Comparative evaluation of energy and amino acid Digestibility in cereals across sows' physiological stages

Zixi Wei

COMMUNAUTÉ FRANÇAISE DE BELGIQUE
UNIVERSITÉ DE LIÈGE – GEMBLOUX AGRO-BIO TECH

Comparative evaluation of energy and amino acid digestibility in cereals across sows' physiological stages

Zixi Wei

Dissertation originale présentée en vue de l'obtention du grade de docteur en sciences agronomiques et ingénierie biologique

Promoteur : Prof. Martine Schroyen
Co-promoteur : Prof. Xilong Li
Année civile : 2026

Abstract

Estimates of standardized ileal digestibility (SID) of amino acids (AA) and energy utilization in sows have traditionally been based on feed ingredient databases developed for growing pigs or extrapolated from models designed for growing pigs, as reflected in the National Research Council (NRC) (2012) feeding tables. However, evidence suggests that sows differ from growing pigs in terms of energy and nutrient digestibility due to differences in body size and metabolism. The current nutritional databases lack precise digestible energy (DE), metabolizable energy (ME), and AA digestibility data specific to sows, particularly regarding how these values vary across physiological stages (gestation, lactation, post-weaning period) and parities. Therefore, in this PhD, we selected three common feed ingredients in pig diets, corn, barley, and wheat bran, to further evaluate their nutrient value and compare differences across sows' physiological stages.

In the first experiment (Chapter III), we focused on nutrient digestibility, as well as the DE and ME values of these ingredients, highlighting differences between gestation, lactation, and the post-weaning period in primiparous sows. A total of 20 primiparous sows were used across gestation, lactation, and the post-weaning period in a randomized complete block design with dietary treatments (control, corn, barley, and wheat bran), where each treatment had 5 replicates. The gestation trial started on d 50 of pregnancy and lasted for 12 days (d 50 to d 62), while lactation and post-weaning trials both commenced at d 1 of their respective physiological periods. For primiparous sows, the apparent total tract digestibility (ATTD) of neutral detergent fiber (NDF) and gross energy (GE) in barley was higher during lactation than during the post-weaning period. Across all ingredients, the ATTD of NDF during lactation was higher than during the post-weaning period. However, no differences were observed in the energy values and digestibility of corn and wheat bran across the different physiological stages. This suggests that lactation enhances fiber digestibility in primiparous sows, likely due to higher energy demands and gut adaptation.

In the second experiment (Chapter III), we focused on nutrient digestibility, as well as the DE and ME values of these ingredients, highlighting differences among gestation, lactation, and the post-weaning period, but now in multiparous sows. Additionally, we compared the differences in digestibility and energy values of these three ingredients between primiparous and multiparous sows. A total of 24 multiparous sows were used across gestation, lactation, and the post-weaning period in a complete randomized design with dietary treatments (control, corn, barley, and wheat bran), where each treatment had 6 replicates. The gestation trial started on d 50 of pregnancy and lasted for 12 days (d 50 to d 62), while lactation and post-weaning trials both commenced at d 1 of their respective physiological periods. The DE and the ATTD of GE in wheat bran was higher during lactation than during the gestating period. For the three ingredients, the ME during lactation was higher than during gestation, and crude protein (CP) during lactation was higher than during the post-weaning period. Parity also influenced the nutrient utilization in sows. In gestation, primiparous sows showed a higher ATTD of GE for corn and barley than multiparous sows. while for wheat bran, they had a higher ATTD of CP, compared to multiparous sows. In lactation, primiparous sows had a higher ATTD of NDF and GE in barley compared to multiparous sows, but no differences in the ATTD of nutrients were found between primiparous and multiparous sows for corn and wheat bran. Moreover, during the post-weaning period, primiparous sows had a higher ME in corn than multiparous sows. However, regardless of the physiological stages, multiparous sows exhibited a higher ATTD of ether extract (EE) in barley than primiparous sows. These parity differences indicate that younger and older sows do not utilize EE and fiber equally, supporting parity-specific feeding strategies.

In the third experiment (Chapter IV), we determined the SID of CP and AA of corn, barley, and wheat bran in primiparous sows. Four physiological stages of primiparous sows were examined: a gestation stage where sows were restricted-fed, a lactation stage where sows were fed *ad libitum*, and then two post-weaning stages, an *ad libitum* fed phase followed by a restricted-fed phase. A total of 8 primiparous sows fitted with T-cannulas in the distal ileum were assigned to an 8×3 Youden square design with four diets (corn, barley, wheat bran, and Nitrogen (N)-free diet) and three periods, resulting in a total of six replicates per treatment. The basal endogenous losses (BEL) of CP and AA were determined after feeding an N-free diet. Regarding the SID of barley in gestating sows, only the SID of His was higher than in lactating sows and restricted-fed post-weaning sows and the SID of Gly was higher than in lactating sows. For wheat bran, the SID of Glu, Ser, and Tyr in gestating sows was lower than in lactating sows. The SID of Val and Tyr in lactating sows was higher than in *ad libitum* access post-weaning sows. For corn, the SID of Lys, Ala, and Gly in gestating sows was higher than in lactating sows. The SID of Ile, Lys, Phe, Thr, and Ala in gestating sows was higher than in *ad libitum* post-weaning sows. Our findings indicate that similar SID values are found for barley in different physiological stages of primiparous sows under the same diet and feed regime, whether *ad libitum* or restricted. However, for wheat bran, which has a high fiber content, lactating sows exhibited higher SID values compared to gestating sows for several AA. For corn, which has a low fiber content, gestating sows exhibited higher SID values compared to lactating sows and *ad libitum* post-weaning sows. These SID results show that high-fiber ingredients (wheat bran) are better digested during lactation, while low-fiber corn is better digested during gestation.

In summary, these findings highlight the effects of physiological stage on nutrient digestibility, DE, ME, and AA utilization in sows. The results emphasize the need for sow-specific nutritional data instead of relying on extrapolated values from growing pigs, providing a basis for precision feeding strategies in sow nutrition.

Keywords: primiparous sows**,** multiparous sows, digestible energy, metabolizable energy, apparent ileal digestibility, standardized ileal digestibility, corn, barley, wheat bran.

Résumé

Chez les truies, la digestibilité iléale standardisée (DIS) des acides aminés (AA) et de l'utilisation de l'énergie sont traditionnellement estimées à partir des bases de données d'ingrédients alimentaires développées pour les porcs en croissance ou extrapolées à partir de modèles conçus pour ces derniers, comme le reflètent les tables d'alimentation du *National Research Council* (NRC, 2012). Cependant, des études démontrent que la digestibilité de l'énergie et des nutriments diffère entre les truies et les porcs en croissance en raison des variations de métabolisme et de taille corporelle. En particulier, des données précises propre aux truies aux différents stades physiologiques (gestation, lactation, période post-sevrage) sont manquantes pour l'énergie digestible (ED), l'énergie métabolisable (EM) et la digestibilité des AA. Pour pallier cela, trois ingrédients couramment utilisés dans l'alimentation porcine (le maïs, l'orge et le son de blé) ont été évalués pour leurs valeurs nutritionnelles et comparés aux différents stades physiologiques des truies.

Dans la première expérience (Chapitre III), nous nous sommes concentrés sur la digestibilité des nutriments ainsi que sur les valeurs d'ED et d'EM de ces ingrédients, en mettant en évidence les différences entre la gestation, la lactation et la période post-sevrage chez les truies primipares. Un total de 20 truies primipares a été utilisé aux différents stades physiologiques (la gestation débute au 50 jour de gravidité et dure 12 jours [du jour 50 au jour 62], tandis que les essais de lactation et de post-sevrage débutent au premier jour de leur phase respective), selon un dispositif expérimental en blocs aléatoires complets avec quatre modalités alimentaires (témoin, maïs, orge et son de blé), et 5 répétitions par traitement. Chez les truies primipares, la digestibilité totale apparente (ATTD) des fibres détergentes neutre (NDF) et de l'énergie brute (EB) de l'orge était plus élevée en phase de lactation qu'en phase de post-sevrage. En revanche, aucune différence n'a été mise en évidence concernant les valeurs énergétiques et la digestibilité du maïs et du son de blé aux les différents stades physiologiques. Cela suggère que la lactation améliore la digestibilité des fibres chez les truies primipares, probablement en raison de besoins énergétiques plus élevés et d'une adaptation intestinale.

Dans la deuxième expérience (Chapitre III), nous nous sommes concentrés sur la digestibilité des nutriments ainsi que sur les valeurs d'ED et d'EM de ces ingrédients, en mettant en évidence les différences entre la gestation, la lactation et la période post-sevrage chez les truies multipares. Nous avons également comparé les données des trois ingrédients entre les truies primipares et multipares. Un total de 24 truies multipares a été utilisé aux différents stades physiologiques (la gestation débute au 50 jour de gravidité et dure 12 jours [du jour 50 au jour 62], tandis que les essais de lactation et de post-sevrage débutent au premier jour de leur phase respective), selon un dispositif expérimental en blocs aléatoires complets avec quatre modalités alimentaires (témoin, maïs, orge et son de blé), et 6 répétitions par traitement. Les valeurs d'énergie digestible (ED), de digestibilité apparente totale des acides aminés (ATTD) et de l'extrait brut (EB) du son de blé étaient plus élevées en lactation qu'en gestation. Pour les trois ingrédients, l'EM était plus élevée en lactation qu'en gestation, et la ATTD de la protéine brute (PB) était plus élevée en lactation qu'en post-sevrage. L'influence de la parité n'est pas sans conséquences pour l'utilisation des nutriments

des truies. En effet, la comparaison des truies primipares et des multipares montre que ces dernières ont une ATTD de l'EB plus élevée pour le maïs et l'orge en gestation, tandis que pour le son de blé, elles présentaient une ATTD de la PB plus élevée. En post-sevrage, les truies primipares présentaient une EM du maïs plus élevée que les truies multipares. Toutefois, indépendamment du stade physiologique, les truies multipares présentaient une ATTD de l'extrait éthéré (EE) de l'orge plus élevée que les truies primipares. Ces différences liées à la parité indiquent que les truies jeunes et âgées n'utilisent pas l'EE et les fibres de manière égale, ce qui plaide en faveur de stratégies d'alimentation spécifiques à la parité.

Dans la troisième expérience (Chapitre IV), nous avons déterminé la digestibilité iléale standardisée (DIS) de la PB et des AA du maïs, de l'orge et du son de blé chez des truies primipares. Quatre périodes ont été visées : une phase de gestation avec rationnement alimentaire, une phase de lactation avec alimentation *ad libitum*, suivi de deux phases post-sevrage, une avec alimentation *ad libitum* et l'autre avec rationnement. Huit truies primipares, équipées de canules en T au niveau de l'iléon distal, ont été utilisées selon un dispositif en carré de Youden 8×3, comprenant quatre régimes alimentaires (maïs, orge, son de blé et régime sans azote (N)) et trois périodes, avec six répétitions par traitement. Les pertes endogènes basales (PEB) de PB et d'AA ont été déterminées après l'administration du régime sans azote. En revanche, pour l'orge, la DIS de l'histidine était plus élevée chez les truies en gestation que chez les truies en lactation. Pour le son de blé, la DIS du glutamate, de la sérine et de la tyrosine chez les truies en gestation étaient inférieures à celles observées chez les truies en lactation. La DIS de la valine et de la tyrosine chez les truies en lactation étaient plus élevées que chez les truies post-sevrage nourries *ad libitum*. Pour le maïs, la DIS de la lysine, de l'alanine et de la glycine chez les truies en gestation était plus élevée que chez les truies en lactation. La DIS de l'isoleucine, de la lysine, de la phénylalanine, de la thréonine et de l'alanine chez les truies en gestation étaient plus élevées que chez les truies post-sevrage nourries *ad libitum*.

Ces résultats montrent que, chez les truies primipares, les valeurs de digestibilité de l'orge restent similaires entre les différents stades physiologiques lorsque le régime alimentaire et le mode d'alimentation sont identiques, qu'ils soient ad libitum ou rationnés. En revanche, pour le son de blé, riche en fibres, les truies en lactation présentaient des valeurs DIS plus élevées pour plusieurs AA par rapport aux truies en gestation. Pour le maïs, pauvre en fibres, les truies en gestation affichaient des valeurs de DIS supérieures à celles observées chez les truies en lactation et post-sevrage nourries ad libitum.

En résumé, ces résultats mettent en évidence l'influence du stade physiologique sur la digestibilité des nutriments, l'énergie digestible, l'énergie métabolisable et l'utilisation des acides aminés chez les truies. Ils soulignent également la nécessité de disposer de données nutritionnelles spécifiques aux truies, plutôt que de se baser sur des valeurs extrapolées à partir des porcs en croissance, et fournissent une base solide pour l'élaboration de stratégies d'alimentation de précision adaptées à ces animaux. These SID results show that high-fiber ingredients (wheat bran) are better digested during lactation, while low-fiber corn is better digested during gestation.

Mots-clés: truies primipares, truies multipares, énergie digestible, énergie métabolisable, digestibilité iléale apparente, digestibilité iléale standardisée, maïs, orge, son de blé.

Acknowledgements

This doctoral thesis is the culmination of the hard work and support of numerous individuals, without whom this project would not have been possible.

Throughout my journey, I have not only gained extensive knowledge but also received invaluable care and guidance from many professors, colleagues, and friends, both at Gembloux Agro-Bio Tech and the Institute of Feed Research at the Chinese Academy of Agricultural Sciences (CAAS).

First and foremost, I would like to express my deepest gratitude to my supervisors, Prof. Martine Schroyen and Prof. Xilong Li. Their dedication, expertise, and continuous support have been crucial to the success of my research. They have shaped my approach to scientific inquiry with their insightful feedback, constructive criticism, and endless encouragement. I am incredibly thankful for their availability and commitment, which has been instrumental in guiding me through every stage of this PhD journey.

I would also like to extend my sincere thanks to Prof. Yu Pi for his valuable guidance, thoughtful advice, and constant encouragement. His contributions have significantly enriched my research.

I am deeply grateful to the members of my PhD committee and jury for their constructive suggestions and for sharing their expertise with me throughout this process. Their insights have been invaluable in refining my work and helping me reach new academic heights.

In addition, I would like to thank the entire faculty and staff of the Zootechnie, Swine Nutrition, and Feed Science laboratory. Their unwavering support, patience, and encouragement have made my time at Gembloux and Beijing both enriching and enjoyable. The knowledge and experiences I have gained here will remain with me throughout my career.

My heartfelt appreciation goes to the China Scholarship Council for providing the financial support that made my studies in Belgium possible. I am also grateful to CAAS and the University of Liège (ULg) for their collaboration and support throughout my research.

Lastly, I want to express my deepest gratitude to my family and friends. Their love, encouragement, and unwavering support have been my foundation during the most challenging times. Their belief in me has been a source of strength, and their advice has been priceless in my personal and professional development.

Zixi Wei
June 2026 in Gembloux, Belgium.

Table of content

List of figures

List of tables

List of abbreviations

AA	Amino acid
ADF	Acid detergent fiber
AID	Apparent ileal digestibility
ATTD	Apparent total tract digestibility
BEL	Basal endogenous losses
CF	Crude fiber
BW	Body weight
CP	Crude protein
Cr	Chromium
CSM	Cottonseed meal
CVB	Central Veevoeder Bureau (Dutch Central Feed Bureau)
DDGS	Distillers dried grains with solubles
DE	Digestive energy
DM	Dry matter
EE	Ether extract
ENL	Endogenous nitrogen losses
GE	Gross energy
HCl	Hydrochloric acid
HI	Heat increment
INRAE	French National Institute for Agriculture
ME	Metabolizable energy
Mg	Magnesium
MOA	Ministry of Agriculture of the People's Republic of China
MRTs	Mean retention times
N	Nitrogen
NDF	Neutral detergent fiber
NE	Net energy
NFE	Nitrogen free extract
NIR	Near-infrared reflectance spectroscopy
NRC	National Research Council
OM	Organic matter
SCFAs	Short chain fatty acids
SID	Standardized ileal digestibility
TID	True ileal amino acid digestibility

UE	Urine energy

Chapter I

General introduction

1. Introduction

In the United States, Europe, and China, swine nutritional standards have been continuously refined over the past decades, driven by advances in nutrition science and evolving production systems. However, compared with the well-established models for growing pigs, substantial gaps remain in the accurate assessment of nutrient requirements and feed ingredient values for sows. Current systems, including the National Research Council (NRC) (2012), largely rely on data derived from growing pigs to estimate sow digestible energy (DE), metabolizable energy (ME), standardized ileal digestibility (SID) of amino acids (AA), and other key parameters, largely due to the limited availability of sow-specific experimental data. This mismatch fails to capture the profound physiological, metabolic, and digestive differences among sows at different reproductive stages: gestation, lactation, and the post-weaning period as well as between primiparous and multiparous sows. Existing evidence shows significant variation in gastrointestinal retention time, hindgut fermentation capacity, fiber degradation, AA absorption, and gut microbiota composition between sows and growing pigs, and among sows across physiological stages. These differences strongly indicate the need for a dedicated sow ingredient evaluation system.

Corn, barley, and wheat bran are widely used ingredients in commercial sow diets, yet their nutritional values for sows remain poorly defined. Factors such as fiber composition, anti-nutritional characteristics, processing methods, storage duration, and physiological status can markedly alter their DE, ME, net energy (NE), and AA digestibility. Establishing a sow-specific feed ingredient database supported by standardized chemical analyses, digestibility trials, ileal sampling techniques, and metabolic studies is essential for improving the precision of sow nutrition. Such advancements would enhance reproductive efficiency, reduce feed costs, support the utilization of unconventional feed resources, and mitigate environmental impacts associated with manure output. Collectively, the development of a comprehensive sow-specific nutritional evaluation framework is critical for advancing precision feeding and promoting sustainability in modern swine production.

2. Evolution and limitations of swine nutritional standards in the U.S., China and europe

2.1. Development of swine nutritional standards

The development of swine nutritional standards in the United States, Europe, and China has steadily evolved, driven by advances in scientific research and changes in production practices.

As summarized by Edward and Naber (1978), the establishment of NRC nutrient requirements relied on available experimental data and methodological principles. In early NRC editions (NRC 1944; NRC 1971), nutrient recommendations for pigs were unified, with no distinction between sows and growing pigs. Stage-specific nutrient requirements were not formally introduced until the 1988 NRC revision (NRC, 1988), when a clear differentiation among growing, gestating, and lactating pigs was first introduced. This marked a shift away from a "one-size-fits-all" approach toward more precise nutritional strategies tailored to physiological stages. The ninth edition, released in 1998, incorporated a considerable amount of new data, especially regarding the chemical composition and digestibility of feed ingredients. Apparent ileal digestibility (AID) values were widely used to evaluate AA digestibility, and predictive nutrient models were explored for the first time. Building on these developments, the eleventh edition, published in 2012, constituted a substantial revision of the NRC system (NRC, 2012) (**Figure 1-1**). This edition introduced dynamic models designed to more accurately predict energy and nutrient requirements. For sows, the gestation period was further divided into early (days 1–30), mid (days 31–90), and late gestation (day 90 to farrowing), with physiological considerations such as fetal tissue growth, placental development, uterine weight, and amniotic fluid incorporated into the model. This edition also expanded the feed ingredient database to include both major cereals and by-products and replaced AID values with standardized ileal digestibility (SID) values to improve the accuracy of amino acid digestibility assessments.

Figure 1-1. Nutrient requirements of swine, 11th edition (NRC, 2012) and Chinese feeding standard of swine (MOA, 2010)

In contrast, China released its first edition of the Chinese feeding standard of swine in 1986 (Ministry of Agriculture of the People's Republic of China (MOA), 1986). This version was largely based on limited domestic research and adapted from NRC standards. It provided general guidelines for energy, protein, and major mineral requirements, but lacked differentiation among pig breeds and physiological stages. Significant improvements were made in 2004, when the NE system was introduced, and distinct requirements were established for pigs at different growth stages, as well as for sows (MOA, 2004). The 2010 edition refined the NE system further by incorporating the ideal protein model and paying closer attention to the nutritional needs of sows during different physiological stages (MOA, 2010; Van Milgen and Dourmad, 2015) (**Figure 1-1**). However, a sow-specific feed ingredient database remained absent.

In Europe, swine nutritional standards have also developed substantially, particularly in France and in the Netherlands. Since the 1980s, France's National Institute for Agriculture, Food, and the Environment (INRAE) has increasingly strengthened research on the nutritional requirements of sows at different physiological stages, with a major emphasis on energy metabolism and AA utilization. Building on this foundation, the development of the InraPorc model provided a mathematical and decision-support tool capable of simulating nutrient requirements and performance in growing pigs and sows throughout gestation, lactation, and the post-weaning period (**Figure 1-2**). The model includes feed, sow, and growing pig modules, allowing for precise calculations based on production stage and feeding conditions, supported by extensive experimental data and a comprehensive feed ingredient database.

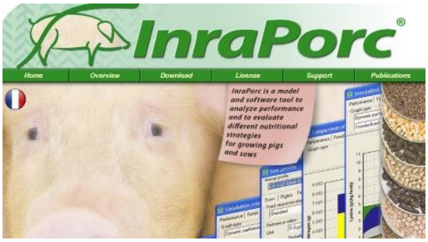


Figure 1-2. The website of InraPorc, a model and software tool to analyze performance and to evaluate different nutritional strategies for growing pigs and sows

In the Netherlands, the CVB (Central Veevoeder Bureau) developed nutritional standards and feed composition tables derived from local research trials and practical feeding conditions (**Figure 1-3**). The CVB system covers all physiological stages of pigs and provides detailed, context-specific coefficient values for energy, AA, and nutrient digestibility. CVB standards are widely applied in feed formulation and farm management, with detailed and operational data enabling precise nutrition. Similarly, Germany has also made substantial contributions to swine nutritional standards, with leading researchers conducting extensive studies on sows. Key references include the DLG-Futterwerttabellen für Schweine and the work of the GfE (Gesellschaft für Ernährungsphysiologie).

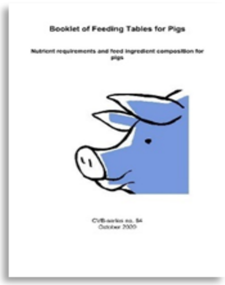


Figure 1-3. The booklet with feeding tables for pigs as developed by the CVB

When comparing the current swine nutrition standards in the United States, China, and Europe, several key differences can be observed. Regarding energy evaluation, China still primarily relies on ME, although NE is increasingly adopted in academic research and some commercial formulations. In contrast, the NE system has been proposed as a more accurate method to estimate pigs' actual energy utilization compared with DE or ME systems (Zijlstra et al., 2007). For protein and AA evaluation, China uses both total AA content and SID values, while the NRC exclusively recommends SID values and emphasizes the concept of the first limiting AA to optimize diet formulation (MOA, 2010). Furthermore, in determining nutrient requirements for different production stages, the NRC applies mathematical models to dynamically predict nutritional needs across physiological states (NRC, 2012). Chinese standards, on the other hand, adopt broader stage classifications, which may not adequately capture the real-time changes in nutrient demand during animal development. Compared with NRC and Chinese standards, European standards place more emphasis on local pig breeds and management conditions. INRAE uses models to dynamically predict nutrient requirements, while CVB focuses on practical feed data. Both rely on SID for AA, like NRC, but integrate it with regional production realities to insure their practical applicability. Overall, European standards provide detailed stage-specific nutritional data and practical tools, supporting precision feeding and research.

2.2. Limitations of the NRC standards for sow nutrition

Although the NRC Nutrient Requirements of Swine have undergone continuous development over more than three decades and the 2012 edition introduced more sophisticated modelling approaches, important limitations remain with respect to sow nutrition. In particular, due to the limited availability of sow-specific experimental data, the energy values (DE, ME and NE) in the NRC feed ingredient database are still largely derived from studies conducted in growing pigs rather than in sows (Noblet and Shi, 1993). As a consequence, empirical data describing energy utilization in sows across different physiological stages remain scarce, and model predictions rely on assumptions that may not fully reflect sow physiology. Previous studies have demonstrated differences in the apparent digestibility of dietary energy between growing pigs and sows, indicating that stage- and category-specific DE, ME and NE values are required to improve the accuracy of energy evaluation (Noblet and

Van Milgen, 2004). Therefore, despite the conceptual advances of the NRC framework, the lack of sow-specific and stage-dependent empirical data limits its practical application in sow nutrition, highlighting the need for targeted research in this area.

3. The necessity of precisely evaluating the nutritional value of feed ingredients for sows

The NRC 2012 edition explicitly points out that there is a lack of SID data for sows, especially for large-size pregnant and lactating sows (NRC, 2012). The NRC feed composition tables are based on a vast collection of literature data and experimental results, primarily gathered from peer-reviewed scientific literature, particularly from North America (NRC, 2012). The U.S. Department of Agriculture has also funded multiple animal nutrition projects over the years, accumulating a large amount of feed ingredient analysis data. Although the 2012 NRC edition made breakthroughs in swine nutrition, much of the data still comes from growing pigs, rather than sows. For many important nutritional parameters, such as SID and ME, the NRC still relies on inferred data based on growing pig research (NRC, 2012). As a result, there is no independent, comprehensive database specifically for sows, which is critical for precise feed ingredient utilization.

The high cost of sow experiments, combined with technical difficulties and substantial individual variability, has resulted in limited data on ileal digestibility in sows. To maintain the general applicability of the swine nutrition standards, the NRC uses SID values derived from growing pigs (20-50 kg) to estimate the SID values for sows' diets. NRC assumes that the SID values in sows remain relatively stable at the ileal absorption level across different physiological stages and believes that the absorption efficiency of AA in sows is similar to that in growing pigs (NRC, 2012). However, a study by Stein et al. has shown that there are differences in SID values between growing pigs and sows, which suggests that using the same SID values for both may not be accurate (Stein et al., 2001). Therefore, theoretically, different SID values should be applied for growing pigs and sows to improve the accuracy of AA utilization in feed. Building a dedicated sow feed ingredient database is crucial for the accurate assessment of sow nutrition and represents the foundation for effective feed ingredient utilization (Le Goff and Noblet, 2001).

Establishing a sow-specific feed ingredient database not only helps in accurately evaluating sow nutrition but also plays an important role in the utilization of unconventional feed resources (Kim et al., 2013; Babatunde et al., 2021). In situations where major feed ingredients such as corn and soybean meal are in short supply, using alternative feed ingredients to replace them becomes even more important (Kiarie and Nyachoti, 2010). Moreover, the development of a precise feed ingredient nutrition evaluation system for sows will contribute to reducing feed costs and alleviating feed resource shortages (Pomar et al., 2019; Yang et al., 2023). For the pig industry, the annual feed consumption of a sow is approximately 4 to 6 times that of a growing pig (Dickerson and Hazel, 1944; Solà-Oriol and Gasa, 2017). In typical pig farms, the feed consumption of sows accounts for about 10-20% of the total feed consumption in the entire farm (Gauthier et al., 2022). Therefore, accurately evaluating sow feed ingredients is a critical aspect of farm nutrition management. By assessing sow feed ingredients precisely, farms can not only reduce costs but also minimize organic matter (OM) in manure, decreasing the environmental impact of livestock waste on water and soil, and thereby promoting ecological improvements and sustainable development (Kornegay et al., 1997).

4. Physiological and nutritional differences among sows across physiological stages and relative to growing pigs

Sows can be classified into three main physiological stages: gestation, lactation, and the post-weaning period, each characterized by distinct physiological traits (Geisert et al., 2020). During the gestation phase, feed restriction is commonly practiced (Dourmad et al., 1993). Among the three stages, gestation is the longest in duration. In the NRC standards, gestation is further subdivided into early, mid, and late stages (NRC, 2012). Compared to early gestation, significant hormonal and nutritional metabolic changes occur during mid to late gestation (Geisert et al., 1997). The early gestation period, typically referring to the first 30 days, is the embryo implantation phase, where embryo development occurs slowly. In the mid and late gestation phases, the fetus, uterus, and mammary gland tissues grow rapidly (Theil et al., 2014). During gestation, sows gradually gain body weight due to conceptus growth and maternal tissue deposition. Their energy and AA requirements increase mainly in late gestation to support fetal development and mammary gland preparation.The lactation phase begins after farrowing and ends at weaning, generally lasting 21 to 28 days (Hurley et al., 2001). Nutritional demands during lactation are extremely high. A lactating sow typically produces 8–12 kg of milk per day, which demands high levels of energy and specific AA, especially lysine for milk protein synthesis. Consequently, sows often mobilize body reserves and lose weight during lactation, with the extent depending on feed intake and parity. Insufficient feed intake during this period can lead to lactation failure, negative energy balance, and body condition loss (Grahofer et al., 2023). The post-weaning phase refers to the period from weaning until the next breeding, typically lasting 4 to 7 days in commercial pig production. During this short but critical stage, the sow restores body condition, the uterus completes involution, and ovarian follicles begin to develop, leading to estrus and associated hormonal activity. During this phase, sows gradually recover body weight and condition, requiring adequate energy and AA to support uterine involution and follicle development. Both primiparous and multiparous sows experience substantial energy and nutrient demands during this phase, making it essential for successful reproductive performance (Poleze et al., 2006; Knox and Zas, 2001). Currently, research on digestive differences among sows at different physiological stages remains limited, as most existing studies primarily focus on reproductive production. Wang et al (2025a) reported that the nutritional value of feed ingredients may vary with the physiological state of sows, indicating that such variations should be considered when formulating diets. Zhuo et al. (2023a) conducted a comparative study assessing the energy values and ATTD of cottonseed meal (CSM) in pregnant and non-pregnant sows. Their results showed that non-pregnant sows exhibited higher ATTD of OM and CP than pregnant sows, although no differences were observed in DE or ME. Differences in AID values between gestating and non-pregnant sows for CSM and soybean meal (Wang et al., 2023; Zhuo et al., 2023b). Casas et al (2022). reported that lactating sows exhibited a higher ATTD of GE, DM, neutral detergent fiber (NDF), and OM than pregnant sows, regardless of whether they were fed a basal diet or a rice bran-based diet. Similarly, other studies have shown that lactating sows, compared with pregnant or non-pregnant sows, have a greater abundance of gut microbiota involved in fermenting dietary fiber, resulting in an increased production of short chain fatty acids (SCFAs). This elevated SCFAs production appeared to stabilize by day 28 of lactation (Liu et al., 2019; Wang et al., 2025).

Comparative studies have shown that sows and growing pigs have different mean retention times (MRTs) of digestive material (Le Goff et al., 2002a). In growing pigs, studies have shown that the MRTs in the stomach, small intestine, and large intestine are 1 hour, 4 hours, and 38 hours, respectively, resulting in a total gastrointestinal transit time of 43 hours. When the diet contains insoluble fiber, retention time is not affected in the stomach, but it reduces in both the small and large intestine (Fioramonti and Bueno, 1980; Knudsen et al., 2012). Other studies have shown that the total transit time in growing pigs fluctuates between 24 and 75 hours (Latymer et al., 1990). In comparison, the MRTs in sows is 81 hours, nearly twice that of growing pigs, with individual variation. The digestibility of dietary fiber in adult sows is higher than in growing pigs, with the difference averaging 0.6 MJ/kg (Noblet and Le Goff, 2001). This difference can be attributed to the distinct physiological stages of the pigs. Compared to growing pigs, sows exhibit a higher degradation rate of dietary fiber in the hindgut, a larger intestinal volume, longer retention time in the digestive tract, and lower feed intake per unit of body weight (Le Goff et al., 2002b).

Le Goff and Noblet designed four experimental diets: a low-fiber control diet (100 g total fiber/kg dry matter) and three high-fiber diets (200 g total fiber/kg dry matter) made from combinations of the low-fiber control diet, supplemented with corn bran, wheat bran, and beet pulp. The study showed that fiber digestibility in adult sows varies with different the diets, with wheat bran having the lowest digestibility (Le Goff and Noblet, 2001). Le Goff and Noblet conducted 16 digestion and metabolism trials with 77 different feed formulations, testing growing pigs (60-65 kg) as well as non-pregnant, non-lactating adult sows. The results indicated that the energy and total tract nutrient digestibility in adult sows were higher than in growing pigs, with this difference related to fiber content in the feed. As body weight increases, pigs exhibit improved energy and total-tract nutrient digestibility, with adult sows showing greater digestibility than growing pigs. The utilization of fibrous components, such as NDF and acid detergent fiber (ADF), is enhanced in sows, while the digestibility of easily digestible components, such as fat and starch, shows little difference (Le Goff and Noblet, 2001). Fernández et al. (1986) found that digestibility rates in sows differ significantly from those in growing pigs. Their study demonstrated a clear linear relationship between the digestibility rates of growing pigs and adult sows. Their results suggest that digestibility data from growing pigs can be used to predict the digestibility in adult sows, though adjustments for energy efficiency are necessary, as hindgut fermentation in sows may be more active than in growing pigs (Fernandez et al., 1986). Stein et al. (1999) demonstrated that gestating and lactating sows generally have higher AID of CP and greater AID of most AA compared to growing pigs when fed the same ingredients . However, in a follow-up study, they pointed out that using AID of AA digestibility in practical feed formulations might be inaccurate because the digestibility coefficients depend on the level of that AA in the feed (Stein et al., 2001). Correcting for non-specific (baseline) endogenous amino acid losses could improve this inaccuracy. The corrected value, known as SID, provides a more accurate estimate of the nutritional value of feed mixtures. Their experimental results showed that the SID values for CP and most AA in maize, soybean meal, and meat and bone meal were higher in pregnant sows than in growing pigs. However, for barley, wheat, and rapeseed meal, the SID values were similar between pregnant sows and growing pigs. Pregnant sows had higher SID values than growing pigs and lactating sows, likely due to differences in feed intake, rather than physiological state (Stein et al., 2001).

Niu et al (2019). demonstrated that sows have a distinct intestinal microbiota structure compared to growing pigs. Certain gut microorganisms are significantly correlated with the ATTD of specific nutrients, suggesting that these microorganisms may play a role in the digestion process. For example, the abundance of *Clostridium* (a genus of Firmicutes) and *Turicibacter* (a genus of Actinobacteria) are positively correlated with the apparent digestibility of EE, indicating that these microorganisms may assist in the breakdown and absorption of lipids. On the other hand, *Anaerofustis* (a genus of Firmicutes) and *Robinsoniella* (a genus of Firmicutes) are positively correlated with the apparent digestibility of crude fiber (CF). Similarly, *Collinsella* (a genus of Actinobacteria) and *Sutterella* (a genus of Proteobacteria) show a positive correlation with the digestibility of NDF, suggesting their potential role in fiber fermentation and degradation in the sow's gut (Niu et al., 2019).

Taken together, these studies clearly demonstrate that nutrient and energy digestibility differ substantially between sows and growing pigs and vary across physiological stages in sows. It is important to clarify here that the majority of studies focus on feed digestibility, that is, the feed's degradability (how efficiently it passes through the intestine) rather than on absorption or the animal's nutritional requirements. In fact, in terms of nutritional requirements, ad libitum feeding is generally recommended to meet the lactation needs of a sow, for example, but this reduces feed digestibility. However, comprehensive and systematic evaluations covering all key physiological stages of sows, including gestation, lactation, and the post-weaning period, remain limited. Most available data focus on comparisons between non-pregnant sows and growing pigs, while stage-specific digestibility data throughout the reproductive cycle of sows are scarce. In addition, many existing studies are based on complete diets rather than individual feed ingredients, which limits their applicability in feed evaluation systems and nutrient requirement databases. Moreover, despite its critical physiological importance for recovery of the body condition and the preparation for the subsequent reproduction cycle, the post-weaning period has received relatively little attention in digestibility studies.

These limitations highlight the need for systematic, stage-specific evaluations of energy and nutrient utilization in sows. Therefore, the objective of this PhD research was to generate comprehensive data on the utilization of energy and nutrients in selected feed ingredients in sows across gestation, lactation, and the post-weaning period. The results aim to improve the accuracy of feed evaluation and diet formulation for sows and to provide valuable data for the refinement of current feed evaluation systems and nutrient requirement databases, such as those used in the NRC.

5. Physiological and nutritional differences between primiparous and multiparous sows

Primiparous sows refer to sows that are pregnant for the first time, generally exhibit lower reproductive performance due to fewer ovulations, incomplete ovarian development, and smaller litter sizes (Whittemore, 1993; Craig et al., 2019). In contrast, multiparous sows have completed at least one farrowing and possess more mature hormonal profiles and fully developed reproductive and mammary systems, resulting in stronger reproductive capacity (Klimas et al., 2020). Primiparous sows are usually mated at 8-12 months of age and are lighter in weight (130-180 kg) than multiparous sows (200-280 kg). On a per kg body weight (BW) basis, primiparous sows have a higher metabolic rate and thus consume more energy per kg BW than multiparous sows, However, due to their larger body size, multiparous sows consume greater absolute amounts of total energy and nutrients (Lucht, 2010; Jin et al., 2017). During lactation, both primiparous sows and multiparous sows lose body weight, but weight loss is greater in multiparous sows due to a higher milk production. The mammary glands of primiparous are less developed, leading to lower milk yield compared to multiparous sows, whose fully developed mammary glands support higher milk output (Farmer and Quesnel, 2009; Theil et al., 2014). Hormonal levels in primiparous sows fluctuate more during the first farrowing, whereas multiparous sows generally exhibit more stable hormonal profiles throughout the reproductive cycle (Yang et al., 2009).

Research comparing the digestive abilities of primiparous and multiparous sows is limited, with most studies again focusing on reproductive performance. Van den Brand reported that primiparous sows use most of their energy for body weight gain, resulting in a relative decrease in lactation capacity compared to multiparous sows (Van den Brand, 2000). The fecal microbiota diversity in primiparous sows was higher than in multiparous sows, with multiparous sows exhibiting a relatively lower microbiota diversity but a more stable community (Law et al., 2024). The microbiota in primiparous sows is rich in genera such as Lachnospira, Megasphaera, and Anaerovibrio. These genera are typically associated with fermentation and the production of SCFAs, which may positively influence gut health and nutrient absorption, leading to better utilization of the nutrients in the feed. On the other hand, *Peptococcus, Peptoniphilus, Porphyromonas, Mobiluncus*, and *Clostridium* is more prevalent in multiparous sows. These genera may be linked to the physiological adaptations these sows undergo through repeated pregnancies and lactation periods. The less stable microbiota in primiparous sows may reflect microbial immaturity, which could affect fermentation volume and digesta transit time, potentially contributing to the observed differences in nutrient digestibility between primiparous and multiparous sows.

Other factors may also contribute to the digestibility differences between primiparous and multiparous sows. Beyond microbial composition, the physiological maturity of the exocrine pancreas is a key determinant. For example, multiparous sows likely have greater pancreatic lipase secretion, along with enhanced trypsin and amylase activities, due to a more mature exocrine pancreas, as pancreatic digestive enzyme activities increase with age and physiological maturity (Charbonneau et al., 1982; Owsley et al., 1986). Moreover, the more responsive secretory machinery and greater bicarbonate output in multiparous sows may help maintain an optimal intestinal pH for enzymatic hydrolysis. In addition, the smaller physical size and length of the gastrointestinal tract in primiparous sows (Le Goff et al., 2002a) suggests a potentially shorter digesta retention time, which may limit the duration of contact between digesta and digestive enzymes and thus contribute to lower nutrient digestibility compared with multiparous sows.

Kemme et al (1997). studied the influence of parity on the ATTD of feed nutrients and minerals during lactation. Their results showed that the ATTD of OM and CP was lower in primiparous sows compared to high-parity sows, though the differences were small. The ATTD of magnesium (Mg) increased with parity, but the increased urinary Mg concentration suggested that animals did not increase Mg retention.

Overall, these studies indicate that parity affects physiological status, metabolic demands, and gut microbiota composition in sows. However, data on the differences in nutrient and energy digestibility between primiparous and multiparous sows are still limited. To enable more precise evaluation of the nutritional value of feed ingredients, it is necessary to assess feed ingredients separately in primiparous and multiparous sows. This approach will provide novel insights into parity-specific nutrient utilization and help refine nutritional strategies for sows at different reproductive stages. In this PhD, energy and selected nutrient digestibility of corn, barley, and wheat bran were evaluated separately in primiparous and multiparous sows to investigate these parity-specific differences. However, due to the increased abdominal fat in multiparous sows, surgical placement of the ileal cannula was technically challenging. Therefore, SID of AA across different physiological stages was determined only in primiparous sows.

6. Evaluation systems for the nutritional value of feed ingredients in swine nutrition

6.1. Swine's energy system

The energy transformation process in animals involves digestion, absorption, metabolism, and the eventual deposition of nutrients. After feed enters the pig's body, energy forms change as the material undergoes digestion, absorption and metabolism (Saha et al., 2021). Initially, the feed energy is present as gross energy (GE). After accounting for energy losses in feces DE is obtained. Further losses from urine and methane result in ME. Finally, after subtracting energy loss as heat increment (HI), we obtain NE (NRC, 2012). Although GE does not account for the energy losses that occur during digestion and metabolism, measuring GE remains the first step in evaluating the energy value of feed. Its magnitude is closely linked to the proportions of carbohydrates, CP, and EE in the diet. DE refers to the energy in the feed that can be digested by the animal, and its value is directly determined by the digestibility of the feed's total energy and its nutrients (Bovera et al., 2014). Noblet et al. demonstrated that the energy digestibility coefficient is negatively correlated with the CF content of the feed. For most complete diets, the energy digestibility coefficient varies between 70 to 90%. However, this variation is even greater for raw feed ingredients, with a range of 0-100%. The majority of energy digestibility variation is due to the different digestibility rates of CF, which are lower than those of other nutrients. Increasing fiber content reduces the ATTD of other nutrients such as CP and CF in the diet (Noblet and Perez, 1993; Noblet and Le Goff, 2001).

ME is the energy remaining after the losses in urine and combustible gases (mainly methane) are deducted from DE, representing the energy absorbed and utilized by the body (Noblet et al., 1994). For growing pigs, methane accounts for approximately 0.4% of DE. In contrast, in adult sows, methane can account for 1.5% of DE during maintenance feeding and can reach 3% in high-fiber diets (Noblet et al., 1993; Ramonet et al., 2000). The increase in methane is mainly influenced by the fiber content of the diet, while urine energy (UE) losses vary due to differences in urinary N excretion, which is largely dependent on dietary protein levels. Therefore, the ratio of ME to DE (ME/DE) is linearly related to the CP content in the diet. Generally, the ME/DE ratio in pig diets is around 0.96, though it can vary depending on the composition of the feed ingredients (Noblet et al., 1994).

NE is ME minus HI resulting from metabolism, feeding, digestion, and other physiological activities (Zuidhof, 2019). Compared to DE, NE reflects the differences in the utilization of energy from different nutrients during metabolism. It is the only measure that accounts for both the animal’s energy requirements and the energy value of the diet on the same basis, making it a precise predictor of pig growth performance (Brett and Groves, 1979). In practical applications, NE values can typically be estimated by multiplying the ME value by the metabolic conversion efficiency. There are many factors that affect conversion efficiency, including the form of energy utilization (maintenance, deposition, lactation), as well as the nutritional characteristics and composition of the feed. In hot stress conditions, low-protein pig diets with NE formulations are more advantageous than traditional digestible energy-based formulas (Van Milgen and Noblet, 2003; Noblet and Van Milgen, 2004).

6.2. Amino acid digestibility evaluation in swine

Kuilken et al. (1948) proposed the total intestinal AA digestibility measurement using fecal analysis, which primarily determined the difference in AA content between the feed and feces. This method is simple and easy to perform, allowing for a rough assessment of the body's utilization of AA, and was widely used in pig nutrition research at the time (Just et al., 1981; Taverner and Farrell, 1981; Zebrowska and Low, 1987). However, as research advanced, it was found that proteins are broken down and utilized by microbes in the hindgut, but the hindgut has almost no role in AA absorption. Therefore, the fecal analysis method tends to overestimate the total intestinal AA digestibility. The ileal sampling method was proposed in the early 1980s as a more accurate alternative to fecal collection for measuring AA digestibility (Just et al., 1984). Currently, ileal digestibility is commonly used to represent AA digestibility in international research. Based on whether endogenous N losses (ENL) are accounted for, ileal AA digestibility can be further divided into AID, SID, and true ileal AA digestibility (TID). AID of AA refers to the measurement that neglects the ENL, which may underestimate the AA digestibility of the ingredient tested. Additionally, AID of AA has poor additive properties (Stein et al., 2005). The main difference between SID and TID lies in the fact that TID excludes both basal endogenous AA and specific endogenous AA losses. To determine SID, basal endogenous AA losses (BEL), also known as non-specific endogenous AA losses, are accounted for. To determine TID, corrections are made for total endogenous losses such as basal losses and diet-specific losses.The most accurate method for determining AA digestibility is TID, but the measurement of specific endogenous AA losses is difficult and can be influenced by factors such as feed ingredient composition, fiber types, and anti-nutritional factors (Schulze et al., 1994). As a result, data on TID for commonly used feed ingredients in pigs is limited.

Figure 1-4. Surgical technique for creating fistulas in sows ileal

In current studies and practical applications on AA digestibility and utilization, the use of fistula technology (**Figure 1-4**) and N-free diet methods for measuring SID is widely adopted. These methods offer good additive properties and are relatively simple to measure, making them internationally recognized. In 2007, Stein et al. summarized and standardized academic terminology and systems, providing technical guidance for measuring AA digestibility, especially for SID (Stein et al., 2007). Since then, major animal nutrition research institutions worldwide have conducted extensive research on SID measurements. Among them, the Stein Laboratory at the University of Illinois, the Mosenthin Laboratory at the University of Hohenheim, the Nyachoti team at the University of Manitoba, the Sijlstra Laboratory at the University of Alberta, and the Li Defa Laboratory at China Agricultural University have measured the AA digestibility of ingredients such as corn and its processed by-products, soybean meal, distillers dried grains with solubles (DDGS), low-glucosinolate rapeseed meal, rice processing by-products, wheat, barley, etc. Their research has provided valuable support for the global AA digestibility database. However, measuring the SID in sows requires ileal fistula surgeries, which are technically challenging due to the large size of sows. The complexity of the surgery, along with the substantial technical expertise and funding required, limits the number of laboratories capable of performing these measurements in sows.

7. Methods for evaluating the nutritional value of feed ingredients

7.1. Chemical analysis

The chemical analysis method is the most used technique for assessing the nutritional value of feed by measuring its nutrient composition, thereby providing the basic nutritional data required. In 1862, the Weende Experiment Station in Germany established a feed analysis system that categorized feed nutrients into six components: moisture, Ash, CP, EE, CF, and N-free extract (NFE). Noblet and Perez developed linear models combining energy values with the concentrations of Ash, EE, CP, and other indicators to predict DE, ME, and NE values. The chemical analysis method is fast, simple, and efficient. However, the results offer only a rough estimate of nutrient content and lack precision, particularly in measuring CF and NFE (Noblet and Perez, 1993). Fiber quantity and quality are especially important for ruminants. In 1967, Van Soest redefined fiber and established the Van Soest Fiber Analysis Method, which measures NDF and ADF (Van Soest, 1967).

Just et al. conducted correlation and regression analyses on digestibility and N balance data from growing pigs between 1966 and 1982 and found that NDF and ADF were the best predictors of ME, showing high prediction accuracy (Just et al. 1984). With the advancement of agricultural technology, near-infrared reflectance spectroscopy (NIR) has become widely used in agriculture (Williams and Norris, 1987; Shenk and Westerhaus, 1994). NIR utilizes the absorption and vibration overtone of hydrogen-containing molecular groups under light to analyze structural, functional group, and molecular state information for quantitative or qualitative assessment of feed nutrients. Compared to traditional analytical methods, NIR offers advantages such as being fast, non-destructive, and easy to operate. NIR is now therefore widely used to evaluate the nutritional value of feed ingredients and to predict energy and nutrient digestibility in pigs. For example, NIR has successfully been applied to rapidly determine DE and ME in corn for growing pigs (Li et al., 2016) and to predict amino acid concentrations and apparent digestibility of protein and AA in feedstuffs for pig diets with acceptable accuracy (Hu et al., 2019). However, NIR requires large reference sample sets to establish accurate mathematical models, and the accuracy of these models directly impacts prediction results (Givens et al. 1997).

7.2. Digestibility trials

The total collection method, used in digestibility trials, involves recording feed intake and collecting all feces over a defined period followed by analysis of nutrient contents in both feed and feces to calculate digestibility. Based on the site of digesta collection, methods for determining AA digestibility can be classified into fecal and ileal collection. Traditionally, fecal collection has been widely used to determine AA digestibility in pigs (Sauer and Ozimek, 1986). The ileal sampling method involves installing a fistula at the terminal ileum through surgery or using an ileo-rectal anastomosis to collect digesta at the anus and is mainly used to measure AA digestibility in pigs. Ileal sampling is generally more accurate than anal sampling, as microbial fermentation in the colon and cecum can alter nutrient composition, leading to an overestimation (by about 5%–10%) of AA digestibility when fecal samples are used (Sauer and Ozimek, 1986; Stein et al., 2007).

For pigs, the total collection method has traditionally been considered the reference approach for determining energy digestibility, as it allows direct measurement of fecal energy losses. However, this method has several practical limitations, particularly when applied to large-bodied animals such as adult sows, including the difficulty of complete fecal collection, the need for individual housing, the high labor requirements, and the increased animal stress (Adeola, 2000; NRC, 2012). Due to these constraints, the indicator method has been widely adopted in pig nutrition studies. This method involves the inclusion of an indigestible marker (e.g., chromic oxide or titanium dioxide) in the diet and estimates nutrient digestibility based on the ratio of the marker and nutrients in feed and feces, thereby eliminating the need for total fecal collection. As a result, the indicator method is currently the most commonly used approach in pig experiments, especially under practical or large-scale experimental conditions.

Nevertheless, compared with the total collection method, the indicator method is generally associated with greater analytical variability and lower accuracy in estimating energy values. Therefore, although the indicator method is widely used in experimental studies, the total collection method remains internationally recommended as the reference method for establishing energy standards and feed ingredient databases (Noblet and Van Milgen, 2004). In this PhD, to obtain more precise measurements of sow energy utilization, we designed custom metabolic cages and conducted complete fecal collection for each individual sow, employing the total collection method throughout the experiment.

7.3. Metabolism trials

Metabolism trials are an extension of digestibility trials and require specialized metabolic cages to allow separate collection of feces and urine. By analyzing the nutrient and energy content in all excretions, the ME of the diet and nutrient metabolic rates can be determined. These cages, as shown in **Figure 1-5**, enable precise measurement of nutrient and energy excretion in pigs. However, nutrient intake and excretion are generally not perfectly balanced, and imbalances in protein metabolism can affect the accuracy of energy metabolism assessments. Noblet et al. (1987) reported that feeding diets high in CP increases the energy requirement for protein catabolism, resulting in greater energy losses through urine and associated heat production. Therefore, measurements of energy metabolism under conditions of protein balance may provide more accurate results.

Figure 1-5. Metabolic cages for sows

7.4. The direct and difference method

The direct method involves feeding animals a single test ingredient and conducting digestibility or metabolism trials. Its application is limited, especially when the test ingredient has poor palatability or low nutritional value. For example, high-fiber ingredients cannot be fed directly to monogastric animals. The difference method, which has been more widely adopted, involves partially replacing the basal diet with the test ingredient at a known ratio to formulate a new diet for evaluation. This method helps improve the palatability of the test feed. However, the proportion of replacement affects the accuracy of the apparent digestibility results (Adeola, 2000).

8. Advances in nutritional value assessment of corn, barley, and wheat bran for pig diets

8.1. Corn

Corn is the most widely used and important feed ingredient in pig production. It is also the cereal grain with the highest energy content among common feedstuffs (**Figure 1-6**). In livestock and poultry farming, the most used diet is the corn–soybean meal-based diet, highlighting the crucial role of corn in animal nutrition (Tilden Wayne Perry, 1988). However, a primary limitation of corn is its imbalanced AA profile, particularly its low lysine content. Lysine is an essential AA for monogastric animals and plays a vital role in protein synthesis within the animal's body (Liao et al., 2015). It is indispensable for building body protein. The lysine content in corn is often considered an indicator of its quality, as it significantly influences an animal’sverage daily gain, feed conversion efficiency, and carcass quality. Due to the low lysine level in corn, it is typically supplemented with oilseed meals to meet the lysine requirements of animals. Additionally, calcium, phosphorus, and carotene must be added to corn-based diets to compensate for nutritional deficiencies in the grain. Corn deep processing typically yields about 30% by-products, which mainly include corn gluten meal, corn fiber, corn germ cake, and DDGS (Jiao et al., 2022). These by-products are also rich in nutrients and can be used as feed for livestock. Due to differences in processing methods, the nutritional composition of these by-products varies significantly.

The nutritional composition of corn is influenced by multiple factors such as variety, harvest time, environmental conditions, and processing methods. Among these, variety is the primary factor affecting the conventional nutrient composition of whole corn plants (Saldana and Brown, 1984). Storage time also affects the nutritional value of corn. Zhang et al. investigated changes in DE, ME, and nutrient digestibility in pigs fed corn stored for 0, 3, and 10 months. Results showed that these parameters initially increased and then decreased over time. This was attributed to a "ripening" phase within the first 3 months post-harvest, during which the nutritional value of corn improves. After this period, respiration consumes nutrients, leading to aging and a subsequent decline in energy and nutrient digestibility (Zhang et al., 2016). In addition to variety and storage time, processing techniques also play an important role in determining the nutritional value of corn. Different processing methods, such as wet milling, dry milling, solvent extraction, and expeller pressing, can markedly alter the chemical composition, energy content, and amino acid digestibility of corn and its by-products when fed to pigs (Zhao et al., 2025).

8.2. Barley

Barley is one of the important cereal feed ingredients and is commonly used as a substitute for corn in swine diets (**Figure 1-6**), particularly when corn prices are high or its supply is limited (Blake et al., 2011). Barley is characterized by higher CP, CF, and soluble non-starch polysaccharides (mainly β-glucans), while its energy density is generally lower than that of corn. Although the rich soluble fiber content in barley may benefit intestinal health to some extent, excessive β-glucan can increase digesta viscosity, impairing nutrient digestion and absorption, especially in weaned piglets (Perera et al., 2022). However, with advancements in feed processing technology, the issues related to anti-nutritional factors in barley have been effectively addressed. As a result, barley can now be used as a high-quality alternative energy feed ingredient (Baik, 2014).

Barley is mainly categorized into hulled barley and hull-less barley. Once the husk is removed, it is referred to as hull-less barley, which is primarily used in brewing. Hulled barley, which retains its husk, is mainly utilized for feed production (Bhatty, 1999). The DE and NE of hulled barley are approximately 88.21% and 84.69% of those of corn, respectively. Therefore, when replacing corn with hulled barley in feed formulations, the energy difference must be considered. Compared to corn, hulled barley contains higher levels of CP and AA, particularly lysine and tryptophan, both of which are nearly twice as abundant in barley as in corn. Barley has a lower starch content than corn, while the CF and Ash content in hulled barley are roughly double those of corn, which is one of the main reasons for its lower energy value in feed (Kim et al., 1998). In addition, the available P content in barley is 9.1% to 18% higher than in corn. Therefore, incorporating barley into feed formulations can reduce the need for inorganic phosphorus supplementation and lower phosphorus levels in pig manure, which contributes to environmental protection.

8.3. Wheat bran

Wheat bran is a by-product of wheat processing (**Figure 1-6**), mainly composed of the bran layer and aleurone layer. In practical milling processes, due to technical limitations, the residual components from extracting the germ and endosperm are collectively classified as wheat bran, accounting for approximately 22% to 25% of the wheat kernel (Skřivan et al., 2024). Wheat bran is rich in protein, with a content ranging from 12% to 18%, and contains 18 AAs required by animals, including 10 essential AAs, with glutamic acid, aspartic acid, and arginine being particularly abundant (Balandrán-Quintana et al., 2015). It also contains high levels of minerals such as potassium, phosphorus, Mg, and calcium. In terms of vitamins, wheat bran is particularly rich in B-group vitamins such as niacin and also contains carotenoids that can contribute to vitamin A activity (Garg et al., 2021). Despite its high nutrient content, wheat bran contains a substantial amount of plant cell wall structures, which are difficult for animals to digest and absorb. The presence of insoluble cellulose, which cannot be digested directly in the gastrointestinal tract, reduces nutrient absorption efficiency and ultimately lowers feed utilization rates.

To improve its nutritional value, wheat bran is typically subjected to microbial fermentation, which alters fiber structures and reduces anti-nutritional factors. Commonly used strains include *Bacillus* spp., lactic acid bacteria, yeasts, and molds. Mixed-strain fermentation is frequently adopted, as it not only decreases the levels of CF and anti-nutritional components but also improves palatability and generates various bioactive substances (Ma, 2024). According to Bhar et al. wheat bran can replace all of the corn in diets for 35–70 kg finishing pigs without negatively impacting growth performance or carcass quality (Bhar et al., 2000). However, the DE value of wheat bran varies greatly due to differences in wheat varieties and processing technologies. Morgan et al. reported a DE value of 8.96 MJ/kg, which is lower than the NRC (1998) recommended value of 11.38 MJ/kg (Morgan et al., 1975). Diggs et al., measured DE values ranging from 11.18 to 12.93 MJ/kg, while Batterham et al. reported higher DE values of 12.59 to 15.82 MJ/kg (Diggs et al., 1965; Batterham et al., 1980). Whole wheat is rarely used directly in pig diets because its soluble non-starch polysaccharides can reduce nutrient digestibility (Choct, 1997). Wheat bran, as a milling by-product, provides concentrated fiber and is commonly included in sow diets. The gluten content of wheat bran is low (approximately 10–15% of its crude protein), and pigs are not sensitive to gluten (NRC, 2012).

Based on NRC (2012) data, the nutritional compositions of corn, hulled barley, and wheat bran are summarized and compared in **Table 1-1**. These marked differences among the three grains highlight the importance of evaluating their effects on nutrient digestibility and metabolic responses in sows across different physiological stages.

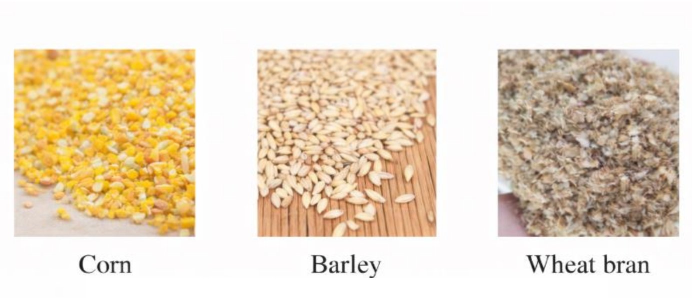


Figure 1-6. Corn, barley and wheat bran

Table 1-1. Nutritional composition of yellow corn, barley and wheat bran (As-fed basis, %)

Items	Corn	Barley	Wheat bran
Dry matter	88.31	89.90	87.38
Crude protein	8.24	11.33	15.08
Ether extract	3.48	2.11	4.72
Crude fiber	1.98	3.90	7.77
Ash	1.30	2.38	4.16
Neutral detergent fiber	9.11	18.29	32.28
Acid detergent fiber	2.88	5.78	11.00
Starch	62.55	50.21	22.56
Gross energy	16.49	16.48	16.79
Digestible energy	14.43	13.18	10.13
Metabolizable energy	14.21	12.86	9.70
Indispensable amino acids			
Arginine	0.37	0.53	0.77
Histidine	0.24	0.27	0.27
Isoleucine	0.28	0.37	0.47
Leucine	0.96	0.72	0.80
Lysine	0.25	0.40	0.52
Methionine	0.18	0.20	0.22
Phenylalanine	0.39	0.53	0.49
Threonine	0.28	0.36	0.39
Tryptophan	0.06	0.13	0.22
Valine	0.38	0.52	0.66
Dispensable amino acids			
Alanine	0.60	0.44	1.79
Aspartate	0.54	0.65	3.74
Cysteine	0.19	0.26	0.43
Glutamate	1.48	2.50	5.03
Glycine	0.31	0.45	1.44
Proline	0.85	1.11	0.00
Serine	0.38	0.45	1.52
Tyrosine	0.26	0.28	0.69

Note: Data were derived from the NRC (National Research Council, 2012).

9. Conclusion and outlook

Currently, the evaluation of nutritional values for sow feed ingredients remains largely unexplored. Establishing a comprehensive nutritional evaluation system for sows would not only enhance reproductive efficiency in large-scale pig production, reduce manure output, and mitigate environmental pollution, but also help conserve conventional feed resources and promote the precise utilization of unconventional feed ingredients. In the context of shortages in key feedstuffs such as soybean meal and corn, such a system would have significant implications for alleviating the pressure on domestic feed supplies. The establishment of a sow-specific nutritional evaluation system requires accurate determination of the nutritional value of a variety of feed ingredients. Corn, barley, and wheat bran are common components in swine diets, and evaluating their nutritional value forms the foundation of this system. Sows experience three physiological stages, gestation, lactation, and the post-weaning phase, each of which is associated with different nutrient digestibility profiles. Therefore, it is essential to assess energy utilization and nutrient digestibility during each stage.

Chapter II

Aims and outline of the thesis

Objectives

Accurately evaluating nutrient digestibility, digestive energy (DE), metabolizable energy (ME), and standardized ileal digestibility (SID) of amino acids (AA) in sows across different physiological stages is crucial for implementing precision feeding strategies. Traditional feeding standards and databases for sows have largely been established based on data from growing pigs. However, differences in body weight, metabolic level, intestinal structure, and gut microbiota composition exist among sows at different physiological stages and parities, which may lead to stage-dependent variations in nutrient digestibility, DE, ME, and SID of AA. Corn, barley, and wheat bran are commonly used feed ingredients in sow diets, yet comprehensive data on their utilization across stages and parities are still lacking.

To address these gaps and improve the accuracy of sow feeding standards, the present PhD study systematically investigated the effects of different physiological stages (gestation, lactation, and the post-weaning period) on nutrient digestibility, DE, ME, as well as theAID and SID of AA in primiparous sows and explored the influence of parity (primiparous vs. multiparous) on nutrient and energy digestibility. Two animal experiments were conducted. A first experiment to evaluate the differences in nutrient digestibility, DE, and ME of common feed ingredients (corn, barley, and wheat bran) across gestation, lactation, and post-weaning stages in primiparous and multiparous sows, including a direct comparison between the two parity groups at each stage. A second experiment to determine the AID and SID of AA for corn, barley, and wheat bran across different physiological stages in primiparous sows.

The objectives of this PhD study were to: (1) analyze the effects of different physiological stages and parity on DE, ME, and the apparent total tract digestibility (ATTD) of nutrients in corn, barley, and wheat bran; (2) determine and analyze the SID values of crude protein (CP) and AA in corn, barley, and wheat bran across different physiological stages in primiparous sows; (3) provide updated, stage- and parity-specific nutrient digestibility data to support the refinement of sow feeding standards, such as NRC guidelines, and to improve diet formulation for precision nutrition.

By filling the gaps in current knowledge, this PhD research did not only contribute to more accurate feed evaluation for sows but also established a solid foundation for future studies on parity- and stage-specific nutrient utilization, ultimately facilitating the development of improved feeding strategies and nutritional guidelines. To achieve these goals, three animal experiments were conducted. The design of each animal experiment is represented in **Figure 2-1**.

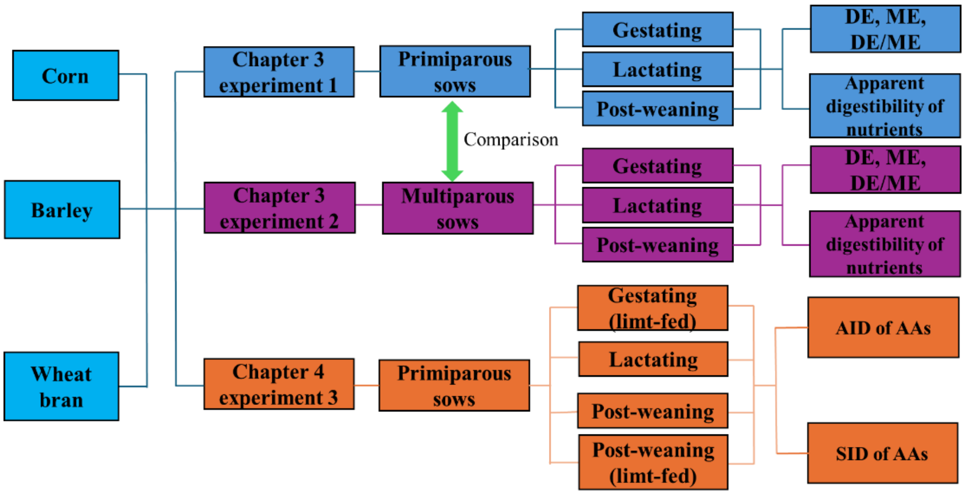


Figure 2-1. The technical route of the thesis

Outline of the PhD thesis

Chapter 1 is a general introduction and a review of relevant literature on the PhD.

Chapter 2 describes the objectives of the PhD thesis and the outline.

Chapter 3 describes an experiment that measured the ATTD of energy and the DE values of corn, barley, and wheat bran in both primiparous and multiparous sows during gestation, lactation, and the post-weaning period. The difference method was used. This chapter tested the following hypotheses: (1) physiological stage (gestation, lactation, post-weaning period) affects the ATTD and DE of the tested ingredients; (2) parity (primiparous vs. multiparous) also affects these values.

Chapter 4 presents an experiment using ileal-cannulated primiparous sows to determine the AID and SID of crude protein and AA in the same three ingredients, across four feeding regimes (gestation restricted, lactation ad libitum, post-weaning ad libitum, and post-weaning restricted).

Chapter 5 is the general discussion, perspectives and conclusion.

Chapter III

Evaluation of energy and nutrient digestibility of corn, barley and wheat bran in primiparous and multiparous sows during the gestation, lactation, and post-weaning period

The experiment described in this chapter is the study published as:

Zixi Wei, Lei Xu, Jiaqi Yang, Qingyue Bi, Martine Schroyen, Xianren Jiang, Sheng Cui, Xilong Li, Yu Pi

Evaluation of energy and nutrient utilization for corn, barley, and wheat bran in primiparous and multiparous sows during the gestation, lactation, and post-weaning period

Journal of Animal Science, 2025, 103, skaf287.

Chapter III. Evaluation of energy and nutrient digestibility of corn, barley and wheat bran in primiparous and multiparous sows during the gestation, lactation, and post-weaning period

Zixi Wei[a,b], Lei Xu[a], Jiaqi Yang[a], Qingyue Bi[a], Martine Schroyen[b], Xianren Jiang[a], Sheng Cui[c], Xilong Li[a], and Yu Pi[a]

[a] Key Laboratory of Feed Biotechnology of Ministry of Agriculture and Rural Affairs, Institute of Feed Research, Chinese Academy of Agricultural Sciences, Beijing 100081, China

[b] Animal Sciences, TERRA Teaching and Research Centre, Gembloux Agro-Bio Tech, University of Liège, Gembloux 5030, Belgium

[c] College of Veterinary Medicine, Yangzhou University, Yangzhou 225009, Jiangsu, China

Keywords: Primiparous sows, Physiological stage, Feed evaluation, Corn, Barley, Wheat bran

1. Abstract

Despite extensive research focusing on feed ingredients for growing pigs, limited studies have systematically evaluated the effect of physiological stage and parity on feed ingredient utilization in sows. This study aimed to evaluate the energy and nutrient utilization of corn, barley, and wheat bran in primiparous and multiparous sows across different physiological stages. A total of 20 primiparous (initial body weight 186.9 ± 4.2 kg) and 24 multiparous (initial body weight 253.9 ± 6.1 kg) were used across the gestation (50 d), lactation, and post-weaning period, using a randomized complete block design with 4 dietary treatments (control, corn, barley, and wheat bran), where primiparous and multiparous sows had 5 and 6 replicates per treatment, respectively. For primiparous sows, the apparent total tract digestibility (ATTD) of neutral detergent fiber (NDF) and gross energy (GE) in barley was higher during lactation than during the post-weaning period ($P < 0.05$), and the ATTD of NDF in wheat bran was also higher during lactation than post-weaning ($P < 0.05$). Across all three ingredients, NDF digestibility was consistently higher during lactation compared to post-weaning ($P < 0.05$). In multiparous sows, the ATTD of crude protein (CP) in corn was higher during gestation and lactation than during post-weaning ($P < 0.05$). Digestible energy and ATTD of GE in wheat bran were greater during lactation than gestation ($P < 0.05$). For all ingredients, metabolizable energy (ME) was higher during lactation than during gestation and post-weaning, and CP digestibility during lactation and gestation exceeded that in the post-weaning period ($P < 0.05$). Parity also influenced nutrient utilization. During gestation, primiparous sows showed higher ATTD of CP in wheat bran ($P < 0.05$), while multiparous sows had higher ATTD of ether extract (EE) in both barley ($P < 0.01$) and wheat bran ($P < 0.05$). During lactation, corn digestibility was not different between different physiological stages. Primiparous sows showed higher ATTD of NDF in barley compared with multiparous sows ($P < 0.01$), whereas multiparous sows exhibited higher ATTD of EE in both barley and wheat bran ($P < 0.05$). In the post-weaning period, primiparous sows had higher ME and ATTD of CP in corn ($P < 0.05$), while multiparous sows had higher ATTD of EE in both barley ($P < 0.05$) and wheat bran ($P < 0.01$). In conclusion, this study demonstrated that physiological stage and parity affect nutrient digestibility and energy utilization in sows. Lactation improved the utilization of barley and wheat bran, and multiparous sows exhibited greater EE digestibility.

2. Introduction

Nutrient digestibility and energy values for sows in NRC databases are incomplete (NRC, 2012). Many energy values are derived from growing pigs or extrapolated from models that were not specifically developed for sows, which makes them not directly applicable to sows (Noblet and Perez, 1993; Le Goff and Noblet, 2001). Le Goff and Noblet (2001) demonstrated that the apparent total tract digestibility (ATTD) of nutrients and energy is higher in adult sows compared to growing pigs. However, feed evaluation studies in sows remain limited due to their larger body size and complex physiological stages. It has been proposed to use two sets of energy values: one for growing-finishing pigs and another for adult sows (Noblet, 2000; Le Goff and Noblet, 2001). Thus, there is an urgent need to refine and expand the feed database for sows to better address their nutritional requirements.

Physiological stage and parity influence sow weight, intestinal structure, metabolism, and gut microbiota (Noblet and Shi, 1994; Koren et al., 2012; Ji et al., 2019; Liu et al., 2019). However, major databases (NRC, INRA, CVB, and BR-PIG) do not distinguish nutrient digestibility of feed ingredients across sow physiological stages. Casas and Stein (2017) found higher ATTD of gross energy (GE) and digestible energy (DE), metabolizable energy (ME) concentrations in rice bran for gestating sows than growing gilts; lactating sows had even higher ATTD for GE, dry matter (DM), neutral detergent fiber (NDF), and organic matter (OM) than gestating sows (Casas and Stein, 2017; Casas et al., 2022). Wang et al. (2022) reported that late-gestating sows had greater ME and metabolizable energy/digestible energy (ME:DE) than mid-gestating sows when fed soybean meal. Conversely, Zhuo et al. (2023) demonstrated that the DE, ME, and ME:DE of cottonseed meal (CSM) were similar between pregnant and non-pregnant sows. Similarly, Wang et al. (2023a) found that ME values of extruded full-fat soybeans were identical in both non-gestating and gestating sows. These findings suggest that DE, ME, and digestibility vary by feed ingredient and physiological stage. However, systematic studies on the effects of parity and physiological stage of sows on nutrient and energy digestibility remain limited.

Therefore, in this study, we selected three energy feed ingredients, corn, barley, and wheat bran to further investigate the effects of parity and different physiological stages on the digestibility of energy and nutrients in sows. The purpose of this experiment was to evaluate and analyze the DE, ME, and nutrient digestibility of corn, barley, and wheat bran during the gestation, lactation, and post-weaning stages in both primiparous and multiparous sows.

3. Materials and methods

The animal protocol for this research was approved by the Animal Care and Use Committee of the Institute of Feed Research of the Chinese Academy of Agricultural Sciences (IFR-CAAS-20230718). All sows were housed in a temperature-controlled enclosed pig barn with consistent ambient conditions during the entire experimental period, eliminating seasonal fluctuations in ambient temperature and natural breeding cycle; accordingly, seasonal effects were excluded as a confounding factor for nutrient digestibility results in the present trial.

3.1. Diets, animals, and experimental design

The corn and wheat bran were procured from Hebei Kangda Co., Ltd. (Langfang, China), while the barley was obtained from Guangdong Haida Co., Ltd. (Guangzhou, China). Before commencing the experiment, an analysis of the chemical composition of the corn, barley, and wheat bran samples was conducted (**Table 3-1**). In this study, all diets were uniformly prepared as mash after the ingredients were purchased and stored under appropriate conditions (cool, dry, and dark) to prevent deterioration. All ingredients were ground using the same mill with a 2.5 mm sieve, ensuring consistent particle size across all diets. The same grinding procedure was applied to all stages, so any potential particle size effect would not confound stage comparisons.

Table 3-1. Nutrient composition of corn, barley, and wheat bran samples (%, as-fed basis)

Items	Corn	Barely	Wheat bran
Dry matter	91.20	90.39	88.38
Gross energy, MJ/kg	17.32	16.54	18.22
Crude protein	8.61	9.37	19.27
Ether extract	3.63	1.56	4.29
Organic matter	90.10	88.47	83.40
Crude fiber	1.03	3.01	5.85
Neutral detergent fiber	11.52	23.02	37.27
Acid detergent fiber	3.98	6.86	11.84
Ash	1.10	1.92	4.98
Indispensable amino acids			
Arginine	0.36	0.45	1.34
Histidine	0.17	0.14	0.19
Isoleucine	0.25	0.29	0.44
Leucine	1.03	0.67	1.19
Lysine	0.24	0.32	0.74
Methionine	0.16	0.12	0.21
Phenylalanine	0.41	0.47	0.69
Threonine	0.26	0.12	0.17
Tryptophan	0.05	0.12	0.24
Valine	0.37	0.41	0.80
Dispensable amino acids			
Alanine	0.66	0.42	1.01
Aspartate	0.57	0.63	1.32
Cysteine	0.10	0.11	0.17
Glutamate	1.68	2.23	3.18
Glycine	0.34	0.40	1.14
Serine	0.46	0.44	0.79
Tyrosine	0.21	0.24	0.45

Note: The nutritional components and amino acid levels of corn, barley, and wheat bran were analyzed in the experiment.

20 primiparous sows (Landrace × Yorkshire; initial body weight 186.9 ± 4.2 kg) and 24 multiparous sows (Landrace × Yorkshire; average parity 5.07; initial body weight 253.9 ± 6.1 kg) were selected for the experiment. The experiment was conducted in a sequential manner, starting with gestation (50 d), lactation, and post-weaning period. At each stage, both primiparous and multiparous sows were randomly allocated to one of 4 dietary treatments in a completely randomized design. The primiparous treatment group included 5 replicates, while the multiparous treatment group had 6 replicates. The diets consisted of a corn-soybean-based control diet and 3 experimental diets, each supplemented with corn, barley, or wheat bran to replace 50% of the corn and soybean in the basal diet (**Table 3-2**). Nutrient analysis values for the primiparous and multiparous diets are presented in **Tables 3-3** and **3-4**, respectively. The DE, ME, and ATTD of corn, barley, and wheat bran were determined using the total fecal and urine collection method for gestating, lactating, and post-weaning sows.

Table 3-2. Ingredient components of experimental diets (as-fed basis)

Ingredients, %	Basal diet	Corn diet	Barley diet	Wheat bran diet
Corn	82.00	89.25	41.00	41.00
Soybean meal, Crude protein 46 %	14.50	7.25	7.25	7.25
Barley	-	-	48.25	-
Wheat bran	-	-	-	48.25
Dicalcium phosphate	1.30	1.30	1.30	1.30
Salt	0.40	0.40	0.40	0.40
Limestone	0.80	0.80	0.80	0.80
Vitamin-mineral permix[1]	1.00	1.00	1.00	1.00
Total	100.00	100.00	100.00	100.00

[1]Premix supplied per kg of diet: vitamin A, 12075 IU; vitamin D_3, 2450 IU; vitamin E, 67 IU; vitamin K_3, 2.98 mg; vitamin B_1, 1.78 mg; vitamin B_2, 3.64 mg; vitamin B_6, 4.46 mg; vitamin B_{12}, 40 μg; Niacin, 42 mg; Calcium pantothenate, 25 mg; Folic acid, 6.92 mg; Biotin, 0.70 mg; Zinc ($ZnSO_4 \cdot H_2O$), 79 mg; Copper ($CuSO_4 \cdot 5H_2O$), 23 mg; Iron ($FeSO_4 \cdot H_2O$), 150 mg; Cobalt ($CoCl_2$), 1.00 mg; Manganese ($MnSO_4 \cdot H_2O$), 100 mg; Iodine ($Ca(IO_3)_2$), 0.23 mg; Selenium (Na_2SeO_3), 0.50 mg.

Table 3-3. Chemical compositions of the experimental diets of primiparous sows in different physiological stages (%, DM basis)

Items, %	Basal diets	Corn diets	Barley diets	Wheat bran diets
Gestation				
GE, MJ/kg	17.80	17.93	17.85	18.01
DM	89.93	90.01	90.14	90.34
CP	13.80	11.30	11.59	16.49
NDF	9.93	8.87	13.52	23.21
ADF	2.76	2.10	3.38	5.88
EE	2.11	2.45	1.58	1.86

Items, %	Basal diets	Corn diets	Barley diets	Wheat bran diets
OM	84.41	85.38	84.82	83.16
Lactation				
GE, MJ/kg	17.95	17.72	17.79	17.98
DM	90.04	90.04	90.12	90.28
CP	13.81	10.32	11.52	16.15
NDF	9.59	9.01	14.28	22.52
ADF	2.33	2.29	4.10	5.63
EE	2.15	2.12	2.77	3.11
OM	84.74	84.89	84.62	82.81
Post-weaning				
GE, MJ/kg	17.94	17.84	17.73	17.93
DM	89.94	89.88	90.09	90.33
CP	13.88	11.05	12.00	16.83
NDF	10.23	9.69	14.25	21.99
ADF	2.80	2.28	4.08	5.33
EE	1.77	2.07	2.76	2.59
OM	84.30	84.97	84.55	83.00

ADF, acid detergent fiber; CP, crude protein; DM, dry matter; EE, ether extract; GE, gross energy; NDF, neutral detergent fiber; OM, organic matter.

Table 3-4. Chemical compositions of the experimental diets of multiparous sows in different physiological stages (%, DM basis)

Items, %	Basal diets	Corn diets	Barley diets	Wheat bran diets
Gestation				
GE, MJ/kg	17.54	17.49	17.69	18.15
DM	87.03	86.80	87.81	88.47
CP	13.84	10.61	11.91	16.50
NDF	11.13	10.97	15.18	23.17
ADF	2.77	2.41	5.17	6.14
EE	2.13	2.29	1.82	2.55
OM	81.64	81.97	81.99	80.84
Lactation				
GE, MJ/kg	17.64	17.57	17.86	18.06
DM	87.02	86.80	87.97	88.42
CP	13.88	11.34	12.10	15.50
NDF	10.13	9.45	14.66	24.33

Items, %	Basal diets	Corn diets	Barley diets	Wheat bran diets
ADF	2.69	2.25	4.14	6.65
EE	2.52	1.99	1.70	2.63
OM	81.27	81.88	82.42	81.25
Post-weaning				
GE, MJ/kg	17.78	17.46	17.62	18.24
DM	86.88	87.05	87.93	88.49
CP	13.85	11.57	12.11	16.05
NDF	11.18	11.61	15.57	23.89
ADF	2.94	2.56	4.69	6.33
EE	2.14	2.21	2.06	2.52
OM	81.43	82.41	82.31	81.26

ADF, acid detergent fiber; CP, crude protein; DM, dry matter; EE, ether extract; GE, gross energy; NDF, neutral detergent fiber; OM, organic matter.

During the experimental phase, gestating sows and post-weaning sows were individually housed in stainless-steel metabolism crates (1.80 m × 0.62 m × 1.30 m). Lactating sows were housed in larger stainless-steel metabolism crates (3.80 m × 1.24 m × 1.30 m) to facilitate the suckling of piglets. Sows underwent a 7-day acclimation period to flush the intestines and acclimate to the diets, followed by the collection of all feces produced from the 5 consecutive days of experimental diet feeding. Taking the beginning of the trial diet as day 1, a color index (2% ferric oxide) was mixed with the diet in the morning on days 8 and 13. The average dry matter intake (DMI) of primiparous and multiparous sows was recorded during the collecting period and is presented in **Table 3-5**. Sows were maintained in an environment held steadily at 22 ± 2 °C and were provided continuous access to drinking water. Gestating sows were allowed 2.5 kg/d of feed. Lactating and post-weaning sows had ad libitum access to experimental diets. Diets were provided daily in two equal meals offered at 0800 and 1600 h, with records of daily feed consumption.

Table 3-5. The dry matter intake (DMI) of primiparous sows and multiparous sows at different physiological stages fed basal, corn, barley, and wheat bran diets

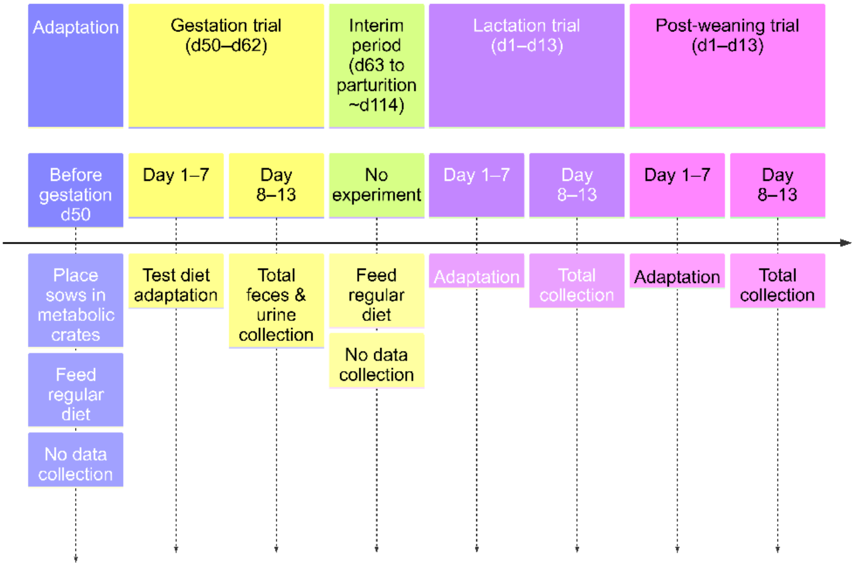
Sow category	Physiological stage	Basal diet DMI[1]	Corn diet DMI	Barley diet DMI	Wheat bran diet DMI	SEM[2]
Primiparous sows	Gestating	2.10	2.10	2.21	2.08	0.109
	Lactating	2.77	3.23	3.62	3.71	0.381
	Post-weaning	4.85	5.00	5.25	3.68	0.368
Multiparous sows	Gestating	2.16	2.17	2.20	2.21	0.005
	Lactating	4.55	4.34	4.45	3.92	0.270
	Post-weaning	4.20	4.36	4.24	4.56	0.136

[1]DMI (kg/day): dry matter intake in grams per day for each type of diet.
[2]SEM: standard Error of the mean for each measurement.

3.2. Sample collection

Feces and urine are easily collected separately in specialized metabolism crates. To make the feces collection accurate, we placed an extra layer of long plastic with grooves between the crates and the floor. Wei implemented procedures to avoid feces and urine contamination, following the methods described in a previous study (Wei et al., 2024). Fecal collection began on day 8 after the appearance of the first red marker in the feces and ended on day 13, when the red marker reappeared in the feces, indicating the end of the collection period. The detailed experimental shcedule is shown in **Figure 3-1**. Fecal weight was recorded every day, and feces were stored at -20°C as soon as collected. Urine collections were initiated on the morning of day 8 at 0900 h and ceased on the morning of day 13 at 0900 h. Urine was collected in buckets placed under the metabolism crates with 50 mL of 6 N hydrochloric acid (Yang et al., 2021). The buckets were emptied 3 to 4 times as scheduled after the total volume of urine had been recorded (Pedersen et al., 2007). One tenth of the collected urine was stored at -20°C. Feed refusals and spillages were gathered, dried, and weighed daily to record accurate feed intake. At the end of the experiment, fecal samples collected on different days were thawed at room temperature and pooled for each sow. Similarly, urine samples from different collection days were thawed and pooled for each sow for subsequent analysis of energy. Finally, a portion of the feces samples was dried at 65°C and crushed, along with a part of the urine samples, and sent to the laboratory for analysis of energy and nutrients (Yang et al., 2021; Lyu et al., 2023). Although fecal consistency and MMA syndrome (mastitis-metritis-agalactia) were not formally scored, all sows remained clinically healthy with normal feed intake and no visible signs of digestive disturbances throughout the study.

Figure 3-1. Timeline of the digestibility and metabolism trial in sows



3.3. Chemical analysis and calculations

The samples of ingredients, diets, and feces were ground to pass through 40 mesh screens were subsequently analyzed for dry matter (method 930.15), crude protein (CP; method 990.03), ether extract (EE; method 920.39), and ash (method 942.05) according to AOAC (2007) methods (AOAC, 2007). Filter bags (model F57; Ankom Technology, Macedon, NY, USA) and fiber analyzer equipment (ANKOM200 Fiber Analyzer, Ankom Technology, Macedon, NY, USA) were used to determine the NDF and acid detergent fiber (ADF) contents (Soest, 1991). Samples of ingredients, diets, feces, and urine were analyzed for GE using an automatic isoperibol oxygen bomb calorimeter (model 6400; Parr1281 Calorimeter, Moline, IL, USA).

The ATTD of a nutrient in the test feedstuff was calculated using the difference method as described by Adeola (2001). The formula is as follows (Adeola, 2001):

$$A = ((T \times Tp) - (B \times Bp))/Ap \times 100\ (\%)$$

where: A = apparent digestibility (%) of the nutrient in the test stuff; T = apparent digestibility (%) of the nutrient in the test diet (basal diet + test feedstuff); B = apparent digestibility (%) of the nutrient in the basal diet; Tp is the sum of Bp and Ap; Bp = proportion (%) of the nutrient in the test diet that originates from the basal diet; Ap = proportion (%) of the nutrient in the test diet that originates from the test feedstuff. Note that Bp + Ap = Tp = 100%, both B and T were determined using the total collection method. This method assumes that the contribution of nutrients from each ingredient is additive and that the substitution does not alter the digestibility of the unchanged portion of the diet.

Energy values (DE and ME) of the diets and raw materials were calculated using the equations as follows (Kong and Adeola, 2014):

(1) $DE_f\ (MJ/kg) = (GE_i - GE_f)/DM_i$

(2) ME_f (MJ/kg) = $(GE_i - GE_f - GE_u)/DM_i$

(3) $DE_{fc} = DE_f/0.965$

(4) $ME_{fc} = ME_f/0.965$

(5) $DE_t = (DE_{fc} - (100\% - X\%) \times DE_{fc(basal)})/ X\%$

(6) $ME_t = (ME_{fc} - (100\% - X\%) \times ME_{fc(basal)})/ X\%$

The apparent digestible energy (DE_f) and metabolizable energy (ME_f) content in each diet (MJ/kg of DM) are calculated by equations (1) and (2), where the total GE intake (GE_i) of each pig (MJ/kg of DM) is calculated as the result of the GE content of the diet intake. The DM_i is the actual total dry matter intake during the collection period; GE_f and GE_u are the GE content of feces and urine (MJ/kg of DM) and are calculated by the product of GE content of the feces or urine multiplied by the dry weight of total feces or the volume of urine record over the collection period, respectively. The corrected apparent digestible and metabolizable energy, excluding the premix, are represented by DEfc and MEfc. The variable X represents the proportion of the test ingredient replacing the ingredient in the basal diets. The digestible and metabolizable energy of the test ingredient is represented by DEt and MEt, respectively.

3.4. Statistical analysis

All data analyses were performed using SAS 9.4 (SAS Inst. Inc., Cary, NC, USA). Data normality and the presence of outliers were assessed using the UNIVARIATE procedure. The primary statistical analysis was conducted using PROC MIXED, with individual sows as the experimental units. The statistical model used to analyze the effects of parity and physiological stage on the response variables is as follows:

$Y_{ij} = \mu + S_j + e_{ij}$

where Y_{ij} is the observed value of the dependent variable, μ is the overall mean, S_j is the fixed effect of the j-th physiological stage or parity, and e_{ij} is the random error associated with the observation.

Least squares means were calculated for each treatment group, and multiple comparisons were performed using Tukey's multiple range test to determine significant differences among treatments. For all statistical analyses, significance and tendency were set at $P < 0.05$ and $0.05 \leq P < 0.10$, respectively.

4. Results

4.1. The energy balance for primiparous and multiparous sows fed on the basal and experimental diets

The energy balance for primiparous and multiparous sows were shown in **Tables 3-6** and **3-7**. The net utilization of GE in corn diet, barley diet, wheat bran diet and basal diet did not differ across physiological stages in primiparous and multiparous sows.

Table 3-6. The energy balance for primiparous sows fed on the basal and experimental diet

Items	Energy balance (MJ/d)				
	GE intake	GE in feces	GE in urine	GE retained	GE net utilization[2], %
Basal diet					
Gestation	37.43	3.14	0.52	33.77	90.24
Lactation	46.88	3.89	0.71	42.28	90.18
Post-weaning	78.27	7.08	0.73	70.46	90.02
SEM	3.57	0.51	0.15	3.38	1.02
Corn diet					
Gestation	39.68	2.90	0.54	36.25	91.35
Lactation	57.32	3.86	0.89	52.56	91.70
Post-weaning	80.54	6.85	1.39	72.30	89.77
SEM	4.07	0.42	0.26	4.04	1.36
Barley diet					
Gestation	39.53	4.53	0.74	34.25	86.66
Lactation	64.35	6.42	0.71	57.23	88.93
Post-weaning	83.67	11.06	1.83	70.79	84.60
SEM	5.59	1.16	0.30	4.51	1.48
Wheat bran diet					
Gestation	37.32	6.38	0.59	30.35	81.32
Lactation	59.41	9.81	1.49	48.11	80.97
Post-weaning	59.44	11.93	0.94	46.57	78.35
SEM	3.41	1.20	0.21	2.76	1.96
***P*-value**					
Stage[1]-Corn diet	-	-	-	-	0.604
Stage-Barley diet	-	-	-	-	0.134
Stage-Wheat bran diet	-	-	-	-	0.516

[1] Stage (corn diet, barley diet, and wheat bran diet) indicates the significance of different physiological stages on the diet.

[2] Net utilization, % = retained/intake × 100

Each physiological stage included 5 replicates.

Table 3-7. The energy balance for multiparous sows fed on the basal and experimental diet

Items	Energy balance (MJ/d)				
	GE intake	**GE in feces**	**GE in urine**	**GE retained**	**GE net utilization[2], %**
Basal diet					
Gestation	38.47	3.54	0.88	34.05	88.52
Lactation	81.15	6.50	1.34	73.31	90.34
Post-weaning	74.97	5.06	1.83	68.08	90.81
SEM	2.34	0.32	0.20	2.19	1.17
Corn diet					
Gestation	38.15	3.36	1.49	33.30	87.29^{y}
Lactation	76.21	5.97	1.18	69.06	90.61^{x}
Post-weaning	76.64	7.04	2.54	67.06	87.50^{xy}
SEM	2.16	0.53	0.43	2.12	0.88
Barley diet					
Gestation	39.25	4.98	1.56	32.71	83.34^{y}
Lactation	79.56	9.16	0.70	69.70	87.61^{x}
Post-weaning	75.89	9.47	1.18	65.24	85.97^{xy}
SEM	2.18	0.57	0.46	2.11	1.11
Wheat bran diet					
Gestation	39.76	8.29	0.60	30.87	77.63
Lactation	70.53	10.74	1.56	58.23	82.56
Post-weaning	82.04	14.85	2.31	64.88	79.08
SEM	3.07	1.02	0.50	2.80	1.62
***P*-value**					
Stage[1]-Corn diet	-	-	-	-	0.060
Stage-Barley diet	-	-	-	-	0.072
Stage-Wheat bran diet	-	-	-	-	0.108

^{x,y} Different superscripts within the same diet indicate significant tendency among physiological stages ($0.05 \le P < 0.1$).

[1] Stage (corn diet, barley diet, and wheat bran diet) indicates the significance of different physiological stages on the diet.

[2] Net utilization, % = retained/intake × 100

Each physiological stage included 6 replicates.

4.2. Comparative energy and nutrient utilization in different diets for primiparous sows across physiological stages

The comparative results of energy and nutrient utilization across different feed ingredients for primiparous sows at various physiological stages are presented in **Tables 3-8**. In the primiparous sows, no differences were observed in the ATTD of nutrients in the corn diets across stages. For barley, the ATTD of NDF was higher during lactation than post-weaning period ($P < 0.05$), and the ATTD of GE was higher during gestation and lactation than post-weaning ($P < 0.01$). For wheat bran, the ATTD of NDF was higher during lactation than during gestation and post-weaning period.

Table 3-8. The energy and apparent total tract digestibility of diets on a dry matter basis in primiparous sows

Items	DE, MJ/kg	ME, MJ/kg	ME/DE, %	Apparent total tract digestibility of diets, %					
				DM	CP	NDF	EE	OM	GE
Gestation									
Basal diet	16.91	16.72	98.84	90.49	88.86	68.29	66.99	92.40	91.52
Corn diet	16.81	16.36	98.36	91.21	88.79	58.96	63.59	92.96	92.30
Barley diet	16.41	16.07	97.87	87.17	85.73	61.60[ab]	63.80	89.22	88.59[a]
Wheat bran diet	15.43	15.12	97.80	80.84	86.77	55.80[b]	58.60	82.59	86.00[a]
Mean	16.39	16.07	98.22	87.43	87.54	61.16[a]	63.25	89.29	89.60[a]
SEM	0.266	0.334	0.662	1.630	1.548	5.536	4.298	1.422	1.491
Lactation									
Basal diet	17.09	16.93	99.00	92.51	89.57	61.17	68.38	93.23	91.91
Corn diet	16.92	16.56	98.95	91.31	87.93	54.37	64.42	93.24	92.15
Barley diet	16.64	16.53	99.33	89.39	86.19	65.60[a]	64.40	91.16	90.27[a]
Wheat bran diet	15.67	15.31	97.60	82.20	85.23	63.80[a]	68.00	85.52	87.20[a]
Mean	16.58	16.33	98.72	88.85	87.23	61.24[a]	66.30	90.79	89.63[a]
SEM	0.339	0.342	0.313	2.050	2.168	6.257	6.725	1.662	1.895
Post-weaning									
Basal diet	16.91	16.82	99.49	89.55	87.76	57.61	60.38	91.49	87.76
Corn diet	16.89	16.58	98.89	92.69	87.32	48.62	56.92	92.69	88.18
Barley diet	16.00	15.77	98.55	85.09	82.94	47.20[b]	58.00	87.69	84.03[b]
Wheat bran diet	14.84	14.66	98.60	76.20	81.54	45.60[b]	71.25	80.02	77.08[b]
Mean	16.16	15.99	98.93	85.07	84.89	49.85[b]	59.60	87.97	86.18[b]
SEM	0.191	0.198	0.221	1.186	1.428	3.887	5.111	0.992	1.033
***P*-value[1]**									
Stage-Corn diet	0.952	0.945	0.272	0.621	0.836	0.152	0.343	0.971	0.128
Stage-Barley diet	0.126	0.184	0.273	0.105	0.314	0.021	0.400	0.146	0.004
Stage-Wheat bran diet	0.263	0.492	0.475	0.336	0.161	0.041	0.226	0.230	0.041
Stage-Four diets	0.348	0.445	0.182	0.180	0.105	0.005	0.402	0.287	0.003
Interaction	0.826	0.875	0.594	0.860	0.918	0.819	0.845	0.787	0.945

[a,b] Different superscripts within the same diet indicate significant differences among physiological stages ($P < 0.05$).

[1] Stage (corn diet, barley diet, wheat bran diet, and four diets) indicates the significance of different physiological stages on the diet; Interaction refers to the interaction between physiological stages and the four diets.

Note: DE = digestive energy; ME = metabolizable energy; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; EE = ether extract; OM = organic matter; GE = gross energy.

4.3. Comparative energy and nutrient utilization in different diets for multiparous sows across physiological stages

The comparative results of energy and nutrient utilization across different feed ingredients for primiparous and multiparous sows at various physiological stages are presented in **Table 3-9**. In the multiparous sows, the ME in the barley diet during lactation and post-weaning were higher than during gestation ($P < 0.05$). The DE and ATTD of NDF, GE in the wheat bran diet during lactation were higher than gestation ($P < 0.05$). For four diets, the ME, ME/DE and the ATTD of NDF in lactation were higher than gestation ($P < 0.05$).

Table 3-9. The energy and apparent total tract digestibility of diets on a dry matter basis in multiparous sows

Items	DE, MJ/kg	ME, MJ/kg	ME/DE, %	Apparent total tract digestibility of diets, %					
				DM	CP	NDF	EE	OM	GE
Gestation									
Basal diet	16.78	16.36	97.44	88.47	87.37	61.84	78.54	92.54	90.81
Corn diet	16.61	15.90^{y}	95.77^{y}	89.06	86.37	63.56	82.65	92.67	91.19
Barley diet	16.18	15.44^{b}	95.74	84.80	83.01	51.22	80.57	88.70	87.31
Wheat bran diet	14.74^{b}	14.46	98.09	76.66^{y}	79.76	44.19^{b}	79.21	82.58	79.14b
Mean	16.08	15.54^{b}	96.69^{b}	84.75	84.12	55.20^{b}	80.24	89.33	87.11
SEM	0.134	0.233	1.102	0.858	0.921	3.137	2.668	0.808	0.728
Lactation									
Basal diet	16.98	16.71	98.44	90.35	87.76	79.14	84.18	93.29	91.86
Corn diet	16.77	16.52^{x}	98.50^{x}	90.83	86.97	68.17	80.97	93.88	92.07
Barley diet	16.40	16.24^{a}	99.01	86.86	83.88	54.64	82.37	90.16	88.51
Wheat bran diet	15.79^{a}	15.44	97.75	82.34^{x}	81.67	59.31^{a}	86.46	86.02	84.78a
Mean	16.49	16.23a	98.42^{a}	87.60	85.07	65.31a	83.49	90.84	89.30
SEM	0.158	0.187	0.650	1.004	1.339	3.730	2.137	0.769	0.856
Post-weaning									
Basal diet	17.24	16.80	97.43	91.06	92.84	73.02	81.25	94.49	93.27
Corn diet	16.55	15.94^{y}	96.28^{xy}	88.25	84.94	63.13	78.19	92.32	90.86
Barley diet	16.36	16.07^{a}	98.28	85.44	82.72	59.05	83.01	89.46	88.28

Items	DE, MJ/kg	ME, MJ/kg	ME/DE, %	Apparent total tract digestibility of diets, %					
				DM	CP	NDF	EE	OM	GE
Wheat bran diet	15.26^{ab}	14.73	96.49	77.58^{xy}	79.92	51.37^{ab}	81.55	82.74	81.92^{ab}
Mean	16.35	16.17^{ab}	97.08^{ab}	85.58	85.11	61.64^{ab}	81.00	89.75	88.58
SEM	0.176	0.248	0.829	1.436	1.617	4.869	3.851	0.947	0.950
***P*-value[1]**									
Stage-Corn diet	0.584	0.056	0.057	0.213	0.524	0.638	0.462	0.227	0.713
Stage-Barley diet	0.459	0.046	0.119	0.178	0.863	0.159	0.726	0.217	0.413
Stage-Wheat bran diet	0.022	0.107	0.264	0.093	0.710	0.043	0.318	0.237	0.017
Stage-Four diets	0.194	0.027	0.034	0.180	0.708	0.026	0.212	0.438	0.273
Interaction	0.053	0.671	0.311	0.361	0.088	0.411	0.694	0.367	0.031

[a,b] Different superscripts within the same diet indicate significant differences among physiological stages ($P < 0.05$).

[1] Stage (corn diet, barley diet, wheat bran diet, and four diets) indicates the significance of different physiological stages on the diet; Interaction refers to the interaction between physiological stages and the four diets.

Note: DE = digestive energy; ME = metabolizable energy; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; EE = ether extract; OM = organic matter; GE = gross energy.

4.4. Comparative energy and nutrient utilization in different ingredients for primiparous sows across physiological stages

The comparative results of energy and nutrient utilization across different feed ingredients for primiparous sows at various physiological stages are presented in **Table 3-10**. The ATTD of nutrients and energy in the corn showed no differences across different physiological stages in primiparous sows. The ATTD of NDF in barley was higher in the lactation than in the post-weaning period ($P < 0.05$), and the ATTD of GE in the barley was also higher during lactation than in the post-weaning period ($P < 0.05$). The ATTD of NDF in wheat bran was higher in the lactation period than in the post-weaning period ($P < 0.05$). Across all ingredients, the ATTD of NDF during lactation was higher than during post-weaning ($P < 0.05$).

Table 3-10. Comparative energy and nutrient utilization of different ingredients on a dry matter basis in primiparous sows at different physiological stages

Items	DE, MJ/kg	ME, MJ/kg	ME/DE, %	Apparent total tract digestibility of diets, %					
				DM	CP	NDF	EE	OM	GE
Corn									
Gestation	16.71	16.36	97.88	91.94	88.70	50.92	84.70	93.43	96.46
Lactation	16.75	16.56	98.88	91.61	86.20	58.72	87.30	93.26	96.12
Post-weaning	16.88	16.58	98.28	89.24	86.68	38.76	84.01	93.70	91.81
Mean	16.78	16.50	98.35	90.93	87.19	49.47	85.34	93.46	94.80
SEM	0.46	0.36	0.58	2.72	3.60	7.22	6.92	2.24	2.60
Barley									
Gestation	15.91	15.43	96.90	83.86	81.58	59.18[ab]	59.59	86.40	88.78[ab]
Lactation	16.19	15.88	99.38	87.77	81.27	67.52[a]	59.77	89.32	90.63[a]
Post-weaning	15.09	14.27	97.62	80.62	76.55	41.95[b]	55.22	84.31	83.21[b]
Mean	15.73	15.19	97.97	84.08	79.80	56.22	58.19	86.68	87.54
SEM	0.41	0.40	0.84	2.60	3.69	5.82	7.58	2.03	2.30
Wheat bran									
Gestation	13.95	13.52	97.03	70.79	85.03	52.63[ab]	54.93	73.21	76.86
Lactation	14.26	13.70	96.42	73.75	83.76	64.39[a]	68.04	78.21	77.85
Post-weaning	12.78	12.52	98.13	62.95	77.40	42.02[b]	58.49	69.44	68.81
Mean	13.66	13.25	97.19	69.16	82.06	53.01	60.49	73.62	74.51
SEM	0.67	0.70	1.11	4.00	3.15	5.26	5.54	3.16	3.68
Three ingredients									
Gestation	15.78	15.41	97.59	84.02	85.72	55.40[ab]	77.36	85.94	88.86
Lactation	15.97	15.68	98.18	85.51	84.79	60.08[a]	80.42	88.09	88.62
Post-weaning	14.92	14.61	98.01	77.60	80.21	40.91[b]	73.91	82.48	81.28
Mean	15.56	15.23	97.93	82.38	83.57	52.13	77.23	85.50	86.25
SEM	0.42	0.48	0.46	2.74	2.01	3.33	3.54	2.39	2.48
***P*-value**									
Stage[1]-Corn	0.973	0.945	0.508	0.751	0.877	0.199	0.877	0.985	0.530
Stage-Barley	0.195	0.227	0.173	0.195	0.500	0.025	0.489	0.272	0.037
Stage-Wheat bran	0.323	0.492	0.654	0.203	0.265	0.043	0.305	0.199	0.218
Stage-Three ingredients	0.439	0.472	0.410	0.268	0.250	0.001	0.686	0.508	0.181
Interaction	0.634	0.742	0.372	0.754	0.869	0.977	0.461	0.535	0.849

[a,b] Different superscripts within the same ingredient indicate significant differences among physiological stages ($P < 0.05$).

[1]Stage (corn, barley, wheat bran, and three ingredients) indicates the significance of different physiological stages on the ingredient; Interaction refers to the interaction between physiological stages and the three ingredients.

Note: DE = digestive energy; ME = metabolizable energy; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; EE = ether extract; OM = organic matter; GE = gross energy.

4.5. Comparative energy and nutrient utilization in different ingredients for multiparous sows across physiological stages

The comparative results of energy and nutrient utilization across different feed ingredients for multiparous sows at various physiological stages are presented in **Table 3-11.** For corn, the ATTD of CP during gestation and lactation was higher than during post-weaning ($P < 0.05$). For barley, the ATTD of nutrients and energy showed no differences across different physiological stages in multiparous sows. For wheat bran, the DE and the ATTD of GE during lactation were higher than during gestation

(P < 0.05). For the three ingredients, ME during lactation was higher than during gestation and the post-weaning period, and ATTD of CP during lactation and gestation was higher than in the post-weaning period (P < 0.05).

Table 3-11. Comparative energy and nutrient utilization of different ingredients on a dry matter basis in multiparous sows at different physiological stages

Items	DE, MJ/kg	ME, MJ/kg	ME/DE, %	Apparent total tract digestibility of diets, %					
				DM	CP	NDF	EE	OM	GE
Corn									
Gestation	16.71	16.36	97.88	91.94	88.70	50.92	84.70	93.43	96.46
Lactation	16.75	16.56	98.88	91.61	86.20	58.72	87.30	93.26	96.12
Post-weaning	16.88	16.58	98.28	89.24	86.68	38.76	84.01	93.70	91.81
Mean	16.78	16.50	98.35	90.93	87.19	49.47	85.34	93.46	94.80
SEM	0.46	0.36	0.58	2.72	3.60	7.22	6.92	2.24	2.60
Barley									
Gestation	15.91	15.43	96.90	83.86	81.58	59.18[ab]	59.59	86.40	88.78[ab]
Lactation	16.19	15.88	99.38	87.77	81.27	67.52[a]	59.77	89.32	90.63[a]
Post-weaning	15.09	14.27	97.62	80.62	76.55	41.95[b]	55.22	84.31	83.21[b]
Mean	15.73	15.19	97.97	84.08	79.80	56.22	58.19	86.68	87.54
SEM	0.41	0.40	0.84	2.60	3.69	5.82	7.58	2.03	2.30
Wheat bran									
Gestation	13.95	13.52	97.03	70.79	85.03	52.63[ab]	54.93	73.21	76.86
Lactation	14.26	13.70	96.42	73.75	83.76	64.39[a]	68.04	78.21	77.85
Post-weaning	12.78	12.52	98.13	62.95	77.40	42.02[b]	58.49	69.44	68.81
Mean	13.66	13.25	97.19	69.16	82.06	53.01	60.49	73.62	74.51
SEM	0.67	0.70	1.11	4.00	3.15	5.26	5.54	3.16	3.68
Three ingredients									
Gestation	15.78	15.41	97.59	84.02	85.72	55.40[ab]	77.36	85.94	88.86
Lactation	15.97	15.68	98.18	85.51	84.79	60.08[a]	80.42	88.09	88.62
Post-weaning	14.92	14.61	98.01	77.60	80.21	40.91[b]	73.91	82.48	81.28
Mean	15.56	15.23	97.93	82.38	83.57	52.13	77.23	85.50	86.25
SEM	0.42	0.48	0.46	2.74	2.01	3.33	3.54	2.39	2.48
***P*-value**									
Stage[1]-Corn	0.973	0.945	0.508	0.751	0.877	0.199	0.877	0.985	0.530
Stage-Barley	0.195	0.227	0.173	0.195	0.500	0.025	0.489	0.272	0.037
Stage-Wheat bran	0.323	0.492	0.654	0.203	0.265	0.043	0.305	0.199	0.218
Stage-Three ingredients	0.439	0.472	0.410	0.268	0.250	0.001	0.686	0.508	0.181
Interaction	0.634	0.742	0.372	0.754	0.869	0.977	0.461	0.535	0.849

[a,b] Different superscripts within the same ingredient indicate significant differences among physiological stages (P < 0.05).

[1]Stage (corn, barley, wheat bran, and three ingredients) indicates the significance of different physiological stages on the ingredient; Interaction refers to the interaction between physiological stages and the three ingredients.

Note: DE = digestive energy; ME = metabolizable energy; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; EE = ether extract; OM = organic matter; GE = gross energy.

4.6 Comparison of energy value and nutrient digestibility between primiparous and multiparous sows

The results comparing energy and nutrient digestibility between primiparous and multiparous sows at different physiological stages are presented in **Table 3-12**. There was no difference in the digestibility of nutrients and energy in corn between multiparous and primiparous sows during gestation. Primiparous sows had a higher ATTD of CP in wheat bran than multiparous sows ($P < 0.05$) during gestation. Multiparous sows had a higher ATTD of EE in barley than primiparous sows ($P < 0.01$) and had a higher ATTD of EE in wheat bran than primiparous sows ($P < 0.05$) during gestation. There was also no difference in the digestibility of energy nutrients in corn between multiparous and primiparous sows during lactation. Primiparous sows had a higher ATTD of NDF in barley than multiparous sows ($P = 0.006$), while multiparous sows showed a higher ATTD of EE in barley during lactation ($P < 0.05$). Multiparous sows had a higher ATTD of EE in wheat bran than primiparous sows during lactation ($P < 0.05$). During post-weaning, primiparous sows had higher ME and ATTD of CP in the corn than multiparous sows ($P < 0.05$). Multiparous sows had a higher ATTD of EE in the barley than primiparous sows ($P < 0.05$) and had a higher ATTD of EE in the wheat bran than primiparous sows during post-weaning period ($P < 0.05$).

Table 3-12. Comparative energy and nutrient utilization of different ingredients on a dry matter basis between primiparous and multiparous sows

Items	DE, MJ/kg	ME, MJ/kg	ME/DE, %	Apparent total tract digestibility of diets, %					
				DM	CP	NDF	EE	OM	GE
Gestation									
Corn									
Primiparous sow	16.71 ± 0.33	16.36 ± 0.40	97.88 ± 0.86	91.94 ± 2.13	88.70 ± 2.94	50.92 ± 6.86	84.70 ± 4.19	93.43 ± 1.71	96.46 ± 1.91
Multiparous sow	16.44 ± 0.31	15.44 ± 0.27	94.05 ± 1.54	89.62 ± 1.67	84.92 ± 2.15	65.09 ± 8.64	84.87 ± 2.44	92.78 ± 1.18	91.55 ± 1.61
P-value	0.566	0.083	0.053	0.395	0.293	0.251	0.318	0.765	0.076
Barley									
Primiparous sow	15.91 ± 0.48	15.43 ± 0.74	96.90 ± 1.68	83.86 ± 3.02	81.58 ± 4.02	59.18 ± 6.12	59.59 ± 5.51	86.40 ± 2.38	88.78 ± 2.69
Multiparous sow	15.57 ± 0.15	14.52 ± 0.54	93.54 ± 3.84	81.28 ± 0.77	77.22 ± 1.72	47.09 ± 2.12	83.48 ± 4.06	85.43 ± 0.53	83.95 ± 0.81
P-value	0.476	0.338	0.481	0.443	0.293	0.073	0.005	0.652	0.095
Wheat bran									
Primiparous sow	13.95 ± 0.58	13.52 ± 0.77	97.03 ± 1.80	70.79 ± 3.38	85.03 ± 2.21	52.63 ± 5.13	54.93 ± 7.33	73.21 ± 2.95	76.86 ± 3.21
Multiparous sow	12.70 ± 0.31	12.56 ± 0.37	98.74 ± 0.78	64.84 ± 2.22	74.90 ± 1.60	39.49 ± 3.39	79.51 ± 5.11	73.74 ± 3.12	69.20 ± 1.55
P-value	0.076	0.262	0.333	0.134	0.005	0.054	0.021	0.886	0.055
Lactation									
Corn									
Primiparous sow	16.75 ± 0.79	16.56 ± 0.79	98.88 ± 0.38	91.61 ± 4.35	86.20 ± 5.97	58.72 ± 9.32	80.30 ± 10.00	93.26 ± 3.63	94.53 ± 4.48
Multiparous sow	16.56 ± 0.25	16.32 ± 0.19	98.55 ± 1.07	93.09 ± 1.48	85.84 ± 2.76	58.44 ± 4.18	79.48 ± 2.74	94.97 ± 0.86	92.27 ± 1.30
P-value	0.816	0.755	0.687	0.81	0.979	0.978	0.331	0.621	0.644
Barley									
Primiparous sow	16.19 ± 0.37	16.13 ± 0.40	99.64 ± 0.38	87.77 ± 2.46	81.72 ± 3.17	67.52 ± 5.27	59.77 ± 8.12	89.32 ± 1.84	90.63 ± 2.08
Multiparous sow	15.82 ± 0.30	15.77 ± 0.41	99.59 ± 0.81	85.32 ± 1.72	78.74 ± 2.97	45.11 ± 3.89	79.76 ± 5.10	88.13 ± 1.28	85.30 ± 1.57
P-value	0.454	0.544	0.916	0.446	0.442	0.006	0.046	0.591	0.064
Wheat bran									
Primiparous sow	14.26 ± 0.95	13.70 ± 0.87	96.42 ± 1.02	73.75 ± 5.73	83.76 ± 4.23	64.39 ± 7.47	68.04 ± 6.68	78.21 ± 4.10	77.85 ± 5.27
Multiparous sow	14.61 ± 0.53	14.17 ± 0.67	97.05 ± 1.68	76.22 ± 3.38	77.77 ± 2.70	54.03 ± 4.99	87.48 ± 3.25	80.23 ± 2.69	78.75 ± 2.64
P-value	0.744	0.675	0.723	0.148	0.241	0.267	0.02	0.692	0.881
Post-weaning period									
Corn									
Primiparous sow	16.88 ± 0.26	16.58 ± 0.24	98.28 ± 0.51	89.24 ± 1.68	86.68 ± 1.89	38.76 ± 5.48	84.01 ± 6.56	93.70 ± 1.37	94.53 ± 4.48
Multiparous sow	16.07 ± 0.31	15.35 ± 0.33	95.12 ± 1.67	88.04 ± 2.63	73.57 ± 4.21	54.37 ± 10.09	76.54 ± 5.77	92.14 ± 1.63	88.63 ± 1.85
P-value	0.101	0.031	0.114	0.745	0.026	0.233	0.151	0.482	0.201
Barley									
Primiparous sow	15.09 ± 0.39	14.72 ± 0.44	97.62 ± 0.46	80.62 ± 2.32	76.55 ± 3.88	41.95 ± 6.07	55.22 ± 9.11	84.31 ± 1.86	83.21 ± 2.12
Multiparous sow	15.47 ± 0.30	15.08 ± 0.50	98.63 ± 1.20	82.53 ± 2.20	69.30 ± 4.30	53.61 ± 4.65	85.54 ± 6.84	86.83 ± 1.24	83.48 ± 1.61
P-value	0.454	0.27	0.512	0.551	0.246	0.148	0.024	0.299	0.898
Wheat bran									
Primiparous sow	12.78 ± 0.48	12.52 ± 0.53	98.13 ± 0.52	62.95 ± 2.91	77.40 ± 3.01	42.02 ± 3.19	58.49 ± 2.61	69.44 ± 2.42	77.85 ± 5.27
Multiparous sow	13.28 ± 0.53	12.67 ± 0.78	95.55 ± 2.13	66.68 ± 4.54	71.66 ± 3.45	45.61 ± 5.97	81.68 ± 5.20	74.04 ± 3.05	72.24 ± 2.64
P-value	0.511	0.877	0.325	0.535	0.238	0.636	0.004	0.277	0.354

Each physiological stage included 5 replicates for primiparous sows and 6 replicates for multiparous sows

Note: DE = digestive energy; ME = metabolizable energy; DM = dry matter; CP = crude protein; NDF = neutral detergent fiber; EE = ether extract; OM = organic matter; GE = gross energy.

5. Discussion

Studies investigating the effects of physiological stage and parity on feed evaluation in sows remain scarce. The present study, to our knowledge, is the first to explore the effects of both physiological stages and parity on nutrient and energy digestibility using various feed ingredients, including corn, barley, and wheat bran.

5.1. Effects of physiological stage on nutrient digestibility and feed value in sows

Currently, there is limited research on the effects of physiological stages on nutrient digestibility in sows. Moreover, due to variations in the nutrient composition and content of different feed ingredients, the observed differences lack consistency and generalizability. An experiment by Wang et al. (2024) demonstrated that the nutritional value of feed ingredients may vary with the physiological state of sows, suggesting that such differences should be considered when formulating diets. Zhuo et al. (2023) conducted a comparison study in which energy values and ATTD of CSM were compared between pregnant and non-pregnant sows. The study revealed that non-pregnant sows exhibited higher ATTD for OM and CP compared to pregnant sows, although no significant differences were observed for DE and ME. The energy values and nutrient digestibility of CSM were found to vary depending on its chemical composition, with a higher protein and lower fiber content exhibiting superior DE and ME values (Zhuo et al., 2023). In our experiment, both primiparous and multiparous sows exhibited higher values in certain digestibility and energy value for barley and wheat bran during lactation compared to the gestation or the post-weaning period. For primiparous sows, the ATTD of NDF and GE in barley and the ATTD of NDF in wheat bran were higher during lactation than during the post-weaning period. For multiparous sows, the ATTD of CP in corn was greater during gestation and lactation than post-weaning. Across all ingredients, ME values and CP digestibility were generally higher during lactation compared to gestation and post-weaning. These findings suggest that part of nutrient digestibility was relatively higher during lactation compared to gestation and the post-weaning period. Our results are consistent with the study of Casas et al. (2022), which reported that lactating sows exhibited significantly higher ATTD for GE, DM, NDF, and OM compared to pregnant sows, regardless of whether they were fed a basal diet or a rice bran-based diet. Lactating sows have significantly higher energy requirements compared to gestating sows, which are often difficult to meet through voluntary feed intake alone. The enhanced digestive capacity during lactation may be related to the increased energy and nutrient demands required to support lactation compared to gestation and the post-weaning period (Noblet and Etienne, 1987). Similarly, studies have shown that lactating sows, compared to pregnant and non-pregnant sows, exhibit an increased abundance of gut microbiota responsible for fermenting dietary fiber, leading to a higher production of short-chain fatty acids (SCFAs). This elevated SCFAs production stabilizes by day 28 of lactation. In addition to maintaining gut health, SCFAs also serve as a direct or indirect energy source for the host (Liu et al., 2019). Both the research of Casas et al. (2022) on rice bran and our findings for the wheat bran and barley indeed indicate that fiber-rich ingredients exhibit greater differences in digestibility and energy values between lactation and gestation when compared to low-fiber ingredients. As indicated by our results, for corn, which has a lower fiber content compared to barley and wheat bran, no significant differences in energy and digestibility were observed across different physiological stages in both primiparous and multiparous sows. We speculate that this disparity can be attributed to the increased population of gut microbiota capable of fiber degradation during lactation. However, Wang et al. (2023a) demonstrated that for full-fat soybeans, the ATTD of NDF was higher in non-pregnant and pregnant sows compared to lactating sows, while the energy values did not show significant differences across physiological stages. This suggests that more comparative studies on feeding different feed ingredients across physiological stages are needed to confirm whether the higher digestibility during lactation is limited to high-fiber ingredients. Difference in feed intake across physiological stages may have contributed to the observed variation in the evaluation of ingredient digestibility. In a recent study by Kim et al. (2025), gestating sows showed greater DE values for corn compared with lactating sows, which was primarily attributed to the lower dry matter intake (DMI) during gestation. However, in our study, the feed intake of lactating sows, both primiparous and multiparous was lower than the 5.4 kg/day reported in their study. This difference in intake may help explain why no difference in DE values between gestating and lactating sows was observed in our experiment. Moreover, the overall digestibility values in our study were slightly higher than those reported in previous studies (Lowell et al., 2015; Kim et al., 2025), which may be attributed to differences in ingredient types, experimental design, and calculation methods. Overall, our results indicate that the type of feed ingredient influences the digestibility of different nutrients across physiological stages. Corn showed relatively stable energy values and nutrient utilization, while both barley and wheat bran exhibited increased digestibility during lactation. The relatively high ME:DE observed in this experiment may be partially attributed to incomplete nitrogen retention due to insufficient acidification during urine collection (Kim et al., 2022).

5.2. Comparison of energy value and nutrient digestibility between primiparous and multiparous sows

Currently, no relevant studies have been reported comparing the digestibility of feed ingredients between primiparous and multiparous sows. In our experiment, we compared the energy utilization and ATTD of nutrients in sows with different parities (primiparous vs. multiparous). Although most parameters showed no differences, we observed that multiparous sows exhibited higher ATTD of EE compared to primiparous sows for barley in three different physiological stages, and multiparous sows also exhibited higher ATTD of EE for wheat bran compared to primiparous sows. We hypothesize that this difference may be related to the maturity of the gastrointestinal tract and the composition of the gut microbiota. Primiparous sows are still in the growth and developmental stage, with certain organs, such as the pancreas, potentially not yet fully developed (Charbonneau, 1982; Owsley et al., 1986). The pancreas, as the primary source of lipase secretion, might not function at its full capacity in primiparous sows, leading to relatively lower lipase secretion levels and consequently reduced fat digestibility. Zhang et al. (2024) reported that the species richness of the gut microbiota in fifth-parity pregnant sows was significantly higher than that in primiparous sows. The gut microbiota of multiparous sows is generally more stable, which may contribute to enhanced fat breakdown and promote the secretion of lipase. Lim et al. (2019) found that the relative abundance of microbiota associated with lipid metabolism pathways increased with age in micro-pigs. The relatively high EE values observed in this experiment may be partially attributed to the analytical method used, such as whether acid hydrolysis was performed prior to ether extraction. In feces, EE can bind to calcium and other minerals to form insoluble complexes, potentially leading to an overestimation of EE digestibility. The NDF content in our study was determined using the Ankom filter bag technique, which is widely used for feed analysis. However, when applied to animal feces, this method may lead to an overestimation of NDF digestibility (Barbosa et al., 2015; Koh et al., 2025). Additionally, our results revealed that primiparous sows exhibited a higher ATTD of GE for the corn during gestation compared to multiparous sows. During lactation, the ATTD of NDF and GE for the barley in primiparous sows was also higher than those in multiparous sows. These findings suggest that, while the ATTD of EE in primiparous sows may be relatively lower than that in multiparous sows, the ATTD of other nutrients is not necessarily inferior and may even surpass that of multiparous sows. Studies have shown a direct relationship between body weight and ATTD of energy in growing pigs. Noblet and Shi (1994) investigated the effect of body weight on feed digestibility by feeding growing pigs at different body weights (45 kg, 100 kg, and 150 kg). This study revealed differences in nutrient digestibility and energy coefficients between the 45 kg group and the 100 kg group. However, the differences between the 100 kg group and the 150 kg group were minimal, with the energy digestibility coefficient differing by only 0.8% (Noblet and Shi, 1994; Noblet, 2000). In our experiment, although the body weight of primiparous sows was smaller compared to multiparous sows, it was still far above 150 kg, and there were no significant differences in most DE and ME between the two groups of sows. This suggests that body weight cannot be used as a direct reference indicator for evaluating energy utilization and the ATTD of nutrients in sows. Additionally, Haydon et al. (1984) reported that feed intake levels have an influence on the apparent digestibility of nutrients throughout the digestive tract in growing pigs; as feed intake levels decrease, digestibility may slightly increase. Primiparous sows typically have lower feed intake compared to multiparous sows in the lactating period, which may result in longer feed retention time in the gastrointestinal tract. This extended retention allows digestive enzymes and gut microbiota to act more effectively on the nutrients. Moreover, primiparous sows require higher nutrient levels to support their growth, and we speculate that aging of the digestive organs in high-parity multiparous sows may also influence nutrient digestibility outcomes (Whittemore, 1996).

6. Conclusion

Our study investigated the effects of physiological stages and parity on the ATTD of nutrients and energy utilization in sows. The results showed that the physiological stage played a critical role, with lactating sows exhibiting higher digestibility of certain nutrients and greater energy utilization for barley and wheat bran compared with post-weaning sows. Parity also influenced nutrient digestibility; multiparous sows generally showed higher EE digestibility for barley and wheat bran, while primiparous sows exhibited higher digestibility of certain nutrients under specific conditions.

Chapter IV

Evaluation of standardized ileal digestibility of amino acids in corn, barley, wheat bran fed to primiparous sows during gestation, lactation, and post-weaning period

The experiment described in this chapter is the study published as:

Zixi Wei, Lei Xu, Jiaqi Yang, Martine Schroyen, Xianren Jiang, Sheng Cui, Xilong Li, Yu Pi

Evaluation of standardized ileal digestibility of amino acids in corn, barley, wheat bran fed to primiparous sows during gestation, lactation, and post-weaning period

Journal of Animal Science, 2025, 103, skaf277.

Chapter IV. Evaluation of standardized ileal digestibility of amino acids in corn, barley, wheat bran fed to primiparous sows during gestation, lactation, and post-weaning period

Zixi Wei[a,b], Lei Xu[a], Jiaqi Yang[a], Martine Schroyen[b], Xianren Jiang[a], Sheng Cui[c], Xilong Li[a], and Yu Pi[a]

[a] Key Laboratory of Feed Biotechnology of Ministry of Agriculture and Rural Affairs, Institute of Feed Research, Chinese Academy of Agricultural Sciences, Beijing 100081, China

[b] Animal Sciences, TERRA Teaching and Research Centre, Gembloux Agro-Bio Tech, University of Liège, Gembloux 5030, Belgium

[c] College of Veterinary Medicine, Yangzhou University, Yangzhou 225009, Jiangsu, China

Keywords: basal endogenous losses, primiparous sows, apparent ileal digestibility, physiological stages, feedstuffs

1. Abstract

This study determined the apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of crude protein (CP) and amino acids (AA) of corn, barley, and wheat bran in primiparous sows. Four physiological stages of primiparous sows were examined: a gestation stage where sows were restricted-fed, a lactation stage where sows were fed ad libitum, and then two post-weaning stages, an ad libitum fed phase followed by a restricted-fed phase. A total of 8 primiparous sows fitted with T-cannulas in the distal ileum were assigned to an 8 × 3 Youden square design with four diets (corn, barley, wheat bran, and nitrogen(N)-free diet) and three periods, resulting in a total of six replicates per treatment. The basal endogenous losses of CP and AA were determined after feeding an N-free diet. For barley, the AID of His, Ile, Lys, and Thr was higher in gestating sows compared to restricted-fed post-weaning sows. For wheat bran, the AID of Ile, Leu, Thr, Val, Ala, Asp, Glu, Gly, Ser, and Tyr were higher in lactating sows compared to gestating sows ($P < 0.05$). For corn, the AID of CP and most AA did not differ across physiological states. Regarding the SID of barley in gestating sows, only the SID of His was higher than in lactating sows and restricted-fed post-weaning sows ($P < 0.01$), and the SID of Gly was higher than in lactating sows ($P < 0.05$). For wheat bran, the SID of Glu, Ser, and Tyr in gestating sows was lower than in lactating sows ($P < 0.01$). The SID of Val and Tyr in lactating sows was higher than in ad libitum access post-weaning sows ($P < 0.05$). For corn, the SID of Lys, Ala, and Gly in gestating sows was higher than in lactating sows ($P < 0.05$). The SID of Ile, Lys, Phe, Thr, and Ala in gestating sows was higher than in ad libitum post-weaning sows ($P < 0.05$). The findings indicate that similar SID values are found for barley in different physiological stages of primiparous sows under the same diet and feed regime, whether ad libitum or restricted. However, for wheat bran, which has a high fiber content, lactating sows exhibited higher AID values and SID values compared to gestating sows for part of AA. For corn, which has a low fiber content, gestating sows exhibited higher SID values compared to lactating sows and ad libitum post-weaning sows.

2. Introduction

Accurate evaluation of amino acid (AA) digestibility is essential for precision feeding in sows. Standardized ileal digestibility (SID) is considered the reliable value. However, SID values in the current guidelines (NRC, 2012) are mostly derived from growing pigs. Considering the physiological differences across reproductive stages, establishing sow-specific SID values is necessary to improve diet formulation and feeding efficiency (Jondreville et al., 1995; Rademacher et al., 1999; NRC, 2012). In 1999, Stein et al. conducted a study on the apparent ileal digestibility (AID) of AA in ingredients such as corn, barley, wheat, and meat and bone meal, comparing the differences between gestating sows, lactating sows, and growing pigs. Their findings indicated that the AID values obtained from growing pigs do not always represent those in gestating and lactating sows (Stein et al., 1999a). In 2001, a study on the SID of protein and AA was conducted in sows and growing pigs. The results revealed that gestating sows had significantly higher SID values for both protein and AA than growing pigs (Stein et al., 2001). Moreover, Zhuo et al. found that the SID of dispensable AA (Cys, Gly, Pro, and Tyr) from cottonseed meal differed significantly between gestating and post-weaning sows under the same diet and feed intake (Zhuo et al., 2023). These studies revealed that there are variations in the SID of AA across different physiological stages of pigs. Consequently, data obtained from growing pigs cannot be applied to sows, and distinct physiological states of sows may exhibit differing SID values for AA. Primiparous sows have not fully matured in terms of weight and physiological status compared to multiparous sows, and their nutritional needs are higher, as they must support both their own growth and fetal development. Currently, there is a lack of data on the SID of AA in feed ingredients for primiparous sows. It is unclear whether primiparous sows have the same AA digestibility for feed ingredients as multiparous sows. Furthermore, the effects of various physiological stages and feeding levels on the AID and SID of AA in primiparous sows are not well-documented. Corn, barley, and wheat bran are utilized as energy-feed ingredients for sows; however, the SID of AA values for these ingredients in primiparous sows remain undocumented. Therefore, the objective of this experiment was to evaluate and compare the SID of CP and AA in typical feedstuffs (barley, wheat bran and corn) across different physiological stages (gestation, lactation, and post-weaning) in primiparous sows.

3. Materials and methods

The animal trials were performed at the Tianpeng experimental farm, located in Lang Fang, Hebei province, China. The animal protocol for this research was approved by the Animal Care and Use Committee of the Institute of Feed Research of the Chinese Academy of Agricultural Sciences (IFR-CAAS20230410). All sows were housed in a temperature-controlled enclosed pig barn with consistent ambient conditions during the entire experimental period, eliminating seasonal fluctuations in ambient temperature and natural breeding cycle; accordingly, seasonal effects were excluded as a confounding factor for nutrient digestibility results in the present trial.

3.1. Diets, animals, and experimental design

Corn and wheat bran were purchased from Hebei Kangda Co., Ltd. (Langfang, China). Barley was purchased from Guangdong Haida Co., Ltd. (Guangzhou, China). Analysis of the chemical composition of corn, barley, and wheat bran samples was conducted before the start of the experiment (**Table 3-1**).

A total of 12 primiparous sows (Landrace × Yorkshire; body weight = 156.5 ± 5.2 kg) were installed a T-cannula in the distal ileum according to a previous method (Stein et al., 1998). Approximately 15 days later, after the wounds had fully healed, T-cannula-fitted sows had a mixture of petroleum jelly and zinc oxide applied to their wounds to help them recover. After recovery from surgery, sows were subjected to a synchronized estrus treatment followed by artificial insemination. Out of the 12 sows, 8 were successfully conceived and subsequently used in the experiment. Four trials were conducted successively to measure AID and SID values for CP and AA under restricted feeding during gestation, ad libitum feeding during lactation, ad libitum feeding during post-weaning, and restricted feeding during post-weaning. 8 sows were randomly allotted to an 8 × 3 Youden square design with 4 diets and 3 periods. Each period included two replicates, resulting in six replications per diet. During the mid-term of pregnancy, one pregnant sow exhibited pyrexia and was transferred for medical intervention to prevent miscarriage. Consequently, data from this sow were excluded for that period, resulting in 5 replicates for the corresponding treatment during gestation.

3.2. Diets and feeding

Diets included a corn starch-based nitrogen (N)-free diet to calculate endogenous losses of protein and AA (Adeola et al., 2016), and three experimental diets including a corn diet, barley diet, and wheat bran diet. The corn diet contained 95.6% corn, and the barley diet contained 95.6% barley as the only source of AA. The wheat bran diet contained 50% wheat bran as the sole source of AA, along with 45.6% corn starch to enhance palatability. All ingredients were ground using the same mill with a 2.5 mm sieve, ensuring consistent particle size across all diets. The same grinding procedure was applied to all stages, so any potential particle size effect would not confound stage comparisons. The dietary composition and analyzed nutrient content are shown in **Tables 4-1 and 4-2**. The same feed formulation was applied for sows across all physiological stages. Chromium trioxide (Cr) was added to each diet at a level of 0.3% as an indigestible index. The minerals and vitamins were designed to meet or exceed the nutrient requirements as suggested (NRC, 2012). In the non-experimental period, sows were fed a standard commercial diet. Sows in gestation and post-weaning periods were individually housed in stainless-steel metabolism crates (1.80 m × 0.62 m × 1.30 m) that were equipped with a nipple drinker, and sows in the lactation period were transferred into the delivery rooms. Sows in gestation (57 ± 5 d) were fed 2.5 kg/day of the experimental diets, which were provided in two meals offered at 0800 and 1400 h. This feeding level was chosen to reflect common commercial practice, as gestating sows are typically limit-fed to control body condition and ensure optimal reproductive performance. Sows in lactation had free access to the experimental diet and water. Sows during the post-weaning period were divided into two feeding regimens: initially, they were fed ad libitum, followed by restricted feeding at 2.5 kg/day. The room temperature was maintained steadily at 22 ± 2 °C. Notably, while post-weaning sows are typically fed ad libitum in practice, a group of post-weaning sows in this experiment was subjected to restricted feeding to better assess the influence of feed intake and physiological stage on digestibility.

Table 4-1. Ingredient composition of experimental diets (%, as-fed basis)

Ingredient	Nitrogen-free diet	Barley diet	Wheat bran diet	Corn diet
Corn	-			95.60
Barley	-	95.60		
Wheat bran	-		50.00	
Corn starch	72.50		45.60	
Sucrose	15.00			
Cellulose acetic acid	4.00			
Soybean oil	3.00			
Monocalcium phosphate	2.32	1.50	1.50	1.50
Potassium carbonate	0.30			
Magnesium oxide	0.10			
Limestone	1.03	1.15	1.15	1.15
Salt	0.45	0.45	0.45	0.45
Chromium trioxide	0.30	0.30	0.30	0.30
Premix[1]	1.00	1.00	1.00	1.00
Total	100.00	100.00	100.00	100.00

[1] Premix supplied per kg of diet: vitamin A, 12075 IU; vitamin D_3, 2450 IU; vitamin E, 67 IU; vitamin K_3, 2.98 mg; vitamin B_1, 1.78 mg; vitamin B_2, 3.64 mg; vitamin B_6, 4.46 mg; vitamin B_{12}, 40 µg; Niacin, 42 mg; Calcium pantothenate, 25 mg; Folic acid, 6.92 mg; Biotin, 0.70 mg; Zn ($ZnSO_4{\cdot}H_2O$), 79 mg; Copper ($CuSO_4{\cdot}5H_2O$), 23 mg; Iron ($FeSO_4{\cdot}H_2O$), 150 mg; Cobalt ($CoCl_2$), 1.00 mg; Manganese ($MnSO_4{\cdot}H_2O$), 100 mg; Iodine ($Ca(IO_3)_2$), 0.23 mg; Selenium (Na_2SeO_3), 0.50 mg.

Table 4-2. Compositional analysis of experimental diets (%, as-fed basis)

Items	Nitrogen-free diet[1]	Experimental diets[2]		
		Barley diet	Wheat bran diet	Corn diet
Dry matter	90.48	88.88	89.31	90.01
Crude protein	0.75	9.03	8.70	8.20
Gross energy, MJ/g	15.99	15.65	15.91	16.29
Indispensable amino acids				
Arginine	-	0.75	0.57	0.31
Histidine	-	0.38	0.28	0.47
Isoleucine	-	0.30	0.35	0.25
Leucine	0.01	0.64	0.73	0.86
Lysine	0.03	0.50	0.48	0.35
Methionine	-	0.13	0.22	0.20
Phenylalanine	0.02	0.42	0.49	0.34
Threonine	0.03	0.29	0.56	0.41
Tryptophan	-	0.13	0.06	0.06

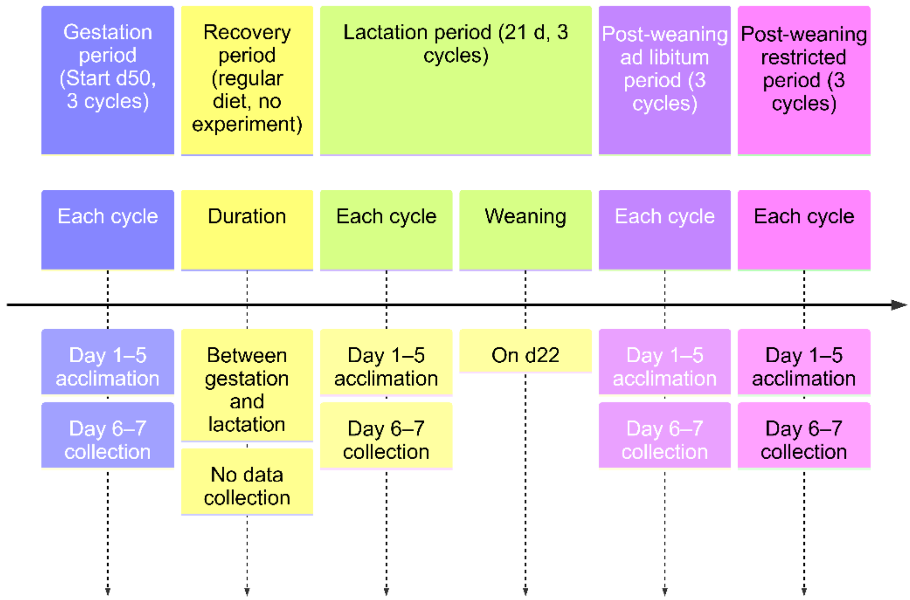
Items	Nitrogen-free diet[1]	Experimental diets[2]		
		Barley diet	Wheat bran diet	Corn diet
Valine	0.02	0.35	0.37	0.58
Dispensable amino acids				
Alanine	0.02	0.54	0.53	0.57
Aspartate	0.03	0.78	0.74	0.56
Cysteine	-	0.20	0.23	0.11
Glutamate	-	0.78	0.57	0.34
Glycine	0.08	2.37	3.06	1.51
Serine	0.01	0.45	0.50	0.32
Tyrosine	-	0.22	0.27	0.21

[1] Nitrogen-free diet, a cornstarch-based diet.
[2] Barley, wheat bran, and corn separately as the only source of amino acids in three test diets.

3.3. Sample collection

Every different stage (gestation, lactation, *ad libitum*-fed post-weaning, and restricted-fed post-weaning) included three periods, each period covering a 5-d acclimation to the diet and a 2-d sample collection period on the 6th and 7th day. Sows were weaned after the completion of the 21-d lactation trial, specifically on 22-d postpartum. The detailed experimental shcedule is shown in **Figure 4-1**. Ileal digesta samples were collected continuously for 12 h from 0700 to 1900 h in each experimental period. During each collection, plastic bags were attached to the T-cannula. The bags were replaced every 15 minutes when the ileal digesta was about to fill the plastic bags. Digesta samples were transferred into containers and frozen at -20°C immediately after collection. The collected digesta samples from each sow were naturally thawed for two days, then mixed evenly before being placed in a freeze-drying machine for drying. After grinding, measurements were conducted.

Figure 4-1. Timeline of the standardized ileal digestibility trial in sows



3.4. Chemical analysis and calculations

Dry matter (DM; method 930.15), crude protein (method 990.03), ether extract (EE; method 920.39), and crude ash (Ash; method 942.15) were analyzed as described previously in the literature (AOAC, 2007). Crude fiber (CF), neutral detergent fiber (NDF), and acid detergent fiber (ADF) were analyzed as described previously (Soest, 1991). Gross energy (GE) was assessed using an automatic oxygen and N calorimeter. We determined the content of AA using high-performance liquid chromatography (Dai et al., 2014). Chromium determination was performed using atomic absorption spectroscopy (Williams et al., 1962). Basal endogenous loss (BEL) was calculated from sows fed the N-free diet, and the AID and SID values of CP and AA were calculated according to the method (Stein et al., 2007).

The formula used for calculating AID was as follows: AID (%) = $[1 - (AA_{digesta}/AA_{diet}) \times (Cr_{diet}/Cr_{digesta})] \times 100$. The concentrations of AA and chromium (Cr) in ileal digesta were denoted as $AA_{digesta}$ and $Cr_{digesta}$, respectively (g/kg), while their concentrations in the diet were represented as AA_{diet} and Cr_{diet}, respectively (g/kg). The formula used for calculating ileal endogenous loss of AA (IAA_{end}) was: $IAA_{end} = (AA_{digesta}) \times (Cr_{diet}/Cr_{digesta})$. In which IAA_{end} referred to the ileal endogenous loss of AA expressed as grams per kilogram of DM intake. Concentrations of amino acids ($AA_{digesta}$) and chromium ($Cr_{digesta}$) in ileal digesta from pigs fed an N-free diet were measured and expressed in g/kg. The chromium content in the diet (Cr_{diet}) was expressed in g/kg DM. The IAA_{end} was referred to as nonspecific endogenous AA loss and was regarded as BEL of AA. The formula used for calculating SID was: SID (%) = AID + $(IAA_{end}/AA_{diet}) \times 100$.

3.5. Statistical analysis

All data analyses were performed using SAS 9.4 (SAS Inst. Inc., Cary, NC, USA). The normality of data distribution and the presence of outliers were assessed using the UNIVARIATE procedure. The main statistical analysis was conducted using PROC MIXED, with individual sows as the experimental units. Between different physiological phases, a variance analysis was performed using physiological phase as a fixed effect and sows and periods as random effects (Wang et al., 2023b). The LSMEANS statement was used to calculate the least squares means for each treatment, and statistical differences were separated by Tukey's multiple range tests. For all statistical analyses, significance was set at $P < 0.05$.

4. Results

4.1. Endogenous protein and AA losses in sows

The BEL of CP and AA are shown in **Table 4-3**. Compared to gestating sows, lactating sows exhibited a lower BEL of CP ($P < 0.01$). The BEL of AA in lactating sows (including Arg, Thr, Ala, Asp, Cys, Glu, Gly, Ser, and Tyr) was lower ($P < 0.05$) than that of gestating sows. When compared to ad libitum-fed post-weaning sows, gestating sows exhibited higher BEL of AA, with differences ($P < 0.05$) observed in Arg, Ala, Asp, Cys, Glu, Gly, Ser, and Tyr. Between gestating and restricted-fed post-weaning sows, no differences in AA losses were observed, except for Glu and Ser ($P < 0.05$). However, restricted-fed post-weaning sows displayed higher BEL compared to ad libitum-fed post-weaning sows, with differences in the BEL of His, Ile, Leu, Thr, Trp, and Cys ($P < 0.05$).

Table 4-3. Basal ileal endogenous losses (mg/kg dry matter intake) of crude protein and amino acids in primiparous sows[1]

Items	**Gestating sows**	**Lactating sows**	**Post-weaning sows**	**Post-weaning sows**	**SEM**	***P*-value**
	Restricted-fed	*Ad libitum* intake	*Ad libitum* intake	Restricted-fed		
Crude protein	16797[a]	6966[b]	11458[ab]	14254[ab]	1186	0.014
Indispensable amino acids						
Arginine	510[a]	197[b]	273[b]	403[ab]	57	0.004
Histidine	207[ab]	105[b]	130[b]	275[a]	25	0.007
Isoleucine	304[ab]	169[b]	185[b]	317[a]	37	0.008
Leucine	610[ab]	303[b]	333[b]	523[a]	51	0.003
Lysine	350[ab]	206[b]	235[ab]	467[a]	52	0.048
Methionine	83	71	85	157	20	0.062
Phenylalanine	307	179	196	274	36	0.096
Threonine	751[ab]	401[c]	459[bc]	1060[a]	95	< 0.001

Items	**Gestating sows**	**Lactating sows**	**Post-weaning sows**	**Post-weaning sows**	**SEM**	***P*-value**
	Restricted-fed	*Ad libitum* intake	*Ad libitum* intake	Restricted-fed		
Tryptophan	88[ab]	35[b]	47[bc]	95[a]	10	< 0.001
Valine	654	385	332	566	58	0.057
Dispensable amino acids						
Alanine	595[a]	308[b]	337[b]	459[ab]	42	0.003
Aspartate	1039[a]	478[b]	583[b]	724[ab]	56	< 0.001
Cysteine	287[a]	99[b]	121[b]	261[a]	25	< 0.001
Glutamate	1471[a]	657[b]	797[b]	876[b]	86	< 0.001
Glycine	1585[a]	526[b]	602[b]	1017[ab]	149	< 0.001
Serine	765[a]	275[b]	316[b]	454[b]	40	< 0.001
Tyrosine	257[a]	122[c]	144[bc]	219[ab]	16	0.002

[1] Each mean represents six observations for sows in different physiological stages (gestating, lactating, and post-weaning).

[a,b,c] Different superscripts indicate that means in the same row differ ($P < 0.05$).

4.2. Apparent ileal digestibility of primiparous sows

The AID of CP of barley in lactating sows had the lowest value but was not different from the other physiological states (**Table 4-4**). The AID of most AA of barley was not different in different physiological states, but the AID of His in gestating sows was higher than lactating and restricted-fed post-weaning sows ($P < 0.01$). The AID of Ile in restricted-fed post-weaning sows was lower than in gestating sows, lactating sows, and *ad libitum*-fed post-weaning sows ($P < 0.05$). The AID of Lys in gestating sows and *ad libitum*-fed post-weaning sows were higher than in restricted-fed post-weaning sows ($P < 0.01$). The AID of Thr in gestating sows was higher than in restricted-fed post-weaning sows ($P < 0.05$).

Table 4-4. Apparent ileal digestibility values for crude protein and amino acids in barley for gestating, lactating, and post-weaning primiparous sows

Items, %	**Gestating sows**	**Lactating sows**	**Post-weaning sows**	**Post-weaning sows**	**SEM**	***P*-value**
	Restricted-fed	*Ad libitum* intake	*Ad libitum* intake	Restricted-fed		
Crude protein	68.91	59.27	62.81	65.74	2.98	0.264
Indispensable amino acids						
Arginine	82.00	78.95	85.34	80.09	2.42	0.385
Histidine	87.02[a]	70.81[b]	77.50[ab]	69.88[b]	2.76	0.005
Isoleucine	77.70[a]	78.73[a]	77.48[a]	70.72[b]	1.54	0.021
Leucine	78.95	80.25	78.53	77.02	1.61	0.708
Lysine	80.01[a]	72.83[ab]	75.14[a]	65.03[b]	1.56	0.008
Methionine	85.51	81.16	81.34	77.75	1.85	0.094
Phenylalanine	81.15	80.28	79.55	78.50	1.64	0.812
Threonine	78.67[a]	72.01[ab]	71.46[ab]	61.31[b]	3.57	0.031
Tryptophan	78.34	74.84	68.71	70.45	2.89	0.261
Valine	70.47	70.55	76.40	66.21	3.80	0.394
Dispensable amino acids						
Alanine	75.58	69.94	77.34	74.12	1.83	0.165
Aspartate	71.53	66.32	74.80	74.09	1.97	0.061
Cysteine	74.87	77.90	80.34	75.81	2.20	0.431
Glutamate	86.35[b]	85.01[b]	87.83[ab]	89.52[a]	0.86	0.026
Glycine	66.98	60.03	66.95	66.23	4.25	0.693
Serine	74.57	74.50	79.86	76.62	2.22	0.355
Tyrosine	78.78	76.85	82.27	78.38	1.85	0.364

[a,b] means within a row with different letters differ significantly ($P < 0.05$) in different physiological stages.

No difference in the AID of CP in wheat bran was observed among gestating, lactating, and post-weaning sows (**Table 4-5**). The AID of Ile, Leu, Thr, Val, Ala, Asp, Glu, Gly, Ser, and Tyr in lactating sows was higher than in gestating sows ($P < 0.05$). For gestating sows compared to restricted-fed post-weaning sows, the AID value of Trp was higher, but Ala, Asp, Glu, and Ser were lower ($P < 0.05$). For lactating sows compared to ad libitum-fed post-weaning sows, the AID of most AA of wheat bran did not differ except for Val ($P < 0.05$). For lactating sows compared to restricted-fed post-weaning sows, the AID of most AA of wheat bran were not different except for Ile, Lys, and Thr ($P < 0.05$). For ad libitum-fed post-weaning sows compared to restricted-fed post-weaning sows, the AID of most AA of wheat bran was not different except for Thr ($P < 0.05$).

Table 4-5. Apparent ileal digestibility values for crude protein and amino acids in wheat bran for gestating, lactating, and post-weaning primiparous sows

Items, %	Gestating sows	Lactating sows	Post-weaning sows	Post-weaning sows	SEM	*P*-value
	Restricted-fed	*Ad libitum* intake	*Ad libitum* intake	Restricted-fed		
Crude protein	63.00	74.10	65.56	74.49	4.10	0.155
Indispensable amino acids						
Arginine	85.04	89.47	88.28	86.02	1.19	0.102
Histidine	83.09	86.71	81.70	81.49	1.97	0.274
Isoleucine	72.00^{b}	81.96^{a}	77.95^{ab}	72.68^{b}	1.90	0.009
Leucine	72.96^{b}	83.04^{a}	79.82^{ab}	78.10^{ab}	1.85	0.015
Lysine	75.97^{ab}	81.10^{a}	77.11^{ab}	70.34^{b}	2.38	0.039
Methionine	86.70^{a}	79.52^{ab}	75.44^{b}	72.19^{ab}	2.62	0.017
Phenylalanine	76.37	84.11	79.73	78.97	1.73	0.067
Threonine	55.34^{b}	71.33^{a}	71.22^{a}	50.12^{b}	2.88	<0.001
Tryptophan	78.39^{a}	72.65^{ab}	67.55^{ab}	64.99^{b}	2.66	0.021
Valine	62.30^{b}	74.33^{a}	62.23^{b}	67.61^{ab}	2.88	0.046
Dispensable amino acids						
Alanine	70.25^{b}	79.63^{a}	76.94^{a}	78.18^{a}	1.56	0.005
Aspartate	66.14^{b}	79.45^{a}	78.56^{a}	79.64^{a}	2.02	0.001
Cysteine	72.99	81.60	75.05	73.45	2.21	0.065
Glutamate	81.87^{b}	91.05^{a}	89.38^{a}	91.53^{a}	0.86	<0.001
Glycine	69.94^{b}	81.19^{a}	79.47^{a}	77.13^{ab}	1.70	0.003
Serine	63.18^{b}	81.13^{a}	79.72^{a}	80.52^{a}	1.71	<0.001
Tyrosine	70.82^{b}	81.23^{a}	75.06^{ab}	77.67^{ab}	1.83	0.010

[a,b] means within a row with different letters differ significantly ($P < 0.05$) in different physiological stages.

The AID of CP and most AA of corn was not different among different physiological states in **Table 4-6**; however, the AID of Arg in lactating sows was higher than in gestating sows and restricted-fed post-weaning sows ($P < 0.05$). The AID of Thr in gestating sows and lactating sows was higher than in restricted-fed post-weaning sows ($P < 0.01$). The AID of Trp in lactating sows was higher than in gestating sows and restricted-fed post-weaning sows ($P < 0.01$).

Table 4-6. Apparent ileal digestibility values for crude protein and amino acids in corn for gestating, lactating, and post-weaning primiparous sows

Items, %	Gestating sows	Lactating sows	Post-weaning sows	Post-weaning sows	SEM	*P*-value
	Restricted-fed	*Ad libitum* intake	*Ad libitum* intake	Restricted-fed		
Crude protein	63.78	65.57	64.64	63.86	4.11	0.989
Indispensable amino acids						
Arginine	66.06^{b}	77.10^{a}	69.14^{ab}	69.71^{b}	2.59	0.046
Histidine	79.40	82.30	83.74	85.49	2.15	0.503
Isoleucine	71.70	67.97	62.96	64.77	2.56	0.194
Leucine	82.10	81.55	83.10	78.62	2.09	0.537
Lysine	72.54	63.24	64.78	60.84	2.56	0.053
Methionine	85.06	83.72	82.34	82.11	2.64	0.875
Phenylalanine	76.53	74.34	72.52	70.60	1.70	0.185
Threonine	77.13^{a}	75.56^{a}	64.73^{ab}	51.34^{b}	4.18	0.002
Tryptophan	64.33^{b}	79.69^{a}	73.08^{ab}	65.89^{b}	2.22	<0.001
Valine	80.13	71.64	74.23	73.67	3.93	0.593
Dispensable amino acids						
Alanine	76.67	68.27	68.33	76.10	2.89	0.131
Aspartate	63.60	65.13	64.64	66.00	3.46	0.974
Cysteine	65.81	72.86	73.24	66.31	3.18	0.068
Glutamate	73.74	78.76	79.18	81.31	2.08	0.160
Glycine	48.44	52.10	60.63	50.97	4.16	0.238
Serine	61.03	62.05	65.89	63.21	3.87	0.861
Tyrosine	73.04	65.78	68.77	71.27	3.43	0.603

^{a,b} means within a row with different letters differ significantly (P < 0.05) in different physiological stages.

4.3. Standardized ileal digestibility of primiparous sows

The SID of CP and AA of barley were shown in **Table 4-7**. The SID of CP in gestating sows was higher than in lactating sows and ad libitum-fed post-weaning sows (P < 0.05). The SID of CP in restricted-fed post-weaning sows was higher than in lactating sows (P < 0.05). The SID of His in gestating sows was higher than in lactating sows and restricted-fed post-weaning sows, and the SID of Gly in gestating sows was higher than in lactating sows (P < 0.05). The SID of Asp and Glu in restricted-fed post-weaning sows was higher than in lactating sows (P < 0.05).

Table 4-7. Standardized ileal digestibility values for crude protein and amino acids in barley for gestating, lactating, and post-weaning primiparous sows.

Items, %	Gestating sows	Lactating sows	Post-weaning sows	Post-weaning sows	SEM	*P*-value
	Restricted-fed	*Ad libitum* intake	*Ad libitum* intake	Restricted-fed		
Crude protein	86.94^{a}	70.64^{c}	75.98^{bc}	82.13^{ab}	3.46	0.015
Indispensable amino acids						
Arginine	87.63	87.77	87.28	87.14	2.65	0.408
Histidine	92.47^{a}	81.18^{b}	80.50^{ab}	79.70^{b}	2.91	0.005
Isoleucine	85.17	84.72	81.60	79.71	1.75	0.408
Leucine	85.96	85.35	82.27	84.21	1.85	0.716
Lysine	85.61	70.19	79.52	74.78	1.95	0.098
Methionine	88.56	88.39	84.22	84.80	2.01	0.387
Phenylalanine	86.34	85.57	82.70	84.07	1.95	0.734
Threonine	92.22	83.47	77.92	77.31	3.11	0.062
Tryptophan	81.99	77.64	72.30	77.77	2.83	0.463
Valine	83.50	84.77	84.06	80.24	3.75	0.916
Dispensable amino acids						
Alanine	84.51	77.71	82.26	82.76	2.19	0.081
Aspartate	81.71^{ab}	73.39^{b}	80.80^{ab}	83.93^{a}	2.27	0.036
Cysteine	86.67	82.44	85.71	87.15	2.50	0.564
Glutamate	90.44^{ab}	88.79^{b}	89.67^{ab}	92.38^{a}	1.04	0.035
Glycine	90.00^{a}	74.16^{b}	74.60^{ab}	83.95^{ab}	5.17	0.025
Serine	87.43	80.62	84.95	85.74	2.34	0.298
Tyrosine	87.90	92.10	93.21	86.49	1.90	0.213

^{a,b} means within a row with different letters differ significantly ($P < 0.05$) in different physiological stages.

The SID of CP and AA of wheat bran were shown in **Table 4-9**. The SID of Glu, Ser, and Tyr in gestating sows were lower than in lactating sows ($P < 0.05$). The SID of Met and Trp in gestating sows was higher than in ad libitum access post-weaning sows, and the SID of Glu in gestating sows was lower than in restricted-fed post-weaning sows ($P < 0.05$). The SID of Val and Tyr in lactating sows was higher than in ad libitum access post-weaning sows ($P < 0.05$). The SID of AA in lactating sows showed no differences with those in restricted-fed post-weaning sows, and the SID of AA in restricted-fed post-weaning sows showed no differences with those in ad libitum access post-weaning sows.

Table 4-9. Standardized ileal digestibility values for crude protein and amino acids in wheat bran for gestating, lactating, and post-weaning primiparous sows.

Items, %	**Gestating sows**	**Lactating sows**	**Post-weaning sows**	**Post-weaning sows**	**SEM**	***P*-value**
	Restricted-fed	*Ad libitum* intake	*Ad libitum* intake	Restricted-fed		
Crude protein	86.94^{a}	70.64^{c}	75.98^{bc}	82.13^{ab}	3.46	0.015
Indispensable amino acids						
Arginine	87.63	87.77	87.28	87.14	2.65	0.408
Histidine	92.47^{a}	81.18^{b}	80.50^{ab}	79.70^{b}	2.91	0.005
Isoleucine	85.17	84.72	81.60	79.71	1.75	0.408
Leucine	85.96	85.35	82.27	84.21	1.85	0.716
Lysine	85.61	70.19	79.52	74.78	1.95	0.098
Methionine	88.56	88.39	84.22	84.80	2.01	0.387
Phenylalanine	86.34	85.57	82.70	84.07	1.95	0.734
Threonine	92.22	83.47	77.92	77.31	3.11	0.062
Tryptophan	81.99	77.64	72.30	77.77	2.83	0.463
Valine	83.50	84.77	84.06	80.24	3.75	0.916
Dispensable amino acids						
Alanine	84.51	77.71	82.26	82.76	2.19	0.081
Aspartate	81.71^{ab}	73.39^{b}	80.80^{ab}	83.93^{a}	2.27	0.036
Cysteine	86.67	82.44	85.71	87.15	2.50	0.564
Glutamate	90.44^{ab}	88.79^{b}	89.67^{ab}	92.38^{a}	1.04	0.035
Glycine	90.00^{a}	74.16^{b}	74.60^{ab}	83.95^{ab}	5.17	0.025
Serine	87.43	80.62	84.95	85.74	2.34	0.298
Tyrosine	87.90	92.10	93.21	86.49	1.90	0.213

^{a,b} means within a row with different letters differ significantly ($P < 0.05$) in different physiological stages.

The SID of CP and AA of corn were shown in **Table 4-10**. For gestating sows, the SID of Lys, Ala, and Gly was higher compared to lactating sows, and the SID of Ile, Lys, Phe, Thr, and Ala were higher compared to ad libitum-fed post-weaning sows ($P < 0.05$). Only the SID of Thr was higher in gestating sows than in restricted-fed post-weaning sows ($P < 0.05$). There were no significant differences in the SID value between lactating sows and restricted-fed or ad libitum-fed post-weaning sows.

Table 4-10. Standardized ileal digestibility values for crude protein and amino acids in corn for gestating, lactating, and post-weaning primiparous sows.

Items, %	**Gestating sows**	**Lactating sows**	**Post-weaning sows**	**Post-weaning sows**	**SEM**	***P*-value**
	Restricted-fed	*Ad libitum* intake	*Ad libitum* intake	Restricted-fed		
Crude protein	86.94[a]	70.64[c]	75.98[bc]	82.13[ab]	3.46	0.015
Indispensable amino acids						
Arginine	87.63	87.77	87.28	87.14	2.65	0.408
Histidine	92.47[a]	81.18[b]	80.50[ab]	79.70[b]	2.91	0.005
Isoleucine	85.17	84.72	81.60	79.71	1.75	0.408
Leucine	85.96	85.35	82.27	84.21	1.85	0.716
Lysine	85.61	70.19	79.52	74.78	1.95	0.098
Methionine	88.56	88.39	84.22	84.80	2.01	0.387
Phenylalanine	86.34	85.57	82.70	84.07	1.95	0.734
Threonine	92.22	83.47	77.92	77.31	3.11	0.062
Tryptophan	81.99	77.64	72.30	77.77	2.83	0.463
Valine	83.50	84.77	84.06	80.24	3.75	0.916
Dispensable amino acids						
Alanine	84.51	77.71	82.26	82.76	2.19	0.081
Aspartate	81.71[ab]	73.39[b]	80.80[ab]	83.93[a]	2.27	0.036
Cysteine	86.67	82.44	85.71	87.15	2.50	0.564
Glutamate	90.44[ab]	88.79[b]	89.67[ab]	92.38[a]	1.04	0.035
Glycine	90.00[a]	74.16[b]	74.60[ab]	83.95[ab]	5.17	0.025
Serine	87.43	80.62	84.95	85.74	2.34	0.298
Tyrosine	87.90	92.10	93.21	86.49	1.90	0.213

[a,b] means within a row with different letters differ significantly ($P < 0.05$) in different physiological stages

Table 4-11. Comparison of the standardized ileal digestibility mean value of gestating, lactating, and post-weaning with the values of NRC (2012) and nutrient requirements of swine (GB/T 39235-2020).

Items, %	Barley	Wheat bran	Corn	Barley		Wheat bran		Corn	
	This study[1]	This study[2]	This study[3]	GB/T	NRC	GB/T	NRC	GB/T	NRC
CP	77.72 ± 2.00	83.85 ± 2.09	79.54 ± 1.99	77	79	72	78	88	80
Indispensable amino acids									
Arginine	87.45 ± 1.44	91.77 ± 0.63	81.46 ± 1.34	82	85	88	90	84	87
Histidine	83.46 ± 2.00	87.86 ± 1.09	85.65 ± 1.86	86	81	91	76	85	83
Isoleucine	82.80 ± 1.11	82.47 ± 1.16	76.17 ± 1.76	83	79	82	75	77	82
Leucine	84.45 ± 1.05	85.55 ± 1.15	86.21 ± 1.12	86	81	86	73	86	87
Lysine	77.53 ± 1.57	83.59 ± 1.35	73.92 ± 1.70	82	75	80	73	69	74
Methionine	86.49 ± 0.99	85.92 ± 1.73	88.11 ± 1.41	74	82	86	72	90	83
Phenylalanine	84.67 ± 1.11	85.68 ± 1.13	80.21 ± 1.12	86	81	82	83	85	85
Threonine	82.73 ± 1.95	81.38 ± 1.47	81.97 ± 2.82	80	76	63	64	71	77
Tryptophan	77.43 ± 2.04	78.94 ± 1.68	84.02 ± 1.16	79	82	79	73	63	80
Valine	83.14 ± 2.28	79.37 ± 2.00	83.44 ± 2.44	79	80	68	79	77	82
Dispensable amino acids									
Alanine	81.81 ± 1.46	83.34 ± 0.93	79.51 ± 2.08	77	73	74	58	78	81
Aspartate	79.96 ± 1.60	84.74 ± 1.26	76.77 ± 1.91	78	75	76	66	74	79
Cysteine	85.49 ± 1.26	85.75 ± 1.24	85.33 ± 1.67	84	81	80	77	81	80
Glutamate	90.32 ± 0.72	92.10 ± 0.71	84.06 ± 1.11	86	87	88	84	83	84
Glycine	80.68 ± 2.68	88.58 ± 1.05	76.29 ± 2.54	76	82	68	67	69	84
Serine	84.69 ± 1.50	85.56 ± 1.22	76.58 ± 2.24	78	80	79	73	79	82
Tyrosine	89.93 ± 1.24	87.07 ± 1.40	82.10 ± 2.07	87	78	89	56	92	79

[1] Standard error of the mean of barley in the different physiological periods.

[2] Standard error of the mean of wheat bran in the different physiological periods.

[3] Standard error of the mean of corn in the different physiological periods.

5. Discussion

To our knowledge, only Stein et al. (1999a) reported AID values for CP and AA of barley, and corn across different physiological stages of sows, such as gestation, and lactation. In our study, the AID of CP and most AA in barley fed to gestating sows and lactating sows was higher or similar to those reports (Stein et al., 1999a; Zhang et al., 2024). Conversely, the AID of CP and most AA in corn fed gestating sows were lower compared to Stein et al.'s findings, except for Lys, Phe, Thr, and Val. For corn fed to lactating sows, the AID of CP and certain AA (Ile, Lys, Phe, Thr, Val, Cys, and Gly) was lower than those reported in Stein et al.'s research, whereas for the other AA, these values were higher (Stein et al., 1999a). Unfortunately, we did not find any data on AID values for wheat bran in sows. It is noteworthy that the current study focused on primiparous sows, whereas Stein et al.'s earlier investigations did not specify the parity of the sows used, which hinders the comparability of results. Additionally, several factors may influence AID values, such as variations in the feed ingredients, the physiological status of the sows, and differences in feed intake levels (Moter and Stein, 2004).

The AID and SID data currently provided in the NRC (2012) are based on growing pigs. In our study, the mean AID values of most AA in barley and wheat bran across different physiological stages of sows (gestating, lactating, and post-weaning) were generally similar to or higher than those reported in the NRC (2012). Likewise, when compared to the data from growing-finishing pigs by Zhang et al. and Stein et al., the mean AID values for most AA in barley for sows at various physiological stages were also higher (Stein et al, 1999b; Zhang et al., 2024). For corn, the mean AID values for Arg, Ile, Phe, Gly, and Ser were lower across different physiological stages of sows compared to the NRC (2012) values, whereas Met and Trp were higher, and other AA were similar (NRC, 2012). The higher AID of AA for barley and wheat bran in gestating and restricted-fed post-weaning sows compared to growing pigs can be attributed to their more efficient digestive system and larger, more developed gastrointestinal tract (Bridges et al., 1986). The increased intestinal volume in sows may result in a longer residence time for digesta, allowing for greater nutrient absorption (Varel, 1987). In lactating and ad libitum-fed post-weaning socws, the higher AID values of AA for barley and wheat bran compared to growing pigs can also be due to different feed intake levels. Previous studies have suggested that feed intake has limited or no direct effects on AID (Sauer et al., 1982; Haydon et al., 1984; Albin et al., 2001). However, other studies have indicated that increased feed intake, particularly in lactating sows under ad libitum feeding conditions, may influence AID indirectly. For example, Stein et al. (1999b) observed that higher feed intake may reduce the relative contribution of endogenous IAAend, thus leading to an apparent increase in AID values. Similarly, Moter and Stein (2004) reported that higher dietary AA concentrations decrease the proportion of IAAend in the digesta, resulting in higher AID values, while lower AA levels may lead to reduced AID.

In the present study, we compared the effects of physiological differences on the AID of AA in barley, wheat bran, and corn. For wheat bran, the AID value of most AA (Ile, Leu, Thr, Val, Ala, Asp, Glu, Gly, Ser, and Tyr) in lactating sows was higher than that in restricted-fed gestating sows. Moter and Stein (2004) demonstrated that such increases in AID with rising feed intake are partially due to a reduced contribution of IAAend to the total outflow at higher feed intakes. As feed intake increases, the proportion of IAAend decreases, resulting in higher AID estimates. Although differences in feed intake may contribute to the observed variation, other physiological factors associated with lactation, such as increased body weight and digestive capacity, are likely to be the factors of improved AA digestibility (Stein et al., 1999b; Moter and Stein, 2004). Regarding barley and corn, no differences were observed with varying intake levels, likely due to the high fiber content in wheat bran. Piel et al. indicated that fiber content can alter the viscosity and passage rate of digesta, thereby affecting endogenous AA losses (Piel et al., 2005). However, there is a lack of research on how cellulose levels influence the determination of basal IAAend. For barley and corn, the AID value of most AA showed no differences across physiological stages. However, during the gestating period, sows had higher AID values in barley for His, Lys, and Thr, and higher values for Lys and Thr in corn compared to restricted-fed non-pregnant sows. Zhuo et al. and Wang et al. also observed differences in AID values between gestating and non-pregnant sows for cottonseed meal and soybean meal (Wang et al., 2023; Zhuo et al., 2023). To date, very few studies have elucidated the mechanisms underlying the physiological differences in nutrient digestibility between pregnant and non-pregnant sows. Changes in sex hormones, as well as alterations in the gut microbiota and intestinal permeability, may be factors affecting these differences (Yeo et al., 2022).

To more effectively illustrate that the SID values obtained in this study are within a reasonable range, we compare the mean SID values of the three feed ingredients across various physiological stages of sows with the corresponding values reported in NRC (2012) and the nutrient requirements of swine (GB/T 39235-2020), as presented in **Table 4-11**. In the current study, the SID value of CP and most AA in barley and corn for primiparous sows (gestating, lactating, and post-weaning) was similar to the SID values reported by Stein et al. for gestating and lactating sows (Stein et al., 2001). This suggests that parity may not significantly affect the SID values for barley and corn, indicating that both multiparous and primiparous sows could utilize the same SID values. In our results, we compared the SID values for barley in restricted-fed gestating sows with those of ad libitum-fed lactating sows, as well as with those from non-pregnant sows in the post-weaning phase, both undergoing feed restriction or fed ad libitum. Differences were only observed in the SID of His for barley when comparing restricted-fed gestating and post-weaning sows. No differences were found between lactating and non-pregnant sows under ad libitum feeding conditions. This aligns with Stein et al.'s conclusion that the physiological stage does not affect most SID values for barley, and Stein et al.(2001) stated that lactating sows and growing pigs can share the same SID values under the same diets and ad libitum feeding conditions (Stein et al., 2001). When comparing our barley's average SID values across different physiological stages with Spindler et al.'s SID values for growing pigs, only CP and certain AA (Ile, Phe, Trp, and Ser) exhibited differences exceeding 5%. This may be attributed to variations in research methodologies, as Spindler et al. employed regression analysis (Spindler et al., 2016). These observations suggest that the SID values for barley may apply to growing pigs, as well as to both primiparous and multiparous sows across different physiological stages, provided that the diets and feeding conditions are similar. In our experiment, we found that corn has a higher SID for certain AA during gestation compared to lactation, ad libitum post-weaning period, and restricted-fed post-weaning period. With little difference in AID, this variation is mainly related to differences in endogenous N loss. Furthermore, Wang et al. indicated that different physiological stages of sows did not affect the SID of CP and most AA in extruded full-fat soybeans (Wang et al., 2023c). However, Zhuo et al. noted that for cottonseed meal, most SID values of AA were differentially affected by the physiological phase (Zhuo et al., 2023). This suggests that the different feed ingredients may result in varying effects of physiological stages on SID values.

To our knowledge, this study is the first to publish SID values for wheat bran in sows across different physiological stages. Our experimental results showed that some SID values for wheat bran in lactating sows were higher than those in gestating sows, with Glu, Ser, and Tyr showing significant differences. This suggests that sows during lactation may exhibit higher digestibility for certain AA. Rapeseed or canola, which also contains a high fiber content, showed similar results as Deepak et al. found that the SID values of certain AA in canola for lactating sows were greater than in gestating sows, despite the higher feed intake (Velayudhan et al., 2019). Tiwari et al. noted differences in the in vitro digestibility of starchy and fibrous feedstuffs (Tiwari et al., 2022). Wang et al. found that extruded full-fat soybeans with relatively higher levels of NDF and crude fiber tended to have lower SID values for AA (Wang et al., 2023c). High fiber content can hinder the binding of proteases to proteins, negatively affecting protein digestion (Dégen et al., 2007; Li et al., 2021). Casas et al. (2022) demonstrated that lactating sows have greater digestibility of CF than gestating sows, which may partly explain the elevated SID values observed during lactation.

Additionally, this study compared the BEL of AA in gestating, lactating, ad libitum-fed post-weaning, and restricted-fed post-weaning sows. Endogenous nitrogen loss (ENL) encompasses nonspecific ENL and specific ENL, which mainly include digestive enzymes, mucin protein, sloughed intestinal epithelial cells, and bacterial protein. Nonspecific ENLs are regarded as BEL (Adeola et al., 2016). Nyachoti et al. (1997) indicated that primary factors influencing ENL include DM intake, body weight, and age. Mariscal-Landín et al. found that pigs of 48 kg had significantly higher ENL at a DM intake of about 60 g/kg metabolic body weight compared to 39 kg pigs consuming about 70 g/kg metabolic body weight (Mariscal-Landín et al., 1995). Wang et al. found that BEL is negatively correlated with feed intake, with higher feed intake levels associated with lower BEL (Wang et al., 2023b). Overall, the BEL observed in gestating sows totaled 16.8 g/kg DM intake, comparable to the 17.8 g/kg DM intake reported by Stein et al., with similar levels of AA losses (Stein et al., 1999a). However, our findings on BEL during gestation were higher than those reported by Wang et al. for the same stage (Wang et al., 2023b), likely due to feed intake differences, as our restricted feeding provided 2.5 kg/day compared to Wang et al.'s 3.0 kg/day. In lactating sows, BEL was lower than that previously reported by Stein et al., likely due to differences in sow body weight and feed intake. Our findings during both gestation and lactation were also lower than those reported by Velayudhan et al., yet aligned with the results by Li et al. and Wang et al. These discrepancies may result from differences in methodologies used to measure BEL, particularly regarding whether casein was included in the N-free diet (Velayudhan et al., 2019; Wang et al., 2023c; Li et al., 2024). Notably, Adeola et al. demonstrated that including casein in the diet elevates endogenous AA losses (Adeola et al., 2016). In our study, primiparous sows exhibited higher BEL during gestation compared to lactation, with higher losses in restricted-fed post-weaning sows than in their ad libitum-fed counterparts. The similarity in BEL during lactation and post-weaning periods aligns with expected feed intake variations in feed intake. Additionally, our findings on BEL in primiparous sows are comparable to those reported for multiparous sows, suggesting minimal differences in BEL between primiparous and multiparous sows (Stein et al., 1999b; Wang et al., 2023c).

6. Conclusion

Our experimental results provide AID and SID values for CP and AA in barley, wheat bran, and corn for primiparous sows at different physiological stages (gestation, lactation, and post-weaning phase). The current findings provided a cornerstone for the precise use of barley, wheat bran, and corn in primiparous sows' diets. Based on the current findings in the present study, we can indicate that similar SID values can be used for barley in different physiological stages of primiparous sows under the same diet and feed regime. However, for wheat bran, which has a high fiber content, lactating sows show higher AID and SID values for certain AA. For corn, which has a low fiber content, gestating sows exhibited higher SID values compared to lactating sows and ad libitum post-weaning sows. This indicates that differences in fiber content among feed ingredients may lead to variation in the AID and SID of AA and protein across different physiological stages of sows.

Chapter V

General discussion, perspectives and conclusion

1. Stage-dependent differences in nutrient digestibility and energy utilization in sows

Previous studies have demonstrated that significant differences in energy values and nutrient utilization occur as sows transition from gestation to lactation and subsequently to the post-weaning stage. These differences are likely associated with stage-related changes in metabolic demand, feeding patterns, endocrine regulation, and gastrointestinal function (Noblet and Shi, 1994; Koren et al., 2012; Ji et al., 2019; Liu et al., 2019). By comparing the digestibility of nutrients and energy values in corn, barley, and wheat bran across different physiological stages, the present PhD research further confirms and extends these observations. The results indicate that physiological stage regulates the ability of sows to extract nutrients from the ingredients, suggesting that digestive capacity itself exhibits stage dependency. It is important to distinguish digestibility from absorption. Digestibility measures nutrient disappearance from the gut, which includes both degradation and absorption; absorption is the actual entry into blood. Ad libitum feeding accelerates digesta passage, reducing digestibility but often increasing total absorbed nutrients due to higher intake. For lactating sows, ad libitum feeding is necessary to meet energy demands despite lower digestibility; for gestating sows, restricted feeding controls body condition. Thus, we do not reject ad libitum feeding entirely, but recommend stage-specific strategies. The observed stage effects reflect both physiological changes and different feeding levels (gestation: restricted; lactation/post-weaning: ad libitum). This feeding strategy mirrors commercial production practices, where sows are restrictively fed during gestation to control body condition and allowed ad libitum access during lactation and the post-weaning period to meet high nutrient demands. Therefore, the digestibility values determined under these conditions are directly applicable to practical feeding scenarios. This finding has important practical implications. In current feeding systems, due to the lack of stage-specific digestibility data for sows, nutrient digestibility is often assumed to remain relatively constant across physiological stages, and uniform reference coefficients are applied. However, such a static assumption may lead to imprecise diet formulation or inefficient feed resource utilization under production conditions.

In the present PhD research, lactating sows exhibited greater digestibility of certain nutrients, such as NDF, compared with post-weaning sows, and this trend was more pronounced in high-fiber ingredients such as wheat bran. This observation raises a key question: why would digestive efficiency increase during lactation, the stage with the highest nutritional demand? We speculate that this may represent a compensatory adaptive response to elevated metabolic load. Lactation is the most energetically demanding phase of the reproductive cycle. When voluntary feed intake is insufficient to fully meet the nutrient requirements for milk synthesis, enhancing dietary nutrient utilization may serve as a physiological mechanism to maintain maternal homeostasis and support piglet growth.

Recent studies provide possible mechanistic explanations for this phenomenon. First, gut microbiota and their fermentation products may play an important role. Feeding high-fiber diets during lactation has been reported to increase the relative abundance of beneficial bacterial families, such as *Prevotellaceae, Ruminococcaceae*, and *Lachnospiraceae*, which are key taxa involved in fiber degradation and short-chain fatty acid (SCFA) production (Wang et al., 2025). Liu et al. (2019) compared Rongchang and Landrace sows during gestation and lactation and found that the lactation period was strongly associated with an increase in SCFA-producing bacteria and elevated SCFA concentrations. Using an *in vitro* fermentation model, Tiwari et al. (2022) compared the effects of starch- and fiber-based substrates on swine gut microbiota and reported that starch primarily enriched functionally similar microbial groups, whereas fiber, due to its structural complexity, induced greater microbial diversity. Although they found that total SCFA production was lower with fiber than with starch, fiber promoted the proliferation of specific fiber-degrading bacteria and altered hindgut microbial community structure (Tiwari et al., 2022). A comprehensive review by Wang et al. (2020) summarized the interactive mechanisms between swine gut microbiota and host nutrient metabolism, highlighting that SCFAs not only serve as energy substrates but also regulate host energy metabolism through activation of G-protein – coupled receptors (GPR41/43) and inhibition of histone deacetylases (HDAC), and may influence feeding behavior via the microbiota–gut–brain axis. SCFAs may therefore enhance energy recovery from carbohydrates, particularly dietary fiber, while also contributing to intestinal barrier integrity and reduced local inflammation, thereby potentially improving nutrient absorption efficiency.

Further research has described dynamic changes in fecal microbiota and SCFA concentrations in sows from early gestation to weaning, showing that *Prevotella* predominated during gestation, whereas fiber-degrading taxa such as *Eubacteriaceae* and *Lachnospiraceae* became dominant during lactation (Sui et al., 2025). Palumbo et al. (2024) demonstrated that improved utilization of fibrous diets during lactation is associated with enhanced hindgut fermentation capacity, as evidenced by increased ATTD of NDF, ADF, and energy values, along with shifts in fecal microbial community structure and increased butyrate and valerate proportions. Collectively, these findings suggest that the succession of microbial populations during lactation, characterized by fiber-degrading bacteria, may enhance SCFA production efficiency and contribute to improved nutrient utilization at this stage. Although microbial parameters were not directly measured in the present PhD, the observed greater increase in digestibility for high-fiber ingredients compared with low-fiber ingredients during lactation is consistent with the proposed enhancement of fermentation capacity. In the present PhD study, digestibility of wheat bran increased more markedly than that of corn during lactation, supporting the notion that enhanced fermentation requires sufficient fiber substrate to translate into measurable improvements in digestibility. However, a methodological caveat should be noted: the NDF system, originally designed for ruminants, measures only insoluble cell wall components and completely loses soluble fibers such as β-glucans and pectins. In monogastric sows, these soluble fractions are physiologically important, they increase digesta viscosity and serve as readily fermentable substrates for hindgut microbiota (Bach Knudsen, 2001). Therefore, the higher NDF digestibility observed during lactation in the present study may only reflect improved utilization of insoluble fiber, while the contribution of soluble fibers to enhanced fermentation remains analytically invisible but potentially substantial. This suggests that relying solely on NDF may underestimate the true extent of stage-related improvements in fiber utilization.

It is noteworthy that this enhancement in hindgut fermentation during lactation appeared more pronounced in multiparous sows. In this PhD we showed that multiparous sows exhibited greater EE digestibility of barley and wheat bran across all physiological stages compared with primiparous sows. Multiparous sows are reported to possess a more mature gut microbial community and greater pancreatic secretory capacity (Charbonneau et al., 1982; Owsley et al., 1986; Zhang et al., 2024), which may allow them to better utilize the digestive advantages associated with enhanced fermentation during lactation. Starch structural properties of the corn sample were not characterized. Corn varieties differ markedly in amylose-to-amylopectin ratio, ranging from ~0% in waxy corn to >50% in high-amylose varieties (Bhatty, 1999). This ratio determines starch crystallinity and susceptibility to α-amylase: high-amylose starch resists enzymatic hydrolysis, slowing digestion kinetics, whereas high-amylopectin starch is rapidly hydrolyzed. Given the stage-dependent differences in feed intake and digesta passage rate, starch composition may modulate the magnitude of the observed stage-related effects.

Compared with ATTD, ileal AA digestibility responded less consistently to physiological stage. After correction for basal endogenous losses, differences between non-pregnant and lactating sows were often attenuated or even disappeared. These findings suggest that hindgut microbial fermentation may play a more prominent role in stage-related differences in total tract nutrient utilization, whereas AA digestibility appears to depend more directly on small intestinal enzymatic digestion, which may be less sensitive to physiological stage per se. Stein et al. (2001) compared SID among growing pigs, gestating sows, and lactating sows and reported that gestating sows (limit-fed) exhibited greater SID for certain ingredients than growing or lactating pigs (ad libitum-fed), concluding that feed intake level rather than physiological state was likely responsible. This suggests that intake level may mask or attenuate true stage effects on AA digestibility.

Overall, Mechanistically, the plasticity of small intestinal enzymatic digestion may be lower than that of hindgut microbial fermentation. Zhang et al. (2016), using a lactating hamster model, reported increased activities of small intestinal enzymes (maltase, sucrase, and aminopeptidase) during peak lactation, indicating some capacity to upregulate digestive function under elevated energy demand. However, the magnitude of this response was limited and was influenced by species, diet composition, and energy balance. In this PhD, high-fiber ingredients such as wheat bran showed certain stage-related differences in SID, consistent with findings in canola meal and other fibrous ingredients (Velayudhan et al., 2019). Potential mechanisms may include increased endogenous AA losses due to altered digesta viscosity and passage rate (Piel et al., 2005; Jo et al., 2023), as well as reduced protease–substrate contact caused by the physical barrier effect of fiber (Dégen et al., 2007; Li et al., 2021). These effects may be amplified or attenuated across physiological stages as feed intake and digesta flow change. Nevertheless, after correcting for basal endogenous losses, these differences remained limited and were substantially smaller than the effects attributable to hindgut fermentation.

Taken together, the present findings suggest that stage-related differences in digestive capacity across the reproductive cycle are closely associated with changes in hindgut microbial function. The increased ATTD observed during lactation may reflect an adaptive response to high metabolic load, potentially involving restructuring of the gut microbiota and enhancement of fermentation capacity to maximize utilization of fibrous feed components. In contrast, stage-related changes in SID appear to be more closely linked to fiber-associated effects on digesta kinetics and protease–substrate interactions. These results challenge the assumption of static digestibility coefficients in conventional nutritional models and provide theoretical support for developing dynamic, stage-specific feeding strategies that account for diet–host interactions.

2. Differences in nutrient digestibility between sows and growing pigs: implications for current feeding standards

The energy values and AA digestibility values adopted in current feeding standards, such as NRC (2012), are primarily derived from studies conducted in growing pigs. However, sows differ systematically from growing pigs in intestinal morphology, physiological status, and microbial community structure. Therefore, directly applying digestibility data obtained from growing pigs to sow diet formulation may introduce potential bias. Although this PhD study did not directly compare sows and growing pigs, comparisons with reference values from feeding standards, together with evidence from recent comparative studies, may provide supportive context for this concern.

Several studies have systematically compared digestibility between adult sows and growing pigs, and the results indicate that the differences are ingredient-specific. Le Goff and Noblet (2001) reported that adult sows generally exhibited greater ATTD of GE, CP, EE, and NDF than growing pigs, and that the magnitude of the difference increased as dietary fiber content increased, suggesting a potentially greater hindgut fermentation capacity in sows. More recently, Lei et al. (2025) reported no significant differences in SID of AA between gestating sows and growing pigs when soybean meal (low fiber) was fed; however, for high-fiber ingredients such as distillers dried grains with solubles (DDGS), rapeseed meal, and cottonseed meal, gestating sows exhibited 5% to 8% greater SID for most AAs. The same study also detected significantly greater chymotrypsin activity in gestating sows than in growing pigs, with the highest trypsin activity observed in the rapeseed meal treatment group, suggesting that enhanced enzymatic activity in sows may be one of the underlying mechanisms. Similarly, Kim et al. (2025) observed comparable patterns in energy studies: lactating sows exhibited significantly greater DE of soybean hulls (high fiber) than growing pigs, whereas no significant difference was observed for soybean meal (low fiber). Furthermore, a study focusing on DDGS evaluated SID values of seven DDGS sources across different physiological stages of sows and found that, compared with NRC values for growing pigs, sows exhibited 6% to 12% greater SID of AA (Wang et al., 2025b). The coefficients of variation for NDF and ADF among DDGS sources exceeded 24%, further highlighting the ingredient-specific nature of digestibility values.

In this PhD, the mean AID and SID of most AAs in barley and wheat bran across physiological stages, as well as the DE and ME values of the three ingredients, were numerically slightly higher than the reference values reported for growing pigs in NRC and Chinese feeding standards. It should be emphasized that cross-study comparisons are inherently limited, as factors such as genotype, feed source, methodology, and genetic progress may affect comparability. Therefore, these comparisons should be interpreted cautiously and considered as reference information only.

However, these comparative findings suggest that sows may exhibit a digestive advantage for certain ingredients, which could potentially be attributed to several physiological characteristics. First, intestinal maturity may play an important role. Compared with growing pigs, adult sows have a longer and larger gastrointestinal tract, resulting in prolonged digesta retention time (Bridges et al., 1986). Such morphological differences may allow more time for enzymatic hydrolysis and microbial fermentation, particularly for fiber fractions that require extended retention for degradation, thereby creating more favorable hindgut fermentation conditions in adult sows (Varel, 1987). This may partly explain why digestibility differences between sows and growing pigs are more pronounced for fibrous ingredients. Second, the structure and stability of intestinal microbiota appear to increase with age. Park et al. (2025) reported that adult sows exhibited greater microbial network complexity, whereas growing pigs showed microbial communities more focused on energy metabolism pathways. A more complex and stable microbial structure may imply greater fiber degradation capacity and more efficient SCFA production in adult sows. In addition, sows may exhibit greater digestive enzyme activity. Lei et al. (2025) reported significantly greater chymotrypsin activity in gestating sows than in growing pigs, with the highest trypsin activity observed in the rapeseed meal treatment group. These results suggest that sows may possess not only more mature intestinal structures but also potentially enhanced pancreatic secretory function, thereby improving the efficiency of protein digestion. Notably, this enzymatic advantage also appears to be ingredient-specific, being evident in high-fiber ingredients such as DDGS and rapeseed meal, but not in low-fiber ingredients such as soybean meal further suggesting that fiber components may be an important factor amplifying these differences.

In summary, differences in digestibility between sows and growing pigs may result from the combined effects of intestinal morphology, microbial structure, and digestive enzyme activity. A longer gastrointestinal tract may provide greater space and retention time for microbial fermentation, a more mature microbial community may enhance fermentation efficiency, and greater enzymatic activity may support efficient foregut digestion, together potentially contributing to the digestive advantage of sows. These observations suggest that directly applying digestibility data derived from growing pigs to sow diet formulation in current feeding standards may lead to misestimation of the true digestive capacity of sows. This practice may underestimate the utilization potential of fibrous ingredients and possibly overestimate certain nutrient requirements, thereby leading to unnecessary feed resource use. Establishing an independent digestibility database for sows, and systematically evaluating the effects of physiological stage, parity, and ingredient characteristics on nutrient digestibility, may therefore be a necessary step toward achieving precision nutrition in sow feeding programs.

3. Limitations

Although the present study provides important reference data on nutrient digestibility in sows, several limitations should be considered when interpreting the results.

First, aspects of the experimental design may influence the generalizability of the findings. A single sow breed was used under controlled environmental conditions, and only one batch of each ingredient was evaluated. While this level of control ensured internal comparability of the results, variation in ingredient type, sow genotype, environmental conditions, individual variability, and batch-to-batch differences in feed ingredients may all contribute to fluctuations in digestibility values. However, these factors also represent inherent sources of variation within databases such as those used by NRC and other feeding standards. Nevertheless, caution should be exercised when extrapolating the present results to other breeds or production systems. Future studies may benefit from including multiple sow breeds and multiple ingredient batches to enhance the representativeness and robustness of the data.

Second, in the determination of energy values and nutrient ATTD, the present PhD employed the difference method, in which 50% of the basal diet was replaced with the test ingredient. A limitation of this approach is that a single, relatively high substitution level was used; although this level was chosen to maximize the detection of stage-related differences, multiple substitution levels across different test ingredients would have provided a more robust dose-response assessment. In addition, the digestibility of the test ingredient is calculated indirectly by mathematically separating the contribution of the basal diet, which may yield values that differ slightly from those obtained using the total substitution method. Furthermore, the test diets were not formulated to be isoenergetic, which may have influenced feed intake patterns; however, digestibility coefficients were calculated based on actual feed intake, allowing valid stage-wise comparisons under the defined experimental conditions. Although such differences are generally considered to be relatively small and are unlikely to affect the directional interpretation of physiological stage effects observed in this study, methodological differences should nevertheless be taken into account when making numerical comparisons with other studies.

Third, the digestibility and metabolism experiments on primiparous and multiparous sows were not performed at the same time. Ideally, both parity groups should be tested simultaneously to avoid potential confounding effects of time, season, or animal batch (Rivera Ferre et al., 2001). Although all sows were housed under similar conditions and fed the same diet batches, the lack of simultaneous comparison remains a limitation when interpreting parity effects in this study. Moreover, multiparous sows in this study covered a range of parities (up to high numbers). Differences between younger (e.g., parity 2) and older (e.g., parity 5) sows, such as gastrointestinal transit time or microbiota composition may exist but were not specifically examined (Bu et al., 2024). Both factors should be considered as limitations when interpreting parity-related results in this PhD.

The difference in feeding regime (restricted feeding for gestating sows vs. ad libitum feeding for lactating sows) could be considered a confounding factor when comparing digestibility across physiological stages. However, It should also be noted that, in the determination of standardized ileal digestibility, feed intake levels in the present PhD study were maintained within the normal physiological range for sows. Wang et al. (2023b) reported that, within typical intake ranges, variations in feed intake did not significantly affect AID or SID of AAs in sows. Therefore, differences in feed intake among physiological stages were unlikely to be the primary drivers of the stage-related changes in digestibility observed in this PhD, and thus do not compromise the reliability of the core conclusions.

Despite the limitations described above, this PhD represents a systematic exploratory evaluation of the energy values and digestibility of corn, barley, and wheat bran in primiparous and multiparous sows across different physiological stages. The stage-specific digestibility data generated herein may serve as foundational reference information for the development of a sow-specific feed ingredient database, thereby providing data support for gradually reducing reliance on digestibility values derived from growing pigs.

4. Perspectives

Building upon these findings, future research directions can be outlined to refine sow feed ingredient evaluation, elucidate underlying mechanisms, and further optimize precision feeding strategies.

The results of the present thesis provide experimental evidence that nutrient digestibility and energy utilization of corn, barley, and wheat bran in sows vary across physiological stages, and that the magnitude of these differences is influenced by feed ingredient characteristics, with more pronounced stage-dependent responses observed for fiber-rich ingredients. These findings highlight that nutrient values determined under a single physiological stage or standardized feeding level may not adequately represent actual production conditions. Therefore, future research should systematically evaluate a broader range of feed ingredients across physiological stages under practical feeding regimes, in order to generate stage-specific digestibility coefficients. Such efforts would contribute to the establishment of a more refined, physiological stage-specific nutritional value database for sow feed ingredients, thereby providing a stronger scientific basis for precision feeding strategies in sow nutrition. Looking forward, a strategic priority lies in the development of a multi-dimensional sow feed database that incorporates not only physiological stage but also parity, ingredient type, and fiber characteristics. Such a database would enable dynamic, stage-specific nutrient modeling and support the transition toward precision nutrition in sow feeding programs. Integrating these data with predictive algorithms or machine learning approaches could further enhance the accuracy and adaptability of diet formulation under diverse production conditions.

The precision nutrition approach advocated here, using stage-specific digestibility coefficients rather than generic values derived from growing pigs or a single physiological stage, helps align nutrient supply more closely with the sow’s actual digestive capacity. Even when the observed differences among physiological stages are modest, feeding based on mismatched reference values (e.g., from growing pigs) can lead to systematic overfeeding of N and phosphorus, because the latter do not fully account for changes in digestive function across gestation, lactation, and post-weaning periods. By improving the accuracy of digestibility estimates for each stage, the risk of excess nutrient supply is reduced, which in turn lowers fecal N and P excretion. Although our study did not include a direct side-by-side comparison of sows and growing pigs under the same experimental conditions, we compared our sow digestibility data with NRC values for growing pigs. This comparison suggests that using stage-specific values is necessary to avoid unintended overfeeding. These findings provide preliminary evidence that stage-specific digestibility coefficients may help reduce environmental pollution from sow herds while maintaining productive performance. However, given the limited number of observations, further studies with larger sample sizes and across different production conditions are needed to validate these results before widespread application can be recommended. Future work should also complement these efforts by addressing mineral requirements and other feedstuffs.

The greater stage-dependent variation observed for high-fiber ingredients suggests that differences in nutrient digestibility among physiological stages may not be solely attributable to changes in host digestive capacity, but may also involve alterations in gut microbial fermentation activity. Future studies could integrate ileal and total tract digestibility measurements with analyses of digestive enzyme activities, gut microbiota composition, and fermentation-related indicators such as short-chain fatty acids. Investigating nutrient utilization from a host-microbiota interaction perspective would help to elucidate the underlying physiological mechanisms driving stage-specific differences in nutrient digestion in sows.

Furthermore, distinguishing the effects of different types of dietary fiber, such as soluble and insoluble fiber, on energy and AA digestibility across physiological stages warrants further investigation. Clarifying how fiber characteristics interact with sow physiological status would improve the interpretation of variability in nutrient utilization among fiber-rich feed ingredients and support more accurate formulation of sow diets.

5. Conclusion

This PhD thesis systematically evaluated the effects of physiological stage on energy utilization and nutrient digestibility in sows, with a particular emphasis on ATTD and ileal AA digestibility of feed ingredients (corn, barley, wheat bran) differing in fiber content. Overall, the results demonstrate that nutrient digestibility in both primiparous and multiparous sows is a dynamic process that varies substantially across physiological stages rather than remaining constant throughout the production cycle.

Across the experiments, physiological stage consistently emerged as a key factor of both energy utilization and nutrient digestibility. Differences among gestation, lactation, and post-weaning phases were evident for multiple nutrients, indicating that metabolic demands and digestive capacity change markedly with reproductive status. Importantly, the magnitude and direction of these differences were closely associated with feed ingredient characteristics, especially dietary fiber concentration. In addition to stage and ingredient effects, parity also influenced nutrient utilization. Multiparous sows consistently exhibited greater ether extract digestibility across physiological stages and ingredients compared with primiparous sows, likely reflecting their more mature gut microbiota and enhanced pancreatic secretory capacity. This finding underscores that parity, alongside physiological stage and ingredient characteristics, is a key factor modulating nutrient utilization efficiency in sows.

High-fiber ingredients showed more pronounced stage-dependent variation in both ATTD and ileal AA digestibility, suggesting an interaction between sow physiological status and fiber fermentation capacity. In contrast, low-fiber ingredients exhibited more stable digestibility values across stages, although stage-related differences were still observable for specific nutrients and AAs. These findings highlight fiber content as a critical factor modulating digestive responses across physiological stages in sows.

Collectively, the results of this thesis provide experimental evidence supporting the use of physiological stage-specific energy values and nutrient digestibility coefficients in sow feeding standards. The findings indicate that applying uniform digestibility values across physiological stages may lead to inaccurate estimation of nutrient supply, particularly for wheat bran, and suggest that stage-specific digestibility data should be considered when formulating sow diets to improve nutrient efficiency and reduce feed wastage. By evaluating stage-dependent differences in corn, barley, and wheat bran, this study provides a more refined understanding of nutrient digestibility in sows. The digestibility data generated here can serve as a reference for developing sow-specific digestibility databases and for the gradual refinement of sow feeding standards, thereby informing more precise feeding strategies. In practice, these stage-specific values could be integrated into diet formulation software or nutrient models, adjusting ingredient digestibility according to physiological stage. Establishing sow-specific digestibility databases for key feedstuffs would allow nutritionists to optimize diets for gestation, lactation, and post-weaning phases, improving nutrient supply, feed efficiency, and reducing wastage. Further experiments incorporating different sow breeds, feed sources, and production conditions would help increase the robustness and applicability of these stage-specific recommendatio

References

Adeola, O. 2000. Digestion and balance techniques in pigs. In: Lewis, A.J., and L.L. Southern (eds.) *Swine Nutrition*. CRC Press, Boca Raton, FL. p. 923–936.

Adeola, O., Xue, P.C., Cowieson, A.J., Ajuwon, K.M. 2016. Basal endogenous losses of amino acids in protein nutrition research for swine and poultry. *Anim. Feed Sci. Technol*. 221: 274–283. doi:10.1016/j.anifeedsci.2016.06.004.

Albin, D.M., Wubben, J.E., Smiricky, M.R., Gabert, V.M. 2001. The effect of feed intake on ileal rate of passage and apparent amino acid digestibility determined with or without correction factors in pigs. *J. Anim. Sci*. 79: 1250–1258. doi:10.2527/2001.7951250x.

AOAC. 2006. Official methods of analysis, 18th ed. Rev.1. Assoc. Offic. Anal. Chem., Arlington, VA.

AOAC. 2007. Official methods of analysis,18th ed. Rev.2. Assoc. Offic. Anal. Chem., Arlington, VA.

Babatunde, O.O., Park, C.S., Adeola, O. 2021. Nutritional potentials of atypical feed ingredients for broiler chickens and pigs. *Animals*. 11: 1196. doi:10.3390/ani11051196.

Bach Knudsen, K.E. 2001. The nutritional significance of dietary fibre analysis. *Anim. Feed Sci. Technol.* 90: 3-20. doi:10.1016/S0377-8401(01)00193-6.

Barbosa, M.M., Detmann, E., Rocha, G.C., Franco, M.D.O., Filho, S.D.C.V. 2015. Evaluation of laboratory procedures to quantify the neutral detergent fiber content in forage, concentrate, and ruminant feces. *J. AOAC Int*. 98: 883–889. doi:10.5740/jaoacint.14-278.

Batterham, E.S., Lewis, C.E., Lowe, R.F., Mcmillan, C. J.1980. Digestible energy content of cereals and wheat by-products for growing pigs. *Anim. Sci*. 31: 259–271. doi:10.1017/S0003356100024594.

Bhar, R., Pathak, N.N., Paul, S. 2000. Performance of crossbred (Landrace × local Indian) finisher barrows fed maize- or wheat bran-based diets: Short note. *Asian-Australas. J. Anim. Sci*. 13: 1429–1432. doi:10.5713/ajas.2000.1429.

Bhatty, R.S. 1999. The potential of hull-less barley. *Cereal Chem*. 76: 589–599. doi:10.1094/CCHEM.1999.76.5.589.

Blake, T., Blake, V. C., Bowman, J. G. P., and Abdel-Haleem, H. 2011. Barley feed uses and quality improvement. In: Ullrich, S.E. (ed.) Barley: Production, Improvement, and Uses. Wiley-Blackwell, Oxford, UK. p. 522.

Bovera, F., Nizza, S., Attia, Y.A., Di Meo, C., Piccolo, G., Nizza, A. 2014. Prediction of digestible energy and gross energy digestibility of feeds and diets in ostriches. *Br. Poult. Sci*. 55: 518–523. doi:10.1080/00071668.2014.935702.

Brett, J.R., and Groves, T.D.D. 1979. Physiological energetics. In: Fish Physiology, Vol. 8. Academic Press, New York, NY. pp. 279–352.

Bridges, T.C., Turner, L.W., Smith, E.M., Stahly, T.S., Loewer, O.J. 1986. A mathematical procedure for estimating animal growth and body composition. *Trans. ASAE*. 29: 1342–1347. doi:10.13031/2013.30320.

Bu, Y., Feng, L., Xu, D., Zhang, S., Liang, L., Si, J., Lu, Y., Liu, Q., Yan, G., Wang, Y., Lan, G., Liang, J. 2024. Changes in gut microbiota associated with parity in large white sows. *Animals*. 14: 112. doi:10.3390/ani14010112.

Casas, G.A., Oliveira, M.S., Espinosa, C.D., Stein, H.H. 2022. Comparative digestibility of energy, dry matter, and nutrients by gestating and lactating sows fed corn–soybean meal diets without or with full-fat or defatted rice bran. *Can. J. Anim. Sci*. 102: 401–405. doi:10.1139/cjas-2021-0086.

Casas, G.A., and Stein, H.H. 2017. Gestating sows have greater digestibility of energy in full-fat rice bran and defatted rice bran than growing gilts regardless of level of feed intake. *J. Anim. Sci*. 95: 3136–3142. doi:10.2527/jas.2017.1585.

Chang, J., X. Jia, Y. Liu, X. Jiang, L. Che, Y. Lin, Y. Zhuo, B. Feng, Z. Fang, J. Li, L. Hua, J. Wang, Z. Ren, D. Wu, and S. Xu. 2024. Microbial mechanistic insight into the role of yeast-derived postbiotics in improving sow reproductive performance in late gestation and lactation sows. *Animals*. 14(1):162. doi:10.3390/ani14010162.

Charbonneau, P., Pelletier, G., and Morisset, J. 1982. Development of the pancreas during gestation and lactation in swine. *Can. J. Physiol. Pharmacol*. 60: 1229–1235. doi:10.1139/y82-179.

Choct, M. 1997. Feed non-starch polysaccharides: Chemical structures and nutritional significance. *Feed Milling Int.* June Issue pp: 13-26.

Craig, J.R., Dunshea, F.R., Cottrell, J.J., Wijesiriwardana, U.A., and Pluske, J.R. 2019. Primiparous and multiparous sows have largely similar colostrum and milk composition profiles throughout lactation. *Animals*. 9: 35. doi:10.3390/ani9020035.

Dai, Z., Wu, Z., Jia, S., and Wu, G. 2014. Analysis of amino acid composition in proteins of animal tissues and foods as pre-column o-phthaldialdehyde derivatives by HPLC with fluorescence detection. *J. Chromatogr*. B. 964: 116–127. doi:10.1016/j.jchromb.2014.03.025.

Dickerson, G., and Hazel, L. 1944. Selection for growth rate of pigs and productivity of sows. *J. Anim. Sci.* 3: 201–212. doi:10.2527/jas1944.32201x.

Diggs, B.G., Becker, D.E., Jensen, A.H., et al. 1965. Energy value of various feeds for the young pig. *J. Anim. Sci*. 24: 555–558. doi:10.2527/jas1965.242555x.

Dourmad, J.Y. 1993. Standing and feeding behaviour of the lactating sow: Effect of feeding level during pregnancy. *Appl. Anim. Behav. Sci*. 37: 311–319. doi:10.1016/0168-1591(93)90120-E.

Dégen, L., Halas, V., and Babinszky, L. 2007. Effect of dietary fibre on protein and fat digestibility and its consequences on diet formulation for growing and fattening pigs: A review. *Acta Agric. Scand. A Anim. Sci.* 57: 1–9. doi:10.1080/09064700701372038.

Farmer, C., and Quesnel, H. 2009. Nutritional, hormonal, and environmental effects on colostrum in sows. *J. Anim. Sci.* 87: 56–64. doi:10.2527/jas.2008-1203.

Fernandez, J.A., Jørgensen, H., and Just, A. 1986. Comparative digestibility experiments with growing pigs and adult sows. *Anim. Sci.* 43: 127–132. doi:10.1017/S0003356100018419.

Fioramonti, J., and Bueno, L. 1980. Motor activity in the large intestine of the pig related to dietary fibre and retention time. *Br. J. Nutr.* 43: 155–162. .doi:10.1079/BJN19800074.

Garg, M., Sharma, A., Vats, S., et al. 2021. Vitamins in cereals: A critical review of content, health effects, processing losses, bioaccessibility, fortification, and biofortification strategies for their improvement. *Front. Nutr.* 8: 586815. doi:10.3389/fnut.2021.586815.

Gauthier, R., Largouët, C., Bussières, D., Martineau, J.-P., and Dourmad, J.-Y. 2022. Precision feeding of lactating sows: Implementation and evaluation of a decision support system in farm conditions. *J. Anim. Sci*. 100: skac222. doi:10.1093/jas/skac222.

GB/T 39235-2020. 2020. Nutrient requirement of swine. National Livestock Standardization Technical Committee, Beijing, China.

Geisert, R.D., and Yelich, J.V. 1997. Regulation of conceptus development and attachment in pigs. *J. Reprod. Fertil. Suppl.* 52: 133–150. doi:10.1007/BF02765755.

Geisert, R.D., Sutovsky, P., Lucy, M.C., et al. 2020. Reproductive physiology of swine. In: Kebreab, E. (ed.) *Animal Agriculture: Sustainability, Challenges and Innovations*. Elsevier, London, UK. p. 263–281. doi:10.1016/B978-0-12-817052-6.00015-X.

Givens, D.I., Boever, J.L.D., and Deaville, E.R. 1997. The principles, practices and some future applications of near infrared spectroscopy for predicting the nutritive value of foods for animals and humans. *Nutr. Res. Rev.* 10(1): 83–114. doi:10.1079/NRR19970006.

Grahofer, A., and Plush, K. 2023. Lactation in swine. *Anim. Front.* 13: 112–118. doi: doi:10.1093/af/vfad020.

Haydon, K.D., Knabe, D.A., and Tanksley, T.D. Jr. 1984. Effects of level of feed intake on nitrogen, amino acid, and energy digestibilities measured at the end of the small intestine and over the total digestive tract of growing pigs. *J. Anim. Sci.* 59: 717–724. doi:10.2527/jas1984.593717x.

Hurley, W.L. 2001. Mammary gland growth in the lactating sow. *Livest. Prod. Sci.* 70: 149–157. doi:10.1016/S0301-6226(01)00208-1.

Ji, Y.J., Li, H., Xie, P.F., Li, Z.H., Li, H.W., Yin, Y.L., Blachier, F., and Kong, X.F. 2019. Stages of pregnancy and weaning influence the gut microbiota diversity and function in sows. *J. Appl. Microbiol*. 127: 867–879. doi:10.1111/jam.14344.

Jiao, Y., Chen, H., Han, H., and Chang, Y. 2022. Development and utilization of corn processing by-products: A review. *Foods* 11(22): 3709. doi:10.3390/foods11223709.

Jin, S.S., Jin, Y.H., Jang, J.C., Hong, J.S., Jung, S.W., and Kim, Y.Y. 2017. Effects of dietary energy levels on physiological parameters and reproductive performance of gestating sows over three consecutive parities. *Asian-Australas. J. Anim. Sci.* 31: 410–418. doi:10.5713/ajas.17.0016.

Jo, H., and B. G. Kim. 2023. Effects of dietary fiber in gestating sow diets—A review. *Anim. Biosci*. 36(11):1619-1632. doi:10.5713/ab.23.0206.

Jondreville, C., Van den Broecke, J., Gatel, F., and Van Cauwenberghe, S. 1995. Ileal digestibility of amino acids in feedstuffs for pigs. *Eurolysine/ITFC Publ.* 53: 1–11. .doi:10.1051/animres:2001120.

Just, A., Jørgensen, H., and Fernández, J.A. 1984. Prediction of metabolizable energy for pigs on the basis of crude nutrients in the feeds. *Livest. Prod. Sci.* 11(1): 105–128. doi:10.1016/0301-6226(84)90012-5.

Kemme, P.A., Radcliffe, J.S., Jongbloed, A.W., and Mroz, Z. 1997. The effects of sow parity on digestibility of proximate components and minerals during lactation as influenced by diet and microbial phytase supplementation. *J. Anim. Sci.* 75: 2147–2153. doi:10.1111/j.1439-0388.1997.tb00516.x.

Kiarie, E., and Nyachoti, C.M. 2010. Alternative feed ingredients in swine diets: A review. *Asian-Australas. J. Anim. Sci.* 23: 331–347. doi:10.5713/ajas.2010.70636.

Kim, S.W., Weaver, A.C., Shen, Y.B., and Zhao, Y. 2013. Improving efficiency of sow productivity: Nutrition and health. *J. Anim. Sci. Biotechnol*. 4: 26. doi:10.1186/2049-1891-4-26.

Kim, Y., Lee, S.A., and Stein, H.H. 2025. Digestible and metabolizable energy in soybean meal and soybean hulls when fed to growing pigs or sows. *Transl. Anim. Sci.* 9: txaf041.

Kim, J., Lee, H.J., Kwon, Y.S., and Kim, B.G. 2022. Demonstration of constant nitrogen and energy amounts in pig urine under acidic conditions at room temperature and determination of the minimum amount of hydrochloric acid required for nitrogen preservation in pig urine. *Anim. Biosci.* 36: 492–500. doi:10.5713/ab.21.0209.

Kim, J.H., Chu, K.S., Han, I.K., et al. 1998. An evaluation of barley in finisher pig diet for high quality pork production. *Korean J. Anim. Nutr. Feedstuffs* 22.

Klimas, R., Klimienė, A., Sobotka, W., Kozera, W., and Matusevičius, P. 2020. Effect of parity on reproductive performance of sows of different breeds. *S. Afr. J. Anim. Sci.* 50: 434–441. DOI:10.4314/sajas.v50i3.10.

Knox, R.V., and Zas, S.R. 2001. Factors influencing estrus and ovulation in weaned sows as determined by transrectal ultrasound. *J. Anim. Sci.* 79: 2957–2963. .doi:10.1046/j.1439-0396.2001.00337.x.

Knudsen, K.E.B., Hedemann, M.S., and Lærke, H.N. 2012. The role of carbohydrates in intestinal health of pigs. *Anim. Feed Sci. Technol.* 173: 41–53. doi:10.1016/j.anifeedsci.2011.12.020.

Koh, Y., Son, J., and Kim, B.G. 2025. Comparison of neutral detergent fiber analysis methods for feed ingredients, diets, and feces of pigs. *J. AOAC Int.* 4: 648–651. doi:10.1093/jaoacint/qsaf030.

Kong, C., and Adeola, O. 2014. Evaluation of amino acid and energy utilization in feedstuff for swine and poultry diets. *Asian-Australas. J. Anim. Sci.* 27: 917–925. doi:10.5713/ajas.2014.r.02.

Koren, O., Goodrich, J.K., Cullender, T.C., Spor, A., Laitinen, K., Bäckhed, H.K., Gonzalez, A., Werner, J.J., Angenent, L.T., Knight, R., and Bäckhed, F. 2012. Host remodeling of the gut microbiome and metabolic changes during pregnancy. *Cell*. 150: 470–480. doi:10.3410/f.717959606.793462880.

Kornegay, E.T., Harper, A.F., Jones, R., and Boyd, L. 1997. Environmental nutrition: Nutrient management strategies to reduce nutrient excretion of swine. *Prof. Anim. Sci.* 13: 99–111. doi:10.15232/S1080-7446(15)31861-1.

Kuiken, K.A., Lyman, C.M., Dieterich, S., and Bradford, M. 1948. Availability of amino acids in some foods. *J. Nutr.* 36(3): 359–368. doi:10.1093/jn/36.3.359.

Latymer, E.A., Low, A.G., Fadden, K., Sambrook, I.E., Woodley, S.C., and Keal, H.D. 1990. Measurement of transit time of digesta through sections of the gastrointestinal tract of pigs fed diets containing various sources of dietary fibre (non-starch polysaccharides). *Arch. Anim. Nutr*. 40: 667–680.

Law, K., Garcia, E.R.M., Hastad, C., Murray, D., Urriola, P.E., and Gomez, A. 2024. Interactions between maternal parity and feed additives drive the composition of pig gut microbiomes in the post-weaning period. *J. Anim. Sci. Biotechnol.* 15: 33.

Le Goff, G., Van Milgen, J., and Noblet, J. 2002a. Influence of dietary fibre on digestive utilization and rate of passage in growing pigs, finishing pigs, and adult sows. *Anim. Sci*. 74: 503–515. doi:10.1017/S1357729800052668.

Le Goff, G., Dubois, S., Van Milgen, J., and Noblet, J. 2002b. Influence of dietary fibre level on digestive and metabolic utilisation of energy in growing and finishing pigs. *Anim. Res*. 51: 245–259. doi:10.1051/animres:2002019.

Le Goff, G., and Noblet, J. 2001. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. *J. Anim. Sci*. 79: 2418–2427. doi:10.2527/2001.7992418x.

Lei, B., Lv, G., X. Mo, L. Hua, X. Jiang, B. Feng, L. Che, S. Xu, Y. Lin, F. Wu, and D. Wu. 2025. Gestating sows exhibit greater ileal amino acid digestibility of corn distillers grains, rapeseed meal, and cottonseed meal than growing pigs, but not soybean meal. *Animal*. 19(7):101556. doi:10.1016/j.animal.2025.101556.

Li, G., Wang, Y., Zhang, J., Xu, S., Lin, Y., Hua, L., Li, J., Feng, B., Fang, Z., Jiang, X., and Zhuo, Y. 2024. Standardized ileal digestibility of amino acids in Chinese fermented soybean meal from different sources fed to mid- and late-gestating sows. *J. Anim. Sci.* 102: skae063. doi:10.1093/jas/skae063.

Li, H., Yin, J., Tan, B., Chen, J., Zhang, H., Li, Z., Ma, X., and Yin, Y. 2021. Physiological function and application of dietary fiber in pig nutrition: A review. *Anim. Nutr*. 7: 259–267. doi:10.1016/j.aninu.2020.11.011.

Liao, S.F., Wang, T., and Regmi, N. 2015. Lysine nutrition in swine and related monogastric animals: Muscle protein biosynthesis and beyond. SpringerPlus 4: 1–12. doi:10.1186/s40064-015-0927-5.

Lim, M.Y., Song, E.J., Kang, K.S., and Nam, Y.D. 2019. Age-related compositional and functional changes in micro-pig gut microbiome. *GeroScience*. 41: 935–944. doi:10.1007/s11357-019-00121-y.

Liu, H., Hou, C., Li, N., Zhang, X., Zhang, G., Yang, F., Zeng, X., Liu, Z., and Qiao, S. 2019. Microbial and metabolic alterations in gut microbiota of sows during pregnancy and lactation. *FASEB J.* 33: 4490–4501. doi:10.1096/fj.201801221RR.

Lowell, J. E., Y. Liu, , H. H. Stein. 2015. Comparative digestibility of energy and nutrients in diets fed to sows and growing pigs. *Arch. Anim. Nutr*. 69: 79–97. doi:10.1080/1745039X.2014.993921.

Lucht, H.L. 2010. First parity productivity of selected commercial sows. PhD Diss. Univ. of Pretoria, Pretoria, South Africa.

Lyu, Z., Chen, Y., Wang, F., Liu, L., Zhang, S., and Lai, C. 2023. Net energy and its establishment of prediction equations for wheat bran in growing pigs. *Anim. Biosci*. 36: 108–118. doi:10.5713/ab.22.0001.

Lærke, H.N., and Hedemann, M.S. 2012. The digestive system of the pig. In: Nutritional Physiology of Pigs (online publication). Videncenter for Svineproduktion, Denmark.

Ma, L., Wang, H., Qiu, Y., et al. 2024. Alternative uses of fermented wheat bran: A mini review. *Fermentation* (Basel) 10(12): 611. doi:10.3390/fermentation10120611.

Mariscal-Landín, G., Sève, B., Colléaux, Y., and Lebreton, Y. 1995. Endogenous amino nitrogen collected from pigs with end-to-end ileorectal anastomosis is affected by the method of estimation and altered by dietary fiber. *J. Nutr.* 125: 136–146. doi:10.1093/jn/125.1.136.

MOA (Ministry of Agriculture of the People's Republic of China). 1986. Chinese feeding standard for swine. Beijing (China): Agriculture Press.

MOA (Ministry of Agriculture of the People's Republic of China). 2004. Chinese feeding standard for swine. Beijing (China): Agriculture Press.

MOA (Ministry of Agriculture of the People's Republic of China). 2010. Chinese feeding standard for swine. Beijing (China): Agriculture Press.

Morgan, D.J., Cole, D.J.A., and Lewis, D. 1975. Energy values in pig nutrition: I. The relationship between digestible energy, metabolizable energy, and total digestible nutrient values of a range of feedstuffs. *J. Agric. Sci*. 84: 7–17. doi:10.1017/S0021859600071823.

Moter, V., and Stein, H.H. 2004. Effect of feed intake on endogenous losses and amino acid and energy digestibility by growing pigs. *J. Anim. Sci*. 82: 3518–3525. doi:10.2527/2004.82123518x.

NRC. 1944. Nutrient requirements of swine. 1st ed. Natl. Res. Council., Washington, DC.

NRC. 1971. Nutrient requirements of swine. 6th ed. Natl. Acad. Press, Washington, DC.

NRC. 1988. Nutrient requirements of swine. 9th ed. Natl. Acad. Press, Washington, DC.

NRC. 2012. Nutrient requirements of swine. 11th ed. Natl. Acad. Press, Washington, DC.

Naber, E.C., and Oltjen, R.R. 1978. NRC nutrient requirements: How they are established. *J. Anim. Sci.* 47: 979–983. doi:10.2527/jas1978.474979x.

Niu, Q., Li, P., Hao, S., Kim, S.W., Du, T., Hua, J., and Huang, R. 2019. Characteristics of gut microbiota in sows and their relationship with apparent nutrient digestibility. *Int. J. Mol. Sci*. 20: 870. doi:10.3390/ijms20040870.

Noblet, J., and Le Goff, G. 2001. Effect of dietary fibre on the energy value of feeds for pigs. *Anim. Feed Sci. Technol.* 90: 35–52. doi:10.1016/S0377-8401(01)00195-X.

Noblet, J., and Perez, J.M. 1993. Prediction of digestibility of nutrients and energy values of pig diets from chemical analysis. *J. Anim. Sci.* 71: 3389–3398. doi:10.1111/j.1439-0388.1993.tb00759.x.

Noblet, J., Fortune, H., Shi, X.S., and Dubois, S. 1994. Prediction of net energy value of feeds for growing pigs. *J. Anim. Sci.* 72: 344–354. doi:10.1016/0168-1591(94)90137-6.

Noblet, J., Shi, X.S., and Dubois, S. 1993. Metabolic utilization of dietary energy and nutrients for maintenance energy requirements in sows: Basis for a net energy system. *Br. J. Nutr*. 70: 407–419. doi:10.1079/BJN19930135.

Noblet, J., and Van Milgen, J. 2004. Energy value of pig feeds: Effect of pig body weight and energy evaluation system. *J. Anim. Sci.* 82: E229–E238. doi:10.1016/j.homp.2003.11.007.

Noblet, J., et al. 1987. Effect of protein and lysine levels in the diet on body gain composition and energy utilization in growing pigs. *J. Anim. Sci.* 65: 717–726. doi:10.1051/gse:19870309.

Noblet, J. 2000. Digestive and metabolic utilization of feed energy in swine: Application to energy evaluation systems. *J. Appl. Anim. Res.* 17: 113–132. doi:10.1080/09712119.2000.9706295.

Noblet, J., and Etienne, M. 1987. Energy utilization and energy requirements in pregnant and lactating sows. *Ann. Zootech.* 36: 308–309. doi:10.1051/animres:19870329.

Noblet, J., and Perez, J.M. 1993. Prediction of digestibility of nutrients and energy values of pig diets from chemical analysis. *J. Anim. Sci*. 71: 3389–3398. doi:10.2527/1993.71123389x.

Noblet, J., and Shi, X.S. 1994. Effect of body weight on digestive utilization of energy and nutrients of ingredients and diets in pigs. *Livest. Prod. Sci*. 37: 323–338. doi:10.1016/0301-6226(94)90126-0.

Noblet, J., and Shi, X. S. 1993. Comparative digestibility of energy and nutrients in growing pigs fed ad libitum and adult sows fed at maintenance. *Livest. Prod. Sci*. 34: 219–232. doi:10.1016/0301-6226(93)90042-G.

Nyachoti, C.M., Lange, C.D., McBride, B.W., Schulze, H. 1997. Significance of endogenous gut nitrogen losses in the nutrition of growing pigs: A review. *Can. J. Anim. Sci*. 77: 149–163. doi: doi.org/10.4141/A96-044.

Owsley, W.F., Orr, D.E. Jr., and Tribble, L.F. 1986. Effects of age and diet on the development of the pancreas and the synthesis and secretion of pancreatic enzymes in the young pig. *J. Anim. Sci*. 63: 497–504. doi:10.2527/jas1986.632497x.

Palumbo, F., Trevisi, P., Correa, F., Bee, G., and Girard, M. 2024. Increasing the level of hemicelluloses in the lactation diet affects the faecal microbiota of sows and their piglets without affecting their performances. *Anim. Microbiome.* 6(1):68. doi:10.1186/s42523-024-00354-z.

Park, S., Lee, S., Kim, H., and Kim, Y. 2025. Maternal microbial effects and the dynamic distribution, networks, and functions of pig gut microbiota across the entire life cycle. *Sci. Rep.* 15:24567. doi:10.1038/s41598-025-20983-x.

Pedersen, C., Boersma, M.G., and Stein, H.H. 2007. Energy and nutrient digestibility in NutriDense corn and other cereal grains fed to growing pigs. *J. Anim. Sci.* 85: 2473–2483. doi:10.2527/jas.2006-620.

Perera, W.N.U., Abdollahi, M.R.; Zaefarian, F.; Wester, T.J.; Ravindran, V. 2022. Barley, an undervalued cereal for poultry diets: Limitations and opportunities. *Animals.* 12: 2525. doi:10.3390/ani12192525.

Piel, C., Montagne, L., Sève, B., and Lallès, J.P. 2005. Increasing digesta viscosity using carboxymethylcellulose in weaned piglets stimulates ileal goblet cell numbers and maturation. *J. Nutr*. 135(1):86-91. doi:10.1093/jn/135.1.86.

Poleze, E., Bernardi, M.L., Filha, W.A., Wentz, I., and Bortolozzo, F.P. 2006. Consequences of variation in weaning-to-estrus interval on reproductive performance of swine females. *Livest. Sci*. 103: 124–130. doi:10.1016/j.livsci.2006.02.007.

Pomar, C., and Remus, A. 2019. Precision pig feeding: A breakthrough toward sustainability. *Anim. Front*. 9: 52–59. doi:10.1093/af/vfz006.

Rademacher, M., Sauer, W., and Jansman, A. 1999. Standardized ileal digestibility of amino acids in pigs. Frankfurt, Germany: Degussa-Hüls.

Ramonet, Y., van Milgen, J., Dourmad, J.Y., Meunier-Salaün, M.C., and Noblet, J. 2000. The effect of dietary fibre on energy utilisation and partitioning of heat production over pregnancy in sows. *Br. J. Nutr.* 84(1): 85–94. doi:10.1017/S0007114500001284.

Rivera Ferre, M.G., Edwards, S.A., Mayes, R.W., Riddoch, I., Hovell, F.D.D. 2001. The effect of season and level of concentrate on the voluntary intake and digestibility of herbage by outdoor sows. *Anim. Sci*. 72: 501-510.

Saha, S.K., and Pathak, N.N. 2021. Digestion, absorption, and metabolism of nutrients. In: Fundamentals of Animal Nutrition. *Springer, Singapore*. pp. 219–246. doi:10.1007/978-981-15-9125-9_14.

Saldaña, G., and Brown, H.E. 1984. Nutritional composition of corn and flour tortillas. *J. Food Sci.* 49: 1202–1203. doi:10.1111/j.1365-2621.1984.tb10430.x.

Sauer, W.C., and Ozimek, L. 1986. Digestibility of amino acids in swine: Results and their practical applications. A review. *Livest. Prod. Sci*. 15: 367–388. doi:10.1016/0301-6226(86)90076-X.

Sauer, W.C., Just, A., and Jørgensen, H. 1982. The influence of daily feed intake on the apparent digestibility of crude protein, amino acids, calcium, and phosphorus at the terminal ileum and overall in pigs. *Z. Tierphysiol. Tierernähr. Futtermittelk.* 48: 177–182. doi:10.1111/j.1439-0396.1982.tb01389.x.

Schulze, H., et al. 1994. Effect of level of dietary neutral detergent fiber on ileal apparent digestibility and ileal nitrogen losses in pigs. *J. Anim. Sci*. 72: 2362–2368. doi:doi:10.1080/00071669408417728.

Shenk, J., and Westerhaus, M. 1994. The application of near infrared reflectance spectroscopy (NIRS) to forage analysis. In: Forage Quality, Evaluation, and Utilization. pp. 406–449.

Skřivan, P., Sluková, M., Stýblová, B., Trusová, Š., Sinica, A., Bleha, R., Švec, I., & Kotrcová, V. 2024. Utilization of the nutritional potential of wheat bran using different fractionation techniques. *Appl. Sci.* 14(16): 7222. doi:10.3390/app14167222.

Solà-Oriol, D., and Gasa, J. 2017. Feeding strategies in pig production: Sows and their piglets. *Anim. Feed Sci. Technol.* 233: 34–52. doi:10.1016/j.anifeedsci.2016.07.018.

Spindler, H.K., Mosenthin, R., Rosenfelder, P., Jørgensen, H., Bach Knudsen, K.E., and Eklund, M. 2016. Determination of basal ileal endogenous losses and standardized ileal digestibility of amino acids in barley fed to growing pigs. *J. Anim. Sci. Biotechnol*. 7: 56. doi:10.1186/s40104-016-0115-7.

Stein, H.H., Aref, S., and Easter, R.A. 1999. Comparative protein and amino acid digestibilities in growing pigs and sows. *J. Anim. Sci.* 77: 1180–1187. doi: 10.2527/1999.7751169x.

Stein, H.H., et al. 2005. Additivity of values for apparent and standardized ileal digestibility of amino acids in mixed diets fed to growing pigs. *J. Anim. Sci.* 83: 2387–2395. doi:10.2527/2005.83102387x.

Stein, H.H., Sève, B., Fuller, M.F., Moughan, P.J., and De Lange, C.F. 2007. Invited review: Amino acid bioavailability and digestibility in pig feed ingredients: Terminology and application. *J. Anim. Sci.* 85: 172–180. doi:10.2527/jas.2005-742.

Stein, H.H., Kim, S.W., Nielsen, T.T., and Easter, R.A. 2001. Standardized ileal protein and amino acid digestibility by growing pigs and sows. *J. Anim. Sci.* 79: 2113–2122. doi:10.2527/2001.7982113x.

Stein, H.H., Shipley, C.F., Easter, R.A. 1998. A technique for inserting a T-Cannula. *J. Anim. Sci*. 76. doi: 10.2527/1998.7651433x.

Stein, H.H., Trottier, N.L., Bellaver, C., and Easter, R.A. 1999. The effect of feeding level and physiological status on total flow and amino acid composition of endogenous protein at the distal ileum in swine. *J. Anim. Sci.* 77: 1180–1187. doi:10.2527/1999.7751180x.

Sui, L., X. Xu, Q. Lan, B. Chen, K. Wang, L. Xiao, W. Chen, W. Wen, C. Liu, L. Yi, J. Liu, X. Fu, and H. Ma. 2025. Temporal dynamics of fecal microbiome and short-chain fatty acids in sows from early pregnancy to weaning. *Animals.* 15(15): 2209. doi:10.3390/ani15152209.

Taverner, M., and Farrell, D. 1981. Availability to pigs of amino acids in cereal grains: 4. Factors influencing the availability of amino acids and energy in grains. *Br. J. Nutr*. 46: 181–192. doi:10.1079/BJN19810020.

Theil, P.K., Lauridsen, C., and Quesnel, H. 2014. Neonatal piglet survival: Impact of sow nutrition around parturition on fetal glycogen deposition, production, and composition of colostrum and transient milk. *Animal*. 8: 1021–1030. doi:10.1017/S1751731114001266.

Perry, T.W. 1988. Corn as a livestock feed. In: Corn and Corn Improvement. Vol. 18. pp. 941–963. doi:10.2134/agronmonogr18.3ed.c16.

Tiwari, U.P., Mandal, R.K., Neupane, K.R., Mishra, B., and Jha, R. 2022. Starchy and fibrous feedstuffs differ in their in vitro digestibility and fermentation characteristics and differently modulate gut microbiota of swine. *J. Anim. Sci*. Biotechnol. 13: 53. doi:10.1186/s40104-022-00699-y.

Van den Brand, H., et al. 2000. Dietary energy source at two feeding levels during lactation of primiparous sows: I. Effects on glucose, insulin, luteinizing hormone, follicle development, weaning-to-estrus interval, and ovulation rate. *J. Anim. Sci.* 78: 396–404. doi:10.1046/j.1439-0396.2000.00249.x.

Van Milgen, J., and Dourmad, J.-Y. 2015. Concept and application of ideal protein for pigs. *J. Anim. Sci. Biotechnol.* 6: 15. doi:10.1186/s40104-015-0016-1.

Van Milgen, J., and Noblet, J. 2003. Partitioning of energy intake to heat, protein, and fat in growing pigs. *J. Anim. Sci*. 81: E86–E93. doi:10.2527/2003.8114_suppl_2E86x.

Van Soest, P.J. 1967. Development of a comprehensive system of feed analyses and its application to forages. *J. Anim. Sci.* 26: 119–128. doi:10.1051/animres:19670405.

Van Soest, P.J., Robertson, J.B., and Lewis, B.A. 1991. Symposium: Carbohydrate methodology, metabolism, and nutritional implications in dairy cattle. *J. Anim. Sci.* 74: 3583–3597. doi:10.2527/1991.69104163x.

Varel, V.H. 1987. Activity of fiber-degrading microorganisms in the pig large intestine. *J. Anim. Sci.* 165: 488–496. doi:10.1016/0168-1591(87)90194-8.

Velayudhan, D.E., Hossain, M.M., Stein, H.H., and Nyachoti, C.M. 2019. Standardized ileal digestibility of amino acids in canola meal fed to gestating and lactating sows. *J. Anim. Sci*. 97: 4219–4226. doi:10.1093/jas/skz283.

Wang, H., Xu, R., Zhang, H., Su, Y., and Zhu, W. 2020. Swine gut microbiota and its interaction with host nutrient metabolism. *Anim. Nutr.* 6(4):410–420. doi:10.1016/j.aninu.2020.10.002.

Wang, K., Huang, L., Yang, P., Zhuo, Y., Che, L., Xu, S., Hua, L., Li, J., Feng, B., Fang, Z., and Zhao, X. 2022. The nutritive value of soybean meal from different sources for sows during mid- and late gestation. *J. Anim. Sci*. 100: skac298. doi:10.1093/jas/skac298.

Wang, K., Wang, Y., Guo, L., Zhuo, Y., Hua, L., Che, L., Xu, S., Zhang, R., Li, J., Feng, B., and Fang, Z. 2023. Standardized ileal digestibility of amino acids in soybean meal fed to non-pregnant and pregnant sows. *J. Anim. Sci*. Biotechnol. 14: 123. doi:10.1186/s40104-023-00928-y.

Wang, K., Huang, L., Yang, P., Zhuo, Y., Che, L., Xu, S., Hua, L., Li, J., Feng, B., Fang, Z., and Zhao, X. 2024. Nutritional values of soybean meal from different sources in multiparous sows. *Anim. Nutr*. doi:10.1016/j.aninu.2024.09.004.

Wang, K., Huang, L., Yang, P., Zhuo, Y., Che, L., Xu, S., Hua, L., et al. 2025a. Nutritional values of soybean meal from different sources in multiparous sows. *Anim. Nutr.* 20: 80–87. doi:10.1016/j.aninu.2024.09.004.

Wang, K., Ma, Z., Yang, M., Che, L., Xu, S., Zhuo, Y., Feng, B., Lun, H., Li, J., Jiang, X., Fang, Z., Wu, D., and Lin, Y. 2025b. Standardized ileal digestibility of amino acids in corn distillers dried grains with solubles fed to gestating and lactating sows. *J. Anim. Sci.* skaf376. doi :10.1093/jas/skaf376.

Wang, T., Langendijk, P., Azevedo, P., Fabà, L., Zuo, B., Zhao, J., and Yang, C. 2025. Effects of fiber concentrations and fermentation rates on reproductive performance, nutrient digestibility, immune response, and microbiota of lactating sows. *J. Anim. Sci.* 103: skaf110. doi:10.1093/jas/skaf110.

Wang, Y., Li, G., Ma, X., Xu, S., Lin, Y., Hua, L., Li, J., Feng, B., Fang, Z., Jiang, X., and Zhuo, Y. 2023a. Chemical composition, energy content, and apparent total tract digestibility of extruded full-fat soybean from different sources fed to non-gestating, gestating, and lactating sows. *J. Anim. Sci.* 101: skad154. doi:10.1093/jas/skad154.

Wang, Y., Ma, X., Li, G., Sun, M., Xu, S., Lin, Y., Hua, L., Li, J., Feng, B., Fang, Z., Jiang, X., Zhuo, Y., Che, L., and Wu, D. 2023b. Effects of feeding levels on ileal amino acid digestibility of extruded full-fat soybeans in nongestating sows. *J. Anim. Sci.* 101: skad052. doi:10.1093/jas/skad052.

Wang, Y., Wang, K., Zou, X., Jiang, X., Zhuo, Y., Che, L., and Wu, D. 2023c. Standardized ileal digestibility of amino acids in extruded full-fat soybean fed to non-gestating, gestating, and lactating sows. *J. Anim. Sci.* 101: skad259. doi:10.1093/jas/skad259.

Wei, Z., Xu, L., Guo, Y., Guo, B., Lu, C., Sun, W., Li, Y., Jiang, X., Li, X., and Pi, Y. 2024. Evaluation of available energy and standardized ileal digestibility of amino acids in fermented flaxseed meal for growing pigs. *Animals* 14: 228. doi:10.3390/ani14020228.

Wei, Z., Xu, L., Yang, J., et al. 2025a. Evaluation of energy and nutrient utilization for corn, barley, and wheat bran in primiparous and multiparous sows during the gestation, lactation, and post-weaning period. *J. Anim. Sci.* skaf287. doi:10.1093/jas/skaf287.

Wei, Z., Xu, L., Yang, J., et al. 2025b. Evaluation of standardized ileal digestibility of amino acids in corn, barley, wheat bran fed to primiparous sows during gestation, lactation, and post-weaning period. *J. Anim. Sci.* 103: skaf277. doi:10.1093/jas/skaf277.

Whittemore, C.T. 1993. The science and practice of pig production. Longman Scientific & Technical, Harlow, UK.

Whittemore, C.T. 1996. Nutrition–reproduction interactions in primiparous sows. *Livest. Prod. Sci.* 46: 65–83. doi:10.1016/0301-6226(96)00019-X.

Williams, P., and Norris, K. 1987. Near-infrared technology in the agricultural and food industries. American Association of Cereal Chemists, St. Paul, MN.

Williams, C.H., David, D.J., and Iismaa, O. 1962. The determination of chromic oxide in faeces samples by atomic absorption spectrophotometry. *J. Agric. Sci.* 59: 381–385. doi:10.1017/S002185960001546X.

Yang, Y.X., Heo, S., Jin, Z., and Yun, J.H. 2008. Effects of lysine intake during late gestation and lactation on blood metabolites, hormones, milk composition and reproductive performance in primiparous and multiparous sows. *Arch. Anim. Nutr.* 62(3-4): 10–21. doi:10.1080/17450390701780227.

Yang, Z., Palowski, A., Jang, J.C., Urriola, P.E., and Shurson, G.C. 2021. Determination, comparison, and prediction of digestible energy, metabolizable energy, and standardized ileal digestibility of amino acids in novel maize co-products and conventional distillers dried grains with solubles for swine. *Anim. Feed Sci. Technol.* 282: 115149. doi:10.1016/j.anifeedsci.2021.115149.

Yang, Z., Urriola, P.E., Johnston, L.J., and Shurson, G.C. 2023. A systems approach to evaluate nitrogen utilization efficiency and environmental impacts of swine growing–finishing feeding programs in U.S. pork production systems. *J. Anim. Sci.* 101: skad188. doi:10.1093/jas/skad188.

Yeo, E., Brubaker, P.L., and Sloboda, D.M. 2022. The intestine and the microbiota in maternal glucose homeostasis during pregnancy. *J. Endocrinol.* 253: R1–R19. doi:10.1530/JOE-21-0354.

Zebrowska, T., and Low, A.G. 1987. The influence of diets based on whole wheat, wheat flour, and wheat bran on exocrine pancreatic secretion in pigs. *J. Nutr.* 117: 1212–1216. doi:10.1093/jn/117.7.1212.

Zhang, L., Li, Y.K., Li, Z.C., Li, Q.F., Lyu, M.B., Li, D.F., and Lai, C.H. 2016. The nutritive values of different varieties of corn planted in one location fed to growing pigs over three consecutive years. *Asian-Australas. J. Anim. Sci.* 29(12): 1768–1773. doi:10.5713/ajas.16.0695.

Zhang, G., Zhang, G., Zhao, J., Liu, L., and Zhang, Z. 2024. Effect of extrusion on available energy and amino acid digestibility of barley, wheat, sorghum, and broken rice in growing pigs. *Anim. Biosci.* 37: 1085. doi:10.5713/ab.23.0285.

Zhang, D., Ji, H., Wang, S., Chen, M., and Liu, H. 2024. Parity changed fecal microbiota of sows and its correlation with milk long-chain fatty acid profiles. *Appl. Microbiol. Biotechnol.* 108: 4. doi:10.1007/s00253-023-12852-2.

Zhang, W., Li, D., Liu, L., Zang, J., Duan, Q., Yang, W., and Zhang, L. 2013. The effects of dietary fiber level on nutrient digestibility in growing pigs. *J. Anim. Sci. Biotechnol.* 4: 17. doi:10.1186/2049-1891-4-17.

Zhao, J., Liu, P., Huang, C., Liu, L., Li, E., Zhang, G., and Zhang, S. 2018. Effect of wheat bran on apparent total tract digestibility, growth performance, fecal microbiota, and their metabolites in growing pigs. *Anim. Feed Sci. Technol.* 239: 14–26. doi:10.1016/j.anifeedsci.2018.02.013.

Zhao, J., Liu, Z., Song, X., Yang, M., Li, Z., and Liu, L. 2025. Effect of processing techniques on energy content and amino acid digestibility in corn germ meal fed to growing pigs. *Anim. Biosci.* 38: 1003. doi:10.5713/ab.24.0581

Zhuo, Y., Zou, X., Wang, Y., Jiang, X., Sun, M., Xu, S., Lin, Y., Hua, L., Li, J., Feng, B., and Fang, Z. 2023a. Standardized ileal digestibility of amino acids in cottonseed meal fed to pregnant and non-pregnant sows. *J. Anim. Sci.* 101: skad132. doi:10.1093/jas/skad132.

Zhuo, Y., Zou, X., Wang, Y., Jiang, X., Sun, M., Xu, S., Lin, Y., Hua, L., Li, J., Feng, B., and Fang, Z. 2023b. Nutritional values of cottonseed meal from different sources fed to gestating and non-pregnant sows. *J. Anim. Sci.* 101: skad118. doi:10.1093/jas/skad118.

Zijlstra, R.T., Payne, R.L., Patterson, J.E., and Barker, J.A. 2007. Net energy system for pigs. In: *Manipulating Pig Production XI*. Australasian Pig Science Association, Werribee, Vic, Australia. pp. 80–90.

Zuidhof, M. 2019. A review of dietary metabolizable and net energy: Uncoupling heat production and retained energy. *J. Appl. Poult. Res.* 28: 231–241. doi:10.3382/japr/pfx062.

Appendices

Scientific publications

Scientific publications

Adapted from the thesis:

Wei, Z., Xu, L., Yang, J., Schroyen, M., Jiang, X., Cui, S., Li, X., and Pi, Y. 2025. Evaluation of standardized ileal digestibility of amino acids in corn, barley, wheat bran fed to primiparous sows during gestation, lactation, and post-weaning period. *J. Anim. Sci.* 103: skaf277. doi:10.1093/jas/skaf277.

Wei, Z., Xu, L., Yang, J., Schroyen, M., Jiang, X., Cui, S., Li, X., and Pi, Y. 2025. Evaluation of energy and nutrient utilization for corn, barley, and wheat bran in primiparous and multiparous sows during the gestation, lactation, and post-weaning period. *J. Anim. Sci.* 103: skaf287. doi:10.1093/jas/skaf287.

Other publications:

Wei, Z., Xu, L., Guo, Y., Yang, J., Schroyen, M., Jiang, X., Cui, S., Li, X., and Pi, Y. 2024. Evaluation of available energy and standardized ileal digestibility of amino acids in fermented flaxseed meal for growing pigs. *Animals* 14(2): 228. doi:10.3390/ani14020228.

Wei, Z., Xu, L., Bai, R., Yang, J., Schroyen, M., Jiang, X., Cui, S., Li, X., and Pi, Y. 2023. Dietary supplementation with different types of potassium and magnesium during late gestation and lactation modulates the reproductive performance, antioxidant capacity, and immune function of sows. *Animals* 13(15): 2456. doi:10.3390/ani13152456.

Wei, Z., Cai, L., Zhao, X., Jiang, X., and Li, X. 2022. Effects of spermidine on cell proliferation, migration, and inflammatory response in porcine enterocytes. *Front. Biosci.-Landmark* 27(6): 194. doi:10.31083/j.fbl2706194.

Cai, L[*]., **Wei, Z**[*]., Li, Y., Zhao, X., Li, X., and Jiang, X. 2020. Gallic acid modulates barrier function by mitigating LPS-induced inflammatory response via NF-κB signaling pathway in IPEC-J2 cells. *J. Anim. Physiol. Anim. Nutr.* 104(6): 1859–1867. doi:10.1111/jpn.13612.