Nutritional Management in Sheep to Stimulate Reproductive Function. Review

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Abstract
Nutritional management is a critical determinant of reproductive performance in sheep, exerting profound effects on endocrine regulation, metabolic status, and the physiological mechanisms underlying estrus cyclicity, ovulation, and fertility. This comprehensive review synthesizes current knowledge on the role of nutrition in stimulating reproductive function in sheep, with an emphasis on the interaction between body condition, energy and protein balance in the diet, and the contribution of essential micronutrients. A key factor highlighted is the relationship between body condition score (BCS) and reproductive efficiency, as both malnutrition and over conditioning are associated with impaired ovarian function, reduced conception rates, and suboptimal embryo development. Strategic nutritional interventions, particularly short-term energy supplementation or "flushing" prior to breeding, have been shown to increase ovulation rates, improve follicular dynamics, and increase lambing rates. Protein nutrition is also crucial, influencing oocyte quality, early embryonic development, and the uterine environment, although excessive intake of degradable proteins can negatively affect reproductive outcomes. The analysis further explores the role of vitamins and trace minerals in supporting reproductive health. Deficiencies or imbalances of these micronutrients can lead to reproductive disorders. The interaction between nutrition and other influencing factors—such as breed, age, seasonality, and production system—is examined to provide a holistic understanding of reproductive variability in sheep. Emerging nutritional strategies are also discussed for their potential to modulate reproductive hormones and improve overall herd productivity. In conclusion, optimized nutritional management is a fundamental tool for improving reproductive performance in sheep. Implementing evidence-based feeding strategies, tailored to physiological stages and production conditions, can significantly improve fertility outcomes, increase reproductive efficiency, and support the sustainability and profitability of sheep production systems.

Keywords: fetal development, gestation, lactation, metabolism, reproduction, sperm quality.

1. Introduction

Livestock nutrition is one of the fundamental components of animal husbandry management, directly influencing the animal's growth, reproductive capacity, milk and meat production, as well as resistance to stressors. Nutritional requirements are not constant throughout an animal's life but vary depending on the intensity of physiological and metabolic processes. Consequently, ration formulation must aim to

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ensure an adequate intake of energy, protein, fiber, vitamins, macronutrients, and micronutrients. In ruminants, nutritional management is of particular importance during the transition period between dry-off, lambing, and the onset of lactation. During this stage, the rapid increase in nutrient requirements—sometimes accompanied by a reduction in voluntary dry matter intake—can lead to a negative energy balance and an increased risk of metabolic disorders. Monitoring body condition, feed intake, and metabolic indicators contributes to the early identification of problems and the improvement of productive performance [1, 2].

Nutrition in sheep affects several reproductive parameters, including age at puberty, ovulation rate, lambing interval, embryo survival, fetal development, and neonatal metabolism. The amount of energy ingested by sheep has a direct impact on several reproductive parameters. A diet with a negative energy balance leads to inhibition of hypothalamic GnRH secretion, absence of LH pulses, low FSH concentrations, inhibition of folliculogenesis, low estradiol levels, increased sensitivity to negative feedback, anovulation, anestrus, and delayed puberty [3].

2. Nutritional Management During Physiological Stages

During the growth period, the diet must support the harmonious development of the skeletal and muscular systems and internal organs, without excessive accumulation of adipose tissue. Energy and protein intake must be tailored to the species, breed, age, and desired growth rate. At the same time, feed quality, nutrient digestibility, and access to water influence the efficiency of feed utilization. In young ruminants, the gradual introduction of solid feed and ensuring an adequate nutrient intake contribute to the functional development of the rumen. Dietary imbalances—whether due to deficiency or excess—can affect development and future performance. Therefore, monitoring average daily weight gain and adjusting rations based on body weight trends are important tools for optimizing growth.

Nutritional management during different physiological stages is a key determinant of reproductive efficiency, health, and productivity in sheep. The nutritional needs of sheep are not constant but vary significantly depending on their physiological status, including the pre-breeding, gestation, and lactation periods. Each stage imposes specific metabolic requirements that must be met through specific feeding strategies to ensure optimal reproductive performance and the viability of the lambs [4, 5].

Inadequate or unbalanced nutrition during critical periods can lead to impaired follicular development, reduced conception rates, increased embryonic mortality, poor fetal growth, and decreased milk production. In contrast, well-managed nutrition, tailored to physiological needs, can enhance fertility, improve lamb survival, and increase overall flock productivity [6]. Over the past two decades, research has highlighted the importance of stage-specific nutritional interventions and the integration of energy, protein, and micronutrient management [7].

The duration of postpartum anestrus is an important economic factor, as a shorter interval between lambing and the resumption of the ovarian cycle allows for conception after lambing. Nutrition plays an important role in follicular development and, consequently, influences the period from lambing to the first estrus and ovulation [8]. During the early postpartum period, adequate nutritional support is necessary for the animals to resume ovarian activity. Nutritional supplementation with high-energy diets stimulates folliculogenesis, which reduces negative feedback and induces compensatory increases in folliculogenesis [8, 9].

This article reviews the principles of nutritional management during key physiological stages in sheep, focusing on their impact on reproductive performance and productivity.

a. Pre-breeding period

The pre-breeding period is essential for preparing ewes for successful conception. Nutritional management during this stage aims to optimize the body condition score (BCS) and stimulate ovarian activity. Ideally, ewes should have a BCS of 2.5–3.5 (on a five-point scale) at mating to achieve optimal reproductive outcomes [10].

Nutrition influences reproductive function through its effects on energy metabolism, hormonal secretion, and embryonic development. An insufficient intake of energy and protein can compromise the onset of estrus, ovulation, and the establishment of pregnancy, while protein and

mineral imbalances can affect the metabolic environment necessary for reproduction. The role of micronutrients, particularly zinc, copper, and selenium, must be evaluated in relation to the species' requirements and their availability in the diet [11].

Short-term energy supplementation prior to mating is a widely used strategy to improve ovulation rates and conception. Increasing energy intake during this period raises levels of metabolic hormones, such as insulin and insulin-like growth factor-1 (IGF-1), which promote follicular development and increase ovulation rates [12, 13]. Protein intake is also important at this stage, as it supports hormone synthesis and follicular growth. However, excessive protein intake should be avoided to prevent negative effects on embryo viability.

To achieve adequate reproductive performance during the breeding season (>95% of ewes pregnant by the end of the season), it is necessary to implement rearing practices outside the breeding season to ensure that both males and females are properly prepared. The standard breeding season for sheep in the Northern Hemisphere runs from September through December, followed by a lambing period that takes place from February through May of the following year. This relatively short timeframe places significant pressure on producers to organize the breeding season effectively and maintain the profitability of their operations.

b. Early pregnancy

During gestation, nutritional requirements change progressively, influenced by fetal development, the number of fetuses, and the female's body condition. In sheep and goats, late pregnancy is a critical period, especially for females carrying twins or triplets. The rapid increase in energy requirements, coupled with limited feed intake capacity due to uterine volume, necessitates the use of diets with adequate nutrient density and good digestibility. Inadequate feed management during this stage can increase the risk of metabolic disorders and production losses [14].

Early gestation (the first 4–6 weeks) is a critical period characterized by embryo implantation and placental development. Although nutritional requirements at this stage are only slightly higher than maintenance levels, adequate nutrition is crucial for embryo survival. Malnutrition during early gestation can lead to increased embryonic mortality due to inadequate nutrient intake and an altered uterine environment [6]. Conversely, overfeeding can negatively affect embryo survival by disrupting hormonal balance. Therefore, maintaining a stable and moderate nutritional regimen is essential at this stage.

c. Mid-gestation

During mid-gestation, fetal growth is relatively slow, and the nutritional requirements of the ewes are moderate. This stage provides an opportunity to adjust body condition, if necessary, ensuring that the ewes enter late gestation in optimal condition.

Both undernutrition and overnutrition during mid-gestation can have long-term effects on fetal development and the subsequent performance of lambs. An adequate intake of protein and micronutrients during this period supports placental function and prepares the ewe for the increased demands of late gestation [15].

d. Late gestation

Late gestation (the last 6–8 weeks) is the most nutritionally demanding period, as approximately 70% of fetal growth occurs during this time. Energy and protein requirements increase significantly to support rapid fetal development and colostrum production. Inadequate nutrition during late gestation can lead to low birth weight, weak lambs, increased perinatal mortality, and metabolic disorders such as pregnancy toxemia [7]. On the other hand, excessive energy intake can lead to oversized fetuses and difficulties during parturition (dystocia).

Micronutrients, particularly selenium and vitamin E, play important roles in preventing oxidative stress and improving lamb viability. Therefore, balanced supplementation is essential at this stage.

e. Lactation

The transition period in dairy cows, conventionally defined as the approximately three-week interval before and after lambing, is one of the most physiologically demanding stages. During this period, the body must simultaneously meet the demands of lambing, colostrum synthesis, and the rapid increase in milk production. If energy intake does not meet requirements, the mobilization of body reserves can lead to increased concentrations of non-

esterified fatty acids and beta-hydroxybutyrate, which are associated with a higher risk of metabolic disorders.

Caixeta and Omontese (2021) emphasize the importance of systematically monitoring health and metabolic status during this period. Effective management involves gradually adjusting the diet, ensuring a sufficient supply of high-quality forage, maintaining ruminal function, and controlling mineral intake, particularly calcium and magnesium. Furthermore, preventing overfeeding during the antepartum period and maintaining an appropriate body condition at lambing are important measures for reducing metabolic risk [16].

Lactation is the most demanding stage of the production cycle, as ewes must sustain milk production while maintaining their own body reserves. Nutritional management during lactation directly affects milk production, lamb growth, and the ewes' ability to return to estrus. Insufficient energy intake during lactation can lead to a negative energy balance, resulting in weight loss, reduced milk production, and delayed resumption of ovarian activity [15]. Adequate protein intake is also essential for milk synthesis and lamb growth.

Feeding strategies during lactation should aim to maximize feed intake and provide high-quality, energy-rich diets. Mineral and vitamin supplementation supports immune function and overall health.

During lactation, the diet must support milk production and limit excessive loss of body reserves. The proportions of energy, metabolizable protein, and effective fiber must be adjusted to the level of production and the animal's intake capacity. The use of high-quality feeds and a balanced diet help maintain ruminal health, milk composition, and reproductive performance.

Functional supplements, such as certain probiotics, prebiotics, lipids, and bioactive compounds, may have beneficial effects under certain conditions; however, their effectiveness depends on the product's composition, dosage, the animal's physiological state, and the composition of the base diet. These interventions should be considered complementary to, rather than a substitute for, a balanced diet [17].

During the dry period, the main objective is to restore body reserves to physiological levels and prepare the animal for the next lactation. The diet must avoid both malnutrition and excessive accumulation of body fat. Periodic assessment of body condition and planning rations based on the expected lambing date contribute to a more efficient transition to the next productive cycle.

f. The post-weaning period and recovery

The post-weaning period allows ewes to regain their body condition and prepare for the next reproductive cycle. Nutritional management during this stage should focus on restoring body reserves without causing excessive fat accumulation.

This period also provides an opportunity to correct any nutritional deficiencies and implement strategic supplementation programs. Proper management during the dry period ensures that ewes enter the next breeding season in optimal condition, thereby improving reproductive performance.

In conclusion, nutritional management tailored to physiological stages is essential for optimizing reproductive performance and productivity in sheep. Each stage—pre-breeding, gestation, lactation, and recovery—has specific nutritional requirements that must be carefully addressed to support metabolic and reproductive functions.

Both undernutrition and overnutrition can have negative effects on fertility, embryo survival, and lamb performance. Therefore, maintaining a balanced, stage-specific feeding program is essential for achieving optimal results.

Advances in nutritional science and precision feeding technologies offer new opportunities for improving the efficiency of sheep production systems. Future research should focus on refining stage-specific nutritional strategies and integrating them with genetic and environmental factors to improve reproductive performance and sustainability.

3. Male Nutrition and Reproductive Function

Male fertility is an important component of the reproductive and economic efficiency of livestock production systems. On modern farms, the use of breeding stock with high genetic value and artificial insemination requires maintaining an appropriate quality of semen. Male reproductive function is influenced by genetic, endocrine, nutritional, and environmental factors, and nutrition is one of the factors that can be directly influenced through farm management.

Nutrition influences testicular development, testosterone secretion, spermatogenesis, and sperm maturation. Research in the fields of reproductive biology and omics highlights the importance of identifying biomarkers associated with fertility, as conventional semen parameters do not always fully reflect male reproductive potential [18].

Although the reproductive management of females often receives greater attention, the nutritional status of rams plays an equally important role in determining mating success, sperm quality, and overall reproductive efficiency. Nutritional imbalances in males can impair spermatogenesis, reduce libido, and negatively affect fertilization rates, ultimately limiting the reproductive performance of the flock [19, 20].

Spermatogenesis is an extremely energy-dependent process that requires adequate intakes of protein, vitamins, and trace minerals. Furthermore, the endocrine regulation of male reproduction is closely linked to metabolic status, with hormones such as testosterone, insulin, and leptin playing key roles in linking nutrition to reproductive function. Over the past two decades, research has increasingly highlighted the importance of optimizing nutritional strategies in rams to improve sperm quality and reproductive outcomes [21, 22].

This article examines the physiological basis of the interactions between nutrition and male reproduction in sheep, focusing on energy balance, protein intake, micronutrient status, and their effects on reproductive performance.

a. Energy Nutrition and Male Reproductive Performance

Energy intake must be tailored to the species, age, body weight, stage of development, and intensity of reproductive activity. During the growth period, meeting energy and protein requirements promotes normal testicular development and the attainment of sexual maturity. In adult males, the diet must support the maintenance of body condition, sperm production, and reproductive activity, without excessive accumulation of adipose tissue.

Severe energy restriction can negatively affect the hypothalamic-pituitary-gonadal axis, with effects on LH and testosterone secretion, libido, and spermatogenesis. Conversely, excess energy intake and obesity can promote metabolic and hormonal imbalances, with potential consequences for sperm quality and embryonic development. These relationships are of particular importance in breeding bulls, where intensive feeding for rapid weight gain must be aligned with reproductive goals.

Proteins provide the amino acids necessary for the synthesis of enzymes, hormones, and cellular structures involved in reproduction. However, increasing protein intake beyond physiological requirements does not guarantee improved fertility. Therefore, the formulation of rations should aim for a balance between energy and protein, based on individual requirements and feed quality [11].

Energy balance is a critical determinant of reproductive function in rams. Both undernutrition and overnutrition can negatively affect testicular function and sperm quality. A negative energy balance reduces circulating testosterone levels and impairs spermatogenesis, leading to decreased sperm concentration and motility [23].

Conversely, excessive energy intake leading to obesity can also affect reproductive performance by altering hormonal profiles and increasing oxidative stress. Therefore, an optimal body condition score (BCS) is essential for maintaining high fertility in rams. Studies have shown that rams maintained at a moderate BCS exhibit improved libido, sperm quality, and mating success [20].

b. Protein Nutrition and Spermatogenesis

Proteins play a central role in male reproductive physiology, as they provide the amino acids necessary for sperm production, hormone synthesis, and testicular development. An adequate protein intake supports normal spermatogenesis and improves sperm quality.

However, imbalances in protein intake can negatively affect reproductive function. An excess of rumen-degradable protein can increase blood urea nitrogen (BUN) levels, which can impair testicular function and reduce sperm quality due to oxidative stress and metabolic disorders [21]. Therefore, maintaining an appropriate balance between rumen-degradable and non-degradable proteins is essential.

c. The Role of Micronutrients in Male Fertility

Micronutrients play a role in cell division, hormone synthesis, sperm maturation, and

protection against oxidative stress. Zinc contributes to the normal functioning of the reproductive system, enzymatic processes, and the structural integrity of sperm. Selenium is involved in the activity of antioxidant selenoproteins, including nd glutathione peroxidases, which protect cellular components from oxidative damage. Deficiencies in these elements can affect testicular function and semen quality.

Vitamin E and vitamin C act as antioxidants, limiting the effects of excess reactive oxygen species. Although reactive oxygen species play a physiological role in the functional maturation of sperm and in fertilization, excessive concentrations can lead to membrane lipid peroxidation, reduced motility, and damage to sperm DNA. The importance of redox balance in male reproduction is highlighted by Moretti and Signorini (2024), who summarize the results of research on the use of antioxidants in human and animal reproduction [24].

Vitamin and mineral supplementation should be based on the composition of the diet, the availability of nutrients, and the species' nutritional requirements. Uncontrolled administration of certain supplements can lead to imbalances or undesirable effects. Consequently, evaluating the base diet and correcting documented deficiencies are more appropriate approaches than the systematic use of high doses of antioxidants.

Micronutrients, particularly trace elements and vitamins, are essential for maintaining male reproductive health. Zinc is a key element involved in testosterone synthesis, sperm maturation, and antioxidant defense. Zinc deficiency has been associated with reduced sperm quality and impaired fertility [25].

Selenium, which often acts in synergy with vitamin E, plays a crucial role in protecting sperm from oxidative damage. Selenium-dependent enzymes, such as glutathione peroxidase, are essential for maintaining the integrity and motility of the sperm membrane [26]. Copper and manganese also contribute to the enzymatic processes involved in energy metabolism and the regulation of reproductive hormones.

Vitamins A, D, and E are important for maintaining testicular function, supporting spermatogenesis, and protecting reproductive tissues from oxidative stress.

d. Oxidative Stress and Sperm Quality

Oxidative stress is one of the main factors affecting male fertility. Reactive oxygen species (ROS) can damage sperm membranes, DNA, and proteins, leading to reduced motility and fertility potential.

Antioxidant nutrients such as selenium, vitamin E, and zinc play a protective role by neutralizing ROS and maintaining sperm integrity. Studies have shown that improved antioxidant status in rams is associated with better sperm quality and higher fertility rates [26, 27].

e. Seasonal Effects and Nutritional Interactions

Reproductive performance in rams is also influenced by seasonal variations, particularly in temperate climates, where photoperiod affects hormonal regulation. During the breeding season, testosterone levels and sperm quality tend to decline.

Nutritional management can help mitigate seasonal declines in fertility. Strategic supplementation with energy, protein, and micronutrients before and during the breeding season has been shown to improve sperm quality and reproductive performance [22].

f. Practical strategies for nutritional management

Effective nutritional management of rams involves maintaining optimal body condition, ensuring a balanced intake of energy and protein, and ensuring an adequate intake of micronutrients. Key strategies include: maintaining a moderate BCS (2.5–3.5) year-round, providing balanced diets with appropriate energy-to-protein ratios, supplementing with zinc, selenium, and vitamin E, avoiding overfeeding that can lead to obesity, and implementing pre-breeding nutritional conditioning programs

These strategies help improve sperm quality, libido, and overall reproductive efficiency.

Effective nutritional management involves coordinating the diet with clinical examination and periodic assessment of reproductive function. In bulls, rams, goats, and boars, monitoring body condition, testicular development, libido, and semen quality can help identify males with reduced reproductive potential. Semen evaluation includes, depending on the species and protocol, ejaculate volume, sperm concentration, motility, morphology, and cell viability.

In mice, oxidative stress is being investigated as a mechanism involved in impaired testicular function and sperm quality. Recent research examines the relationship between redox balance, autophagy mechanisms, and reproductive function, highlighting the need to integrate nutrition with thermal, sanitary, and housing management [28].

In practice, rations must be tailored to the species and the season, while ensuring a constant supply of water and high-quality feed. During periods of intense reproductive activity, nutrient requirements must be reassessed based on body condition and semen analysis results. Supplements with antioxidant effects or plant extracts may represent promising avenues for research, but the results must be interpreted in light of the products' composition, dosages, and experimental conditions [29].

In conclusion, male nutrition plays a crucial role in regulating reproductive performance in sheep through its effects on hormonal balance, spermatogenesis, and sperm quality. Both nutrient deficiencies and excesses can affect fertility, underscoring the importance of balanced and targeted nutritional management. Energy, protein, and micronutrients—such as zinc, selenium, and vitamins A and E—are particularly important for maintaining optimal male reproductive function. Antioxidant protection is also essential for preserving sperm integrity and fertility potential. A better understanding of the nutritional regulation of male reproduction enables the development of more effective feeding strategies. Future research should focus on precision nutrition approaches and the identification of new dietary interventions to improve ram fertility and overall herd productivity.

4. Fetal Programming and Long-Term Effects

Fetal programming refers to the process by which environmental factors—particularly maternal nutrition during gestation—permanently shape the physiology, metabolism, and reproductive potential of lambs. In farm animals, the intrauterine environment is influenced by the female's diet, age, and physiological status, the number of fetuses, milk production levels, metabolic diseases, and climatic conditions. The placenta is the primary structure through which nutrients and oxygen are transferred to the fetus, and changes in its development and function can affect the availability of substrates necessary for fetal growth. Depending on the timing, intensity, and duration of the disruptive factor, responses can range from temporary changes in birth weight to persistent metabolic adaptations [30, 31].

In sheep, this concept has attracted significant attention over the past two decades due to its implications for long-term productivity, health, and reproductive efficiency. The prenatal environment plays a crucial role in determining fetal development, influencing organ formation, endocrine function, and metabolic pathways that persist into adulthood [32, 33].

Maternal malnutrition, overnutrition, or micronutrient imbalances during pregnancy can induce structural and functional changes in the developing fetus, leading to alterations in growth patterns, reduced fertility, and an increased susceptibility to metabolic and reproductive disorders later in life. These effects are mediated by epigenetic changes, hormonal changes, and alterations in placental function [34]. This article explores the physiological basis of fetal programming and its long-term consequences in sheep, based on research published since 2000.

a. Maternal nutrition and placental function

The placenta is the primary interface between the mother and the fetus, regulating the transfer of nutrients and oxygen. Maternal nutrition directly influences the development and function of the placenta, which, in turn, determines fetal growth and development. Malnutrition during early or mid-pregnancy can reduce the size and efficiency of the placenta, leading to restricted fetal growth [33].

Conversely, overnutrition or excessive energy intake can also affect placental function by altering vascular development and nutrient transport mechanisms. These changes can have long-lasting effects on the offspring's metabolic and reproductive systems.

The effects of maternal malnutrition on the reproductive health of lambs are likely to be observed during prolonged periods of malnutrition [35]. The maternal diet not only affects the reproductive life of the ewe but can also alter the reproductive parameters of her offspring. As early as the 1970s, researchers recognized that metabolic changes occurring during prenatal nutrition can affect the productivity of offspring

after birth. Kenyon and Blair (2014) reported that studies demonstrating the effects of nutritional levels higher than those required to maintain pregnancy on the reproductive performance of offspring are rare.

b. Mechanisms involved in fetal programming

One of the main factors involved in fetal programming is an insufficient or unbalanced maternal intake of nutrients. Energy and protein restriction can limit placental development and the transfer of nutrients to the fetus, leading to adaptations designed to prioritize the development of vital organs. Under certain conditions, these adaptive mechanisms can affect skeletal muscle development, pancreatic function, insulin sensitivity, and adipose tissue storage.

Fetal programming may also involve epigenetic mechanisms, such as changes in DNA methylation and gene expression, without altering the nucleotide sequence. These mechanisms can influence cell differentiation and the functioning of certain tissues involved in metabolism, growth, and reproduction. The availability of nutrients such as methionine, choline, folate, and vitamin B12 may contribute to metabolic processes associated with epigenetic regulation. However, the effects depend on the nutrient, dose, species, and stage of gestation, and nutritional interventions do not produce uniform results in all situations [36].

Another important factor is maternal heat stress. High temperatures can alter uterine blood flow, placental function, and the female's metabolic balance, reducing the availability of nutrients to the fetus. In cattle and sheep, prenatal exposure to heat stress has been associated with changes in birth weight, immune development, and subsequent performance. These findings highlight the need to integrate microclimate control with the nutritional management of pregnant females [30].

c. Epigenetic mechanisms of fetal programming

One of the key mechanisms underlying fetal programming is epigenetic modification, which includes DNA methylation, histone modification, and the regulation of noncoding RNA. These modifications can alter gene expression without changing the DNA sequence and can persist throughout life.

Maternal nutrition during gestation can influence the epigenetic regulation of genes involved in growth, metabolism, and reproduction. For example, restricted protein or energy intake during pregnancy has been associated with altered expression of genes that regulate insulin signaling and reproductive hormonal pathways [32, 37]. These epigenetic changes can lead to permanent alterations in physiological function, affecting the fertility and productivity of adult ewes.

d. Effects on fetal growth and development

Fetal growth is highly sensitive to the mother's nutritional status. Inadequate nutrient intake during gestation can lead to intrauterine growth restriction (IUGR), resulting in lambs with low birth weight and impaired organ development.

These lambs often exhibit reduced muscle mass, impaired endocrine function, and a compromised immune system. It is important to note that IUGR is also associated with reduced reproductive performance in adulthood, including delayed puberty, lower ovulation rates, and reduced fertility [34].

e. Long-term effects on growth and metabolism

One of the possible consequences of fetal programming is a change in the postnatal growth rate. Nutritional restriction during gestation can lead to low birth weight and insufficient muscle development. In some cases, after birth, animals exhibit rapid compensatory growth. However, this does not guarantee complete recovery of tissue development, as weight gain may be associated with disproportionate fat accumulation and changes in body composition.

In ruminants, review studies indicate that maternal nutrition can influence the development of metabolic tissues, nutrient utilization efficiency, and carcass characteristics. A meta-analysis of studies on prenatal nutrition in beef cattle highlights the variability of responses depending on experimental conditions, gestational stage, and the characteristics of the animals included [38].

Changes in glucose metabolism, insulin sensitivity, and energy distribution may persist after weaning. Consequently, intrauterine conditions may contribute to differences in productive efficiency among animals subsequently reared under similar conditions. However, these effects are not inevitable and should not be interpreted as identical outcomes for all species or all types of nutritional interventions [30].

Fetal programming has long-term consequences that extend into postnatal life. Animals exposed to suboptimal maternal nutrition during gestation often exhibit impaired glucose and lipid metabolism, increased susceptibility to metabolic disorders, and reduced growth efficiency.

From a reproductive perspective, both male and female offspring may experience impaired fertility. In females, this includes a reduced ovarian reserve, altered estrous cycles, and low conception rates. In males, fetal programming can affect testicular development, sperm quality, and hormonal regulation [33].

These effects highlight the importance of maternal nutrition in shaping the reproductive potential of future generations.

f. Influence on Immunity and Reproductive Function

Fetal programming can influence the development of the immune system and the ability of offspring to respond to infectious agents. Maternal stress and insufficient nutrient intake can alter the development of organs involved in the immune response and affect neonatal adaptation. In calves, these changes are particularly important because health during the first weeks of life influences survival, growth, and future performance.

With regard to reproduction, the intrauterine environment can influence the development of reproductive organs and reproductive capacity in adulthood. The scientific literature shows that nutritional, hormonal, and environmental factors during fetal development can lead to changes in later reproductive function in both females and males. Chavatte-Palmer (2024) highlights the role of the maternal-fetal environment and placental function in establishing physiological trajectories that can persist into adulthood.

In the case of dairy cattle, developmental programming is also analyzed in relation to productive longevity, milk production, fertility, and the health of future cows. However, the relationships between prenatal conditions and adult performance are complex, and the effects must be interpreted in the context of postnatal nutrition, health, genetics, and farm management [39].

g. The Role of Micronutrients in Fetal Programming

Micronutrients such as vitamins and trace minerals play a crucial role in fetal development. Selenium, zinc, and vitamin E are particularly important due to their involvement in antioxidant defense and cellular protection.

Deficiencies in these nutrients during pregnancy can increase oxidative stress in the fetus, leading to cellular damage and impaired development. Vitamins A and D also play roles in organogenesis and the development of the immune system [40].

Adequate micronutrient supplementation during pregnancy has been shown to improve fetal survival, growth, and long-term health outcomes.

h. Intergenerational effects

One of the most significant aspects of fetal programming is its potential intergenerational impact. The mother's nutritional status can influence not only her immediate offspring but also subsequent generations through epigenetic inheritance.

This means that poor maternal nutrition can have cascading effects on herd productivity and reproductive efficiency over several generations. Conversely, optimal nutritional management during pregnancy can enhance long-term productivity and genetic potential [37].

i. Prevention Strategies and Zootechnical Implications

Preventing the adverse effects of fetal programming involves ensuring a balanced diet throughout gestation, with energy, protein, mineral, and vitamin intake adjusted according to the female's requirements. Monitoring body condition, managing metabolic diseases, ensuring access to water, and reducing heat stress are important measures for maintaining placental function and normal fetal development.

Strategic micronutrient supplementation can have beneficial effects when it corrects deficiencies or meets specific physiological needs. However, the use of supplements must be based on the composition of the diet and the species' nutritional requirements, as an excess of certain nutrients can be just as problematic as a deficiency. Swanson et al. (2026) emphasize the importance of an integrated assessment of maternal nutrition, placental function, and postnatal outcomes to identify effective interventions [36].

In conclusion, fetal programming is a critical biological process through which maternal nutrition during pregnancy exerts long-term effects on the health, growth, and reproductive performance of lambs. Nutritional imbalances during gestation can permanently alter physiological and endocrine systems, leading to reduced productivity and fertility in adult animals.
Both undernutrition and overnutrition during pregnancy can negatively affect fetal development through mechanisms involving placental dysfunction, epigenetic changes, and metabolic reprogramming. Micronutrient status is also essential for ensuring normal fetal growth and preventing long-term deficiencies.
Understanding fetal programming provides valuable insights for improving sheep production systems. Implementing optimal maternal nutrition strategies during gestation is essential not only for immediate reproductive success but also for improving the long-term performance and sustainability of the flock.

5. Interaction with Environmental and Management Factors

Reproductive performance in sheep is the result of a complex interaction between nutritional status, environmental conditions, and management practices. Although nutrition is a primary factor in fertility and productivity, its effects are strongly modulated by external factors such as temperature, photoperiod, stress, housing conditions, and overall flock management. Understanding these interactions is essential for optimizing reproductive efficiency across diverse production systems [15, 41].
Environmental factors, such as seasonal variation and climate, significantly influence reproductive physiology in sheep, particularly in temperate breeds that exhibit seasonal reproductive patterns. Management practices, including stocking density, handling, health management, and reproductive scheduling, further affect levels of physiological stress and metabolic status, which, in turn, interact with nutritional signals to regulate reproductive function [42]. This article examines how environmental and management factors interact with nutrition to influence reproductive outcomes in sheep.

a. Photoperiod and Seasonal Reproduction
Sheep are seasonal breeders, and their reproductive activity is strongly influenced by photoperiod. Short days stimulate reproductive activity, while long days suppress it through neuroendocrine regulation involving melatonin secretion. This hormonal signal affects the hypothalamic-pituitary-gonadal (HPG) axis, altering gonadotropin release and ovarian function [41].
Nutritional status can modulate sheep's sensitivity to photoperiodic signals. Sheep in good body condition respond more effectively to the breeding season, exhibiting higher ovulation and fertility rates compared to undernourished animals. Therefore, nutrition and photoperiod act synergistically to regulate reproduction.

b. Heat stress and climatic conditions
Heat stress is a major environmental factor that affects reproductive efficiency, particularly in regions with high ambient temperatures. High temperatures can reduce feed intake, leading to a negative energy balance and impaired reproductive performance. Heat stress also directly affects reproductive physiology by altering hormone secretion, reducing oocyte quality, and increasing embryonic mortality [43].
Cold stress, although less studied, can also increase energy requirements for maintenance, indirectly affecting reproductive function by raising metabolic demands.
Proper nutritional management, including a higher energy density in diets during periods of stress, can help mitigate the negative effects of extreme temperatures.

c. Nutritional-Environmental Interactions
The interaction between nutrition and environmental conditions is highly dynamic. For example, during periods of heat stress, reduced feed intake leads to energy deficits, which negatively impact the secretion of reproductive hormones. Similarly, cold environments increase energy requirements, making an adequate intake of dietary energy essential for maintaining reproductive performance.
Micronutrient requirements may also increase under environmental stress due to high levels of oxidative stress. Antioxidants such as selenium and vitamin E play important roles in protecting

reproductive tissues from heat-induced oxidative damage [44].

d. Management Practices and Reproductive Efficiency

Management practices have a significant impact on reproductive performance in sheep. Factors such as stocking density, frequency of handling, housing conditions, and herd health management can influence stress levels and metabolic status.

High stocking densities and poor handling practices increase physiological stress, which can suppress reproductive hormones and reduce fertility. In contrast, well-managed herds with low-stress environments exhibit improved reproductive performance [15].

Reproductive management strategies, such as controlled breeding seasons, ram introduction techniques, and synchronization protocols, are also influenced by nutritional status. Rams and ewes in optimal body condition respond more effectively to reproductive technologies.

e. Health status and nutrition-disease interactions

Health status is another critical factor that interacts with nutrition and the environment. Infectious and parasitic diseases can reduce nutrient availability by increasing metabolic demands and decreasing feed efficiency.

Diseases such as parasitic infections or mastitis can affect reproductive function by diverting nutrients from reproductive processes to immune responses. Adequate nutrition supports immune function and reduces the negative impact of diseases on reproduction [45].

f. Integrated management systems

Modern sheep production systems increasingly rely on integrated management approaches that combine nutrition, environmental control, and reproductive technologies. Precision agriculture techniques, including monitoring body condition score (BCS), feed intake, and environmental parameters, enable more efficient management of reproductive performance.

Reproductive synchronization, strategic supplementation, and adaptation to the environment are key components of successful reproductive management systems. These approaches aim to minimize the negative effects of environmental stress while maximizing the benefits of optimal nutrition [19].

In conclusion, reproductive performance in sheep is strongly influenced by the interaction between nutrition, environmental conditions, and management practices. These factors do not act independently but are closely interrelated, with each influencing the effectiveness of the others.

Environmental stressors, such as extreme temperatures and photoperiod, interact with nutritional status to regulate reproductive physiology. Similarly, management practices, such as housing, handling, and health monitoring, significantly affect stress levels and reproductive outcomes.

Therefore, optimizing reproductive efficiency requires an integrated approach that takes all these factors into account simultaneously. Future improvements in sheep production will depend on precision management strategies that align nutrition with environmental and management conditions to enhance fertility and productivity.

5. Precision Nutrition and Future Prospects

Precision nutrition is an advanced approach in animal production systems that aims to optimize nutrient intake based on the specific physiological, metabolic, and reproductive needs of animals. In sheep production, this concept has gained increasing importance due to its potential to improve reproductive efficiency, reduce feed waste, and enhance the overall productivity of the flock. Unlike conventional feeding systems, precision nutrition integrates animal-specific data, environmental conditions, and production goals to formulate individualized or group-based dietary strategies [46, 47].

Reproductive performance in sheep is highly sensitive to nutritional status, and even small deviations in energy, protein, or micronutrient intake can significantly affect fertility outcomes. Precision nutrition aims to bridge the gap between nutrient requirements and actual intake through the use of real-time monitoring, predictive modeling, and advanced feeding technologies. Over the past two decades, advances in sensor technology, data analysis, and animal physiology have significantly improved the feasibility of precision feeding systems in livestock production [48].

This article explores the principles of precision nutrition in sheep, its applications in reproductive management, and future prospects for improving

reproductive efficiency through technological innovation.

a. The Concept of Precision Nutrition in Sheep Production

Precision nutrition is based on the principle that nutrient requirements vary among individuals and depending on physiological stages. In sheep, factors such as age, body condition score (BCS), reproductive stage, and environmental conditions influence nutrient requirements.

Traditional feeding systems are often based on average requirements, which can lead to overfeeding or underfeeding. However, precision nutrition uses data-driven approaches to adjust nutrient intake in real time, ensuring optimal metabolic and reproductive responses [47].

b. Role in Reproductive Efficiency

Reproductive performance is closely linked to energy balance, protein intake, and micronutrient status. Precision nutrition allows for the fine-tuning of these components to support key reproductive processes, such as follicular development, ovulation, and embryo survival.

For example, targeted energy supplementation prior to breeding (flushing) can be optimized by individually monitoring BCS and metabolic indicators. Similarly, protein and amino acid intake can be adjusted to prevent both deficiency and excess, reducing risks such as poor embryo development due to high levels of urea nitrogen in the blood [46].

c. Technologies Supporting Precision Nutrition

Recent advances in technology have enabled the practical implementation of precision nutrition in sheep farming systems. These include: electronic identification (EID) systems for individual animal tracking, automatic feeders that adjust feed intake based on the animals' requirements, sensor technologies for monitoring body temperature, activity, and rumination, remote sensing and imaging tools for assessing body condition scores, data analysis, and predictive modeling to estimate nutrient requirements. These technologies enable continuous monitoring and adjustment of diets, improving both efficiency and reproductive performance [48].

d. Integration with reproductive management

Precision nutrition is most effective when integrated with reproductive management strategies. Synchronization protocols, artificial insemination programs, and ram management can be optimized through precise nutritional support.

For example, ewes on synchronization programs benefit from a carefully controlled intake of energy and protein to maximize the ovulatory response. Similarly, rams require optimized nutrition to maintain sperm quality and libido during the breeding season [19].

e. Environmental sustainability and efficiency

One of the main advantages of precision nutrition is its contribution to environmental sustainability. By tailoring nutrient intake to actual requirements, feed waste and nitrogen excretion are reduced, thereby minimizing the environmental impact.

Improved feed efficiency also reduces production costs and enhances the sustainability of sheep-raising systems. This is particularly important in the context of climate change and increasing pressure on natural resources [47].

f. Future Prospects

The future of precision nutrition in sheep production is closely linked to advances in digital agriculture and biotechnology. Emerging trends include: the integration of artificial intelligence (AI) for predictive nutritional modeling, the use of genomic information to tailor diets based on genetic potential, the development of smart feeding systems with real-time adjustment capabilities, the application of metabolomics and biomarker analysis to assess nutritional status, and the increased use of big data analysis for herd-level decision-making. These innovations are expected to significantly improve reproductive efficiency, reduce production variability, and enhance animal welfare [46].

In conclusion, precision nutrition represents a transformative approach in sheep production, offering significant potential for improving reproductive performance, productivity, and sustainability. By tailoring nutrient intake to individual animal needs and physiological states, precision feeding systems can optimize metabolic and reproductive functions. The integration of advanced technologies, data-driven decision-making, and reproductive management strategies is essential for maximizing the benefits of

precision nutrition. Although still under development, this approach is expected to play a central role in the future of sheep production systems. Ongoing research is needed to refine predictive models, improve technological accessibility, and better understand the complex interactions between nutrition, genetics, and reproduction.

4. Conclusions

Nutritional management tailored to physiological stages is essential for maintaining health and improving the productive and reproductive performance of sheep. The most important measures include formulating rations based on individual requirements, ensuring high-quality feed, monitoring body condition, and preventing energy and mineral imbalances. Particular attention must be paid to late gestation and the transition to lactation, when metabolic changes are intense and the risk of disease increases. Integrating the principles of precision nutrition and systematic monitoring can help increase economic efficiency, improve animal welfare, and develop sustainable livestock systems.

Nutrition is a key determinant of male reproductive function in farm animals, influencing testicular development, testosterone secretion, spermatogenesis, and semen quality. Ensuring a balanced intake of energy, protein, vitamins, minerals, and essential fatty acids helps maintain fertility and optimize reproductive performance. Nutritional deficiencies, excess energy intake, and antioxidant imbalances can compromise reproductive performance. Therefore, nutritional management must be integrated with periodic assessments of body condition and semen quality to support the efficient use of breeding males and achieve predictable reproductive outcomes.

Fetal programming is an important mechanism through which nutrition and environmental conditions during gestation can influence the health, growth, metabolism, and reproductive function of offspring. These effects can persist into adulthood and influence the productive and economic efficiency of livestock operations. Proper management of maternal nutrition, prevention of heat stress, and monitoring the health of pregnant females are essential measures for reducing these risks. Further longitudinal studies are needed to clarify the epigenetic mechanisms and to identify nutritional interventions with reproducible, long-term beneficial effects.

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