the control piglets. This is important because the epitheliochorial nature of the porcine placenta prevents the transfer of immunoglobulins across the placenta, which means that newborn piglets must acquire all their passive immunity from colostrum after birth until their own IgG synthesis begins (Rooke and Bland, 2002). Inadequate colostrum intake has been identified as one of the major causes of preweaning mortality (Edwards, 2002). The amount of piglet plasma or serum IgG can be used to estimate the amount of colostrum intake during the first couple days of life (Devillers et al., 2011). The mechanism behind the increased IgG concentrations observed in the current study could be due to increased levels of sow prolactin and oxytocin. Prolactin is necessary for colostrum production by mammary epithelial cells and for lactose synthesis (Foisnet et al., 2010), therefore the levels of prolactin may result in an increase in colostrum yield, thus impacting piglet IgG concentrations. An increase in prolactin can also increase oxytocin which plays a key role in mammary growth and maternal behavior (Uvnas-Moberg et al., 2011). Nesting materials have been shown to increase both prolactin and oxytocin concentrations (Wischner et al., 2009; Yun et al., 2013). This can influence nursing behavior, because increased oxytocin encourages sows to nurse their piglets which results in the stimulation of milk production (Uvnas-Moberg et al., 2011). The increase in colostrum intake can also be explained by improved udder access by the sow or more frequent suckling, which would be explained by an increase in maternal behavior due to the oxytocin (Plush et al., 2021). In addition, the increased stress experienced by control sows could have led to decreased oxytocin concentrations by increasing levels of opioids (Yun et

al., 2013). It has been demonstrated that piglets which die before weaning consumed less colostrum and had lower IgG intake (Devillers et al., 2011), demonstrating the importance of colostrum intake and IgG attainment.

The increased IgG concentrations could also be explained by an increased thermoregulatory ability, demonstrated by the higher skin temperatures shown in the Nest piglets. The interpretation behind this is that if the piglet is warm, less energy is used for shivering thermogenesis to keep warm, and more energy is available for suckling and competing for a teat, thus the piglet can acquire greater amounts of colostrum and IgG (Kielland et al., 2015). It was predicted that the piglet mats would promote homeothermy and reduce heat loss, since piglets themselves are poorly insulated, thus reducing the risk of hypothermia. Colostrum is a vital energy source for the maintenance of homeothermy (Herpin et al., 2002), therefore piglets with a greater colostrum intake can likely thermoregulate better. The decreased IgG in control piglets could also be because cold stress reduces vigor of the piglet which leads to less aggressive nursing behavior and reduces the amount of colostrum and IgG obtained (Herpin et al., 2002). An improved ability to remain euthermic has implications for growth and survival (Herpin et al., 2002). Piglets who stay warmer are less susceptible to chilling and subsequently less susceptible to starvation and crushing, which are usually predated by chilling (Herpin et al., 2002).

The current study found that Nest piglets tended to be heavier on d 7 of age. This could possibly be due to the increased concentrations of IgG and the increased ability to remain euthermic, as demonstrated by the increased skin temperature. These piglets could have had a higher colostrum intake, thus greater growth. Piglets who have a greater colostrum intake have more energy and can devote that energy to suckling (Herpin et al., 2002). Although there was a difference in weights at d 7 of age, this did not translate into increased weight at weaning or improved survival between treatments. Although there is a link between sow nesting behavior and survival (Ocepek et al., 2017), the current findings agree with Cronin and Smith (1992) who reported no change in piglet preweaning survival when sows in crates were provided with nesting material. In addition, sows that engage in more nesting behavior have been shown to crush fewer piglets (Ocepek and Andersen, 2017). Nest sows in the current study crushed 0.8 fewer piglets than control sows, however this was not statistically significant.

2.6 Conclusion

Although straw is biologically relevant for the sow since it closely resembles the nesting substrate used under natural conditions, the jute material still resulted in improvements in sow and piglet welfare. Jute provided to sows in farrowing crates alleviated sow stress around the parturition period, as shown by decreased cortisol concentrations and decreased crate-directed behaviors. The combination of jute nesting material and piglet mats improved piglets' growth at d 7 of age, improved piglet immune response, and improved the ability of piglets to remain euthermic. Although the jute only had a minor effect on piglet measures and did not result in a reduced farrowing duration or increased piglet survival, it can be concluded that the presentation and type of material is at least somewhat beneficial for sows in farrowing crates. Sows may have been more satisfied behaviorally if they had a greater amount of nesting material than the three pieces of jute they were given, thus we may have seen further impacts on piglet growth and survival, as the provision of abundant nesting material versus minimal nesting material has been shown to be beneficial in stimulating nesting behavior. It can also be concluded that the provision of an improved micro-climate for the piglets, such as the microfiber mat used in this study, can be beneficial in improving piglet ability to remain euthermic.

2.7 Tables and Figures

Table 2.1. Sow lactation diet ingredients.

Ingredient	%
Corn	50.373
Soybean meal, 48% CP	31.500
DDGS – 7% fat	10.000
Swine grease	3.000
Limestone	1.450
MonoCal. Phosphate	1.310
Vitamin Premix ¹	0.300
Sow Vitamin Premix ²	0.250
Trace Mineral Premix ³	0.125
Se Premix ⁴	0.050
Phytase ⁵	0.100
Salt	0.500
Plasma protein	0.500
Citristim ⁶	0.150
Availa Zn 120 ⁷	0.042
Clarify ⁸	0.100
Defusion Plus ⁹	0.250
Total	100.000

¹ Provided per kg of diet: vitamin A, 4,961 IU; vitamin D₃, 1984 IU; vitamin E, 53 IU; vitamin K, 4 mg; riboflavin, 9.9 mg; pantothenic acid, 33 mg; niacin, 59 mg; and B₁₂, 0.040 mg.

² Provided per kg of diet: biotin, 0.22 mg; folic acid, 1.65 mg; choline, 551 mg; pyridoxine, 4.96 mg; vitamin E, 22 IU; chromium, 0.20 mg; and carnitine 49.6 mg.

³ Provided per kg of diet: iron, 121.3 mg; zinc, 121.3 mg; manganese, 15.0 mg; copper, 11.3 mg; and iodine, 0.46 mg.

⁴ Provided per kg of diet: 0.3 ppm selenium.

⁵ Phyzyme® (Danisco Animal Nutrition, Morlborough, UK) providing 600 phytase units (FTU)/kg.

⁶ CitriStim (ADM Animal Nutrition, Quincy, IL) is a proprietary strain of *Pichia guilliermondii*, a whole-cell inactivated yeast product. Nutrient value was assumed to be equal to corn that it replaced in the control diet.

⁷ Availa Zn 120 (Zinpro Corporation, Eden Prairie, MN) is an organic zinc amino acid complex that provides 50.4 ppm Zn.

⁸ Clarify® Larvicide (Central Life Sciences, Schaumburg, IL).

⁹ Defusion Plus preservatives (Provimi, Lewisburg, OH)

Table 2.2. Sow lactation diet calculated nutrients.

Calculated Nutrient ¹	
ME, Kcal/kg	3,340.60
NE, Kcal/kg	2,459.80
CP, %	22.21
Total Lysine, %	1.185
SID ² Lys, %	1.001
SID Met, %	0.308
SID Met+Cys, %	0.614
SID Thr, %	0.694
SID Tryp, %	0.231
SID Iso, %	0.800
SID Val, %	0.888
Ca, %	0.900
Total Phos, %	0.725
Available Phos, %	0.498

¹ Calculated nutrients were targeted to meet or exceed the NRC 2012. Nutrient Requirements of Swine. 11th ed. Natl. Acad. Press, Washington, DC.

²SID = Standardized ileal digestible.

Table 2.3. Piglet performance data for Nest sows provided jute nesting material and enriched piglet mats and Control sows not given nesting material or enriched mats.

Variable	Control	Nest	<i>P</i> -value
# of sows	10	10	
Litter weight d 1 pre-CF ¹ , kg	18.8 ± 1.31	20.5 ± 1.18	0.306
Litter weight d 1 post-CF ¹ , kg	18.2 ± 0.91	19.1 ± 0.76	0.441
Individual weights d 0, kg	1.4 ± 0.04	1.5 ± 0.03	0.210
Individual weights d 3, kg	2.0 ± 0.05	2.1 ± 0.05	0.179
Individual weights d 7, kg	2.8 ± 0.07	3.0 ± 0.07	0.095
Individual weaning weights, kg	5.8 ± 0.15	5.5 ± 0.14	0.246
Weaning litter weight, kg	64.2 ± 3.17	62.9 ± 4.41	0.912
Litter weight gain, kg	45.9 ± 2.73	43.6 ± 3.86	0.953
Daily litter weight gain, kg/d	2.9 ± 0.18	2.8 ± 0.23	0.923
Plasma IgG ² , mg/mL	65.4 ± 6.80	84.9 ± 6.70	0.029

¹CF = cross-fostering.

²IgG = Immunoglobulin G.

Table 2.4. Litter size and parturition data for Nest sows provided jute nesting material and enriched piglet mats and Control sows not given nesting material or enriched mats.

Variable	Control	Nest	<i>P</i> -value
# of sows	10	10	
Total born, #	14.1 ± 1.15	14.0 ± 1.05	0.819
Total born alive, #	13.7 ± 1.10	13.7 ± 1.00	0.838
Stillborn, #	0.4 ± 0.31	0.3 ± 0.21	0.792
Mummies, #	0.8 ± 0.25	0.4 ± 0.22	0.384
Crushed, #	1.7 ± 0.62	0.9 ± 0.31	0.266
Litter size post cross-fostering	12.0 ± 0.26	12.2 ± 0.44	0.665
Weaning litter size	11.3 ± 0.21	11.3 ± 0.37	0.999
Farrowing duration, min ¹	234.7 ± 20.95	219.4 ± 32.08	0.702

¹Control n = 9 due to lost video files.

Table 2.5. Sow salivary stress parameters for Nest sows provided jute nesting material and enriched piglet mats and Control sows not given nesting material or enriched mats.

Variable	Control	Nest	<i>P</i> -value		
			Treatment	Day	Treatment*Day
# of sows	10	10			
Cortisol, ug/mL	26.4 ± 2.98	21.3 ± 2.0	0.084	0.043	0.197
Day -1 ¹	17.3 ± 2.83 ^a	19.1 ± 2.30 ^a			
Day 0 ¹	39.8 ± 9.95 ^b	24.4 ± 4.95 ^b			
Day 1 ¹	33.2 ± 6.64 ^{ab}	18.8 ± 3.96 ^{ab}			
Day 2 ¹	22.1 ± 2.59 ^{ab}	19.7 ± 6.63 ^{ab}			
Weaning	18.2 ± 3.47 ^{ab}	22.7 ± 4.32 ^{ab}			
IgA ² , ug/mL	1,713.1 ± 245.19	1,929.0 ± 284.03	0.484	0.142	0.998
Day -1 ¹	1,439.3 ± 405.14	1,735.6 ± 627.37			
Day 0 ¹	1,693.0 ± 692.69	1,863.0 ± 715.97			
Day 1 ¹	2,752.1 ± 663.08	2,842.7 ± 695.16			
Day 2 ¹	1,755.8 ± 384.92	1,839.9 ± 802.65			
Weaning	1,141.5 ± 481.84	1,513.4 ± 438.52			

^{a,b}Means within a column with different superscripts differ ($P < 0.05$).

¹Relative to farrowing.

²IgA = Immunoglobulin A.

Table 2.6. Piglet mat usage for Nest sows provided jute nesting material and enriched piglet mats and Control sows not given nesting material or enriched mats for first 3 d of age. Percentage of piglets that were on the plastic or enriched (Nest) mats when scan sampling in 20-min intervals.

Variable	Control	Nest	<i>P</i> -value
# of sows	10	9	
Total mat usage, %	56.9 ± 1.98	58.7 ± 2.68	0.538
D 1 mat usage, %	41.5 ± 1.61	37.6 ± 4.55	0.567
D 2 mat usage, %	62.9 ± 2.02	64.7 ± 2.13	0.485
D 3 mat usage, %	66.0 ± 2.48	66.9 ± 2.70	0.797

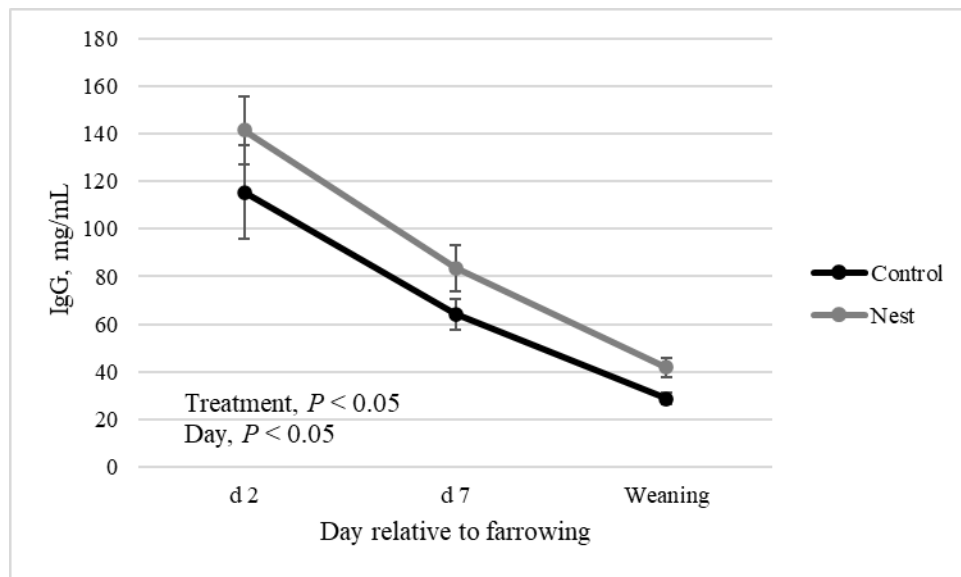


Figure 2.1. Piglet IgG (Immunoglobulin G) concentrations over time relative to farrowing for Nest sows provided jute nesting material and enriched piglet mats and Control sows not given nesting material or enriched mats.

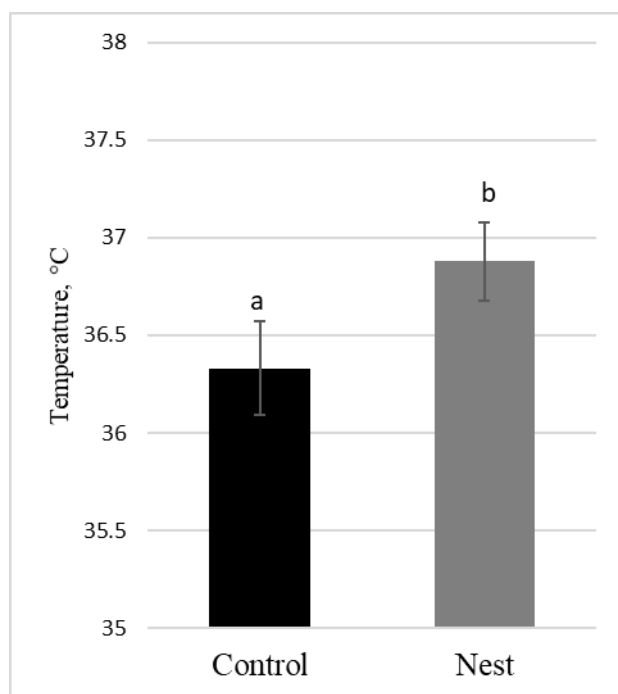


Figure 2.2. Average piglet skin temperatures (d 0 to d3) for Nest sows provided jute nesting material and enriched piglet mats and Control sows not given nesting material or enriched mats. Letters indicate treatment effect.

CHAPTER THREE. THE EFFECT OF FEEDING RESISTANT STARCH ON SOW AND PIGLET FARROWING PERFORMANCE AND BLOOD PARAMETERS

3.1 Abstract

Hyperprolific sows can have a long duration of farrowing, negatively impacting piglet survival and vitality. This study's objective was to assess the effect of a diet containing 6.6% resistant starch (**RS**) on sow and piglet farrowing performance. We hypothesized that a diet containing RS would decrease sow farrowing duration and improve piglet survival. Forty-two sows were balanced for parity and randomly assigned to 1 of 2 treatments: standard lactation diet (Control, $n = 21$) or diet containing RS (RS, $n = 21$). Sows were fed their respective diets from approximately 7 d pre-farrowing throughout lactation. Sow blood was drawn at three time points on d 106 ± 1.0 and d 113 ± 1.0 of gestation (pre-feeding, 2 and 6 h post-feeding) and during farrowing to measure blood glucose. Piglet umbilical blood (~ 3 piglets/litter; beginning, middle, end of birth order) was collected at birth and analyzed for glucose, lactate, pH, PCO_2 , PO_2 , TCO_2 , HCO_3 , BE_{ecf} , and sO_2 . Piglets were visually assessed at birth to score meconium staining. Data collected included farrowing duration, piglet birth intervals, number of stillborn piglets/litter, sow and piglet weights, piglet mortality, and sow feed and water intake. Average litter sizes post-cross-foster for Control and RS were similar, 12.1 ± 0.4 and 11.6 ± 0.4 piglets, respectively ($P > 0.05$). Litter weight gain was similar between control and RS (44.97 vs. 47.54 kg, $P = 0.33$), respectively. Feeding resistant starch had no effect on number of stillborn piglets or pre-weaning survival ($P > 0.75$). Farrowing duration (178.9 ± 17.6 min vs 165.2 ± 18.0 min, $P = 0.59$) and piglet birth intervals (16.57 ± 1.7 min and 14.89 ± 1.8 min, $P = 0.51$) did not differ between Control and RS, respectively. There tended to be a diet by birth order interaction on piglet blood glucose concentrations with RS piglet blood glucose increasing as farrowing progressed ($P = 0.07$), but no other effects on piglet blood parameters were observed. Resistant starch fed sow blood glucose increased between the beginning and end of farrowing while Control sow blood glucose decreased ($P = .04$). Sow fecal short-chain fatty acid concentrations at d 114 of gestation did not differ between treatments ($P > 0.05$). In conclusion, feeding RS to sows pre-farrowing can modify sow and piglet blood glucose but did not result in reduced farrowing duration or improved piglet survival.

3.2 Introduction

Perinatal mortality is a contributor to reduced herd productivity in modern swine production (Muns et al., 2016). Length of farrowing duration plays a major role in perinatal deaths, including stillbirths and low vitality piglets that struggle with growth and survival (van Dijk et al., 2005). This is primarily due to the cumulative duration of farrowing causing piglets to suffer from in-utero asphyxiation (Langendijk and Plush, 2019). Piglets that experience a long farrowing are more likely to be stillborn or suffer from low vitality upon birth since they are experiencing more contractions during farrowing, thus oxygen delivery to the brain is being repeatedly impaired (Langendijk and Plush, 2019). Approximately 8.6% of piglets are stillborn while an additional 15% to 20% of liveborn piglets will have suffered from asphyxiation, resulting in low postnatal vitality (Langendijk and Plush, 2019; NAHMS, 2012). Farrowing is an energy demanding process and it has been hypothesized that a large percentage of sows suffer from low energy during the farrowing process, thus contributing to the extended farrowing duration (Feyera et al., 2018).

There is growing evidence that the amount and type of carbohydrate subtypes in the diet can have effects on pig productivity and welfare, including the farrowing process. Starch is the main energy source for monogastric species and different dietary starch sources have differing effects on its digestion (Giuberti et al., 2012). Resistant starch is an example of a modified carbohydrate that bypasses digestion in the small intestine and passes to the large intestine where it is broken down (Higgins, 2004). Resistant starch is a substrate for fermentation in the large intestine and increases short-chain fatty acid (SCFA) production in the hindgut, which are beneficial for increased energy uptake in the hindgut. Resistant starch has been shown to lower blood glucose levels postprandially due to the delayed absorption of carbohydrates and to assist in prolonging the release of glucose (Higgins, 2004). In the case of digestible starch, glucose typically increases sharply postprandially with a spike after 1 to 2 h, then drops 4 h postprandially. Delayed peaks in glucose concentrations have been observed in studies on the effects of fibrous diets (de Leeuw et al., 2004). Although resistant starch can cause acute attenuation of blood glucose concentrations postprandially, it can also assist in extending the release of glucose hours later, versus sharply plummeting approximately 4 h postprandially (de Leeuw et al., 2004). Because fermentation and production of SCFA in the hindgut may be elevated several hours after feeding, SCFA may be available as a source of energy at times when the glucose supply from the gut is decreasing (de Leeuw et al., 2004). Sows are limit fed prior to farrowing and do not have the ability

to choose their mealtime. Thus, it may be beneficial to stabilize interprandial glucose levels and prevent sharp decreases in glucose levels, such that glucose is more likely to be elevated during farrowing. This can provide the sow with more energy during farrowing to complete the farrowing process more quickly.

Given that resistant starch can assist in stabilizing blood glucose levels after feeding and produce SCFA that increase energy, it was hypothesized that a diet containing resistant starch would prolong the energy release in sows during farrowing, thus decreasing farrowing duration and asphyxiation, thereby increasing piglet survival and vitality.

3.3 Materials and Methods

All procedures involving animal use were approved by the Purdue University Animal Care and Use Committee (protocol #2010002080) and animal care and use standards were based upon the Guide for the Care and Use of Agricultural Animals in Research and Teaching (Federation of Animal Science Societies, 2010). The experiment took place in the farrowing facilities at the Purdue University Animal Science Research and Education Center (ASREC, West Lafayette, IN).

A total of 42 York x Landrace cross gilts and sows (parity range 1-10, parity average 3.2 ± 2.43) were used in the study. On approximately d 106 of gestation sows were blocked by parity, randomly allocated to dietary treatments, and moved from gestation pens into farrowing crates. Sows were individually housed in farrowing crates until the end of lactation. Each farrowing crate was equipped with a stainless steel feeder and nipple drinker for the sows, and a single heat lamp, rubber mat, and nipple drinker for the piglets. Sows were continuously monitored during 0700 to 2300 h during farrowing days. Farrowing assistance was given to the sow if the birth interval exceeded 45 min between piglets. A total of 510 piglets (492 live-born and 18 stillborn) from 42 sows were included in the study.

Sows were fed the lactation diet (Table 3.1) at 2.7 kg/d twice daily in evenly divided meals (0700 and 1500 h) from d 106 until farrowing. Post-farrowing sows were fed the lactation diets ad libitum until weaning. The lactation diets (1.0% SID Lysine) were one of two dietary treatments: 1) control (Control), 2) resistant starch, RS; 6.6% resistant starch.

As each piglet was born, birth time, birth order, meconium staining score (Mota-Rojas et al., 2002), and farrowing assistance were recorded. Each piglet was assessed as born alive, stillborn, or mummy. Immediately after birth, cord umbilical blood was collected in a microtainer tube (BD

Microtainer® Lithium Heparin/PST™ Gel 600uL tube, Becton, Dickinson and Company, Franklin Lakes, NJ) from 3 piglets per litter. Blood was collected from one piglet from the beginning (1 to 2), middle (4 to 5), and end of the birth order (8+). Blood was analyzed using a handheld blood analyzer (iSTAT® portable clinical analyzer, iSTAT® Alinity, Abbott Point of Care Inc., Princeton, NJ) using the CG4+ cartridge (Abbott Point of Care Inc., Princeton, NJ) for concentrations of pH, carbon dioxide partial pressure (pCO₂), oxygen partial pressure (pO₂), lactate, bicarbonate (HCO₃), total carbon dioxide (TCO₂), base excess (BE_{ecf}), and oxygen saturation (sO₂). An additional drop of blood was analyzed for glucose using a handheld glucometer (AimStrip® Plus, Blood Glucose Meter, Germain Laboratories, Inc., San Antonio, TX). On d 1 after birth, all piglets were processed (ears notched, tails docked, teeth clipped, iron dextran injection, males castrated) and weighed. Piglets were weighed again at weaning (18.3 ± 1.83 d of age). Litter size was standardized via cross-fostering within dietary treatment to an average of 11.9 ± 1.64 piglets within 48 h after birth.

Video cameras (KPC-N502NUB, KT&C, Fairfield, NJ) were placed above the back end of the farrowing crates (2 cameras/sow) and sows were continuously video recorded from d 113 of gestation until d 3 of lactation using management software (GeoVision Network Video Recorder, Taipei, Taiwan). Videos were analyzed for behavior using commercial software (The Observer XT 15, Noldus, Wageningen, The Netherlands) for 12 h prior to farrowing through the end of farrowing (birth of the last piglet). Farrowing duration was calculated as time between birth of the first and last piglet. Sow weight was measured on approximately d 106 of gestation, d 2 postpartum, and at weaning. Sow backfat thickness and loin muscle depth were measured using an ultrasound (Aloka 500, Aloka Co., Ltd., Japan) on d 107 of gestation and at weaning. On approximately d 106 and d 113 of gestation sow blood glucose was measured via the ear vein prick using a handheld glucometer at three timepoints: pre-feeding (0630 h), 2 h post-feeding, and 6 h post-feeding. During farrowing, sow blood glucose was measured via the ear vein prick using a handheld glucometer at three time points: beginning, middle, and end of farrowing, lining up with the piglet blood that was collected during those same time points. Colostrum (25 mL) was collected from the sows within 8 h after the start of farrowing to measure Immunoglobulin G (IgG) using a Brix refractometer (Misco PA201, Misco, Solon, OH, USA). Sow fecal samples were collected on d 107 and d 114 of gestation and analyzed for SCFA: acetate, propionate, butyrate, iso-butyrate,

valerate, and iso-valerate. The fecal samples were quantified with Liquid Chromatography tandem Mass Spectrometry (Agilent 6460 Triple Quadrupole, QQQ; Santa Clara, CA, USA).

All data except non-normal behavioral data were analyzed using a mixed model analysis of variance (PROC Mixed, SAS 9.4, Cary, NC), with crate as the experimental unit. The statistical model consisted of fixed effects of treatment (RS and Control) and day. Parity was used as a random effect. No sex differences were observed with any analysis, so it was removed from the final model. Interactions were explored and included in the model when necessary to account for their effects. Repeated measures analysis was included for multiple measures over time. Weaning age was used as a covariate for piglet and litter weaning weight data. Baseline pre-feeding glucose concentrations were used as a covariate for sow glucose analysis. Tukey-Kramer adjustment was made for multiple comparisons. Data that were not normal were transformed, and if normality was not accomplished data were analyzed using the Wilcoxon-Mann-Whitney test. These data included: for the pre-farrowing behavior, lying laterally on the right side, standing, and total lateral lying; for the farrowing behavior, posture changes per h, lying ventrally, lying laterally on the left side, lying laterally on the right side, standing, total lateral lying and total lying. Significance is denoted by $P < 0.05$ and trends by $0.05 < P \leq 0.10$. Data are presented as means \pm SE.

3.4 Results

Sows from both groups on average lost 15.8 ± 2.80 kg during lactation ($P > 0.30$). Sow BW and BW change were not different between treatments ($P > 0.38$; Table 3.4). Similarly, sow backfat thickness and loin muscle depth were not affected by dietary treatment ($P > 0.34$; Table 3.4). Average daily water intake during week 1 post-farrowing tended to be greater in the treatment sows compared to control sows ($P < 0.07$), while there was no difference during the remaining periods ($P > 0.10$; Table 3.4). Sow colostrum IgG averaged 27.9% and was not different between treatments ($P > 0.60$; Table 3.4).

Number of piglets born alive, stillborns, number of meconium stained piglets, and number of piglets crushed were 11.7 ± 0.65 , 0.4 ± 0.18 , 3.7 ± 0.57 , and 0.7 ± 0.23 , respectively, and did not differ between treatments ($P > 0.36$; Table 3.5). The stillbirth rates for RS and control sows were 3.3% and 3.1%, respectively ($P > 0.80$). There were no differences in individual piglet weights at d 1 or weaning ($P > 0.10$; Table 3.4). Litter weights were not statistically different between treatments, but RS litter weaning weight was 2.1 kg heavier than the control group's litter

weaning weight ($P > 0.30$; Table 3.4). The pre-weaning survival rate was an 87.6% and did not differ between treatments ($P > 0.70$). Farrowing duration ranged from 58 to 344 min with an average of 176.2 ± 17.50 min and was not affected by dietary treatment ($P > 0.50$; Table 3.5).

Sow pre-farrowing and farrowing average blood glucose concentrations did not differ between treatments ($P > 0.60$; Table 3.6). There was a significant effect of time on sow pre-farrowing blood glucose concentrations, with each time point (30 min pre-feeding, 2 h post-feeding, and 6 h post-feeding) differing ($P < 0.0001$; Figure 3.1). Pre-farrowing blood glucose concentrations increased at 2 h post-feeding then slightly decreased at 6 h post-feeding, although not decreasing to their pre-feeding baseline concentrations. The average blood glucose during farrowing tended to be lower for sows fed the RS diet ($P < 0.10$; Table 3.6). The change in blood glucose between the beginning and end of farrowing was greater for RS sows compared with control sows ($P < 0.04$; Table 3.6). Change in blood glucose for the remaining time points during pre-farrowing and farrowing were similar ($P > 0.10$).

An interaction between diet and piglet birth order tended to be observed for piglet blood glucose concentrations ($P < 0.08$; Table 3.7). Control piglets in the middle and end of the birth order tended to have a lower blood glucose concentration than the control piglets in the beginning of the birth order, while RS piglet blood glucose increased as birth order increased (Table 3.7). Additionally, control piglets in the beginning of the birth order tended to have a greater blood glucose concentration than the RS piglets in the beginning of the birth order ($P < 0.08$). There was a tendency for a birth order effect on piglet pH with the piglets at the end of the birth order having lower blood pH ($P < 0.09$; Table 3.7). There were no other differences in the piglet blood parameters ($P > 0.1$). Sow fecal SCFA and their change from d 107 – d 114 were not affected by dietary treatment ($P > 0.36$; Table 3.8).

Postural behavior before and during farrowing was not different between treatments ($P > 0.3$; Table 3.9). Sows fed RS spent 53.3% of their time lying (ventral plus lateral) during the 12 h before farrowing, while control sows spent 58.6% of their time lying ($P > 0.2$). Total lying during farrowing was also similar between RS and control sows, at 89.2% and 88.4% respectively ($P > 0.8$).

3.5 Discussion

The effects of dietary fiber fed to sows during late gestation on sow and piglet performance are often varied. One reason for this could be because there is a large variation in physiological effects between fiber ingredients due to different fiber structures, compositions, and doses (Mou et al., 2020). The current study aimed to increase understanding of these results by investigating the impact of feeding 6.6% of a pure RS, a type of fiber, to sows on sow farrowing performance and piglet survival, vitality, and growth. It was hypothesized that a diet containing RS would increase SCFA availability, consequently stabilizing blood glucose concentrations during farrowing. This could decrease sow farrowing duration, thus positively influencing piglet survival and vitality.

The current finding revealed that feeding sows RS 1 wk prior to farrowing did not significantly reduce farrowing duration, although the RS group did have a numerically shorter duration by 15 min. Several studies have reported no change in farrowing duration when sows were fed a high fiber diet (Valadares et al., 2021; Zhuo et al., 2020; Guillemet et al., 2007), while others have reported a shortened farrowing duration (Li et al., 2021; Wang et al., 2016; Bilkei, 1990). The average farrowing duration has been reported to range from 156 to 262 min (Oliviero et al., 2010). The average farrowing duration in this study was 176 min, at the lower end of that range. This may be because farrowing duration positively correlates with litter size, and our study's average litter sizes were smaller (12.1 piglets/litter) than the average European litter sizes (16 piglets/litter) that the Oliviero et al. (2010) study analyzed.

A long farrowing duration increases the risk of fetal asphyxiation, or oxygen deprivation, and increases the risk of perinatal mortality (Langendijk and Plush, 2019). There are a number of reasons theorized as to why diets containing high levels of dietary fiber can decrease farrowing duration. Li et al. (2021) found that sows fed the high fiber diet had greater plasma oxytocin and epinephrine concentrations. Increases of both hormones can be beneficial in reducing farrowing duration and promoting piglet survival. Oxytocin plays a vital role in the regulation of parturition and lactation, by initiating contractions and milk secretion (Kim et al., 2017). Fiber can also be beneficial because the SCFA produced from fiber fermentation can be used as energy by the sow, assisting in the farrowing process (Zhuo et al., 2020). It's been suggested that a large proportion of sows suffer from low-energy status at the onset of farrowing, and this can negatively impact the farrowing process, resulting in a prolonged farrowing duration (Feyera et al., 2018). Short-chain

fatty acids can be used as an energy source, as well as help stabilize blood glucose levels for longer periods after meals (de Leeuw et al., 2004; Higgins, 2004), although a difference in blood glucose concentrations after meals was not seen in the present study. It has been hypothesized that increased energy uptake from the hindgut can help improve the farrowing process and shorten the farrowing duration. Although the current study demonstrated that the change in blood glucose from beginning to end of farrowing was greater in RS sows, the overall farrowing blood glucose tended to be lower in RS sows. Another reason the farrowing duration can be shortened due to dietary fiber is by reducing constipation in sows. Wang et al. (2016) found that a high fiber diet shortened the farrowing duration in sows as well as improved sow constipation. Other studies have also found a reduction in constipation when feeding a diet containing fiber (Oliviero et al., 2009).

Number of stillbirths did not differ between treatments, consistent with several studies (Oliviero et al., 2009; Zhuo et al., 2020; Sun et al., 2014; Holt et al., 2006), though in contrast with others that did find a reduction in stillbirth rate (Huang et al., 2020; Deng et al., 2021). The lack of a detectable effect for both farrowing duration and number of stillbirths could be due to the small sample size used in the present study; other studies had much greater sample sizes. Huang et al. (2020), for example, used a total of 78 sows while the current study used 42 sows. This could also be influenced by a large number of sows in both groups not having any stillbirths. The average stillbirth rate for our study was only 3.2%, which is less than the national average of 8.6% (USDA, 2012). This low stillbirth rate may be attributed to increase farrowing supervision. Researchers were present during most farrowings and therefore could assist when the birth intervals exceeded 45 minutes, which is consistent with the farm protocol. In this study, 42.6% of sows were assisted at least once during farrowing.

Although dietary fiber has been shown to reduce physical activity in sows (de Leeuw et al., 2004), which can be measured via posture changes, there were no treatment differences in posture changes prior to or during farrowing. Activity during farrowing can be an indicator of farrowing ease (Mainau et al., 2010). It was hypothesized that if sows could get through their farrowing process quicker, they would be less stressed and show less signs of restlessness, demonstrated via fewer posture changes during farrowing, however we did not see this in the current study.

The diet containing RS improved water intake during the first week post-farrowing, but this did not translate into increased piglet growth. Improved water consumption was also found by Oliviero et al. (2009) when sows were fed a high fiber diet prior to farrowing. It is important for

sows to return to water and feed quickly after farrowing so they have enough nutrients for high milk production. It has been documented that piglets from sows with low water intake during the beginning of lactation have low average weight gains during the same time period (Fraser and Phillips, 1989). Although the RS sows did have a greater water intake 1 wk post-farrowing, this did not translate into a statistically significant increase in piglet growth. However, the RS weaning litter weight was numerically 2 kg greater than the control weaning litter weight and the RS group tended to have fewer lightweight piglets under 3.6 kg at weaning, which could be economically valuable for producers. In addition, heavier piglets at weaning are heavier at 56 d of age and reach slaughter weight sooner than light piglets (Wolter and Ellis, 2001). Previous studies have indicated that fiber supplementation in gestation diets can increase piglet body weight at weaning (Quesnel et al., 2009; Wang et al., 2016). Although, these studies attributed the increase to an increase in greater feed intake during lactation, which was not seen in the current study. This could be because resistant starch has been documented to promote satiety in pigs (Souza da Silva et al., 2014). Colostrum and milk composition and yield of sows could also contribute to increased piglet weaning weight. Diets containing greater amounts of fiber have been shown to have a positive impact on colostrum and milk composition and yield (Theil et al., 2014). The mechanism behind dietary fiber increasing colostrum yield is not entirely clear, however it has been hypothesized that the inclusion of dietary fiber in the diet can increase synthesis of lipids in colostrum by increasing the plasma concentration of SCFA. It has also been theorized that the change in composition and yield could be due to an increase in prolactin, which was seen when Li et al. (2021) fed sows a high fiber diet. Prolactin is essential for the initiation of lactation. With that being said, IgG was the only colostrum component measured in this study and it was not affected by diet, so we cannot conclude that colostrum composition and yield was a factor that could have affected piglet weights.

There were no differences in concentrations of PCO_2 , BE_{ecf} , PCO_2 , HCO_3 , TCO_2 , sO_2 , lactate, or pH values of the piglets. An effect of birth order on metabolic measures is typically observed in piglets (Islas-Fabila et al., 2018), however that was not seen in the current study. Islas-Fabila et al. (2018) found that the piglets in the 1st quarter and the 4th quarter of the birth order had the most pronounced metabolic alterations, shown by greater concentrations of pCO_2 , lower blood pH, lower pO_2 concentrations, lower bicarbonate concentrations, and greater lactate concentrations. These are indicators of fetal hypoxia and can result in an increased risk of prenatal mortality (Trujillo-Ortega et al., 2011; Mota-Rojas et al., 2015), but we did not find differences between

treatments. The average blood physiometabolic measures for the current study are consistent with Sanchez-Salcedo et al. (2020) who reported a $p\text{CO}_2$ average of 36.1 ± 2.03 mmHg and a $p\text{O}_2$ average of 32.7 ± 3.03 mmHg for healthy neonatal piglets, while varying with Islas-Fabila et al. (2018) who reported higher values for $p\text{CO}_2$ and lower values for $p\text{O}_2$. The lack of an observable effect of diet on piglet blood parameters could possibly be due to the small sample size of 3 piglets per litter being sampled and not obtaining a great enough representation of the piglet population to detect differences in piglet vitality blood parameters. Most studies, such as Islas-Fabila et al. (2018) sampled every piglet in the birth order. Differences in blood values compared to previous studies could also be due to how the blood was collected and how long after birth it was collected. In the current study, umbilical cord blood was collected from piglets within 1 minute after birth, while Islas-Fabila et al. (2018), for example, performed retro-orbital sinus bleeding from the piglets after other behavioral and physiological tests were performed postnatally, which took approximately 5+ minutes to evaluate. A large variety in blood metabolite values exists depending on the site where blood sampling takes place (umbilical cord vs. vena cava vs. retro-orbital sinus) (Orozco-Gregorio et al., 2007; Sanchez-Salcedo et al., 2020). Furthermore, Sanchez-Salcedo et al. (2020) reported that the umbilical cord values were more reliable for diagnoses of gas exchange during asphyxia, while retro-orbital sinus values were more accurate in determining glucose and lactate.

The only detected effect in piglet blood parameters was a tendency to have a diet by birth order interaction. Piglet blood glucose concentrations for RS sows did tend to increase as the birth order increased, while the blood glucose concentrations for the piglets from the control sows tended to decrease as the birth order increased. This somewhat mimics the RS sow's blood glucose pattern during farrowing, which most likely explains the increase in the piglet glucose pattern. Average piglet blood glucose values for both groups are consistent with previous findings that reported an average blood glucose measured via umbilical cord blood to be 52.3 mg/dL (Rootwelt et al., 2014). Greater blood glucose concentrations at birth are typically seen in piglets who die within 10 d of age, thus implying they have lower vitality (Tuchsher et al., 2000). Likewise, Herpin et al. (1996) reported greater glucose concentrations in low compared to high vitality piglets. Hyperglycemia in the neonates could be a result of the mobilization of glycogen stores in neonates who experienced fetal distress (Herpin et al., 1996). The distress experienced during in-utero asphyxia could result in the release of catecholamines and stimulation of liver glycogenolysis,

thus elevating blood glucose. Although the RS piglets' blood glucose concentrations increased as the farrowing process progressed, the average values did not greatly exceed the average blood glucose levels documented for a healthy piglet upon birth (Rootwelt et al., 2014). Hypoglycemia is also a concern in neonates. Initial hypoglycemia at birth is a risk factor for perinatal brain injury in human babies (Basu et al., 2009). Basu et al. (2009) found that the severity of asphyxia in human babies was proportional to the degree of hypoglycemia. However, average piglet blood glucose values in this study were not in the range of hypoglycemia.

Sows fed RS had blood glucose concentrations that showed a pattern of increasing as the farrowing process progressed. A greater positive change in glucose concentrations between the beginning and end of farrowing was observed in the RS sows. As the farrowing process progressed, the glucose for control sows largely stayed the same, while the glucose for the RS sows increased. This could be due to the RS prolonging the blood glucose release as expected, a result of slow fermentation of the RS. The increase in glucose as the farrowing progressed could be the result of a sparing process. During periods of fasting, glycogen is broken down in the liver and released as glucose into the blood stream. The RS sows could have more glycogen stored in the liver due to SCFA produced via fermentation in the hind gut. In specific, acetic and propionic acid can function as substrates for gluconeogenesis in the liver (Williams et al., 2017). This could result in RS sows having a greater store of glycogen thus greater levels of blood glucose as the farrowing process progresses. A drop in blood glucose during parturition could demonstrate that the stores of glucose are being depleted quickly (Sanchez-Salcedo et al., 2020). Thus, it could be a positive sign that RS sow blood glucose was not on a decline during farrowing.

Although a blood glucose stabilization was seen in the RS sows during farrowing, blood glucose concentrations during the pre-farrowing period were not different between treatments. Both groups experienced a spike in glucose concentrations 2 h post-feeding, then a decrease at 6 h post-feeding, although still greater than the basal (30 min pre-feeding) levels. There were no differences in the 6 h post-feeding glucose levels during pre-farrowing as expected. It was predicted that the blood glucose levels for RS sows would stabilize post-prandially and decrease at 6 h post-feeding to a lesser degree than the control sows. This was hypothesized because high dietary fiber diets have been shown to maintain blood glucose levels in sows due to the slow and continuous fermentation process (de Leeuw et al., 2004). This stabilization was not observed in the current study, although this could be because we did not measure at a time point far enough

after eating to observe the stabilization, or because the RS supplementation did not work in modifying blood glucose levels possibly due to only being fed for 6 d prior to testing and on a limit fed basis. Thus, 6 h post-feeding may not have been long enough after feeding to observe the stabilization of blood glucose. De Leeuw et al. (2004) found that glucose levels of sows fed a high-fiber diet were more stable several hours after feeding compared to a low-fiber diet, but their study took more blood glucose samples after feeding than the current study. Therefore, they may have been better able to observe the stabilization. They were able to observe the drop below basal pre-feeding levels in the low-fiber sows 7 h after feeding, while the high-fiber sows never dropped below basal levels. It is possible the current study may have seen a stabilization if blood glucose concentrations were measured for an additional hour or more post-prandially.

Microbiota in the hindgut can ferment dietary fiber to produce SCFA which can be used as energy (Higgins, 2004), but the present study exhibited no significant effect on fermentability, in agreement with Huang et al. (2020). Although we did not find any differences in fecal SCFA concentration, there is still a possibility that total SCFA absorption was greater in the RS sows, shown by the increase in glucose change during farrowing. Most SCFA are absorbed through the gastrointestinal wall and enter the blood stream via the portal vein (Williams et al., 2017). Solely measuring fecal SCFA does not account for the amount of SCFA that were absorbed into the blood stream, which is why we may not have seen differences in fecal fermentation.

3.6 Conclusion

The inconclusive results observed in this study could be because the RS diet was only fed to sows for approximately one week prior to farrowing, while many of the other studies fed their diets for a longer period before farrowing. Although the RS did modify blood glucose concentrations during farrowing by increasing the RS sow's blood glucose between the beginning and end of farrowing, the RS may have not had enough time to substantially affect the SCFA and glucose concentrations robustly enough to translate into an improved farrowing process. Multiple studies (Huang et al., 2020; Wang et al., 2016) found effects on the farrowing process when beginning to feed their diets in early-mid gestation, although Feyera et al. (2017) found that stillbirth rate was reduced when feeding a high fiber diet in only the last 2 weeks of gestation. The lack of an effect found using RS could also be due to the concentration and type of fermentable fiber chosen for the current experiment. We conclude that 6.6% RS fed to sows 1 week prior to

farrowing and through the lactation period did not effectively prolong sow energy status enough to significantly decrease farrowing duration and improve piglet survival or vitality.

3.7 Tables and Figures

Table 3.1. Sow lactation diet ingredients.

Ingredient, %	Control	RS
Corn	59.085	49.075
Soybean meal, 48% CP	33.820	34.550
ADM Fibersol-2	0.000	6.600
Swine grease	3.000	5.640
Limestone	1.430	1.410
MonoCal. Phosphate	1.340	1.400
Swine Vitamin Premix ¹	0.300	0.300
Sow Vitamin Premix ²	0.250	0.250
Trace Mineral Premix ³	0.125	0.125
Se Premix ⁴	0.050	0.050
Phytase ⁵	0.100	0.100
Salt	0.500	0.500
Total	100.000	100.000

¹ Provided per kg of diet: vitamin A, 4,961 IU; vitamin D₃, 1984 IU; vitamin E, 53 IU; vitamin K, 4 mg; riboflavin, 9.9 mg; pantothenic acid, 33 mg; niacin, 59 mg; and B₁₂, 0.040 mg.

² Provided per kg of diet: biotin, 0.22 mg; folic acid, 1.65 mg; choline, 551 mg; pyridoxine, 4.96 mg; vitamin E, 22 IU; chromium, 0.20 mg; and carnitine 49.6 mg.

³ Provided per kg of diet: iron, 121.3 mg; zinc, 121.3 mg; manganese, 15.0 mg; copper, 11.3 mg; and iodine, 0.46 mg.

⁴ Provided per kg of diet: 0.3 ppm selenium.

⁵ Phyzyme® (Danisco Animal Nutrition, Morlborough, UK) providing 600 phytase units (FTU)/kg.

Table 3.2. Sow lactation diet calculated nutrients for control and resistant starch (RS) fed sows.

Calculated Nutrient ¹	Control	RS
ME, Kcal/kg	3,358.6	3,358.4
NE, Kcal/kg	2,499.8	2,499.9
SID ² Lys, %	1.000	1.000
Ca, %	0.900	0.903
Phos, %	0.682	0.674
Avail. P, %	0.450	0.451
Soluble Fiber, %	1.480	7.390

¹ Calculated nutrients were targeted to meet or exceed the NRC 2012. Nutrient Requirements of Swine. 11th ed. Natl. Acad. Press, Washington, DC.

²SID = Standardized ileal digestible.

Table 3.3. Diet Analysis for Control and Resistant Starch (RS) lactation diets (as is basis).

Calculated Nutrient ¹	Control	RS
Amino acids, %		
Lysine	1.34	1.28
Threonine	0.88	0.88
Methionine	0.29	0.30
Cysteine	0.33	0.36
Tryptophan	0.29	0.28
Valine	1.15	1.14
Isoleucine	1.08	1.03
Leucine	1.94	2.08
Tyrosine	0.77	0.76
Phenylalanine	1.24	1.20
Histidine	0.61	0.62
Arginine	1.58	1.45
Gross Energy, kcal/kg	3,968.60	4,129.30
CP, %	22.77	22.52
Moisture, %	10.51	11.67
Ash, %	5.97	5.46
Crude Fat, %	4.42	4.73
Crude Fiber, %	2.33	2.96
NDF, %	7.11	10.79
ADF, %	3.93	4.93
TDF, %	9.55	13.88
Ca, %	1.12	0.98
P, %	0.70	0.69

¹Analysis conducted by University of Missouri Experiment Station Chemical Laboratories.

Table 3.4. Effect of dietary resistant starch (RS) on sow and piglet performance.

Variable	Control	RS	<i>P</i> -value
# of sows	21	21	
Average parity	3.1 ± 0.53	3.2 ± 0.56	0.781
Sow BW, kg			
d 106 of gestation	224.7 ± 9.8	225.1 ± 10.00	0.969
d 2 of lactation	229.3 ± 8.9	227.9 ± 9.73	0.641
Weaning	211.3 ± 7.8	214.1 ± 9.41	0.889
Sow BW change, kg			
d 106 of gestation to d 2 of lactation	4.1 ± 2.65	2.8 ± 1.34	0.724
d 2 of lactation to weaning	-17.7 ± 2.3	-13.8 ± 3.26	0.386
Sow backfat depth, mm			
d 106	17.7 ± 1.10	18.3 ± 1.15	0.683
Weaning	13.7 ± 0.73	13.5 ± 0.77	0.820
Δ from d 106 to weaning	-4.0 ± 0.72	-4.9 ± 0.87	0.446
Sow loin muscle depth, mm			
d 106	55.3 ± 1.85	54.2 ± 1.60	0.650
Weaning	51.5 ± 3.50	54.0 ± 1.48	0.518
Δ from d 106 to weaning	-3.8 ± 3.57	-0.2 ± 1.10	0.342
Sow ADFI d 106 to d 2, kg/d	3.1 ± 0.87	3.2 ± 0.11	0.455
Sow ADFI d 2 to weaning, kg/d	6.4 ± 0.35	6.2 ± 0.31	0.611
Total water intake pre-farrowing, L	221.7 ± 26.7	172.8 ± 26.07	0.156
Daily water intake pre-farrowing, L	20.2 ± 2.21	16.2 ± 2.24	0.205
Daily water intake week 1 post-farrowing, L	21.1 ± 0.95	24.9 ± 1.87	0.069
Daily water intake week 2 post-farrowing, L	32.2 ± 2.19	33.9 ± 2.02	0.558
Daily water intake week 3 post-farrowing, L	34.0 ± 3.17	36.6 ± 1.72	0.474
Daily water intake post-farrowing, L	28.7 ± 1.82	32.9 ± 2.54	0.171
Sow colostrum IgG, %	28.2 ± 0.71	27.6 ± 0.80	0.614
Litter weight d1 pre-CF ¹ , kg	17.7 ± 0.93	17.9 ± 1.05	0.913
Litter weight d1 post-CF ¹ , kg	17.8 ± 0.61	18.0 ± 0.74	0.815

Table 3.4. Continued

Weaning litter weight, kg	62.8 ± 1.86	64.9 ± 2.68	0.482
Litter weight gain, kg	45.1 ± 1.79	46.9 ± 2.03	0.330
Daily litter weight gain, kg/d	2.6 ± 0.11	2.8 ± 0.13	0.441
Piglet weight d1 pre-CF ¹ , kg	1.5 ± 0.06	1.6 ± 0.07	0.375
Piglet weight d1 post-CF ¹ , kg	1.5 ± 0.07	1.6 ± 0.06	0.664
Weaning piglet weight, kg	6.1 ± 0.18	6.4 ± 0.19	0.194
Piglets under 3.6 kg at weaning, %	4.1 ± 1.55	1.5 ± 0.81	0.140

¹CF = cross-fostering

Table 3.5. Effect of dietary resistant starch (RS) on litter size and parturition characteristics.

Variable	Control	RS	<i>P</i> -value
# of sows	21	21	
Total born, #	12.4 ± 0.74	11.9 ± 0.62	0.557
Born alive, #	12.0 ± 0.70	11.4 ± 0.60	0.539
Stillborn, #	0.4 ± 0.15	0.4 ± 0.20	0.999
Mummies, #	0.3 ± 0.14	0.3 ± 0.13	0.999
Meconium stained, #	3.3 ± 0.47	4.1 ± 0.67	0.364
Crushed, #	0.8 ± 0.25	0.6 ± 0.20	0.527
Litter size post-CF ¹	12.1 ± 0.48	11.6 ± 0.20	0.338
Litter size weaning	10.4 ± 0.18	10.1 ± 0.25	0.363
Farrowing duration, min	178.9 ± 19.86	165.2 ± 15.13	0.591
Piglet birth interval, min	16.6 ± 1.85	14.9 ± 1.68	0.510

¹CF= cross-fostering

Table 3.6. Effect of dietary resistant starch (RS) on sow blood glucose.

Variable	Control	RS	<i>P</i> -value		
			Diet	Time	Diet*time
# of sows	21	21			
Pre-farrow glucose, mg/dL	68.0 ± 1.44	66.9 ± 1.33	0.639	< 0.0001	0.336
Pre-feeding	57.0 ± 0.98 ^a	58.7 ± 1.17 ^a			
2 h post-feeding	77.4 ± 2.33 ^b	74.0 ± 2.33 ^b			
6 h post-feeding	69.6 ± 1.50 ^c	68.1 ± 1.67 ^c			
Δ glucose 1 ¹	19.9 ± 2.24	14.6 ± 2.51	0.137		
Δ glucose 2 ²	12.6 ± 1.40	9.4 ± 1.74	0.123		
Δ glucose 3 ³	-7.8 ± 1.88	-5.9 ± 2.86	0.623		
Farrowing glucose, mg/dL	78.6 ± 1.65	74.1 ± 1.45	0.104	0.460	0.205
Beginning ⁴	78.8 ± 2.52	71.5 ± 1.67			
Middle ⁵	79.2 ± 3.03	73.1 ± 2.51			
End ⁶	77.9 ± 3.14	78.3 ± 3.32			
Δ glucose 1 ⁷	-2.5 ± 4.07	4.6 ± 1.93	0.156		
Δ glucose 2 ⁸	-1.1 ± 2.37	7.5 ± 3.51	0.036		
Δ glucose 3 ⁹	6.9 ± 6.50	4.5 ± 3.27	0.918		

^{a-c}Means within a column with different superscripts differ ($P < 0.05$).

¹Change in blood glucose concentrations from 30 min pre-feeding to 2 h post-feeding.

²Change in blood glucose concentrations from 30 min pre-feeding to 6 h post-feeding.

³Change in blood glucose concentrations from 2 h post-feeding to 6 h post-feeding.

⁴Beginning = blood glucose measured at the beginning (piglet #1 to 2) of the birth order.

⁵Middle = blood glucose measured at the middle (piglet #4 to 5) of the birth order.

⁶End = blood glucose measured at the end (piglet #8+) of the birth order.

⁷Change in blood glucose concentrations from beginning of farrowing to middle of farrowing.

⁸Change in blood glucose concentrations from beginning of farrowing to end of farrowing.

⁹Change in blood glucose concentrations from middle of farrowing to end of farrowing.

Table 3.7. Effect of dietary resistant starch (RS) on piglet blood parameters.

Variable	Control	RS	<i>P</i> -value		
			Diet	Birth order	Diet*birth order
# of piglets	48	50			
Glucose, mg/dL	51.7 ± 1.93	52.1 ± 1.54	0.869	0.801	0.073
Beginning ¹	56.5 ± 4.88	48.2 ± 1.78			
Middle ²	49.0 ± 2.72	53.2 ± 2.36			
End ³	51.2 ± 2.57	54.8 ± 3.30			
pH	7.46 ± 0.017	7.45 ± 0.017	0.607	0.081	0.887
Beginning ¹	7.47 ± 0.034	7.47 ± 0.029			
Middle ²	7.49 ± 0.027	7.47 ± 0.028			
End ³	7.42 ± 0.029	7.42 ± 0.027			
PCO ₂ , mmHg	38.8 ± 1.38	39.0 ± 1.57	0.945	0.543	0.986
Beginning ¹	37.9 ± 2.74	38.3 ± 2.21			
Middle ²	38.2 ± 2.10	37.8 ± 3.04			
End ³	40.3 ± 2.56	40.7 ± 2.94			
PO ₂ , mmHg	38.8 ± 1.42	39.0 ± 1.56	0.187	0.965	0.933
Beginning ¹	57.2 ± 16.50	74.3 ± 12.60			
Middle ²	64.5 ± 10.34	72.2 ± 11.22			
End ³	54.5 ± 9.57	76.3 ± 12.83			
BE _{ecf} ⁴ , mmol/L	3.4 ± 0.62	2.9 ± 0.87	0.738	0.252	0.398
Beginning ¹	3.4 ± 1.24	3.5 ± 1.25			
Middle ²	5.2 ± 0.73	2.8 ± 1.61			
End ³	1.3 ± 1.30	2.4 ± 1.94			
HCO ₃ , mmol/L	27.2 ± 0.53	26.8 ± 0.81	0.753	0.495	0.450
Beginning ¹	26.9 ± 1.04	27.3 ± 1.08			
Middle ²	28.5 ± 0.77	26.5 ± 1.41			
End ³	25.8 ± 1.10	26.6 ± 1.62			
TCO ₂ ⁵ , mmol/L	28.4 ± 0.55	28.0 ± 0.84	0.781	0.572	0.501
Beginning ¹	28.3 ± 1.05	28.4 ± 1.11			

Table 3.7 Continued

Middle ²	29.6 ± 0.73	27.7 ± 1.42			
End ³	27.0 ± 1.08	27.8 ± 1.71			
sO ₂ , %	76.9 ± 2.8	78.1 ± 3.5	0.770	0.438	0.200
Beginning ¹	69.8 ± 6.04	83.6 ± 4.11			
Middle ²	84.5 ± 3.28	76.7 ± 6.94			
End ³	73.2 ± 5.41	74.4 ± 6.70			
Lactate, mmol/L	4.5 ± 0.23	5.0 ± 0.32	0.231	0.540	0.612
Beginning ¹	4.8 ± 0.41	5.1 ± 0.44			
Middle ²	4.1 ± 0.29	5.0 ± 0.54			
End ³	4.9 ± 0.38	5.0 ± 0.51			

¹Beginning = piglets born at the beginning (#1 to 2) of the birth order.

²Middle = piglets born at the middle (#4 to 5) of the birth order.

³End = piglets born at the end (#8+) of the birth order.

⁴BE_{ecf} = Base excess in the extracellular fluid.

⁵TCO₂ = Total carbon dioxide.

Table 3.8. Effect of dietary resistant starch (RS) on sow fecal SCFA¹ concentrations on d 114 of gestation.

Variable	Control	RS	<i>P</i> -value
# of sows	19	19	
Acetate, ug/g	28,622.8 ± 2,697.26	26,715.5 ± 2,767.08	0.489
Δ acetate ² , ug/g	3,956.4 ± 2,289.62	636.3 ± 3,053.29	0.489
Propionate, ug/g	10,664.5 ± 1,171.68	9,354.1 ± 943.29	0.382
Δ propionate ³ , ug/g	1,104.3 ± 906.40	-376.6 ± 1,521.54	0.382
Butyrate, ug/g	8,312.5 ± 1,017.50	7,424.2 ± 979.43	0.586
Δ butyrate ⁴ , ug/g	1,817.3 ± 859.66	1,138.5 ± 1,429.34	0.586
Iso-butyrate, ug/g	4,007.9 ± 767.42	3,808.7 ± 814.76	0.760
Δ iso-butyrate ⁵ , ug/g	1,983.4 ± 1082.70	2,207.8 ± 1,049.24	0.760
Valerate, ug/g	5,928.5 ± 1,101.16	5,497.3 ± 1,243.17	0.670
Δ valerate ⁶ , ug/g	3,052.0 ± 1,535.23	3,288.1 ± 1,594.37	0.670
Iso-valerate, ug/g	6,399.6 ± 1,149.70	6,154.0 ± 1,223.63	0.776
Δ iso-valerate ⁷ , ug/g	3,022.9 ± 1,615.15	3,461.0 ± 1,613.18	0.776

¹SCFA = short-chain fatty acid.

²Change in acetate from baseline (d107) to d114 of gestation.

³Change in propionate from baseline (d107) to d114 of gestation.

⁴Change in butyrate from baseline (d107) to d114 of gestation.

⁵Change in iso-butyrate from baseline (d107) to d114 of gestation.

⁶Change in valerate from baseline (d107) to d114 of gestation.

⁷Change in iso-valerate from baseline (d107) to d114 of gestation.

Table 3.9. The effect of dietary resistant starch (RS) on sow postural behavior pre-farrowing.
The percentage of time spent performing each behavior 12 h prior to farrowing.

Variable	Control	RS	<i>P</i> -value
# of sows	20	18	
Lying ventrally, %	37.7 ± 3.21	31.4 ± 1.86	0.363
Lying laterally, %	20.9 ± 3.83	21.9 ± 3.15	0.810
Sitting, %	12.8 ± 1.67	13.8 ± 2.82	0.963
Standing, %	28.6 ± 3.30	32.9 ± 3.35	0.295
Posture changes per hour, #	15.8 ± 1.24	15.0 ± 1.31	0.640

Table 3.10. The effect of dietary resistant starch (RS) on sow postural behavior during farrowing. The percentage of time spent performing each behavior during farrowing.

Variable	Control	RS	<i>P</i> -value
# of sows	20	18	
Lying ventrally, %	2.7 ± 0.49	7.0 ± 3.26	0.727
Lying laterally, %	86.4 ± 3.40	84.1 ± 4.04	0.651
Sitting, %	3.7 ± 0.87	3.8 ± 1.23	0.883
Standing, %	8.8 ± 3.14	8.2 ± 2.37	0.897
Posture changes per hour, #	7.1 ± 1.20	9.2 ± 2.44	0.932

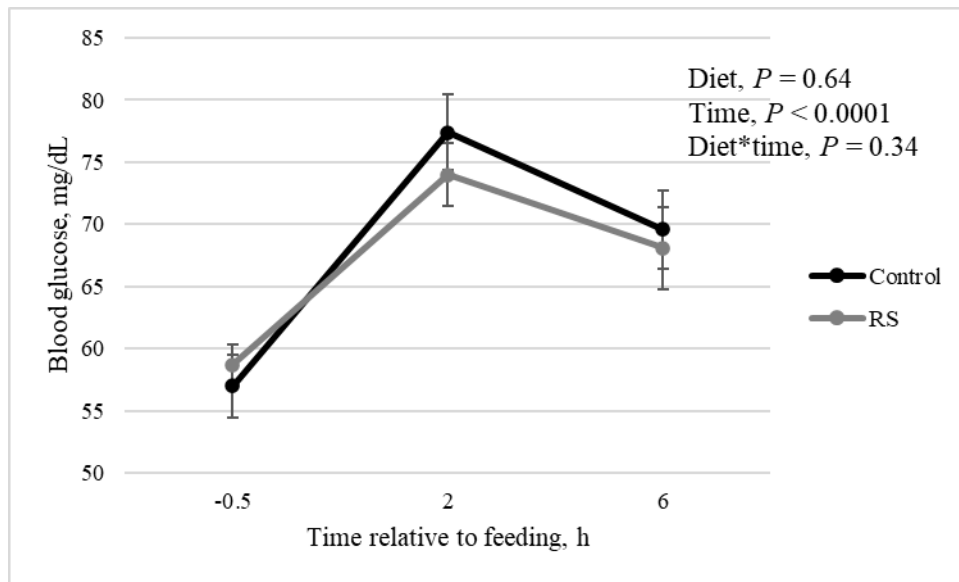


Figure 3.1. Sow blood glucose concentrations relative to time during the pre-farrowing day (d 114 of gestation) for RS (resistant starch) and Control sows at 30 min pre-feeding, 2 h post-feeding, and 6 h post-feeding.

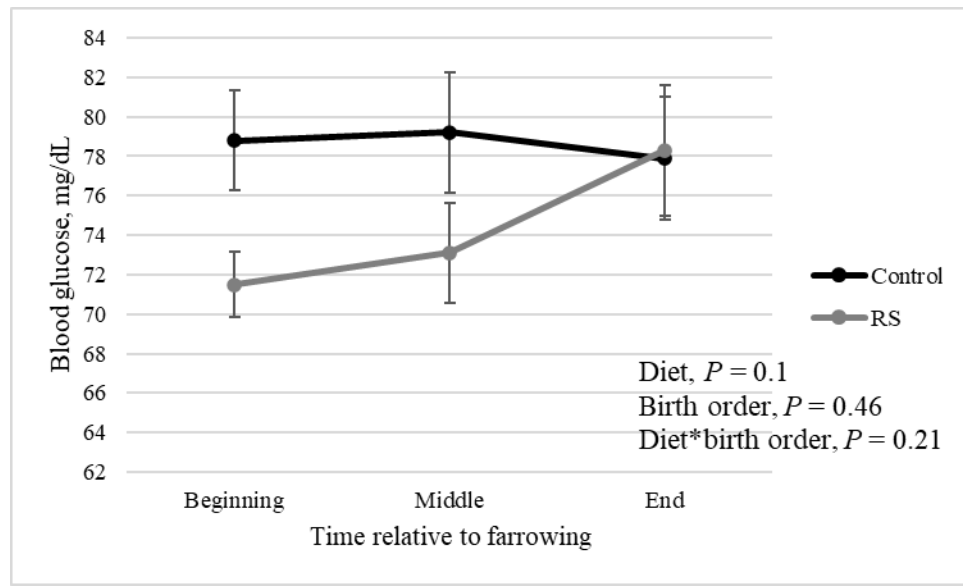


Figure 3.2. Sow blood glucose concentrations relative to time during the farrowing process for RS (resistant starch) and Control sows at the beginning (piglet #1 to 2), middle (piglet #4 to 5), and end (piglet #8+) of farrowing.

CHAPTER FOUR. FUTURE DIRECTIONS

4.1 Future Directions

With increasing litter sizes worldwide, it is necessary to find ways to prevent prolonged farrowing durations in sows and increase piglet survival. Regarding nesting material, it would be beneficial to develop a way to present nesting material that allows the sow to perform the most important parts of nesting behavior, such as pawing, rooting, or gathering. To do that, one must identify the nesting behaviors that are of particular importance to the sow and give the most behavioral satisfaction. In addition, providing this material must be logistically and financially practical to producers. Regarding nutritional supplements, since it is believed that sows suffer from low energy during farrowing, a nutritional supplement that gives additional energy or prolongs her energy would likely be of benefit to promote a more efficient farrowing process. It could also be beneficial to combine strategies.

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