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Optimizing Animal Energy Metabolism: Nutritional Strategies in Agricultural Production

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Abstract The study found that tailored nutritional management significantly impacts milk production, metabolic status, and body condition in dairy cows, with specific genotypes responding differently to nutritional strategies. Additionally, increasing the amount of energetic-protein supplements in post-weaning phases improved metabolic profiles and ovarian activity in heifers. Integrating crop and livestock systems and using co-product feeds were identified as effective strategies to enhance the efficiency and sustainability of livestock production. Furthermore, leveraging genetic selection and advanced nutritional management practices can significantly improve feed efficiency and reduce environmental impacts in beef production systems. The findings suggest that optimizing nutritional strategies tailored to specific animal needs and integrating advanced genetic and management practices can significantly enhance energy metabolism, productivity, and sustainability in agricultural production. These strategies not only improve animal health and productivity but also contribute to more sustainable and efficient agricultural systems.

Keywords Nutritional strategies; Energy metabolism; Agricultural production; Dairy cows; Heifers; Feed efficiency; Sustainability; Genetic selection

1 Introduction

Animal energy metabolism encompasses the physiological and biochemical processes that convert feedstuffs into energy and nutrients necessary for growth, maintenance, and production. This involves a complex interplay of digestive and metabolic mechanisms that ensure the efficient use and storage of energy and nutrients within the animal's body (Kerr, 2021). The efficiency of these processes is critical for optimizing animal productivity and maintaining economic viability in agricultural production (VandeHaar et al., 2016). Understanding the fundamental aspects of energy metabolism, including nutrient partitioning and the regulation of metabolic pathways, is essential for developing effective nutritional strategies (Hocquette et al., 2007).

Nutritional strategies play a pivotal role in enhancing the efficiency of animal production systems. By optimizing the intake and utilization of nutrients, these strategies can significantly improve feed efficiency, reduce production costs, and enhance the overall health and productivity of farm animals (VandeHaar et al., 2016; Mulliniks and Beard, 2018). For instance, targeted nutritional management during key physiological periods, such as the transition period in dairy cows, can support metabolic adaptations and prevent metabolic dysfunctions (Overton and Waldron, 2004). Additionally, advancements in genetic selection and nutritional management have led to substantial improvements in feed efficiency and productivity in the dairy industry (VandeHaar et al., 2016). The integration of nutrition with other management practices, such as grouping and total mixed ration feeding, further underscores the importance of a holistic approach to optimizing animal energy metabolism (VandeHaar et al., 2016).

This study aims to provide a comprehensive overview of the current understanding of animal energy metabolism and the role of nutritional strategies in optimizing agricultural production. The objectives are to summarize the key physiological and biochemical processes involved in animal energy metabolism, highlight the importance of nutritional strategies in enhancing feed efficiency and productivity, and discuss recent advancements and future directions in the field, including the integration of genetic, nutritional, and management practices.

2 Fundamentals of Animal Energy Metabolism

2.1 Basic concepts of energy metabolism

Energy metabolism in animals encompasses a series of biochemical reactions that occur within cells to sustain life. These processes are organized into metabolic pathways that either synthesize (anabolism) or degrade (catabolism) complex macromolecules to provide energy for cellular functions (Judge and Dodd, 2020). The primary pathways include glycolysis, the citric acid cycle, and oxidative phosphorylation, which collectively convert nutrients into adenosine triphosphate (ATP), the energy currency of the cell. Understanding these pathways is crucial for optimizing animal productivity and efficiency in agricultural settings (Kerr, 2021).

Macronutrients play distinct roles in energy metabolism. Carbohydrates are primarily broken down into glucose, which enters glycolysis and the citric acid cycle to produce ATP. Fats are metabolized into fatty acids and glycerol, with fatty acids undergoing β-oxidation to generate acetyl-CoA, which then enters the citric acid cycle (Judge and Dodd, 2020). Proteins are broken down into amino acids, which can be deaminated to enter various points in the citric acid cycle (Nafikov and Beitz, 2007). The efficiency of these processes and the balance between them are critical for maintaining optimal energy levels and supporting growth and development in farm animals (Drackley et al., 2006; Nafikov and Beitz, 2007).

2.2 Measurement of energy metabolism

Several techniques are employed to measure energy metabolism in livestock. Indirect calorimetry is commonly used to estimate heat production and energy expenditure by measuring oxygen consumption and carbon dioxide production (McBride and Kelly, 1990). Multicatheterization techniques allow for the quantification of nutrient fluxes and energy use by specific tissues, such as the liver and digestive tract (Drackley et al., 2006). Additionally, molecular biology approaches, including the measurement of mRNA abundance for key metabolic enzymes, provide insights into the regulation of metabolic pathways. These methods collectively enhance our understanding of how different nutritional strategies impact energy metabolism and animal productivity (McBride and Kelly, 1990; Drackley et al., 2006).

Energy metabolism in animals is influenced by various factors, including age, breed, and environmental conditions. Younger animals typically have higher metabolic rates due to growth demands, while older animals may have reduced metabolic efficiency. Breed differences can affect metabolic rates and nutrient utilization, with some breeds being more efficient in converting feed into energy (Hocquette et al., 2007). Environmental factors, such as temperature and housing conditions, also play a significant role in energy metabolism. For instance, extreme temperatures can increase energy expenditure as animals work to maintain homeostasis (McBride and Kelly, 1990). Understanding these factors is essential for developing nutritional strategies that optimize energy use and enhance productivity in agricultural production systems (McBride and Kelly, 1990; Hocquette et al., 2007).

3 Nutritional Strategies to Optimize Energy Metabolism

3.1 Carbohydrate management

Carbohydrates are a primary energy source for many animals, including monogastric species like pigs and ruminants like cattle. They play a crucial role in maintaining metabolic functions and supporting growth and production. For instance, in dairy cows, non-fibrous carbohydrates (NFC) are recommended during the prepartum period to facilitate the transition to lactation, although results on their effectiveness are mixed (Mendoza et al., 2019). In weaned piglets, the structure of dietary starch significantly affects serum glucose levels and intestinal health, highlighting the importance of carbohydrate type in energy metabolism (Gao et al., 2020).

Optimizing carbohydrate utilization involves selecting appropriate carbohydrate sources and managing their intake. For example, in dairy cows, increasing NFC intake prepartum can marginally affect postpartum intake and metabolic status (Mendoza et al., 2019). In weaned piglets, diets with higher amylose ratios improve blood glucose and insulin concentrations, while high amylopectin diets enhance nutrient digestibility (Gao et al., 2020). Additionally, the use of carbohydrases in grazing beef cattle can improve ruminal fermentation and nutrient absorption, particularly during the dry season (Acosta et al., 2021).

3.2 Fatty acid optimization

Fats are a dense energy source and play a vital role in energy metabolism. They are essential for the absorption of fat-soluble vitamins and the production of essential fatty acids. In poultry, optimizing dietary energy utilization through fats can significantly impact production costs and sustainability (Musigwa et al., 2021).

Balancing omega-3 and omega-6 fatty acids is crucial for maintaining optimal energy production and overall health. An appropriate balance can enhance metabolic efficiency and reduce inflammation, which is beneficial for animal growth and productivity. Research indicates that precise energy evaluation and the use of exogenous enzymes can improve the digestibility and utilization of fats in poultry diets (Musigwa et al., 2021).

3.3 Protein utilization

The quality and quantity of protein in animal diets significantly affect energy metabolism. High-quality proteins provide essential amino acids that are crucial for growth and metabolic functions. In dairy cows, different genotypes respond differently to protein intake, affecting milk production and metabolic status (Brady et al., 2021).

Enhancing protein efficiency involves using high-quality protein sources and optimizing their inclusion in diets. For instance, in dairy cows, tailored total mixed rations (TMR) can improve milk output and metabolic status compared to traditional pasture-based diets (Brady et al., 2021). Additionally, the use of legumes with high protein content can improve rumen feed efficiency and reduce methane production, contributing to sustainable animal production (Singh et al., 2023).

3.4 Micronutrient and mineral supplementation

Vitamins and minerals are essential for supporting various metabolic processes, including energy metabolism. They act as cofactors for enzymes involved in metabolic pathways. For example, alpha-lipoic acid (α-LA) supplementation in prawns improves antioxidant status and carbohydrate metabolism, highlighting the importance of micronutrients in energy utilization (Ding et al., 2022).

Effective micronutrient supplementation involves providing balanced and bioavailable forms of vitamins and minerals. In dairy cattle, using feeds rich in water-soluble carbohydrates (WSC) can enhance rumen health and sustainability, indirectly supporting energy metabolism by improving nutrient absorption and reducing the risk of acidosis (Klevenhusen and Zebeli, 2021) (Figure 1). Additionally, the inclusion of specific enzyme blends can enhance nutrient digestion and absorption, further supporting energy metabolism (Acosta et al., 2021).

4 Advanced Nutritional Technologies

4.1 Nutrient partitioning

Nutrient partitioning in animals involves the distribution of nutrients among various physiological processes such as maintenance, growth, reproduction, and lactation. This process is influenced by several factors including hormonal signals, metabolic pathways, and the animal's physiological state. For instance, during early lactation, dairy cows exhibit low plasma insulin concentration and insulin sensitivity, which directs nutrients towards milk synthesis rather than body reserves (Piantoni and VandeHaar, 2022) (Figure 2). Additionally, adaptive processes in beef cows allow them to adjust their metabolic energy utilization to match environmental conditions, thereby maintaining reproductive competence (Mulliniks and Beard, 2018). Understanding these mechanisms is crucial for optimizing nutrient use and improving animal productivity.

Nutritional strategies can significantly influence nutrient partitioning towards energy production. For example, the inclusion of glucogenic substrates like glucose in the diet of dairy cows has been shown to stimulate energy retention in body tissues and increase plasma glucose and insulin concentrations, thereby enhancing energy availability for productive purposes (Nichols et al., 2019). Similarly, feeding strategies that involve the use of biofortified forage crops with essential micronutrients such as zinc and copper can improve the overall nutrient profile of the diet, leading to better energy metabolism and animal health (Dhaliwal et al., 2022). These strategies highlight the importance of targeted nutritional interventions in optimizing energy production in livestock.

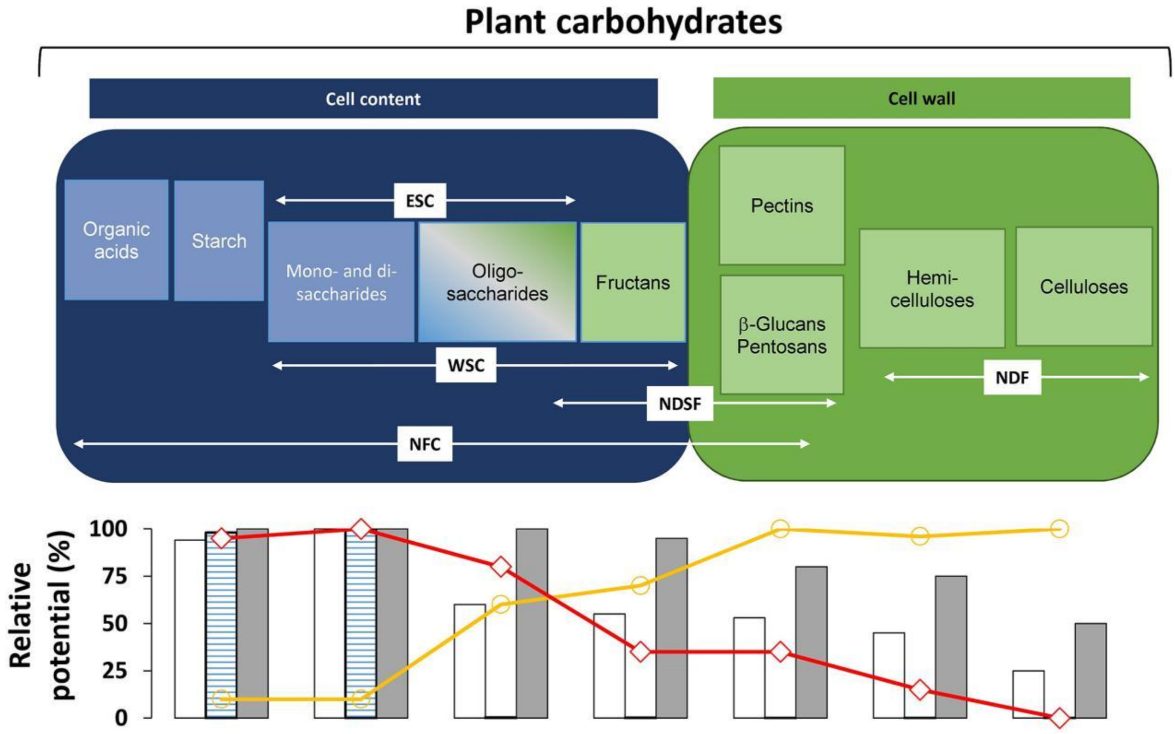

Figure 1 Distribution of carbohydrates in the plant (modified from Hall and Eastridge, 2014) and their respective ruminal degradation and fermentation properties (estimated as the relative potential in %) (Adopted from Klevenhusen and Zebeli, 2021)

Image caption: The blue colored carbohydrates indicate digestibility by the animal and gut microbes; green colored carbohydrates can only be digested by gut microbes. Relative potential in the rumen of ruminal degradation rate (image), lactate release (image), SCFA formation (image), acetate-to-propionate ratio (image) and the risk of causing subacute ruminal acidosis (image). Abbreviations: ESC, ethanol-soluble carbohydrates; WSC, water-soluble carbohydrates; NFC, non-fiber carbohydrates; NDSF, neutral-detergent-soluble fiber; NDF, neutral-detergent fiber (Adopted from Klevenhusen and Zebeli, 2021)

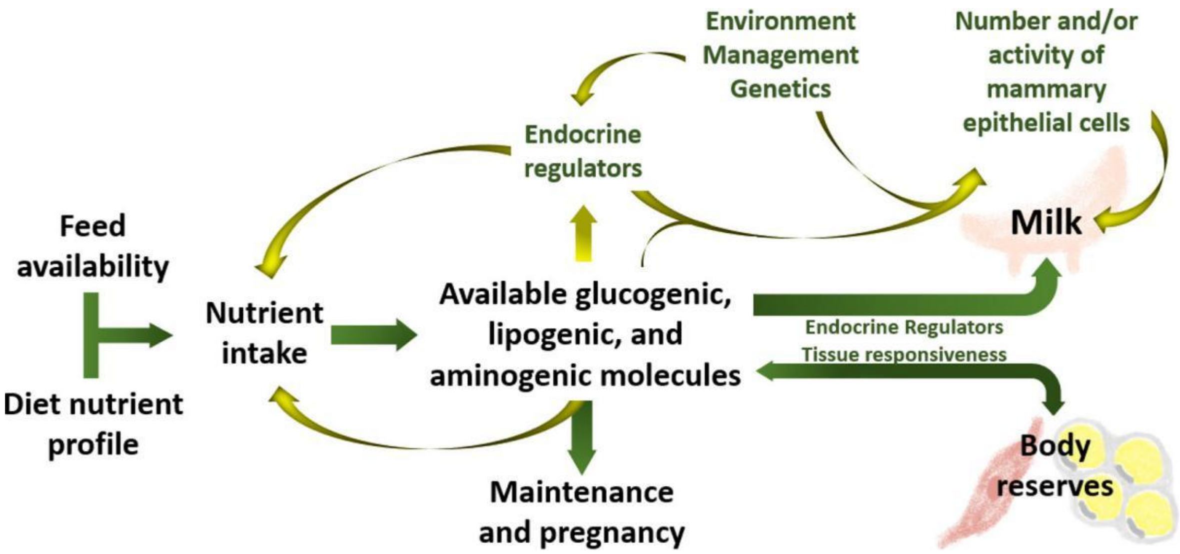

Figure 2 Feed availability and diet nutrient profile determine nutrient intake, which is affected by endocrine regulators such as gut peptides and by other mechanisms of control of intake such as hepatic energy charge or gut fill (Adopted from Piantoni and VandeHaar, 2022)

Image caption: Nutrients will be used for maintenance, pregnancy, body reserves, or milk depending on stage of lactation or gestation. Endocrine regulators, such as growth hormone and insulin, and tissue responsiveness to them will determine the partitioning of nutrients between milk and body reserves. Several factors can affect the synthetic capacity of the mammary gland, including endocrine regulators (e.g., growth hormone), available nutrients (e.g., certain amino acids and fatty acids), environment (e.g., heat stress), management (e.g., milking frequency), and genetics, and therefore, the pull of nutrients to produce milk (Adopted from Piantoni and VandeHaar, 2022)

4.2 Use of feed additives

Feed additives play a crucial role in supporting energy metabolism in livestock. Enzymes such as cellulase can enhance the digestibility of fibrous feed components, thereby increasing the availability of energy from the diet. Probiotics like *Lactobacillus casei* have been shown to improve ruminal fermentation and nutrient absorption, leading to better energy utilization (So et al., 2021). Additionally, the use of chemical compounds to inhibit rumen methanogenesis can redirect energy from methane production to more valuable fermentation products, potentially increasing ruminant productivity (Ungerfeld, 2018). These additives are essential tools in modern animal nutrition for enhancing energy metabolism and overall performance.

Numerous studies have demonstrated the effectiveness of feed additives in improving energy metabolism. For instance, a study on Thai native steers fed with fermented sugarcane bagasse treated with *Lactobacillus casei*, cellulase, and molasses showed significant improvements in nutrient digestibility, ruminal fermentation, and energy partitioning compared to conventional rice straw feeding (So et al., 2021). Another meta-analysis on the inhibition of rumen methanogenesis found that while the relationship between methane inhibition and productivity was complex, there was a tendency for increased milk production efficiency in some cases (Ungerfeld, 2018). These findings underscore the potential benefits of feed additives in enhancing energy metabolism in livestock.

4.3 Precision nutrition

Precision feeding involves tailoring the diet to meet the specific nutritional needs of individual animals or groups of animals, thereby optimizing energy metabolism and improving overall efficiency. This approach takes into account factors such as the animal's physiological state, production goals, and environmental conditions. For example, precision feeding can help ensure that dairy cows receive the right balance of nutrients to support both milk production and body condition throughout lactation (Piantoni and VandeHaar, 2022). By closely matching nutrient supply with nutrient requirements, precision feeding minimizes waste and maximizes the efficiency of energy use in livestock production.

Technological advancements have greatly enhanced the ability to implement precision nutrition in livestock. Tools such as automated feeding systems, real-time monitoring of animal health and performance, and advanced data analytics allow for more precise control of nutrient intake and better decision-making. For instance, climate respiration chambers can be used to measure energy and nitrogen balance in dairy cows, providing valuable insights into how different dietary treatments affect energy partitioning and overall productivity (Nichols et al., 2019). These technologies enable more accurate and efficient feeding strategies, ultimately leading to improved energy metabolism and animal performance.

5 Case Studies

5.1 Dairy cattle

Nutritional strategies in dairy cattle focus on managing energy balance, especially during critical periods such as early lactation and heat stress. One approach involves feeding a tailored total mixed ration (TMR) during the first 30 days postpartum, which has been shown to improve milk output, metabolic status, and body condition score (BCS) compared to ad libitum access to fresh pasture plus concentrates (Brady et al., 2021). Additionally, strategies to mitigate heat stress, such as adjusting diets to support physiological responses and incorporating supplements like propionates and dietary buffers, are crucial for maintaining energy metabolism under high-temperature conditions (Sammad et al., 2020) (Figure 3). Concentrate supplementation strategies during the transition period also play a significant role, with different timings of concentrate build-up affecting energy supply and metabolic status (Steinwidder et al., 2021).

5.2 Poultry

In poultry production, enhancing energy metabolism involves optimizing feed energy utilization through the use of exogenous enzymes and accurate energy requirement predictions. Exogenous carbohydrases, for example, can significantly improve nutrient digestion and absorption, particularly in diets with viscous ingredients, leading to better energy utilization and gut health (Musigwa et al., 2021). Additionally, transitioning from metabolisable energy (ME) systems to net energy (NE) systems can provide more accurate measurements of dietary energy, accounting for energy losses as heat during feed ingestion, absorption, and metabolism.

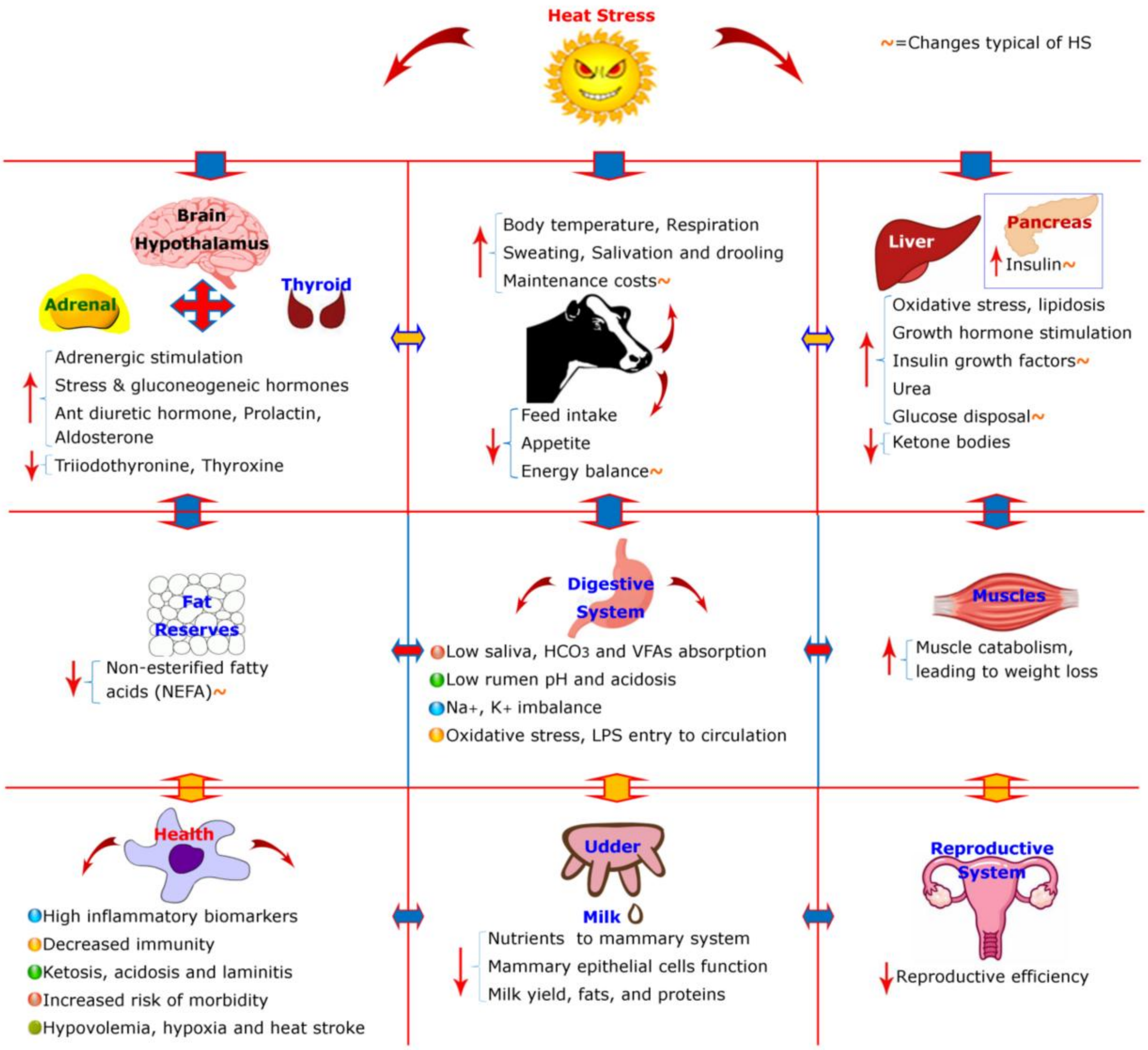

Figure 3 Summary of various heat stress-related physiological and biochemical changes occurring at various systems level in the body of the dairy cows. Phrases with the indication of "~" indicate changes typical of heat stressed animals. (LPS= lipopolysaccharides, VFAs= volatile fatty acids) (Adopted from Sammad et al., 2020)

Feeding TMR in early lactation has demonstrated positive outcomes, including higher fat-plus-protein and lactose yields, reduced concentrations of nonesterified fatty acids, and smaller BCS losses (Brady et al., 2021). However, challenges such as managing the negative energy balance (NEBAL) during heat stress remain, as high milk production increases internal heat loads, leading to reduced milk yield and reproductive performance (Sammad et al., 2020). Additionally, while concentrate supplementation strategies can improve energy balance, they require careful management to avoid metabolic disorders and ensure optimal health and productivity (Steinwidder et al., 2021).

The use of exogenous enzymes like carbohydrases has been shown to enhance the digestibility of saturated fat and protein, improving energy utilization by approximately 4%. This not only boosts growth performance but also enhances feed efficiency by reducing nutrient flow into the hindgut, which can otherwise fuel pathogenic bacteria proliferation (Musigwa et al., 2021). Accurate energy evaluation through NE systems further supports precision feeding, leading to optimized growth and cost-effectiveness in poultry production.

5.3 Swine

Optimizing energy utilization in swine involves nutritional grouping and the use of machine-learning techniques to better sort animals according to their energy and protein requirements. This approach allows for more precise feeding strategies, improving feed efficiency and overall production (Lopez et al., 2022). Additionally, incorporating energy additives into the diet can enhance metabolism and nitrogen use, further supporting growth and development (Nafikova et al., 2021).

Nutritional grouping and machine-learning techniques have shown potential in improving feed efficiency by better matching diets to the specific requirements of different groups of animals, which can lead to improved growth performance and meat quality (Lopez et al., 2022). The use of energy additives has also been associated with increased nitrogen use and improved feed digestion, resulting in better growth rates and potentially enhanced meat quality (Nafikova et al., 2021). However, these strategies require careful implementation to ensure they meet the specific needs of the animals and do not lead to imbalances or health issues (Nafikova et al., 2021; Lopez et al., 2022).

6 Challenges and Future Perspectives

6.1 Current limitations in nutritional strategies

Current nutritional strategies in agricultural production face several limitations and challenges. One significant issue is the variability in metabolic efficiency among animals, which can be influenced by environmental conditions and genetic factors. For instance, beef cows often encounter dynamic and highly variable nutritional environments that periodically fail to meet their nutrient and energy requirements, leading to reduced metabolic efficiency (Mulliniks and Beard, 2018). Additionally, the metabolic challenges during high milk production periods in dairy cows can negatively impact their immune system, reproductive performance, and overall animal welfare (Gross and Bruckmaier, 2019).

Another challenge is the need for a more integrated approach that considers the interactions between nutrition, genetics, and environmental conditions. The lack of complete integration of these factors often results in substantial variation in metabolic and reproductive efficiency among animals within production systems (Mulliniks and Beard, 2018). Furthermore, traditional methodologies in animal nutrition research, while still valuable, need to be complemented with modern technologies and genomic tools to provide more targeted nutritional strategies tailored to individual genetic potential (Harmon, 2021).

6.2 Emerging research and innovations

6.2.1 Potential future strategies and technologies for improving energy metabolism

Emerging research and innovations offer promising strategies for improving energy metabolism in agricultural production. One potential approach is the development of metabolically potent supplementation strategies that target enhanced energy metabolism and endocrine mechanisms. These strategies could increase metabolic and economic efficiency in beef cows by enabling them to adapt better to environmental changes and optimize their energy utilization (Mulliniks and Beard, 2018).

Additionally, the use of tailored total mixed rations (TMR) in dairy cows during early lactation has shown positive effects on milk output, metabolic status, and body condition score (BCS) profile. Feeding TMR can reduce concentrations of nonesterified fatty acids and β-hydroxybutyric acid, leading to improved metabolic health and productivity (Brady et al., 2021).

6.2.2 Role of genetics and personalized nutrition in future advancements

The role of genetics and personalized nutrition is becoming increasingly important in advancing animal energy metabolism. Genetic improvement dictates that nutritional requirements be continually reassessed and refined to match the evolving genetic potential of animals (Harmon, 2021). Personalized nutrition strategies that consider individual genetic profiles can optimize nutrient intake and improve overall metabolic efficiency.

Moreover, breeding for high metabolic plasticity in early-lactating dairy cows could enhance their resilience and performance without compromising health. This approach emphasizes the importance of metabolic adaptation and plasticity at different functional stages of the mammary gland, which can lead to more sustainable milk production (Gross and Bruckmaier, 2019).

7 Concluding Remarks

The research on optimizing animal energy metabolism through nutritional strategies in agricultural production has yielded several key insights. Firstly, optimal nutrition is crucial for supporting the growth and development of farm animals, which in turn enhances productivity and efficiency. Genetic selection, nutrition, and management practices have significantly improved feed efficiency in dairy cows, with a focus on enhancing digestive and metabolic efficiency. Nutritional management during critical periods, such as the transition period in dairy cows, is essential for supporting metabolic adaptations and preventing metabolic dysfunction. Additionally, tailored nutritional strategies, such as the use of total mixed rations (TMR), have shown positive effects on milk output, metabolic status, and body condition score (BCS) in dairy cows. Nutritional interventions can also modulate gene expression and metabolic enzyme activity, thereby influencing meat and milk quality. Furthermore, specific nutritional strategies can reduce environmental emissions from nonruminants by enhancing nutrient utilization and minimizing nutrient excretion.

Based on the findings, several recommendations for optimizing animal energy metabolism in agricultural practices can be made. First, implementing precision nutrition by developing feeding programs tailored to an animal's genetic makeup, age, and physiological state ensures optimal nutrient utilization and minimizes waste. Phase feeding should also be adopted to meet animals' changing nutritional needs at different growth and production stages, enhancing feed efficiency and reducing nutrient excretion. Utilizing advanced feed formulations with highly digestible ingredients and synthetic amino acids further improves nutrient absorption while lowering environmental emissions. Regular monitoring of metabolic health through blood metabolites and hormones allows for targeted nutritional interventions that support metabolic health and reproductive performance. Genomic technologies should be leveraged to identify animals with superior feed efficiency and incorporate these traits into breeding programs. Lastly, enhancing rumen function through management practices such as total mixed ration feeding and nutritional grouping improves overall feed efficiency and rumen health.

Optimizing animal energy metabolism through strategic nutritional interventions is pivotal for enhancing productivity, efficiency, and sustainability in agricultural production. By integrating advanced nutritional strategies with genetic selection and management practices, it is possible to achieve significant improvements in animal performance and environmental sustainability. Future research should continue to explore the complex interactions between nutrition, genetics, and metabolism to develop more effective and sustainable agricultural practices. The ultimate goal is to create a balanced approach that maximizes animal health and productivity while minimizing environmental impact.

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Conflict of Interest Disclosure

Author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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