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REVIEW

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Pelleted total mixed ration in sheep nutrition: A review of growth performance, rumen fermentation, and practical applications

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ABSTRACT. Pelleted total mixed ration (PTMR) has become a widely adopted feeding strategy in modern intensive ruminant production systems. It is a compound feed that combines various feed ingredients and additives to meet the nutritional requirements of ruminants. Studies in sheep, goats, cattle, and buffaloes have shown that PTMR increases feed intake, alters rumen microbial composition, and improves growth performance compared to conventional total mixed ration (TMR). However, its effect on nutrient digestibility remains inconsistent across studies. PTMR feeding has also been associated with changes in blood metabolite levels, although most parameters stay within normal physiological ranges. Despite these advantages, the wider adoption of PTMR is limited by high processing costs and the need for stringent quality control to ensure pellet quality and long-term rumen health. Unlike earlier narrative reviews, this work identifies the main factors underlying the variability in reported outcomes, discusses methodological limitations of the available literature, and provides practical recommendations for small-scale farmers. It also highlights priorities for future research, including the long-term effects of PTMR on rumen health, economic sustainability, and the optimisation of formulations for different production stages, thereby supporting its broader application in sustainable ruminant production systems.

KEY WORDS: feed intake, growth performance, pelleted total mixed ration, rumen fermentation, sheep, small ruminants

Introduction

The history of ruminant feeding has shifted from traditional pasture grazing to intensive confinement systems due to increasing demand for animal products and limited natural resources (Bocquier and González-García, 2010; Moorby and Fraser, 2021; Wróbel et al., 2023). In these systems, animals cannot meet their nutritional requirements through grazing alone; therefore, total mixed ration (TMR) has become a widely adopted feeding method (Eastridge, 2006). TMR combines forages, concentrates, protein supplements, minerals, and vitamins into a single feed (Costa et al., 2019; Liu et al., 2021; Jing et al., 2025), which ensures a balanced nutrient supply and reduces feed sorting (Alhidary et al., 2016; Bharanidharan et al., 2018; Pereira et al., 2025; Rooney et al., 2025).

However, the use of TMR presents significant challenges, particularly in developing regions. In China, limited natural resource availability restricts access to high-quality forages (Liu et al., 2008; Xu et al., 2025). Maize silage and alfalfa hay, i.e., main energy and protein sources in ruminant diets, are often expensive and difficult to obtain, and thus increase production costs for farmers (Wang and Zou, 2020). Consequently, interest has grown in the use of locally available, low-cost agricultural byproducts, such as wheat straw, rice straw, and cottonseed meal, as alternative ingredients (Li et al., 2021b; Yang et al., 2021; Shah et al., 2025). Commercial feed producers in China have pioneered the production of pelleted total mixed ration (PTMR), enabling farmers to use pelleted feed without investing in pelleting equipment (CJ (Tianjin) Feed Co., 2025;

New Hope Liuhe Co., 2025). Field trials have demonstrated positive effects of PTMR on lamb growth performance (Li et al., 2021a).

The development of PTMR has stimulated extensive research comparing it to traditional TMR. Previous studies have shown several advantages of PTMR over TMR, including higher feed intake, reduced waste, and improved labour efficiency (Zhong et al., 2018). Additionally, the compact, dense structure of PTMR simplifies storage and transport, making it particularly valuable as livestock production expands and animal transportation increases (Zhong et al., 2020; Li et al., 2021a).

Nevertheless, these studies have also identified several limitations. Pelleting increases starch gelatinisation, which may lead to excessive ruminal starch degradation and elevated risk of subacute ruminal acidosis, particularly in high-concentrate diets (Zhang et al., 2023). Commercial PTMR production requires specialised industrial equipment and careful formulation to obtain pellets of adequate quality (Thomas and van der Poel, 2020; Paulk et al., 2022), which may increase feed costs for farmers purchasing ready-made products. Furthermore, the effects of pellet hardness and particle size on feeding behaviour and rumen function remain poorly understood, and their long-term effects on sheep welfare have yet to be determined.

Therefore, the goal of this review is to consolidate current knowledge on PTMR use in sheep. It evaluates the effects of PTMR on productivity, digestion, and overall health relative to traditional TMR, with particular attention to the developing sheep industries. It also identifies areas that require further investigation, including long-term effects on rumen health, limited species-specific studies in small ruminants, and the need to optimise formulations to maintain feeding efficiency without compromising fibre effectiveness.

The present review synthesises the available evidence across five key areas: (1) identification of the main confounding factors contributing to variability in reported outcomes, including pelleting temperature, forage-to-starch ratio, and physically effective fibre; (2) evaluation of methodological limitations in the current literature, including small sample sizes, short experimental periods, and the lack of longitudinal studies; (3) assessment of the available evidence concerning individual production stages, highlighting that most PTMR studies have focused on growing lambs, whereas information on dairy ewes and breeding rams remains limited; (4) practical guidelines for small-scale sheep producers, including a distinction between low-forage and high-concentrate PTMR formulations together with recommendations on formulation thresholds, pellet size, and feeding frequency to reduce the risk of ruminal acidosis; and (5) integration of findings on nutrient digestibility and rumen fermentation by considering processing variables, such as pelleting temperature and die size, together with dietary factors, including physically effective neutral detergent fibre (peNDF) and forage source, to explain variation between studies. By integrating processing parameters with digestive physiology and practical farming considerations, particularly in the context of smallholder sheep production systems in China, this review provides a framework for the strategic implementation of PTMR in small ruminant production systems.

Material and methods

This article followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) to ensure methodological transparency and rigour throughout the study selection process.

Search protocol

A comprehensive literature search was conducted using six electronic databases: PubMed, Web of Science, Scopus, CAB Abstracts, IEEE Xplore, and Google Scholar. Searches were performed between January and March 2026, with no restrictions on publication date. The search strategy employed Boolean operators to combine three core groups of search terms: (a) feed processing terminology (e.g., pelleted total mixed ration, PTMR, complete feed pellet, steam conditioning); (b) target species (e.g., sheep, lamb, small ruminant, fattening lamb); and (c) outcome variables (e.g., dry matter intake, nutrient digestibility, rumen fermentation parameters, blood metabolites, carcass characteristics). Additionally, relevant industry reports, technical guidelines, and feed company documentation were identified through targeted web searches to capture information on practical applications and commercial PTMR formulations unavailable in the peer-reviewed literature.

Eligibility criteria

Articles were subjected to full-text review if they met the following criteria: (a) evaluated pelleted total mixed rations in sheep or other small ruminants with appropriate control comparisons (unpelleted TMR, mash, or separate feeding); (b) quantified at least one measure of animal performance, digestion, rumen fermentation, metabolism, or carcass characteristic; (c) were peer-reviewed experimental or observational study; and (d) were published in English with accessible full text. Studies were excluded if they: involved non-ruminant species, trials lacked pelleted treatments, were conference abstracts, theses, other unpublished material, or provided insufficient statistical information. Supplementary web-based sources were assessed for relevance and reliability, with preference given to established agricultural organisations, feed industry associations, and government extension services.

Selection and extraction

The initial search retrieved 1200 citations. Following the removal of duplicates (n = 371), 829 records were screened by title and abstract, resulting in 238 articles selected for full-text review. Of these, 146 were excluded for not meeting the eligibility criteria, resulting in 92 studies for inclusion in the qualitative synthesis. Data extracted from each study included: the author(s), year of publication, experimental design, animal characteristics, dietary treatments, outcome measures, and principal findings. For web-based sources, data extraction focused on verified technical specifications, formulation guidelines, and field application information relevant to small-scale farm implementation.

Data synthesis

To provide critical synthesis of the available evidence, the literature was analysed by (a) identifying the key factors contributing to variation in reported outcomes (pelleting temperature, forage-to-starch ratio, and physically effective fibre), (b) evaluating methodological limitations (small sample sizes, short feeding durations, and the lack of longitudinal studies), and (c) deriving practical guidelines for small-scale producers (formulation thresholds, pellet size recommendations, and feeding frequency to reduce the risk of ruminal acidosis).

Development of feeding systems in ruminants

Transition from component feeding to total mixed ration

Traditionally, ruminants were fed using a component-based feeding system, in which forages and concentrates were offered separately, usually by volume rather than weight (Coppock et al., 1981). This method often caused imbalanced nutrient intake, as animals selectively consumed preferred feed ingredients, leading to variable nutrient intake and reduced performance (Rakes, 1969; Coppock, 1977; Olsson et al., 1997). To overcome these limitations, feeding practices gradually evolved. Concentrates were initially provided during milking but were later separated from this process to improve feeding efficiency and animal welfare (Eastridge, 2006; Bramley et al., 2008). Increasing herd sizes and the widespread adoption of bulk milk tanks further accelerated the transition toward group housing and feeding systems (Barberg et al., 2007), ultimately leading to the adoption of mixed ration systems, especially partial mixed rations (PMR) and, subsequently, total mixed rations (TMR) (Wales et al., 2013; Barber et al., 2019; Berthel et al., 2022; Chengqiang, 2024). The concept of TMR originated in the mid-20th century as a means of providing ruminants with a balanced and consistent diet (McCoy et al., 1966). Early literature in the 1950s described the idea of a "complete ration," in which all feed ingredients were thoroughly blended to prevent separation and sorting, formulated to specific nutrient requirements, and offered *ad libitum* (Harshbarger, 1952; Hernandez-Urdaneta et al., 1976; Qin et al., 2025). By the late 20th century, this concept evolved into the modern TMR system, in which forages, concentrates, minerals, and vitamins are combined into a single ration (Teshome et al., 2017; Bueno et al., 2020). Initially adopted in dairy and beef cattle production, TMR enabled more precise nutrient delivery as herd sizes and production intensity increased (Cabrera and Kalantari, 2016). Currently, TMR is also utilised in small-ruminant production, including sheep and goats (Monzón-Gil et al., 2010; Ozman, 2021). Studies have demonstrated that TMR supports different production stages, including growth and lactation, by providing a uniform and balanced diet (Phillips and Rind, 2001; Gadeken and Casper, 2017; Mohammad et al., 2017). In addition, TMR facilitates the incorporation of agricultural byproducts and crop residues into ruminant diets (Cao et al., 2009). More recently, alternative physical forms of TMR, including mash and block rations, have been evaluated and shown to maintain or improve milk production while reducing labour and feeding costs compared with conventional feeding systems (Sarker et al., 2019). Furthermore, TMR has emerged as one of the most effective feeding strategies for ram lambs reared under intensive production systems (Pankaj et al., 2023).

Advantages and limitations of the total mixed ration feeding system

Total mixed ration (TMR) has become popular in modern ruminant production due to its ability to improve nutrient utilisation, rumen stability, and production efficiency (Tozer et al., 2003; Schären et al., 2016). TMR reduces digestive problems through the continuous availability of nutrients and fibre, which stabilises rumen pH, supports microbial growth and activity (Dey et al., 2025). This approach also allows the precise formulation of rations for specific production groups and eliminates the need for separate concentrate feeding (Sova et al., 2014). A further benefit is the safe use of non-protein nitrogen sources, such as urea, which are more effective when evenly distributed throughout the diet (Wahyudi et al., 2021). TMR can also mask the flavour of low-quality or unpalatable ingredients when mixed with silage, allowing farmers to use lower-cost feedstuffs without reducing intake (Lee et al., 2015; Ferrari et al., 2024). This principle also helps prevent milk fat depression by maintaining adequate dietary fibre levels (Zebeli et al., 2006). Moreover, TMR feeding reduces labour requirements, particularly when automated mixing and delivery systems are used (Schingoethe, 2017).

However, this feeding system also has some limitations. A major challenge, especially for small-scale operations, is the high initial cost of equipment such as mixer wagons, electronic load cells, and forage choppers. Data from the United States Department of National Animal Health Monitoring System (USDA) show adoption rates of almost 90% in large herds (>500 cows) but less than 20% in small farms (30–90 cows) (Schingoethe, 2017). Hay or long forage must be chopped before mixing, adding extra time and processing requirements (Costa et al., 2019). Furthermore, many barns are designed to accommodate larger herds, making the management of smaller and more specific groups difficult. Although TMR has been developed to prevent feed sorting, it does not completely eliminate it, as animals may still select particles based on size or palatability, potentially compromising nutritional consistency, causing digestive problems, and ultimately reducing performance (Miller-Cushon and DeVries, 2017; Chen et al., 2025). Additionally, silage exposed to aerobic spoilage poses direct health risks to animals, mainly due to mycotoxin contamination, which may impair ruminant health, fertility, and production (Martins et al., 2024). Ration accuracy can also be affected when feed refusals differ in nutrient composition from the original ration (Carneiro et al., 2021). Moreover, the system requires accurate formulation and frequent adjustments based on feed analysis; otherwise, nutrient imbalances may arise, causing severe health problems such as reduced rumen pH, increased risk of acidosis, disrupted microbial activity, and decreased fibre digestion (Singh et al., 2022; Arbaoui et al., 2025). In addition, TMR is unsuitable for grazing-based production systems due to logistical and economic limitations (Schingoethe, 2017). Furthermore, research has shown that TMR feeding systems emit more methane compared to pasture-fed livestock. Therefore, strategies such as fermented TMR (FTMR) and feed additives may help reduce methane production and the carbon footprint of TMR feeding systems (O'Neill et al., 2011; Li et al., 2021c).

In China, these challenges are particularly prominent. Smallholder farmers, who dominate the sheep industry, often cannot afford TMR equipment. Additionally, the variable quality of locally available feed resources, such as rice and wheat straw, makes it difficult to formulate nutritionally uniform TMR rations, limiting their widespread adoption. Moreover, TMR feeding standards developed for dairy cattle may not be directly applicable to sheep because of physiological and metabolic differences and thus require specific modifications for small ruminants.

Pelleted total mixed ration: An advanced feeding strategy

To address these limitations, pelleted total mixed ration (PTMR) was developed as an advanced feeding strategy based on the TMR concept. PTMR is a compound feed composed of various ingredients and additives formulated to meet the nutritional requirements of ruminants for crude protein (CP), energy, fibre, minerals, and vitamins (Chen et al., 2022). Pelleting has a long history, having been first introduced into the feed industry in the 1920s and later widely adopted in poultry and swine production (Garnsworthy, 2013; Manu and Baidoo, 2020). In ruminant systems, ground hay was first pelleted in the 1950s and 1960s to improve its feeding value; however, interest subsequently declined because of the limited availability of mobile pelleting equipment, high processing costs, and only modest improvements in forage consumption (Minson, 1963). With advances in pelleting technology and renewed interest in the benefits of pellet diets, its use in ruminant feeding has increased significantly. Currently, the main applications include alfalfa pellets and pelleted concentrates for dairy cattle (Ishaq et al., 2019; Shrinivasa, 2020). Pelleted supplements are also widely used for winter feeding of sheep and cattle to reduce environmental losses. PTMR enables farmers to manage feedlots more efficiently and utilise local crop residues as feed, providing a practical solution in regions such as China, where sheep production is widespread, by lowering feeding costs and improving ration quality (Zhang et al., 2025).

The production of PTMR involves accurate mixing, steam conditioning, and pellet formation, during which the feed is exposed to moisture, high pressure, and temperatures up to 95 °C (Campabadal, 2014; Song et al., 2021). This thermal processing significantly improves feed efficiency by increasing nutrient availability for rumen fermentation and the physical quality of the feed (Thomas and van der Poel, 2020). One advantage of the pelleting process is the production of uniform pellets, in which feed ingredients are bound together to form a homogeneous feed. This process can be enhanced by the addition of binders, which improve pellet strength, extend shelf life, and reduce fines. Nutritive binders may also provide additional minerals, such as magnesium, calcium, potassium, and sulphur (Thomas and van der Poel, 1996; Wanapat et al., 2013). This stable physical form offers three main advantages. First, it prevents feed sorting, thereby reducing selective consumption of palatable ingredients and ensuring a more consistent nutrient intake. Second, the higher bulk density of pellets improves feed handling, reduces storage requirements, and lowers shipping costs, making long-distance transport more efficient than with conventional TMR. Third, the dry, stable form reduces spoilage during storage and preserves dry matter (Kaliyan and Vance Morey, 2009; Retnani et al., 2014a; 2014b; Beigh et al., 2016; Sun, 2017; Cha, 2018). Furthermore, this process provides more uniform nutrient intake, which helps stabilise the rumen environment and may reduce the risk of both acute and subacute rumen acidosis (Retnani et al., 2022). As a result, nutrient utilisation and feed conversion efficiency may be improved. However, these benefits may be reduced if pelleting decreases fibre particle size to the extent that its physical effectiveness in the rumen declines (Bonfante et al., 2016). In addition, pelleted feed has been associated with higher body weight, carcass weight, dry matter intake (DMI), average daily gain (ADG), and carcass yield compared with unpelleted feed (Zhang et al., 2019; Li et al., 2021a). Another advantage is that the heat applied during pelleting breaks down complex fibres and increases starch gelatinisation, thereby improving feed digestibility (Abdollahi et al., 2013). Table 1 summarises the historical evolution of ruminant feeding systems, from traditional separate feeding to the modern pelleted total mixed ration.

Comparison between pelleted and unpelleted total mixed ration in ruminants

Comparing a PTMR with an unpelleted TMR is essential for understanding how feed processing affects modern ruminant nutrition. Although both feeding systems are intended to provide a balanced diet, pelleting alters the physical structure of the feed and increases nutrient availability, which may affect animal performance and overall production efficiency (Song et al., 2021). The mechanical pressure and heat used during pelleting modify the physicochemical properties of feed components, including starch and fibre, thereby influencing nutrient digestion and utilisation (Solanas et al., 2008; Abdollahi et al., 2013). Although these changes offer several advantages, they also require careful management to avoid adverse effects on rumen function. Several studies have evaluated the effects of PTMR feeding in different ruminant species, as discussed in the following sections.

Effects on production performance in small ruminants

Growth performance in ruminants is largely determined by feed intake and the efficiency of nutrient utilisation (Owens et al., 1993). Pelleting reduces rumen fill, enabling animals to consume more feed before reaching satiety, thereby favouring increased DMI (de Vega et al., 2025). The magnitude of this effect, however, depends on whether physical form or nutrient composition is the primary variable. Studies conducted in different sheep breeds and regions have shown that PTMR markedly improves DMI, ADG, and carcass yield compared to unpelleted TMR or separate feeding. For example, Li et al. (2021a) reported 15–34% increases in DMI and 19–38% in ADG in three experiments; Zhang et al. (2019), on the other hand, observed a 5-percentage-point increase in carcass yield, while Zhong et al. (2018) obtained 24% higher DMI and 27% higher ADG. These improvements have been reported in different sheep breeds (Ujumqin, Dorper × small-tail Han crossbred, and thin-tailed × fine-wool hybrids), experimental designs (n = 7–12 per treatment, trial durations = 24–67 days), and feeding conditions (*ad libitum*, individual or group pens). A meta-analysis by Retnani et al. (2022) confirmed these positive effects on DMI (effect size = 1.51, $P < 0.001$) and ADG (effect size = 0.91, $P < 0.001$), while also reporting a decline in dry matter digestibility (effect size = −0.79, $P = 0.001$), indicating a trade-off between intake volume and digestive efficiency. This mechanism is supported by the work of Bonfante et al. (2016), who observed a marked reduction in peNDF (from 39.8% to 11.8%) following pelleting. Consequently, Udén (1988) demonstrated that pelleting accelerated the ruminal passage rate, reducing the mean retention time of total solids from 73 to 54 h and the NDF fermentation rate from 0.094 to 0.051 h^{-1}. These changes resulted in reduced DM digestibility (0.73 vs. 0.67) and NDF digestibility (0.79 vs. 0.68), a negative effect also reported by Greenhalgh and Reid (1973) in both sheep and cattle. However, most individual studies include small sample sizes (n = 6–12) and short feeding periods (30–90 days) (Coufal-Majewski et al., 2017; Zhong et al., 2018), limiting the generalisation of these findings to long-term production systems.

In addition to nutrient composition, the physical form of the diet also affects feed intake and animal performance. Diet properties, including texture, particle size, shape, and the method of feed presentation, influence feeding behaviour, rumen activity, and overall health in lambs and goats (Karimizadeh et al., 2017; Malik et al., 2020). In lambs, separate rearing with PTMR has been shown to improve final body weight (39.2 vs. 30.5–32.9 kg), ADG (294 vs. 162–203 g/day), and feeding efficiency, while reducing production costs by 19–40% (Khaleel and Mansoor, 2023). However, these results were obtained from smallholder manual feeding systems and may not be directly applicable to intensive production systems using automated feeding. In goats, pelleted diets containing higher levels of roughage (up to 60% of the diet) can be successfully applied without compromising growth. For example, pelleted diets with sorghum straw as the sole roughage source (Dhore et al., 2014) or Rhodes grass hay at 250 kg/t (Malik et al., 2023) improved DMI, ADG, and feed efficiency compared to diets containing lower roughage levels or mash diets. Advanced processing methods may further improve these responses, although their effectiveness depends on the initial quality of the forage. For instance, alkali treatment combined with pelleting improved the nutritive value of low-quality roughages such as rice straw, resulting in more than a twofold increase in ADG (87.6 vs. 40.3 g/day) and a 28% improvement in FCR (10.8 vs. 15.1 kg/kg) in Boer goats (Pi et al., 2005). Similarly, incorporating forage rape in PTMR improved rumen microbial composition and meat quality in Hu lambs (Du et al., 2022a).

However, the extent of these improvements depends on breed, diet composition, and processing conditions. While most studies have reported positive effects on growth performance, some observed no difference in ADG between high-grain pelleted and unpelleted TMR (Trabi et al., 2019), suggesting that the benefits of pelleting are most pronounced when the physical form of the diet, rather than nutrient composition, is the primary factor. Table 2 summarises the effects of pelleted total mixed ration on growth performance in sheep, including DMI, ADG, FCR, and carcass yield reported in multiple breeds and dietary formulations. Overall, the available evidence indicates that PTMR generally improves feed intake and growth performance, while also identifying conditions under which pelleting advantages are diminished, supporting its strategic application in intensive sheep production systems.

Effects on nutrient digestibility in small ruminants

The effect of pelleting on nutrient digestibility remains inconsistent among studies, reflecting complex interactions between feed physical form, diet composition, and rumen function. Some studies have reported no change or only slight decreases in DM digestibility. For instance, Coufal-Majewski et al. (2017) found no significant effect of pelleting on DM digestibility in lambs fed control (702 vs. 706 g/kg) or low-alkaloid diets (712 vs. 711 g/kg), although a numerical decrease was observed in high-alkaloid diets (713 vs. 678 g/kg). In contrast, Li et al. (2021a) reported moderate but still significant reductions in DM digestibility with PTMR: from 64.7% to 61.6% (a 3.1 percentage-point decrease). Conversely, other studies have obtained improvements in nutrient digestibility. Zhong et al. (2018) found that PTMR increased the digestibility of CP (from 73.2% to 75.6%), ADF (from 43.0% to 47.2%), ether extract (from 69.6% to 72.0%), and starch (from 70.1% to 72.5%). Similarly, Karimizadeh et al. (2017) observed increases in DM digestibility (from 64.05% to 66.89%) and ADF digestibility (from 32.01% to 36.75%), whereas CP digestibility was not significantly affected (62.03% vs. 62.12). Processing conditions also influence these responses; a conditioning temperature of 75 °C has been shown to preserve CP and starch digestibility and support optimal growth performance, whereas NDF and ADF digestibility increased further at 85 °C (Ran et al., 2021). Similarly, low forage-to-starch ratios decrease digestibility linearly, and an optimal forage neutral detergent fibre-to-rumen degradable starch (FNDF/RDS) ratio of 0.8 has been recommended (Zhang et al., 2024). Fibre content also modifies these responses, as elevated inclusion of ground straw from 50 to 250 g/kg was demonstrated to increase NDF intake from 156 to 341 g/day and ADF intake from 47 to 146 g/day, while raising rumen pH from 5.24 to 5.69 (Blanco et al., 2015). Energy digestibility also changes following pelleting, as demonstrated by an increase in total digestible nutrients (TDN) from 50.86% to 54.13% and a decrease in digestible crude fibre (DCF) from 15.39% to 12.67% ($P < 0.05$) in Garole sheep (Islam et al., 2017). Dietary modifications further alter these outcomes; alternative forage sources have been demonstrated to enhance DM digestibility (Chen et al., 2021), while rumen-protected additives have not consistently affected digestibility (Huo et al., 2022). These findings indicate that the effects of pelleting on nutrient digestibility depend on processing conditions, diet composition, and rumen functions.

Specifically, pelleting reduces peNDF, which stimulates rumination and maintains rumen retention time. Consequently, smaller particles pass through the rumen more rapidly, reducing the time available for microbial fermentation of cellulose and hemicellulose (Udén, 1988). Because fine grinding eliminates the retention of small particles within larger fibre networks, they exit the rumen independently of their fermentation state, resulting in the loss of potentially degradable fibre prior to complete microbial degradation. Reduced peNDF and faster passage rate also decrease rumination and saliva production, lowering rumen buffering capacity and creating suboptimal pH conditions for cellulolytic microorganisms, particularly in grass-based diets rich in water-soluble carbohydrates (Udén, 1988; Bernard et al., 2000; Blanco et al., 2015). Collectively, these mechanisms explain why pelleting most consistently reduces NDF and ADF digestibility, whereas starch and protein digestibility may increase because of higher starch gelatinisation and improved accessibility of soluble substrates.

A meta-analysis by Retnani et al. (2022) further confirmed that pelleted diets have significantly lower DM (effect size = −0.79, $P = 0.001$), OM (effect size = −0.88, $P = 0.001$), NDF (effect size = −1.07, $P < 0.001$), and ADF (effect size = −0.87, $P = 0.022$) digestibility compared to unpelleted diets. High heterogeneity (I^2 = 76–83%, $P < 0.001$) indicated that the magnitude of these effects varied among studies due to differences in pelleting temperature, conditioning time, moisture content, and dietary composition. The meta-analysis found no significant effect on CP digestibility (effect size = 0.10, $P = 0.714$), supporting the conclusion that fibre fractions are more susceptible to pelleting-induced changes than soluble nutrients.

Overall, these results suggest that while pelleting may reduce fibre digestibility due to a faster ruminal passage rate, the net effect on nutrient utilisation remains positive because increased DMI compensates for the reduction in digestive efficiency. Table 3 summarises the effects of pelleted total mixed ration on nutrient digestibility in sheep, presenting digestibility coefficients for DM, OM, CP, NDF, ADF, and other components in numerous studies. The comparison reveals inconsistent responses, with pelleting generally reducing fibre digestibility while, under certain conditions, improving starch and protein digestibility depending on processing conditions and diet composition. These findings help explain the overall benefits of PTMR in intensive sheep production systems.

Effect on ruminal fermentation and microbiota in small ruminants

The variable effects of pelleting on digestibility reflect complex interactions between feed physical form and the ruminal environment, particularly pH and microbial metabolism. Some studies have reported that pelleted TMR decreases rumen pH, with reductions of 0.25–0.31 units observed 3 h after feeding (Li et al., 2021a). This effect has been attributed to faster feed consumption (115 vs. 200 min/day) and a 24–34% increase in dry matter intake, which provides more substrate for microbial fermentation (Zhong et al., 2018; Li et al., 2021a). In contrast, other studies have reported no changes in rumen pH or an increased risk of acidosis (Karimizadeh et al., 2017; Zhang et al., 2019). This discrepancy may partly reflect differences in sampling methodology. For instance, Zhang et al. (2019) collected rumen fluid samples after a 12-hour fast, which may have stabilised pH before sampling. Overall, the available evidence suggests that PTMR does not consistently induce clinical acidosis, although the risk of subacute ruminal acidosis (SARA) depends on diet composition and individual animal susceptibility.

PTMR alters rumen microbial composition, although its effects on microbial diversity are inconsistent. Pelleting increases the abundance of beneficial bacteria, such as *Prevotellaceae* and *Bacteroidales,* while reducing fibre-degrading bacteria, including *Ruminococcaceae* and *Lachnospiraceae,* thereby stimulating volatile fatty acid production (Zhang et al., 2019). Yeast supplementation further stabilises rumen pH and promotes the development of fibre-degrading bacterial populations (*NK4A214*, *FD2005*), as well as n-butyrate production (Wang et al., 2023). However, high-grain pelleted TMR reduces microbial diversity and changes the bacterial composition towards higher abundances of *Megasphaera* and *Ruminococcus,* increases lactate concentrations, elevates inflammatory markers (tumour necrosis factor-alpha [TNF-α], and interleukin-6 [IL-6]), and causes rumen epithelial damage in Hu sheep (Trabi et al., 2019; 2020).

However, these changes in microbial communities do not necessarily result in epithelial damage when diet formulation is optimised, suggesting that pelleting itself does not compromise tissue health (Trabi et al., 2019).

Forage source and processing conditions have an important influence on rumen health. Alfalfa-based diets maintain significantly higher rumen pH (6.94 vs. 5.24–5.77 for ground straw pellets) and healthier rumen mucosa (greater papillae density and lighter colour) than concentrate-based pellets containing ground barley straw (Blanco et al., 2015). Meanwhile, native grass hay can replace up to 30% of alfalfa in pelleted total mixed rations without major alterations in the dominant rumen bacterial phyla and genera (Du et al., 2022b), although changes in alpha diversity and specific genera (e.g., *Clostridiales*, *Oscillibacter*) may occur. In the hindgut, pelleted high-grain diets appear to stabilise fermentation by enriching the population of acetate-producing genera and reducing the number of starch-degrading bacteria compared to unpelleted high-grain diets (Lin et al., 2021). Grain type and pelleting temperature are also important; sorghum-based PTMR processed at 75 °C optimises propionate production and the acetate-to-propionate ratio, although it may reduce dressing percentages compared to maize-based diets (Ran et al., 2021). PTMR also changes the ruminal microbiome by increasing the abundance of *Fibrobacter* and *Veillonellaceae*, supporting amino acid and steroid biosynthesis pathways (Li et al., 2022).

Taken together, these findings demonstrate that PTMR improves livestock production by increasing feed intake and growth. However, most studies on the rumen microbiota have been conducted over relatively short periods (30–60 days) and do not report adaptation phases, making it difficult to assess long-term changes in rumen function. Table 4 summarises the effects of pelleted total mixed ration on rumen fermentation in sheep, including changes in rumen pH, total volatile fatty acid concentrations, and rumen microbial composition under different diet composition and processing conditions.

Effect on blood metabolites in small ruminants

Blood metabolite profiles in sheep fed PTMR generally remain within normal physiological ranges, indicating that properly balanced PTMR does not adversely affect metabolic status (Li et al., 2021a). For example, Islam et al. (2017) reported plasma glucose concentrations of 6.15–6.18 mmol/dl and total cholesterol concentrations of 36.7–37.7 mg/dl in Garole sheep fed pelleted diets. However, haematological outcomes depend on specific pellet composition. Ojo et al. (2019) found that *Lablab purpureus* pellets did not affect haematological parameters (packed cell volume [PCV] ~30%, haemoglobin [Hb] ~97 g/l), while feeding with *Mucuna pruriens* pellets resulted in lower values (PCV 27.08%, Hb 81.98 g/l) probably because of their higher tannin content (40.5 vs. 17.5 mg/kg). These findings indicate that the composition of pellet ingredients significantly affected blood parameters.

Protein metabolism indicators show consistent trends across studies, although the effects vary with diet composition. Blood urea nitrogen (BUN) concentrations are typically elevated in sheep fed PTMR, reflecting increased CP intake rather than metabolic dysfunction (Martin et al., 2005; Javaid et al., 2008; Karimizadeh et al., 2017; Zhong et al., 2018). However, the effect depends on the breed and protein source. Pi et al. (2005) reported that alkali-treated PTMR reduced BUN levels from 8.6 to 7.3 mmol/l ($P < 0.05$) in goats, indicating improved nitrogen use efficiency, whereas urea-treated dried rumen digesta (DRD), included in concentrate pellets (0–15%) did not affect BUN concentrations in Djallonké sheep, which ranged from 4.72 to 8.44 mg/dl, with no significant differences among treatments (Agolisi and Ansah, 2023). Similarly, broiler litter supplementation reduced BUN concentrations in Qizil lambs, with the lowest value (19.14 mg/dl) observed at 10% inclusion compared with 31.42 mg/dl in the control group (Rahimi et al., 2018). In contrast, rumen-protected choline supplementation had no consistent effect on BUN or total protein concentrations (Huo et al., 2022), suggesting that the additive effects are formulation-specific.

Energy metabolism is also affected by dietary composition. Yahaghi et al. (2013) reported increased portal glucose concentrations (135.7 vs. 111.0 mg/dl) in sheep fed a 50:50 barley–sorghum mix, indicating enhanced glucose absorption from the small intestine. Similarly, Ran et al. (2021) found that fattening lambs fed sorghum-based PTMR had higher plasma glucose concentrations ($P < 0.01$), an increased molar proportion of ruminal propionate ($P < 0.03$), and a lower acetate-to-propionate ratio ($P < 0.04$) compared to lambs fed maize-based diets. These results confirm that replacing rapidly fermenting grains (barley or maize) with sorghum increases ruminal propionate production and blood glucose concentrations.

Lipid parameters generally indicate improved metabolism. PTMR feeding typically raises high-density lipoprotein cholesterol (HDL-C) and lowers low-density lipoprotein cholesterol (LDL-C), reflecting favourable changes in rumen fermentation profile (Zhong et al., 2018). However, some feed additives, such as rumen-protected choline, may increase LDL-C in fattening lambs (Huo et al., 2022). Total cholesterol and triglycerides are generally unaffected by pelleting itself (Ran et al., 2021).

Mineral and enzyme markers reflect normal physiological adaptation. For instance, goats fed alkali-treated and pelleted rice straw TMR had higher serum calcium (2.44 vs. 2.18 mmol/l), phosphorus (4.03 vs. 3.22 mmol/l), and alkaline phosphatase (282.5 vs. 157.2 IU/l) levels than goats fed the control diet. Pi et al. (2005) attributed these differences to improved mineral utilisation resulting from improved energy and protein status. Similarly, Song et al. (2021) observed that yeast culture supplementation did not adversely affect ALP or other liver-related enzymes, confirming that these changes were within normal physiological ranges.

Taken together, these findings suggest that properly balanced PTMR maintains blood metabolites within normal values. However, this conclusion is based mainly on short-term studies in healthy animals, and the effects of prolonged feeding or physiological stress remain unclear. Table 5 summarises the effects of PTMR on blood metabolites in sheep. Most blood parameters were within limits, whereas BUN and glucose concentrations generally increased, reflecting higher protein and energy intake. Changes in lipid profiles and enzyme markers were rather not significant.

Critical reconciliation of contradictory findings

Divergent outcomes in PTMR studies are primarily due to four factors: processing parameters (conditioning temperature, die diameter, and moisture content), dietary composition (forage source, grain type, and peNDF), animal characteristics (breed, age, and adaptation period), and experimental design (sampling timing, and fasting vs. post-feeding sampling). For example, reduced DM digestibility has been reported when pelleting temperatures exceeded 80 °C (Li et al., 2021a), whereas digestibility was preserved at 75 °C (Ran et al., 2021). Similarly, unchanged NDF digestibility reported in some studies (Zhong et al., 2018) may be related to the use of larger die diameters (≥6 mm) that retain peNDF, while finer grinding reduces peNDF and decreases NDF digestibility. Findings concerning rumen pH appear contradictory but can be largely explained by sampling time. Studies collecting rumen fluid 3–6 h after feeding reported lower pH (Li et al., 2021a), whereas no differences were observed in samples collected after a 12-hour fast (Zhang et al., 2019). The length of the adaptation period may also influence the results, as differences in digestibility often diminish after longer adaptation periods (≥21 days). Considering study quality (randomisation, sample size, and control group), the strongest evidence indicates that PTMR increases ADG (effect size = 0.91, 95% CI: 0.60–1.21, $P < 0.001$) and DMI (effect size = 1.51, 95% CI: 1.09–1.93, $P < 0.001$), while reducing NDF digestibility (effect size = −1.07, 95% CI:

−1.71 to −0.44, $P < 0.001$) a reduction generally compensated by increased feed intake (Retnani et al., 2022).

Challenges and future directions

Current technical and practical limitations

Despite the benefits of PTMR, several technical and practical constraints limit its widespread adoption. Unlike TMR systems, which require on-farm mixing equipment (e.g., mixer wagons, electronic load cells, and feeding choppers), PTMR is predominantly produced by commercial feed manufacturers and purchased as a ready-made feed. While this eliminates the need for on-farm equipment, production costs are reflected in higher feed prices, which may reduce profitability for small-scale producers. Ahmed et al. (2021) evaluated the economic viability of complete pelleted diets and reported higher growth rates (100.67 g/day on-station and 84.98 g/day on-farm vs. 22.42 g/day with traditional feeding), while feed cost per kg of gain (Tk 168.58–197.70), total cost per kg of gain (Tk 219.15–257.01), and the benefit-cost ratio (1.18–1.37) did not differ significantly between treatment. However, further studies are needed to compare PTMR with on-farm TMR mixing and grazing-based feeding systems while accounting for transport costs, labour requirements, and regional variation in ingredient price.

Pellet durability and handling present additional challenges. Excessive moisture during production softens pellets and increases breakage, whereas insufficient hydration makes them brittle and prone to crumbling during transport and augering (Anitox, 2023). This generates fodder fines (dust particles), which are associated with bloat, respiratory problems, and reduced feed intake in sheep (Australian Livestock Export Corporation, 2026). Maintaining optimal moisture content (10–12%) and exercising caution during handling are important to preserve pellet integrity (Prinz and Röser, 2011).

Storage stability is another limitation. Although heat-treated pellets can typically be stored for 3–6 months, extended storage may lead to vitamin degradation and reduced palatability, while fat-containing ingredients are more susceptible to rancidity. In humid climates, moisture absorption can promote mould growth, increasing health risks and requiring stringent inventory management.

Mycotoxin contamination also poses a significant health risk. Feed ingredients such as maize and cottonseed products are susceptible to contamination with aflatoxin B1 (AFB1) and deoxynivalenol (DON), which can impair liver function, reduce feed intake, and suppress immune responses in animals (Ward et al., 2021). The risk of contamination increases during rainy seasons or under poor storage conditions, emphasising the need for rigorous quality control.

Ingredient selection presents additional challenges. Suitable feed components that sustain pellet structure while providing a nutritionally balanced diet may be costly or difficult to obtain, particularly in resource-limited regions. Moreover, modern PTMR systems often involve processing and quality-control issues, including reduced pellet durability, inconsistent product quality, and changes in nutritional characteristics during milling and pelleting (Rayhan, 2020). Finally, information on greenhouse gas emissions from PTMR systems is very limited, making it difficult to assess their environmental sustainability.

Current limitations and future research

While PTMR offers clear benefits for feed intake and growth performance, several critical drawbacks remain unresolved, particularly concerning long-term rumen health and application in different production systems.

First, the long-term effects of PTMR on rumen health remain poorly understood. It is well established that PTMR reduces particle size and feed sorting, which can alter rumination and saliva production; however, the duration of these adaptations and their long-term effects on rumen health remain unexplored. For instance, Zhang et al. (2023) demonstrated considerable variation among individual sheep in their susceptibility to subacute ruminal acidosis (SARA) when fed the same high-grain PTMR. Whether this variability persists during prolonged feeding or whether the rumen epithelium can adapt over time is not known. Longitudinal studies spanning entire fattening periods or consecutive parities are urgently needed to determine if the trade-off between increased feed intake and reduced physically effective fibre results in cumulative negative effects.

Second, although PTMR has been studied in growing lambs (Trabi et al., 2019; Wang et al., 2023; Zhang et al., 2025), information on other productive stages, particularly high-yielding dairy ewes, is limited. To date, no study has directly compared unpelleted and pelleted TMR with identical formulations to determine whether pelleting can sustain high milk production while reducing the risk of ruminal acidosis. Likewise, the effects of PTMR on reproductive performance in breeding rams have not been investigated, and few studies have examined its use as a supplement for grazing sheep, where nutritional requirements differ from those under confinement. Studies involving different physiological stages and production systems are required to develop phase-specific PTMR feeding recommendations.

Third, PTMR formulations require further optimisation to maintain high feeding efficiency without compromising fibre effectiveness or rumen function due to fine grinding. As discussed in the section *Effects on Nutrient Digestibility in Small Ruminants*, reducing particle size during pelleting lowers peNDF, potentially decreasing rumination time, saliva buffer production, and ultimately fibre digestibility. Current recommendations for the minimum peNDF requirements in sheep are based largely on unpelleted diets, and little information is available on the interaction between processing intensity, particle size, and rumen health in sheep fed PTMR. Future research should explore innovative processing techniques that preserve peNDF while maintaining the intake and digestibility benefits of PTMR. Potential strategies include incorporating coarsely ground forage into pellets, adding structural fibre sources after pelleting, or evaluating graded levels of long fibre to determine the threshold at which rumination time begins to decline. In addition, the effects of processing conditions, including temperature, pressure, and die diameter, on fibre functionality, starch gelatinisation, and pellet durability have not been systematically evaluated for sheep PTMR formulations.

Fourth, further economic and environmental evaluations are needed. Available studies indicate that PTMR can improve profitability, although comprehensive economic assessments are lacking. Li et al. (2021a) reported that pelleted TMR increased profit per lamb from USD 6.77 to USD 22.60 and reduced feed cost per kg of gain from USD 2.27 to USD 1.94. Similarly, Khaleel and Mansoor (2023) found that pelleted TMR lowered the cost of producing 1 kg of gain (IQD 4238 vs. 5557), with individually housed lambs fed pelleted diets achieving the lowest cost (IQD 3779). Rahimi et al. (2018) also showed that including 5% broiler litter in pelleted diets reduced production costs without affecting animal performance. However, pelleting increases feed production costs by at least 10% (Zhang et al., 2019), and no life-cycle assessment has compared PTMR with conventional TMR or pasture systems. The environmental costs associated with pelleting, including energy consumption and transport emissions, have also received little attention and should be included in future evaluations of PTMR ability.

Practical considerations for PTMR use on small-scale farms

Successful PTMR use on small-scale farms begins with selecting the appropriate formulation. Two fundamentally different PTMR types should be distinguished. Low-forage PTMR is typically formulated with a forage-to-concentrate ratio that favours the former, using locally available agricultural by-products such as rice bran, soybean meal, and barley straw. Its moderate net energy makes it suitable for maintenance, late gestation, or strategic supplementation.

However, although pelleting can increase dry matter intake by reducing rumen fill (de Vega et al., 2025), it does not increase the energy value of low-quality forage. Consequently, low-forage PTMR alone may not provide sufficient energy to support the growth of rapidly developing lambs or heavy-lactating ewes. In contrast, high-concentrate PTMR contains a substantially greater proportion of concentrate and is intended to maximise average daily gain in intensive production systems. Because of its higher energy density, this type more closely resembles commercial concentrates and carries a-greater SARA risk (Zhang et al., 2023). Reducing this risk requires maintaining an appropriate balance between FNDF and RDS. Zhang et al. (2024) recommended an FNDF/RDS ratio of 0.8 for fattening male Hu sheep fed pelleted TMR, although this ratio may vary with breed, production stage, and diet composition.

When applying PTMR in small-scale lamb production, manufacturers should match energy density to production stage. Maintenance and late gestation can be supported by lower-energy, forage-based PTMR, whereas growing and finishing lambs require diets with higher energy density (Filley, 2019). If low-forage PTMR is used for growing animals, it should be supplemented with additional energy sources. Likewise, pelleting improves feed intake but does not increase the nutritional value of poor-quality forage, therefore highest-quality forage available should be used when formulating PTMR. When PTMR is intended as a-supplement for grazing animals, it should also provide sufficient fermentable carbohydrates to utilise the crude protein supplied by pasture, which may not be achieved with low-forage formulations alone. The physical changes caused by pelleting, particularly reduced particle size and a faster passage rate, also affect rumination time and digestibility at individual production stages in a different manner. Consequently, PTMR recommendations should be tailored to specific production stages, for example, lower-energy formulations for dry ewes and late gestation and higher-energy formulations for early weaned or finishing lambs.

Field studies further support the practical use of PTMR. A study by Ahmed et al. (2021) showed that a complete pelleted diet containing 40% rice straw and 60% concentrate achieved daily weight gains of 84.98 g under on-farm conditions and 100.67 g under on-station conditions, compared to only 22.42 g in traditional feeding systems, without any clinical signs of disease. Similarly, Walli (2012) reported that densified pellets produced from straw, minerals, and oilseed cakes improved palatability and reduced feed wastage on small-scale farms in developing regions.

Several management practices may further improve PTMR use on small-scale farms. The risk of ruminal acidosis can be reduced by maintaining an appropriate forage-to-concentrate ratio, adding dietary buffers where necessary, and producing pellets with a diameter of approximately 6–8 mm to encourage chewing activity. Feeding PTMR at least twice daily may also reduce diurnal fluctuations in rumen pH. Future research should evaluate feed additives, e.g., yeast cultures and essential oils, improve quality control standards for commercial PTMR production, establish regional feed cooperatives to reduce purchasing costs for smallholders, and identify affordable local byproducts that can replace more expensive feed ingredients in commercial formulations.

Conclusions

This review summarises current knowledge on the use of pelleted total mixed rations (PTMR) in sheep and evaluates their effects in relation to productivity, nutrient digestibility, rumen function, and practical application. Three main conclusions can be drawn. First, differences among studies are largely explained by processing conditions, diet composition, and fibre characteristics, highlighting the importance of appropriate PTMR formulation. Second, although PTMR has been widely adopted in commercial production, most available studies are short-term, and evidence from different production stages and long-term evaluations of rumen health remains limited. Third, the successful application of PTMR depends on balancing feed processing, diet formulation, and animal physiology, while further research is needed to establish practical recommendations for different production systems and physiological stages.

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Conflict of interest

The Authors declare that there is no conflict of interest.

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Table 1. Showing the evolution of feeding systems in ruminants

Date/Period	Feeding system	Key milestones/development	References
Pre–1950s	Separate feeding (forage and concentrate)	Traditional method: forages and concentrates fed separately; nutrient balance often inconsistent. Common in small-scale farming.	Schingoethe (2017)
1930s	Early milking parlors with concentrate feeding	First rotary milking parlor (Rotolactor) introduced in 1930s, enabling automated milking and concentrate feeding during milking session.	Otter (2023); Gorden (2025)
1950s–1960s	TMR concept development	First scientific article on TMR published in 1966. Mechanical mixers and TMR adoption began in dairy herds, driven by larger herd sizes and indoor housing.	Schingoethe (2017); Khejornsart et al. (2022)
1970s	PMR	PMR developed: Roughages and some concentrates are mixed, rest fed separately; used during pasture shortages	Wales et al. (2013); Schingoethe (2017)
1970s	TMR adoption	All diet components mixed thoroughly; adoption increased to prevent feed sorting and improve rumen health.	Dey et al. (2022)
1980s–1990s	TMR with by-product inclusion	Use of silage, agro-industrial by-products (e.g., soybean meal, grain by-products), and supplements increased in TMR systems for cost efficiency and nutrient optimization.	Khejornsart et al. (2025)
2000s–2010s	TMR applied to small ruminants (sheep)	TMR adopted in intensive sheep systems; aimed to boost intake, reduce sorting, and improve growth. PTMR research began.	González-Reyna et al. (2025); Martín et al. (2025); Yang et al. (2025)
2010s–Present	PTMR	PTMR introduced to improve handling, reduce feed losses, and limit sorting; widely adopted for sheep fattening.	Zhong et al. (2018); Li et al. (2021a)

TMR – total mixed ration, PMR – partial mixed ration, PTMR – pelleted total mixed ration

Table 2. Effects of pelleted total mixed ration on growth performance in sheep

Species/Breed	PTMR type	Effects	Reference
Fattening lambs	PTMR + LY (0.8 g/kg)	11% higher ADG (+36 g/day)	Sun et al. (2022)
Crossbred lambs	PTMR	higher ADG (341 vs. 265 g/day), ADFI (1.86 vs. 1.44 kg/day), and higher carcass yield (54.5% vs. 49.4%)	Zhang et al. (2019)
Hu sheep lambs	High-grain PTMR (70% concentrate)	No ADG difference vs. high-grain non-pelleted lower rumen pH	Trabi et al. (2019)
Sheep	Pelleted vs. unpelleted TMR	Higher feed intake and ADG with pelleted TMR	Li et al. (2021c)
Fattening lambs	PTMR (vs. unpelleted TMR)	Higher DMI (1.49 vs. 1.12 kg/day) and ADG (296 vs. 214 g/day)	Li et al. (2021a)
Light fattening lambs	Pelleted TMR + 15% ground straw	Higher ADG (339 g/day), improved feed/gain ratio (2.74)	Blanco et al. (2015)
Rams (sheep)	PCF	Higher DMI: 1,074.48 g/day; intermediate ADG: 150 g/day; better FCR: 7.63; eating rate faster (0.24 min/g DMI) than mash form	Adiwinarti et al. (2024)
Native Bengal sheep (lambs)	Complete pellet feed (40% rice straw, 60% concentrate)	Higher final BW and total gain than conventional feeding; significantly higher ADG (100.67 g/d on-station, 84.98 g/day on-farm vs. 22.42–64.78 g/day in controls); higher DMI (0.768 kg/day) than conventional groups; similar FCR to control groups	Ahmed et al. (2021)
Fattening lambs (Ujumqin breed)	PTMR	Higher DMI (1102 vs. 890 g/day; $P < 0.001$); higher ADG (223 vs. 176 g/day; $P < 0.001$); similar FCR (5.03 vs. 5.09; $P > 0.10$)	(Zhong et al., 2018)
Fattening lambs (Ujumojin breed)	PTMR at 75 °C (for both sorghum- and corn-based diets)	Higher ADG and FCR at 75 °C vs. 65 °C or 85°C	(Ran et al., 2021)
Light fattening lambs	PTMR + 25% ground straw	Highest ADG (353 g/day); highest total DMI & fibre intake	(Blanco et al., 2015)

BW – body weight, ADG – average daily gain, DMI – dry matter intake, ADFI – average daily feed intake, FCR – feed conversion ratio, TMR – total mixed ration; PTMR – pelleted total mixed ration, PCF – pelleted complete feed, LY – live yeast (*Saccharomyces cerevisiae*)

Table 3. Effects of pelleted total mixed ration on nutrient digestibility in sheep

Species/Breed	PTMR type	Effects	Reference
Fattening lambs	PTMR + LY (0.8 g/kg)	Increased DM (38 g/kg), OM (41 g/kg), NDF (193 g/kg), and ADF (122 g/kg) digestibility	Sun et al. (2022)
Fattening lambs	PTMR (vs. unpelleted TMR)	Lower DM digestibility (61.6% vs. 64.7%)	Li et al. (2021a)
Fattening lambs	Sorghum-based PTMR	↑ CP digestibility, ↓ NDF digestibility vs. corn-based PTMR. ↑ NDF & ADF digestibility at 85 °C, but ↓ CP digestibility. Highest starch digestibility at 75 °C	Ran et al. (2021)
Rams (sheep)	PCF	CP digestibility lower than separate feeding (RCF); DM, OM, NDF, and ADF digestibility similar to mash and separate feeding	Adiwinarti et al. (2024)
Fattening lambs (Ujumqin)	PTMR	Higher CP digestibility (0.756 vs. 0.732; *P* < 0.001); higher ADFom digestibility (0.472 vs. 0.430; *P* < 0.001); higher ether extract digestibility (0.720 vs. 0.696; *P* < 0.01); higher starch digestibility (0.725 vs. 0.701; *P* < 0.001); similar DM and aNDFom digestibility	Zhong et al. (2018)
Light fattening lambs	All TMR pellet groups (5%, 15% and 25% ground barley straw)	Increased NDF & ADF intake with higher straw inclusion, highest fibre intake in 25% group (341 g NDF/day)	Blanco et al. (2015)
Garole sheep	PTMR	Increased TDN (54.13 vs. 50.86 g/100 g DM); increased DNFE (27.02 vs. 23.58 g/100 g DM); decreased DCF (12.67 vs. 15.39 g/100 g DM) and no significant effect on DCP or DEE	Islam et al. (2017)
Fattening lambs	PTMR + RPC (0 to 5 g/kg)	No significant effect on DM, CP, or ADF digestibility. A tendency (*P* = 0.08) for increased NDF digestibility with higher RPC levels	Huo et al. (2022)
Small ruminants (sheep, goats, lambs)	Pelleted vs. unpelleted TMR or forage	Significantly decreased digestibility of DM, OM, NDF, and ADF (*P* < 0.05), with no significant effect on CP digestibility	Retnani et al. (2022)

Hu sheep	PTMR (low FNDF/RDS ratio)	Linear decrease in the digestibility of DM, OM, NDF, and ADF as FRR lowered. Optimal FRR of 0.8 recommended	Zhang et al. (2024)

DM – dry matter, OM – organic matter, CP – crude protein, PCF – pelleted complete feed, NDF – neutral detergent fibre, ADF – acid detergent fibre, TMR – total mixed ration, PTMR – pelleted total mixed ration, LY – live yeast (*Saccharomyces cerevisiae*), EE – ether extract, ADFom – ash-free acid detergent fibre, aNDFom – amylase-treated ash-free neutral detergent fibre, TDN – total digestible nutrients, DNFE – digestible nitrogen-free extract, DCF – digestible crude fibre, DCP – digestible crude protein, DEE – digestible ether extract, RPC – rumen-protected choline, FNDF – forage neutral detergent fibre, RDS – rumen degradable starch, FRR – forage-to-starch ratio, ↑ – increase, ↓ – decrease

Table 4. Effects of pelleted total mixed ration on rumen fermentation in sheep

Species/Breed	PTMR type	Effects	Reference
Crossbred lambs	PTMR	Higher acetate (49.8 vs. 45.7 mmol/l), propionate (24.8 vs. 21.4 mmol/l), ↑ *Prevotellaceae* (rumen), ↓ *Ruminococcaceae*	Zhang et al. (2019)
Hu sheep lambs	High-grain pelleted TMR	Lower pH, increased lactate, and reduced *Fibrobacteres*	Trabi et al. (2019)
Wethers (Sheep)	Pelleted TMR + 1% yeast culture	Higher mean pH, reduced time below pH 5.8, ↑ total VFA, propionate, and n-butyrate, ↑ *Fibrolytic bacteria* (NK4A214, FD2005)	Wang et al. (2023)
Fattening lambs	Pelleted TMR (vs. unpelleted TMR)	Lower rumen pH (6.04 vs. 6.36 after feeding); higher total SCFA (71.1 vs. 59.9 mM); no change in dominant microbial phyla; minor genus-level shifts (e.g., ↓ *Prevotellaceae* UCG-001, ↑ *Fibrobacter*)	Li et al. (2021a)
Fattening lambs (Ujumojin breed)	Sorghum-based PTMR pelleted at 75 °C	↓ Ruminal pH, ↑ molar proportion of propionate, ↓ A:P ratio, ↑ total VFA (optimal at 75 °C), shift in community function favoring propionate-producing bacteria (glucogenic fermentation)	Ran et al. (2021)
Hu sheep	Pelleted high-grain TMR	Significantly lower ruminal pH (5.32 vs. 5.60). VFA: Significantly higher concentrations of lactate and valerate	Trabi et al. (2020)
Rams (sheep)	PCF	Similar rumen pH (~6.1); lower total VFA than separate feeding (RCF); lower methane production than RCF; similar microbial protein yield to other forms	Adiwinarti et al. (2024)
Light fattening lambs	Pelleted TMR + 15% or 25% ground straw	Moderate rumen pH (5.56–5.69), high VFA concentration, reduced papillae count & darker mucosa vs. alfalfa	Blanco et al. (2015)
Fattening lambs	Pelleted TMR ± Live yeast	Lower rumen pH with high corn, higher total SCFA with high corn, altered VFA profile (acetate ↓, propionate ↑), increased bacterial richness and Cyanobacteria with yeast	Sun et al. (2022)
Fattening lambs (Ujumqin)	PTMR	Lower ruminal pH (6.43 vs. 6.51; $P <$ 0.001); higher ammonia N (64.39 vs. 61.39 mmol/l; $P < 0.001$); higher total VFA (54.79 vs. 50.16 mmol/l; $P < 0.001$); higher A:P ratio (2.50 vs. 2.30; $P < 0.001$)	Zhong et al. (2018)

PTMR – pelleted total mixed ration, TMR – total mixed ration, PCF – pelleted complete feed, VFA – volatile fatty acids, SCFA – short-chain fatty acids, A:P ratio – acetate to propionate ratio, pH – potential of hydrogen, ammonia N – ammonia nitrogen, RCF – roughage and concentrate fed separately, ↑ – increase, ↓ – decrease

Table 5. Effects of pelleted total mixed ration on blood metabolites in sheep

Species/Breed	PTMR type	Effects	Reference
Fattening lambs	Sorghum-based PTMR	↑ Plasma urea N, ↑ glucose, ↑ and alkaline phosphatase vs. corn-based PTMR. Total protein, albumin, globulin, triglycerides, and cholesterol were unaffected	Ran et al. (2021)
Fattening lambs (Ujumqin)	PTMR	Higher total protein (41.63 vs. 38.96 g/l; $P < 0.10$); higher plasma urea N (5.86 vs. 5.04 mg/dl; $P < 0.01$); higher HDL-C (0.72 vs. 0.61 mmol/l; $P < 0.001$); lower LDL-C (0.29 vs. 0.39 mmol/l; $P < 0.001$); similar albumin, globulin, glucose, triglyceride, total cholesterol	Zhong et al. (2018)
Fattening lambs (Hybrid)	Pelleted TMR + RPC (0 to 5 g/kg)	↑ LDL-cholesterol with RPC level; albumin & A:G ratio highest at 0 g/kg RPC. Total protein, BUN, triglycerides, total cholesterol, and HDL were unaffected	Huo et al. (2022)
Fattening lambs	PTMR (vs. unpelleted)	No significant changes in most serum metabolites (protein, lipids, enzymes). Numerical increases in BUN and ALP were observed	Li et al. (2021a)
Light fattening lambs	Concentrate pellets with ground barley straw (5–25%)	Altered blood electrolytes (lower K^+, higher Na^+ & Cl^-) compared to an alfalfa diet. No significant effect on overall blood pH, white blood cell counts, or cytokine production	Blanco et al. (2015)
Djallonké sheep	Urea-treated DRDP concentrate (0–15% inclusion)	↑ BUN with DRDP inclusion (final: 4.72–8.44 mg/dl). Albumin significantly affected ($P < 0.005$), final range 24.7–27.1 g/dl. Total protein, glucose, cholesterol, and liver/kidney markers (AST, creatinine) remained within normal ranges and were not negatively impacted	Agolisi and Ansah (2023)
West African Dwarf sheep	Herbaceous forage legume pellets supplemented to a *Panicum maximum* basal diet	Most haematological and serum parameters remained within normal physiological ranges	Ojo et al. (2019)
Qizil lambs	Broiler litter pellets at 0%, 5%, 10%, and	BUN and glucose levels were significantly affected by dietary treatments. BUN decreased in lambs fed broiler	Rahimi et al. (2018)

	15% inclusion in a total mixed ration	litter diets. Other metabolites (cholesterol, triglyceride, and total protein) were not significantly affected	
Dalagh lambs	Pelleted vs. mash concentrate, each with two mineral buffers (sesqui sodium carbonate or sodium bicarbonate)	Blood glucose concentration was significantly higher (*P* < 0.05) in lambs fed the pelleted concentrate compared to those fed the mash concentrate	Asadi et al. (2024)

PTMR – pelleted total mixed ration, TMR – total mixed ration, BUN – blood urea nitrogen, urea N – urea nitrogen, HDL-C – high-density lipoprotein cholesterol, LDL-C – low-density lipoprotein cholesterol, RPC – rumen-protected choline, A:G ratio – albumin to globulin ratio, ALP – alkaline phosphatase, DRDP – dried rumen digesta pellets, AST – aspartate aminotransferase, K^+ – potassium ion, Na^+ – sodium ion, Cl^- – chloride ion, pH – potential of hydrogen, ↑ – increase