

Physical, metabolic, and microbial rumen development in goat kids: a review on the challenges and strategies of early weaning

Article

Published Version

Creative Commons: Attribution 4.0 (CC-BY)

Open Access

Abdelsattar, Mahmoud M. ORCID logoORCID:
<https://orcid.org/0000-0002-1650-3062>, Zhao, Wei, Saleem,
Atef M. ORCID logoORCID: <https://orcid.org/0000-0001-7421-3074>, Kholif, Ahmed E. ORCID logoORCID:
<https://orcid.org/0000-0003-0472-4770>, Vargas Bello Pérez,
Einar ORCID logoORCID: <https://orcid.org/0000-0001-7105-5752> and Zhang, Naifeng ORCID logoORCID:
<https://orcid.org/0000-0001-6272-7553> (2023) Physical,
metabolic, and microbial rumen development in goat kids: a
review on the challenges and strategies of early weaning.
Animals, 13 (15). 2420. ISSN 2076-2615 doi:
<https://doi.org/10.3390/ani13152420> Available at
<https://centaur.reading.ac.uk/112857/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.3390/ani13152420>

Publisher: MDPI AG

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur






CentAUR

Central Archive at the University of Reading

Reading's research outputs online

Review

Physical, Metabolic, and Microbial Rumen Development in Goat Kids: A Review on the Challenges and Strategies of Early Weaning

Mahmoud M. Abdelsattar ^{1,2}, Wei Zhao ^{1,3}, Atef M. Saleem ², Ahmed E. Kholif ⁴,
Einar Vargas-Bello-Pérez ^{5,6} and Naifeng Zhang ^{1,*}

¹ Key Laboratory of Feed Biotechnology of the Ministry of Agriculture and Rural Affairs, Institute of Feed Research of Chinese Academy of Agricultural Sciences, Beijing 100081, China; m.m.abdelsattar@agr.svu.edu.eg (M.M.A.); zhaowei45@nwafu.edu.cn (W.Z.)

² Department of Animal and Poultry Production, Faculty of Agriculture, South Valley University, Qena 83523, Egypt; a.seliem@agr.svu.edu.eg

³ College of Animal Science and Technology, Northwest A&F University, Xianyang 712100, China

⁴ Department of Dairy Science, National Research Centre, Giza 12622, Egypt; ae_kholif@live.com

⁵ Department of Animal Sciences, School of Agriculture, Policy and Development, University of Reading, P.O. Box 237, Earley Gate, Reading RG6 6EU, UK; e.vargasbelloperez@reading.ac.uk

⁶ Facultad de Zootecnia y Ecología, Universidad Autónoma de Chihuahua, Periférico R. Aldama Km 1, Chihuahua 31031, Mexico

* Correspondence: zhangnaifeng@caas.cn; Tel.: +86-010-8210-6056

Simple Summary: The rumen development process that includes the physical, metabolic, and microbial development from birth to postweaning stage in goat kids was reviewed. Moreover, the role of different rearing systems on rumen development was extensively elaborated, especially those related to early weaning strategies. This review emphasized strong structural and functional changes related to rumen development in newborn goats, which often occurs at weaning.

Abstract: The digestive system of newborn ruminant functions is similar to monogastric animals, and therefore milk flows into the abomasum instead of rumen for digestion. The rumen undergoes tremendous changes over time in terms of structure, function, and microbiome. These changes contribute to the smooth transition from the dependence on liquid diets to solid diets. Goat kids are usually separated at early ages from their dams in commercial intensive systems. The separation from dams minimizes the transfer of microbiota from dams to newborns. In this review, understanding how weaning times and methodologies could affect the normal development and growth of newborn goats may facilitate the development of new feeding strategies to control stress in further studies.

Keywords: goat kids; rumen development; early weaning; weaning stress



Citation: Abdelsattar, M.M.; Zhao, W.; Saleem, A.M.; Kholif, A.E.; Vargas-Bello-Pérez, E.; Zhang, N. Physical, Metabolic, and Microbial Rumen Development in Goat Kids: A Review on the Challenges and Strategies of Early Weaning. *Animals* **2023**, *13*, 2420. <https://doi.org/10.3390/ani13152420>

Academic Editor: Massimo Trabalza-Marinucci

Received: 14 June 2023
Revised: 21 July 2023
Accepted: 25 July 2023
Published: 26 July 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The demand for safe and healthy goat milk and meat products is increasing with the growth of population and income increases [1]. With about one billion stock and 200 breeds, goats produce milk with high nutritional value, meat with high protein and low cholesterol, and wool of high quality [2]. Accordingly, goats play an important role in agricultural economics and ecological niches [3]. Compared with large ruminants, goats have a shorter production cycle, higher development rate, and greater environmental adaptation, and can cope with different stressors, harsh environments, and diseases [4]. Compared to sheep, goats are an intermediate browser preferring trees and shrubs [5,6].

As small ruminant species, goat kids are born with deficient physical, metabolic, and microbial rumen development [7]. The rumen is the point of contact between the host and the nutrients consumed [8], where most nutrient digestion and metabolism occur [9]. The process of rumen development, including morphology, metabolic function, and microbial colonization, is a temporal and successional process during the early stage of life [10]. The

microbiota colonization process has been defined as a co-evolutionary process because of the interplay between the host and the microbes [11]. The microbiota population is established through consecutive waves in which microbial populations converge and a more stable population structure emerges [12]. Ingested microorganisms colonize and establish in a definite and progressive sequence in juvenile ruminants' rumens, according to several studies [13–15]. The early colonization of rumen microorganisms influences the maturation of rumen function and affects the rumen microbiome composition throughout life [16–18], as well as has a long-term effect on the health of adult ruminants and animal production [19]. In newborn calves, colonization of the stomach with symbiotic and commensal bacteria has been shown to be critical for the establishment and maintenance of the neonate's immune system [20]. In addition, methanogen colonization in the rumen's early life contributes to the knowledge of the modulation of the rumen microbiome, methane mitigation, and production efficiency [21].

Several goat rearing practices are practiced including extensive rearing, semi-intensive, and intensive. In traditional extensive rearing systems, goats are continuously kept in the open field compared to goats under intensive rearing systems, where they are kept indoors and stall-fed. In the traditional rearing system, the long lactation period and high mortality rate of goat kids have caused serious shortages of productive wealth sources, which restricts the development of goat production. Therefore, early weaning technology has become a common practice for goat breeding in many countries because it can reduce the production costs and increase the birth rate of the dam and the marketable milk as well as the adaptation of young ruminants to the new solid diet [22–25]. However, compared to the traditional weaning, early weaning may cause a stronger postweaning stress due to the immature rumen function [7]. Weaning stress causes impairment of the digestive system, growth retardation, diarrhea, and lower respiratory tract infection, leading to the increase in mortality rates [23,26–28]. Sudden and early weaning can disturb the microbial composition in the gastrointestinal tract, change the metabolic function and the construction of the intestine, affect the newborn performance, and increase the rate of neonatal diarrhea and mortality [26,27]. Consequently, in intensive feeding systems, early weaning requires strict management practices and deep attention [29]. The present review discusses available data that could be useful for the development of feeding strategies to manipulate rumen development and mitigate early weaning stress and reduce high mortality rates.

2. Materials and Methods

The information search focused on studies reporting physical, metabolic, and microbial rumen development in goat kids in relation to weaning. The literature search was conducted (up to June 2023) using PubMed, Science Direct, Web of Science, Scopus, and Google Scholar databases. It summarized only peer-reviewed papers written in English language and findings from recent years concerning the rumen development in goats from neonatal to postweaning stage, whilst conference and congress contributions were excluded. While an effort was made to focus on research carried out in goat kids, we chose to include studies in other ruminant species pertinent to the discussion.

3. Rumen Development of Goats

3.1. Rumen Morphology and Rumination Function

The rumen mucosa structure, including size and shape of papilla, has a significant role in nutrient digestion or absorption [30]. The main factors affecting rumen epithelial development are diets and age [10,31,32]. At birth, the rumen papillae growth is minimal in goat kids [10] and calves [33]. The rumen is not engaged in the digestion of plant material or milk during the suckling stage [34–36]. This is because a reflex mechanism closes the esophageal groove directing the colostrum and milk flow to the abomasum for enzymatic digestion [19,37,38].

The transition period starts from 3 to 8 weeks of age when the rumen gradually develops [39] and adapts to the consumption of solid feed [40]. Several studies reported the

beneficial effects of solid feed in stimulating rumen development through the early stage of life in ruminants [32,41]. As a result of the introduction of a solid diet, the length and size of the rumen papillae in goat kids rose gradually during the transition period [10,42]. This is supported by Chai et al. [43], who observed that the most important factor that altered rumen microbiota and epithelial gene expression in pre-weaning ruminants was the amount of neutral detergent fiber. It may be due to the solid feed providing butyrate as well as a physical stimulus favoring rumen anatomical development [31,32]. Htoo et al. [44] showed that the large particle size of roughage and the content of fiber increased the rumen wall by physical stimulation, and consequently enhanced rumen motility, muscularization, and rumen volume in goat kids with free access to creep feed with roughage. In addition, Malhi et al. [45] reported that intraruminal infusion of sodium butyrate at 0.3 g/kg of body weight for 28 days in goats improved the rumen papillae size, density, and surface area. Ruminal infusion of butyrate at 0.3 g/kg of body weight in goats increased the full weight of rumen as percent of total stomach weight [46]. In addition, infusion of sodium butyrate at 0.3 g/kg of body weight can improve ruminal epithelial growth by modulating both proliferative and apoptotic genes, i.e., Bax, caspase 3, and caspase 9 [47]. Moreover, sodium butyrate supplementation at 3.2% of diet increased rumen epithelium thickness in growing rams [48]. Accordingly, the transition period should be considered by a goat nutritionist for the adaptation of rumen papillae to the dietary changes.

After sequential dynamic changes of development [10], the rumen development of a mature animal accounts for 60 to 80% of the complex stomach volume [38,49]. It has been reported that the microbial colonization in the rumen of goats occurred earlier and is achieved at 1 month of age, functional achievement is at 2 months, and anatomic development is achieved after 2 months [10]. Meanwhile, the rumen transforms to a fully functional fermenter with capabilities of utilizing fibrous diets [38]. At this stage, goats are able to break down and extract nutrients from tough fibrous plants through a process of microbial fermentation and regurgitation. The mature rumen serves as a fermentation chamber, where bacteria and protozoa break down cellulose and hemicellulose into simple sugars, organic acids, and gases, which allows goats to efficiently extract nutrients from low-quality and less digestible forages, and adapt to grazing on a variety of vegetations [6].

In addition, the development of rumen absorption function in goat kids after birth is a crucial process that enables animals to adapt to solid diets. Initially, the rumen is a small pouch-like structure with a thin lining and lacks the necessary capacity to perform efficient absorption of nutrients. However, the rumen gradually expands due to the induced cell proliferation and differentiation as the kid starts to consume solid feed [50,51]. Papillae can greatly enhance the absorptive capacity of the rumen by increasing its surface area [45,52]. High-fiber diets induce the expression of genes related to short-chain fatty acid absorption in the rumen epithelium of goats [53]. A similar improvement in absorption capacity of the rumen epithelium was observed in sheep [52] and cows [54], even with unchanged absorptive surface area of the rumen papillae [54]. On the other hand, low-fiber diets can cause insufficient rumen development and impede proper nutrient digestion and absorption [35]. Therefore, it is important to carefully evaluate the impact of age and diets in further studies to determine their effectiveness in enhancing the absorptive capacity of the rumen.

Daily, goats spend much time eating and ruminating [55]. Rumination is a complex process involving regurgitation and chewing of previously swallowed feed. Lickliter [56] reported that kids start mouthing soil and grasses during their first week following birth but ruminating is first observed during week 3 of age. Before weaning, kids ruminate for over 3 h/day [25]. After weaning, removal of dietary milk results in a dramatic increase in the time spent for rumination (5.2 h/day) [25], indicating the major roles of age and feeding [25,55,56]. Finally, it has been reported that the adult goats spend 7.2 h/day reaching about one third of their day for rumination [57,58].

3.2. Microbiota

3.2.1. The Importance of Rumen Microbes

Various prokaryotic (bacteria and archaea) and eukaryotic (protozoa and fungal) microorganisms live in the rumen and work together to digest and ferment feed [11]. The ruminal microbiota has a symbiotic relationship with the host and is distinguished by its high population density, diversity, and complexity of interactions [21,34]. Rumen microbes have a remarkable ability to ferment and transform plant feed into microbial matter, volatile fatty acids (VFAs), fermentation gases (methane and carbon dioxide), and ammonia, as well as producing heat [43,59,60]. The VFA and microbial proteins provide nutrients for the host's maintenance and growth [34,61]. The rumen microorganisms, especially bacteria and their end products, are essential for regulating rumen function and nutrient digestion [38], thereby improving production efficiency and health status [38,62,63]. In addition, the rumen microbiota plays an essential role in the development of the rumen during the early stages of life [11]. Early weaning disrupts the development of the rumen microbiota, leading to a less diverse microbial community and impaired fermentation [64]. This, in turn, can result in reduced nutrient absorption and growth in the young animal. Therefore, appropriate management practices are necessary to ensure the early establishment and development of a healthy rumen microbiota in early-weaned ruminants [65].

3.2.2. The Bacterial Colonization at Rumen

It is debatable whether the gut microbial community colonizes prenatally or postnatally [40]. Bacterial communities found in numerous maternal-associated sources, including the colostrum, vagina, udder skin, and saliva, have been shown to colonize the gastrointestinal system of newborns within days of birth [40,66,67]. The first day, rumen bacterial communities of goat offspring may also be acquired from the intake of amniotic fluid in pregnancy [67]. Moreover, a recent study showed that the bacterial colonization of the fetal gut commences in utero [68]. In goats, colonization of the bacterial population has been shown to be age-dependent [39,69]. It takes 3 to 4 weeks for the bacterial community structure to stabilize, implying that this period is essential [16]. The rumen bacterial communities of goat kids exhibited remarkable alterations in three stages within the first two months after birth, according to recent longitudinal studies [10,67]. The three stages of rumen development and microbial colonization are the non-rumination phase, transition phase, and rumination phase [10,67,70]. From the non-ruminant to the ruminant phase, aerobic and facultative anaerobic microbial taxa are primarily replaced by anaerobic species in the gastrointestinal tract colonizers [71].

The microbiome gradually matures into a complex microbial community [19,72]. Most alpha diversity indices, including the Shannon index, observed bacteria, and Chao1 estimator, increase with age, suggesting that the microbiota in older age groups is more diverse than in earlier age groups [39]. This is similar to microbial colonization of the rumen contents in calves [14,73]. The three predominant phyla in newborn goats are Proteobacteria, *Bacteroidetes* and *Firmicutes* [27,40,66]. The abundance of *Proteobacteria* decreased quadratically with age at 7 days, but *Bacteroidetes* and *Firmicutes* increased [39,74]. Most of genera detected within *Firmicutes* and *Bacteroidetes* are anaerobes [74]. This could be related to the shift from an aerobic or facultative anaerobic environment niche occurring close to birth to an exclusively anaerobic one with the development of rumen [73,74]. The reduction in the phylum *Proteobacteria* and the increase in the phylum *Bacteroidetes* were found in rumen as a result of weaning [9]. As *Bacteroidetes* have a strong ability to degrade proteins and polysaccharides, they could enhance nutrient digestion and metabolism in the rumen [75]. *Bacteroidetes* were more reliant on solid diet intake than milk removal, reaching a consistent abundance after 7 weeks of age [76]. As the rumen bacterial communities are not only influenced by diet, but also by age, the fetal and newborn communities were dominated by species from the *Proteobacteria* while *Bacteroidetes* and *Firmicutes* were the two major phyla from weaning to adulthood [9,73]. However, it has been reported that after two weeks of age, the community no longer demonstrated large temporal variations at the

phylum level, albeit the relative abundance of certain species remained variable [14,39,77]. *Firmicutes*, for example, was the dominant phylum in the rumen on the first day of life, and its members *Bacillus* and *Lactococcus* were prominent genera [67]. Following lactation, the primary bacterial phylum detected was *Bacteroidetes*, with extremely low amounts of *Bacillus* and *Lactobacillus* [67]. Additionally, at the genus level, the proportion of *Bacteroides* family was undetectable on the first day after birth but increased from 3 to 14 days of age [67]. Similarly, Jiao et al. [69] showed that *Bacteroides* surged in abundance during the first week. The bacterial biomarkers for goat kids during the non-rumination stage (i.e., 7 to 21 days) were mainly *Bacteroidetes* and its members (e.g., *Bacteroidaceae*, *Bacteroides*, and *Alistipes*) and several members of *Firmicutes* (e.g., *Lactobacillaceae*, *Lactobacillus*, and *Butyrivibrio*), which can be attributed to the dam's milk-dominated feeding that is rich in lactose, protein, and fat [66]. In addition, Jiao et al. [69] indicated that the lactic acid bacteria in the phylum *Firmicutes*, such as *Enterococcus* and *Lactobacillus*, were found in the rumen of newborn goats. However, during the primary stages of development, *Bacteroides*, as the main genus within phylum *Bacteroidetes*, is immediately replaced by the *Prevotella* in the rumen after the provision of solid feed at three months of life in goats [9,39,67]. Thus, solid food disrupted the ruminal epithelial microbiota by selecting bacterial taxa that were more specific and were adapted to new substrates [39]. Irrespective of feeding type, relative abundances of ruminal *Prevotella*, *Fibrobacter*, *Ruminococcus*, and *Butyrivibrio* increased with age [69].

3.2.3. Methanogens Colonization in the Rumen

Methanogens are important for digestion and gas production, and understanding the colonization of methanogens is important for the healthy gut microbiota and digestion in both infants and adults. Diversity within the archaea is much lower than that of bacteria, with only a few methanogenic groups being the top three most abundant active methanogens (*Methanosphaera*, *Methanobacteriaceae*, and/or *Methanobrevibacter*) [21,59]. The age-dependent tendency of alpha diversity did not show in the archaeal community of the goat's rumen and gut [21,27]. *Methanogens* that use hydrogen as an energy source to reduce carbon dioxide or acetate to methane have a negative relationship with the oxidative condition within the rumen [78]. It has been reported that the methanogens initially colonized rumen on the first day after birth in goats [10,21]. Jiao et al. [10] showed that the archaeal copy numbers increased with age in goat kids. Moreover, irrespective of feeding type, relative abundances of ruminal *Methanobrevibacter* increased with age in goats [69]. Other studies showed that the methanogenic archaeal populations began to increase and stabilize after the starter feed intake due to the starter's starchy components, which promote hydrogen production [21]. After weaning 40-day-old kids, the abundance of *Methanomicrobium* spp. and *Methanimicrococcus* spp. increased, while the abundance of the genus *Methanimicrococcus* decreased from 50 to 60 days and lost its dominance [21].

3.2.4. Fungi and Protozoa Colonization in the Rumen

Whereas rumen bacteria and methanogens are early rumen colonizers [16], other microbiomes such as protozoa and fungi colonize the rumen later than bacteria and methanogens do [17]. This could be attributed to protozoa being highly sensitive to oxygen and requiring direct contact between young and adult animals for effective transmission [79]. Thus, ruminants are born protozoa-free, and rumen protozoa only become established after direct and continuous nose–nose contact with adult animals [79]. Protozoa can usually be found within 15 days postpartum in the rumen of young ruminants [10,40]. The genera *Entodinium* and *Epidinium* are dominant protozoa [59]. In neonatal ruminants, anaerobic fungi mainly composed of *Neocallimastix frontalis* appear in rumen samples collected at 7 days of age [10] or between 8 and 10 days after birth [40]. However, several invasive fungal pathogens, such as *Aspergillus* and *Candida*, were observed during the first week, suggesting that fungi may also play a role in developing ruminal mucosal innate immune function [67,69]. However, these pathogens declined to undetectable levels from 3 days to

14 days of life and replaced several predominant microbes with the changes in diet after 14 days of life, such as *Neocallimastix* sp. and *Orpinomyces* sp., which may be involved in the digestion of feed fiber in rumen [67]. Solid feeds play an indispensable role in the fungi and protozoa colonization as their levels surged during 28 days of life [10]. Moreover, Jiao et al. [69] showed that the relative abundances of ruminal *Neocallimastix* and *Entodinium* increased with age irrespective of feeding type. Overall, the rumen colonization of bacteria, protozoa, and fungi in animals is a complex and dynamic process that plays a vital role in the digestive system of ruminants.

3.3. Metabolic Functions

Kids rely on their dam's milk in the early weeks of life because the rumen is physically and metabolically immature [80]. At this stage, the ruminal milieu does not form VFA and lacks activities of enzymes such as amylase, urease, protease, and xylanase, as well as a very low ammonia nitrogen production, implying a deficiency in fermentation ability and enzyme activities in the newborn goat kids [10]. Meanwhile, the intestinal microbiota can use milk carbohydrates such as lactose and oligosaccharides to produce a variety of metabolites, including VFA. As a result, a slight increase in acetate molar proportion in kids was observed at 14 days of age [10], indicating the slight increase in fermentation capability during the non-rumination period by the consumption of only milk [81]. Thus, the varied nutrition sources and hormonal signals during rumen development cause irreversible alterations in body composition (protein, fat, carbohydrates, minerals, vitamins, and water) and metabolic function of newborn ruminants [17,82]. Metabolic hormones from the adipose (leptin), liver (Insulin-Like Growth Factor 1), and gut (Ghrelin) act as signaling factors that regulate the activity of the gonadotropin-releasing hormone in the hypothalamus, which control appetite and feeding behavior [83,84]. Thus, animals with high levels of dietary protein and energy have greater concentrations of leptin and Insulin-Like Growth Factor 1 [85].

During growth, the goats' feed supply is substantially altered from a high-fat milk diet to a forage- and concentrate-based diet [10]. The pattern of nutrient absorption shifts from glucose, fatty acids, and milk-derived amino acids to substances from both feed and microbial sources [35]. Rumen microorganisms ferment carbohydrates to produce VFA such acetate, propionate, and butyrate, all of which are used as energy sources in the ruminant body [86]. VFA and ketone bodies are considered the most reliable indicators of a completely functional rumen [35,80]. Thus, a significant increase was observed in VFA followed by a decline in acetate-to-propionate ratio due to the rise in starch digestion and amylolytic microbes degrading starch in weaned goats compared to goat kids fed on milk [10]. Furthermore, ammonia nitrogen concentration increased to reach its levels in adult goats along with the microbiota colonization processes [10]. The blood urea nitrogen increased in 30-days-old kids with increasing ruminal degradation of protein and ammonia production due to the increasing microbial activity [80]. Several enzymes such as amylase, xylanase, and carboxymethyl cellulase increased in 14-days-old kids even before the introduction of solid diets due to the significant role of microbial colonization, which occurs before the functional changes [10]. Overall, the rumen functional development occurs at 2 months in goats [10].

4. Weaning and Rumen Development of Young Goats

4.1. Weaning Methods

Choosing the best weaning protocol is important for minimizing weaning stress and maintaining the healthy growth of weaned kids [22,82]. Weaning is not recommended until the rumen has sufficient anatomical, physiological, and microbiological development [76]. Weaning methods include abrupt weaning, progressive weaning, skipping milk feedings, or different techniques as reviewed by Bélanger-Naud et al. [82]. Progressive weaning, which includes decreasing the milk quantity and/or the number of meals per day over the transition period, is the most suitable to wean kids with minimal digestive stress [25,28,82].

Before weaning, it has been suggested that animals should consume a sufficient amount of solid feed or both concentrates and hay [82]. Other methods are utilized to wean the goat kids, such as weaning according to the weight. Higher body weight indicates higher rumen development and consequently enhanced solid diet intake. Goat kids can be weaned as they reach 2 to 2.5 times their birth weight [82]. However, it was found that female kids of Saanen, Alpine, or Toggenburg breeds weaned at 15 kg grew faster and reached their optimal reproductive weight earlier as opposed to kids weaned at 10 kg [87].

Moreover, weaning age is one of the critical parameters for the success of early weaning due to the underdevelopment of the gastrointestinal tract and immune system [88]. However, the best weaning age of young ruminants can vary due to the animal's diversity of feeding, management practices, and genotypes [22]. With increasing weaning age, the intestinal bacteria involved in the degradation of fiber and carbohydrates, such as *Ruminococcaceae*, *Lachnospiraceae*, and *Ruminococcus*, were increased in weaned goats, resulting in the improvement in intestinal digestion efficiency and the ability to resist stress [22]. However, it is important to note that weaning kids too late is costly and can be harmful to the development of the kid's reticulo-rumen because it delays the stimulation of solid feed [18,89]. Late weaning will decrease the proactive life of ewes due to the longer lactation period, which could increase the necessity of ewes' forage supply [90].

In intensive goat husbandry, abrupt and early weaning as a strategy to adapt the suckling ruminants to a diet composed of forage and concentrates is a key technology to increase the birth rate and lower the breeding cycle and production costs [22–25]. Weaning at early stages would benefit economic profitability because of the highest marketable milk [91,92]. Thus, compared to late weaning, early weaning reduces the postpartum convalescence, increases the reproductive efficiency, and promotes the development of digestive organs and survival of goats [29,93]. The advantages and disadvantages of early weaning in the rumen development of young goats will be addressed in detail in the following review.

4.2. Effects of Early Weaning on the Rumen Development of Young Goats

4.2.1. Rumen Morphology

The rumen role in digestion depends on its mucosal structure, mainly the ruminal papilla shape and size [94]. Minimal rumen development was observed in goats solely fed on the dam's milk [95]. Whereas the solid feed supplementation increased the ruminal VFA concentrations and promoted the growth of rumen papillae [43], the creep feed supplementation improved the rumen morphology, structure, and function, especially the surface area of the rumen papillae of goats during the pre- and post-weaning periods [44]. The early weaning and *ad libitum* supply of semi-solid concentrate diet increased the length, width, density, and surface area of rumen papillae in Malabari male kids as compared to natural suckling with green grass [42]. This could be due to the enhanced average daily dry matter intake because the early-weaned ruminants are more efficient in terms of the adaptation to the new solid diet [42]. Solid feed as an initiating agent promoted the development of the rumen epithelium (epithelium thickness and rumen papillae height and width) and concentration of rumen VFA in goat kids, by regulating the expression of proteins related to cell construction, fatty acid metabolism, signal transduction, and ketone body synthesis [50]. The early-weaned kids are more experienced in consuming solid feeds, which significantly benefits the small ruminants for better development [35,80,96]. Accordingly, Abdelsattar et al. [51] found that goats after weaning showed the highest papillae height, lamina propria, muscle layer thickness, and epithelial thickness. In addition, Carballo et al. [97] showed that lambs weaned at 4 weeks had a higher papillary epithelial thickness than lambs weaned at 6 weeks.

4.2.2. Rumen Microbiota

Abruptly changing from a liquid diet into a complete solid feed can modify the composition of the gastrointestinal tract microbiota in young ruminants. By weaning,

the proportion of *Proteobacteria* increased while most of the proportions of *Firmicutes* and *Bacteroidetes* were reduced [74], suggesting that weaning disturbs the rumen bacteria communities due to the sudden dietary changes [98]. Rumen microbial alterations in early-weaned goats are affected by both age and dietary factors [99]. According to several studies, the bacterial populations in the gastrointestinal system are regulated not just by diet but also by the animal's age [39,67,100]. Other researchers have found that individual animals' bacterial patterns have changed [14,39]. Shifts in rumen microbial community may be more significant when the rumen microbiota is less stable and relatively simple compared to a higher, diverse, and well-established microbial community, which has higher resilience and is more resistant to disturbances [101]. It has been reported that the young ruminant gut microbiota is more sensitive to dietary changes due to the immature gastrointestinal tract [99]. As a result, it has been claimed that an animal's early dietary experiences have a greater and longer-lasting impact than those that occur later in life [102]. This suggests that changing the rumen microbial population during the early stages of rumen development could result in long-term effects, i.e., microbial programming [16,74]. Thus, the early nutritional interventions can manipulate the establishment of rumen microbiota to make rumen microbes able to efficiently digest fiber after weaning [103].

4.2.3. Rumen Metabolic Function

Weaning is a metabolic event for the young ruminant due to the shift of the diet from liquid (milk/milk replacer) to solid (starter feed or grass) [104]. Early weaning can increase psychological stress and induces unfavorable changes in gut structure and function in goats [28]. For example, Liao et al. [23] showed that early weaning stress induced repression of the expression profiles in goats, including salivary secretion, bile secretion, vascular smooth muscle contraction, and calcium signaling pathways. Therefore, early weaning could cause impairment of the digestive system and growth retardation. Weaning reduced the dry matter, crude protein, and ether extract intake and digestion in lambs but increased the starch, neutral detergent fiber, and acid detergent fiber intake and digestion [105]. Jiao et al. [10] found that amylase and protease activity potentials showed a sharp decline 42 days after weaning in goats. The rumen epithelium is a unique site of interaction between the rumen microbial metabolism and the host [106]. An undeveloped rumen at weaning has a negative effect on nutrient digestion and absorption, which may cause diseases such as diarrhea and respiratory infections [10]. A higher starter diet intake and lower ruminal VFA and nitrogen concentrations were observed in abruptly weaned lambs on day 49 than suckling lambs, leading to low rumen epithelium thickness and papilla width in the weaning lambs [107]. Thus, rumen development requires both enough rumen VFAs and the physical stimulus of feed [107]. Therefore, it has been reported that throughout the early rumen development in goats, the co-development between the rumen and its microbiomes boosts the increasing ability of nitrogen metabolism in the rumen and the expression of genes involved in the immune response and antimicrobial activity [108].

4.3. Impact of Rearing System on the Rumen Development of Early Weaning Goats

Suitable feeding management and rearing systems should be considered when developing nutritional intervention techniques in the early stages of life. Kids in commercial dairy goat systems are often removed from their dam immediately after birth or within the first few hours of life and artificially nurtured until weaning [7,25,109]. This is due to the higher total feed costs of the traditional system [110]. Furthermore, the artificial feeding of kids early is critical to overcoming the paucity of milk provided by dams [95]. However, artificial rearing can limit the rumen microbiological colonization leading to negative health and digestive problems on the weaning process [76,89]. Suckling plays a significant role in the strength of the mother–newborn interaction [111]. As a result, having adult companion goats might help the transition from liquid to solid nutrition, thereby improving the weaning process compared with the separation from the dam [7,18,109]. Furthermore, the naturally suckled goat kids grew considerably faster than the early-

weaned and the artificially reared goat kids [112]. Furthermore, Abecia et al. [113] showed that natural milk feeding via the dam improved rumen anatomic development, VFA, and acetate-to-propionate ratio, and decreased rumen pH, indicating greater concentrate intake in naturally fed kids compared to artificially reared kids with milk replacer. Accordingly, different colonization patterns were observed for different rearing systems, indicating that artificial milk feeding could jeopardize an optimal microbial gut colonization, especially for the protozoa and the bacteria concentration [113]. The early-isolated individuals may have a limited colonization of protozoa that transfers directly by saliva [40], as well as lower colonization of cellulolytic bacteria [11]. As a result, bacterial diversity indices grew with age and were higher in kids that remained with their mother than in kids in the absence of adults [114]. The lack of interaction with adult animals hampered rumen microbial growth, which had a detrimental impact on feed digestibility and production [115]. Furthermore, growing newborn goat kids in the presence of adult partners resulted in a more complex protozoal population and a more diversified bacterial community, as well as greater rumen pH, butyrate, and ammonia contents, indicating increased fibrolytic and proteolytic activities [109]. It is important to understand that artificial rearing stress can be reduced by providing a high-quality nutritional supply; thus, a rearing strategy involving semi-solid concentrate feeding significantly increased rumen development when compared to kids suckled on green grass [42].

In grazing systems, goat kids are usually reared with their dams, which could decrease their access to the concentrate feeds. Total VFA concentrations, total protease activity, the length of rumen papillae, and liquid-associated bacterial and archaeal copy numbers were lower in grazing goats compared to goats supplemented with concentrate [10]. Furthermore, there were significant decreases in total VFA concentrations and acetate proportions in rumen fluid of grazing kids compared to kids kept indoors, most likely due to the lower digestibility and less total energy in the grazing goats' diet [116], while the alpha diversity of the rumen bacterial and archaeal communities increased in grazing goats fed with or without concentrate as compared to goats kept indoors [116], which could be due to the presence of adult partners. In the end, the ruminal development in relation to early weaning has become clear in this literature review.

5. Challenges for the Future

The development of rumen morphological structure, microbial contents, and metabolic functions starts after birth with both age and feeding system being the most important influences. Compared to milk-based diets, the early and progressive evolution of solid diet intake encourages the healthy transition from monogastric to ruminant livestock. Moreover, early weaning is usually used in intensive feeding systems to increase the economic profitability and the reproductive efficiency of dams and the ability of young goats to adapt to the new solid starter diet. However, the abrupt and early weaning could harm the goat kid's digestive functions. Accordingly, the early-weaned goat kids may suffer due to the deficient rumen development compared to the naturally reared kids. Proper weaning time and new feeding strategies are recommended for the smooth transition from milk to solid stage to avoid stress. Further research should be conducted for quick rumen development and animal growth depending on nutritional feed supplements such as volatile fatty acids and growth promoters.

Author Contributions: Conceptualization, M.M.A., W.Z., E.V.-B.-P. and N.Z.; methodology, M.M.A. and N.Z.; software, M.M.A. and W.Z.; investigation, M.M.A. and N.Z.; resources, N.Z.; writing—original draft preparation, M.M.A.; writing—review and editing, M.M.A., A.M.S., A.E.K., E.V.-B.-P. and N.Z.; supervision, N.Z.; project administration, N.Z.; funding acquisition, N.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by grants from Cooperative Guidance Project of "Prospering Inner Mongolia through Science and Technology" in 2021 (2021CG0024) and the National Key R&D Program Projects (2018YFD0501902).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sohaib, M.; Jamil, F. An Insight of Meat Industry in Pakistan with Special Reference to Halal Meat: A Comprehensive Review. *Korean J. Food Sci. Anim. Resour.* **2017**, *37*, 329–341. [[CrossRef](#)] [[PubMed](#)]
2. FAO. *World Food and Agriculture—Statistical Yearbook 2021*; FAO: Rome, Italy, 2021.
3. Tian, C.X.; Wu, J.; Jiao, J.Z.; Zhou, C.S.; Tan, Z.L. Short communication: A high-grain diet entails alteration in nutrient chemosensing of the rumen epithelium in goats. *Anim. Feed Sci. Technol.* **2020**, *262*, 114410. [[CrossRef](#)]
4. Visser, C. A review on goats in southern Africa: An untapped genetic resource. *Small Rumin. Res.* **2019**, *176*, 11–16. [[CrossRef](#)]
5. Chebli, Y.; El Otmani, S.; Chentouf, M.; Hornick, J.L.; Bindelle, J.; Cabaraux, J.F. Foraging Behavior of Goats Browsing in Southern Mediterranean Forest Rangeland. *Animals* **2020**, *10*, 196. [[CrossRef](#)]
6. NRC. *Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids*; The National Academies Press: Washington, DC, USA, 2007.
7. Belanche, A.; Palma-Hidalgo, J.M.; Nejjam, I.; Jimenez, E.; Martin-Garcia, A.I.; Yanez-Ruiz, D.R. Inoculation with rumen fluid in early life as a strategy to optimize the weaning process in intensive dairy goat systems. *J. Dairy Sci.* **2020**, *103*, 5047–5060. [[CrossRef](#)]
8. Xu, L.; Wang, Y.; Liu, J.; Zhu, W.; Mao, S. Morphological adaptation of sheep's rumen epithelium to high-grain diet entails alteration in the expression of genes involved in cell cycle regulation, cell proliferation and apoptosis. *J. Anim. Sci. Biotechnol.* **2018**, *9*, 32. [[CrossRef](#)]
9. Zou, X.; Liu, G.; Meng, F.; Hong, L.; Li, Y.; Lian, Z.; Yang, Z.; Luo, C.; Liu, D. Exploring the Rumen and Cecum Microbial Community from Fetus to Adulthood in Goat. *Animals* **2020**, *10*, 1639. [[CrossRef](#)]
10. Jiao, J.; Li, X.; Beauchemin, K.A.; Tan, Z.; Tang, S.; Zhou, C. Rumen development process in goats as affected by supplemental feeding v. grazing: Age-related anatomic development, functional achievement and microbial colonisation. *Br. J. Nutr.* **2015**, *113*, 888–900. [[CrossRef](#)]
11. Malmuthuge, N.; Griebel, P.J.; Guan Le, L. The Gut Microbiome and Its Potential Role in the Development and Function of Newborn Calf Gastrointestinal Tract. *Front. Vet. Sci.* **2015**, *2*, 36. [[CrossRef](#)]
12. Furman, O.; Shenhav, L.; Sasson, G.; Kokou, F.; Honig, H.; Jacoby, S.; Hertz, T.; Cordero, O.X.; Halperin, E.; Mizrahi, I. Stochasticity constrained by deterministic effects of diet and age drive rumen microbiome assembly dynamics. *Nat. Commun.* **2020**, *11*, 1904. [[CrossRef](#)]
13. Abecia, L.; Martin-Garcia, A.I.; Martinez, G.; Newbold, C.J.; Yanez-Ruiz, D.R. Nutritional intervention in early life to manipulate rumen microbial colonization and methane output by kid goats postweaning. *J. Anim. Sci.* **2013**, *91*, 4832–4840. [[CrossRef](#)]
14. Rey, M.; Enjalbert, F.; Combes, S.; Cauquil, L.; Bouchez, O.; Monteils, V. Establishment of ruminal bacterial community in dairy calves from birth to weaning is sequential. *J. Appl. Microbiol.* **2014**, *116*, 245–257. [[CrossRef](#)]
15. Li, Z.; Si, H.; Nan, W.; Wang, X.; Zhang, T.; Li, G. Bacterial community and metabolome shifts in the cecum and colon of captive sika deer (*Cervus nippon*) from birth to post weaning. *FEMS Microbiol. Lett.* **2019**, *366*, fnz010. [[CrossRef](#)]
16. Abecia, L.; Waddams, K.E.; Martinez-Fernandez, G.; Martin-Garcia, A.I.; Ramos-Morales, E.; Newbold, C.J.; Yanez-Ruiz, D.R. An antimethanogenic nutritional intervention in early life of ruminants modifies ruminal colonization by Archaea. *Archaea* **2014**, *2014*, 841463. [[CrossRef](#)]
17. Yanez-Ruiz, D.R.; Abecia, L.; Newbold, C.J. Manipulating rumen microbiome and fermentation through interventions during early life: A review. *Front. Microbiol.* **2015**, *6*, 1133. [[CrossRef](#)]
18. Palma-Hidalgo, J.M.; Jimenez, E.; Popova, M.; Morgavi, D.P.; Martin-Garcia, A.I.; Yanez-Ruiz, D.R.; Belanche, A. Inoculation with rumen fluid in early life accelerates the rumen microbial development and favours the weaning process in goats. *Anim. Microbiome* **2021**, *3*, 11. [[CrossRef](#)]
19. Dill-McFarland, K.A.; Breaker, J.D.; Suen, G. Microbial succession in the gastrointestinal tract of dairy cows from 2 weeks to first lactation. *Sci. Rep.* **2017**, *7*, 40864. [[CrossRef](#)]
20. Martin, C.C.; de Oliveira, S.; Costa, J.; Baccili, C.C.; Silva, B.T.; Hurley, D.J.; Gomes, V. Influence of feeding fresh colostrum from the dam or frozen colostrum from a pool on indicator gut microbes and the inflammatory response in neonatal calves. *Res. Vet. Sci.* **2021**, *135*, 355–365. [[CrossRef](#)]
21. Wang, Z.; Elekwachi, C.O.; Jiao, J.; Wang, M.; Tang, S.; Zhou, C.; Tan, Z.; Forster, R.J. Investigation and manipulation of metabolically active methanogen community composition during rumen development in black goats. *Sci. Rep.* **2017**, *7*, 422. [[CrossRef](#)]
22. Liao, R.; Xie, X.; Lv, Y.; Dai, J.; Lin, Y.; Zhu, L. Ages of weaning influence the gut microbiota diversity and function in Chongming white goats. *Appl. Microbiol. Biotechnol.* **2021**, *105*, 3649–3658. [[CrossRef](#)]
23. Liao, R.; Lv, Y.; Zhu, L.; Lin, Y. Altered expression of miRNAs and mRNAs reveals the potential regulatory role of miRNAs in the developmental process of early weaned goats. *PLoS ONE* **2019**, *14*, e0220907. [[CrossRef](#)] [[PubMed](#)]

24. Wang, S.; Ma, T.; Zhao, G.; Zhang, N.; Tu, Y.; Li, F.; Cui, K.; Bi, Y.; Ding, H.; Diao, Q. Effect of Age and Weaning on Growth Performance, Rumen Fermentation, and Serum Parameters in Lambs Fed Starter with Limited Ewe-Lamb Interaction. *Animals* **2019**, *9*, 825. [[CrossRef](#)] [[PubMed](#)]
25. Zobel, G.; Freeman, H.; Watson, T.; Cameron, C.; Sutherland, M. Effect of different milk-removal strategies at weaning on feed intake and behavior of goat kids. *J. Vet. Behav.* **2020**, *35*, 62–68. [[CrossRef](#)]
26. Meale, S.J.; Li, S.; Azevedo, P.; Derakhshani, H.; Plaizier, J.C.; Khafipour, E.; Steele, M.A. Development of Ruminal and Fecal Microbiomes Are Affected by Weaning but Not Weaning Strategy in Dairy Calves. *Front. Microbiol.* **2016**, *7*, 582. [[CrossRef](#)] [[PubMed](#)]
27. Wang, L.; Xu, Q.; Kong, F.; Yang, Y.; Wu, D.; Mishra, S.; Li, Y. Exploring the Goat Rumen Microbiome from Seven Days to Two Years. *PLoS ONE* **2016**, *11*, e0154354. [[CrossRef](#)]
28. Magistrelli, D.; Aufy, A.A.; Pinotti, L.; Rosi, F. Analysis of weaning-induced stress in Saanen goat kids. *J. Anim. Physiol. Anim. Nutr.* **2013**, *97*, 732–739. [[CrossRef](#)]
29. Rangaswamy, R.; Patel, B.H.M.; Upadhyay, D.; Sahu, S.; Tomar, A.K.S.; Gaur, G.K.; Dutt, T.; Verma, M.R.; Bhusan, B. Performance of kids of Rohilkhandi under different weaning systems. *Indian J. Anim. Sci.* **2015**, *85*, 431–434.
30. Graham, C.; Simmons, N.L. Functional organization of the bovine rumen epithelium. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **2005**, *288*, R173–R181. [[CrossRef](#)]
31. Suarez, B.J.; Van Reenen, C.G.; Beldman, G.; van Delen, J.; Dijkstra, J.; Gerrits, W.J. Effects of supplementing concentrates differing in carbohydrate composition in veal calf diets: I. Animal performance and rumen fermentation characteristics. *J. Dairy Sci.* **2006**, *89*, 4365–4375. [[CrossRef](#)]
32. Khan, M.A.; Weary, D.M.; von Keyserlingk, M.A. Invited review: Effects of milk ration on solid feed intake, weaning, and performance in dairy heifers. *J. Dairy Sci.* **2011**, *94*, 1071–1081. [[CrossRef](#)]
33. Tamate, H.; McGilliard, A.; Jacobson, N.; Getty, R. Effect of various dietaries on the anatomical development of the stomach in the calf. *J. Dairy Sci.* **1962**, *45*, 408–420. [[CrossRef](#)]
34. Huws, S.A.; Creevey, C.J.; Oyama, L.B.; Mizrahi, I.; Denman, S.E.; Popova, M.; Munoz-Tamayo, R.; Forano, E.; Waters, S.M.; Hess, M.; et al. Addressing Global Ruminant Agricultural Challenges through Understanding the Rumen Microbiome: Past, Present, and Future. *Front. Microbiol.* **2018**, *9*, 2161. [[CrossRef](#)]
35. Baldwin, R.L.; McLeod, K.R.; Klotz, J.L.; Heitmann, R.N. Rumen Development, Intestinal Growth and Hepatic Metabolism in the Pre- and Postweaning Ruminant. *J. Dairy Sci.* **2004**, *87*, E55–E65. [[CrossRef](#)]
36. Khan, M.A.; Weary, D.M.; von Keyserlingk, M.A. Hay intake improves performance and rumen development of calves fed higher quantities of milk. *J. Dairy Sci.* **2011**, *94*, 3547–3553. [[CrossRef](#)]
37. Braun, U.; Brammertz, C. Ultrasonographic examination of the oesophageal groove reflex in young calves under various feeding conditions. *Schweiz. Arch. Tierheilkd.* **2015**, *157*, 457–463. [[CrossRef](#)]
38. Arshad, M.A.; Hassan, F.U.; Rehman, M.S.; Huws, S.A.; Cheng, Y.; Din, A.U. Gut microbiome colonization and development in neonatal ruminants: Strategies, prospects, and opportunities. *Anim. Nutr.* **2021**, *7*, 883–895. [[CrossRef](#)]
39. Jiao, J.; Huang, J.; Zhou, C.; Tan, Z. Taxonomic Identification of Ruminal Epithelial Bacterial Diversity during Rumen Development in Goats. *Appl. Environ. Microbiol.* **2015**, *81*, 3502–3509. [[CrossRef](#)]
40. Zhang, Y.; Choi, S.H.; Nogoy, K.M.; Liang, S. Review: The development of the gastrointestinal tract microbiota and intervention in neonatal ruminants. *Animal* **2021**, *15*, 100316. [[CrossRef](#)]
41. Castells, L.; Bach, A.; Aris, A.; Terre, M. Effects of forage provision to young calves on rumen fermentation and development of the gastrointestinal tract. *J. Dairy Sci.* **2013**, *96*, 5226–5236. [[CrossRef](#)]
42. Kotresh Prasad, C.; Abraham, J.; Panchbhai, G.; Barman, D.; Nag, P.; Ajithakumar, H.M. Growth performance and rumen development in Malabari kids reared under different production systems. *Trop. Anim. Health Prod.* **2019**, *51*, 119–129. [[CrossRef](#)]
43. Chai, J.; Lv, X.; Diao, Q.; Usdrowski, H.; Zhuang, Y.; Huang, W.; Cui, K.; Zhang, N. Solid diet manipulates rumen epithelial microbiota and its interactions with host transcriptomic in young ruminants. *Environ. Microbiol.* **2021**, *23*, 6557–6568. [[CrossRef](#)] [[PubMed](#)]
44. Htoo, N.N.; Zeshan, B.; Khaing, A.T.; Kyaw, T.; Woldegiorgis, E.A.; Khan, M.A. Creep Feeding Supplemented with Roughages Improve Rumen Morphology in Pre-Weaning Goat Kids. *Pak. J. Zool.* **2018**, *50*, 703–709. [[CrossRef](#)]
45. Malhi, M.; Gui, H.; Yao, L.; Aschenbach, J.R.; Gabel, G.; Shen, Z. Increased papillae growth and enhanced short-chain fatty acid absorption in the rumen of goats are associated with transient increases in cyclin D1 expression after ruminal butyrate infusion. *J. Dairy Sci.* **2013**, *96*, 7603–7616. [[CrossRef](#)] [[PubMed](#)]
46. Moolchand, M.; Wang, J.; Gui, H.; Shen, Z. Ruminal butyrate infusion increased papillae size and digesta weight but did not change liquid flow rate in the rumen of goats. *J. Anim. Plant Sci.* **2013**, *23*, 1516–1521.
47. Soomro, J.; Lu, Z.; Gui, H.; Zhang, B.; Shen, Z. Synchronous and Time-Dependent Expression of Cyclins, Cyclin-Dependant Kinases, and Apoptotic Genes in the Rumen Epithelia of Butyrate-Infused Goats. *Front. Physiol.* **2018**, *9*, 496. [[CrossRef](#)]
48. Samanta, Ś.; Marcin, P.; Jadwiga, F.; Kinga, S.; Aleksandra, G.-P.; Weronika, B.; Edyta, M.; Dorota, W.; Renata, M.; Paweł, G. Effect of increased intake of concentrates and sodium butyrate supplementation on ruminal epithelium structure and function in growing rams. *Animal* **2023**, 100898, *in press*. [[CrossRef](#)]
49. Lane, M.A.; Jesse, B.W. Effect of volatile fatty acid infusion on development of the rumen epithelium in neonatal sheep. *J. Dairy Sci.* **1997**, *80*, 740–746. [[CrossRef](#)]
50. Zhuang, Y.; Lv, X.; Cui, K.; Chai, J.; Zhang, N. Early Solid Diet Supplementation Influences the Proteomics of Rumen Epithelium in Goat Kids. *Biology* **2023**, *12*, 684. [[CrossRef](#)]

51. Abdelsattar, M.M.; Zhuang, Y.; Cui, K.; Bi, Y.; Haridy, M.; Zhang, N. Longitudinal investigations of anatomical and morphological development of the gastrointestinal tract in goats from colostrum to postweaning. *J. Dairy Sci.* **2022**, *105*, 2597–2611. [[CrossRef](#)]
52. Gabel, G.; Bestmann, M.; Martens, H. Influences of diet, short-chain fatty acids, lactate and chloride on bicarbonate movement across the reticulo-rumen wall of sheep. *J. Vet. Med. Ser. A* **1991**, *38*, 523–529. [[CrossRef](#)]
53. Yan, L.; Zhang, B.; Shen, Z. Dietary modulation of the expression of genes involved in short-chain fatty acid absorption in the rumen epithelium is related to short-chain fatty acid concentration and pH in the rumen of goats. *J. Dairy Sci.* **2014**, *97*, 5668–5675. [[CrossRef](#)]
54. Sehested, J.; Andersen, J.B.; Aaes, O.; Kristensen, N.B.; Diernaes, L.; Moller, P.D.; Skadhauge, E. Feed-induced changes in the transport of butyrate, sodium and chloride ions across the isolated bovine rumen epithelium. *Acta Agric. Scand. Sect. A—Anim. Sci.* **2000**, *50*, 47–55. [[CrossRef](#)]
55. Lu, C.D. Grazing behavior and diet selection of goats. *Small Rumin. Res.* **1988**, *1*, 205–216. [[CrossRef](#)]
56. Lickliter, R.E. Activity Patterns and Companion Preferences of Domestic Goat Kids. *Appl. Anim. Behav. Sci.* **1987**, *19*, 137–145. [[CrossRef](#)]
57. Jalali, A.R.; Norgaard, P.; Weisbjerg, M.R.; Nielsen, M.O. Effect of forage quality on intake, chewing activity, faecal particle size distribution, and digestibility of neutral detergent fibre in sheep, goats, and llamas. *Small Rumin. Res.* **2012**, *103*, 143–151. [[CrossRef](#)]
58. von Engelhardt, W.; Haarmeyer, P.; Kaske, M.; Lechner-Doll, M. Chewing activities and oesophageal motility during feed intake, rumination and eructation in camels. *J. Comp. Physiol. B* **2006**, *176*, 117–124. [[CrossRef](#)]
59. Giger-Reverdin, S.; Domange, C.; Broudiscou, L.P.; Sauviant, D.; Berthelot, V. Rumen function in goats, an example of adaptive capacity. *J. Dairy Res.* **2020**, *87*, 45–51. [[CrossRef](#)]
60. Mackie, R.I. Mutualistic fermentative digestion in the gastrointestinal tract: Diversity and evolution. *Integr. Comp. Biol.* **2002**, *42*, 319–326. [[CrossRef](#)]
61. Lin, L.; Xie, F.; Sun, D.; Liu, J.; Zhu, W.; Mao, S. Ruminal microbiome-host crosstalk stimulates the development of the ruminal epithelium in a lamb model. *Microbiome* **2019**, *7*, 83. [[CrossRef](#)]
62. Zhang, N.; Wang, L.; Wei, Y. Effects of *Bacillus amyloliquefaciens* and *Bacillus pumilus* on Rumen and Intestine Morphology and Microbiota in Weanling Jintang Black Goat. *Animals* **2020**, *10*, 1604. [[CrossRef](#)]
63. Miron, J.; Ben-Ghedalia, D.; Morrison, M. Invited review: Adhesion mechanisms of rumen cellulolytic bacteria. *J. Dairy Sci.* **2001**, *84*, 1294–1309. [[CrossRef](#)] [[PubMed](#)]
64. Pitta, D.W.; Kumar, S.; Veiccharelli, B.; Parmar, N.; Reddy, B.; Joshi, C.G. Bacterial diversity associated with feeding dry forage at different dietary concentrations in the rumen contents of Mehshana buffalo (*Bubalus bubalis*) using 16S pyrotags. *Anaerobe* **2014**, *25*, 31–41. [[CrossRef](#)]
65. Ungerfeld, E.M. Shifts in metabolic hydrogen sinks in the methanogenesis-inhibited ruminal fermentation: A meta-analysis. *Front. Microbiol.* **2015**, *6*, 37. [[CrossRef](#)] [[PubMed](#)]
66. Guo, J.; Li, P.; Zhang, K.; Zhang, L.; Wang, X.; Li, L.; Zhang, H. Distinct Stage Changes in Early-Life Colonization and Acquisition of the Gut Microbiota and Its Correlations with Volatile Fatty Acids in Goat Kids. *Front. Microbiol.* **2020**, *11*, 584742. [[CrossRef](#)] [[PubMed](#)]
67. Zhang, K.; Li, B.; Guo, M.; Liu, G.; Yang, Y.; Wang, X.; Chen, Y.; Zhang, E. Maturation of the Goat Rumen Microbiota Involves Three Stages of Microbial Colonization. *Animals* **2019**, *9*, 1028. [[CrossRef](#)]
68. Bi, Y.; Tu, Y.; Zhang, N.; Wang, S.; Zhang, F.; Suen, G.; Shao, D.; Li, S.; Diao, Q. Multiomics analysis reveals the presence of a microbiome in the gut of fetal lambs. *Gut* **2021**, *70*, 853–864. [[CrossRef](#)]
69. Jiao, J.; Zhou, C.; Guan, L.L.; McSweeney, C.S.; Tang, S.; Wang, M.; Tan, Z. Shifts in Host Mucosal Innate Immune Function Are Associated with Ruminal Microbial Succession in Supplemental Feeding and Grazing Goats at Different Ages. *Front. Microbiol.* **2017**, *8*, 1655. [[CrossRef](#)]
70. Lane, M.A.; Baldwin, R.L., IV; Jesse, B.W. Developmental changes in ketogenic enzyme gene expression during sheep rumen development. *J. Anim. Sci.* **2002**, *80*, 1538–1544. [[CrossRef](#)]
71. Nylund, L.; Satokari, R.; Salminen, S.; de Vos, W.M. Intestinal microbiota during early life—Impact on health and disease. *Proc. Nutr. Soc.* **2014**, *73*, 457–469. [[CrossRef](#)]
72. Jiao, J.; Wu, J.; Zhou, C.; Tang, S.; Wang, M.; Tan, Z. Composition of Ileal Bacterial Community in Grazing Goats Varies across Non-rumination, Transition and Rumination Stages of Life. *Front. Microbiol.* **2016**, *7*, 1364. [[CrossRef](#)]
73. Jami, E.; Israel, A.; Kotser, A.; Mizrahi, I. Exploring the bovine rumen bacterial community from birth to adulthood. *ISME J.* **2013**, *7*, 1069–1079. [[CrossRef](#)]
74. Wang, Z.; Elekwachi, C.; Jiao, J.; Wang, M.; Tang, S.; Zhou, C.; Tan, Z.; Forster, R.J. Changes in Metabolically Active Bacterial Community during Rumen Development, and Their Alteration by Rhubarb Root Powder Revealed by 16S rRNA Amplicon Sequencing. *Front. Microbiol.* **2017**, *8*, 159. [[CrossRef](#)]
75. Pitta, D.W.; Pinchak, W.E.; Indugu, N.; Vecchiarelli, B.; Sinha, R.; Fulford, J.D. Metagenomic Analysis of the Rumen Microbiome of Steers with Wheat-Induced Frothy Bloat. *Front. Microbiol.* **2016**, *7*, 689. [[CrossRef](#)]
76. Meale, S.J.; Li, S.C.; Azevedo, P.; Derakhshani, H.; DeVries, T.J.; Plaizier, J.C.; Steele, M.A.; Khafipour, E. Weaning age influences the severity of gastrointestinal microbiome shifts in dairy calves. *Sci. Rep.* **2017**, *7*, 198. [[CrossRef](#)]
77. Li, R.W.; Connor, E.E.; Li, C.; Baldwin, R.L.; Sparks, M.E. Characterization of the rumen microbiota of pre-ruminant calves using metagenomic tools. *Environ. Microbiol.* **2012**, *14*, 129–139. [[CrossRef](#)]
78. Friedman, N.; Shriker, E.; Gold, B.; Durman, T.; Zarecki, R.; Ruppin, E.; Mizrahi, I. Diet-induced changes of redox potential underlie compositional shifts in the rumen archaeal community. *Environ. Microbiol.* **2017**, *19*, 174–184. [[CrossRef](#)]

79. Bird, S.H.; Hegarty, R.S.; Woodgate, R. Modes of transmission of rumen protozoa between mature sheep. *Anim. Prod. Sci.* **2010**, *50*, 414–417. [[CrossRef](#)]
80. Paez Lama, S.; Grilli, D.; Egea, V.; Fucili, M.; Allegretti, L.; Guevara, J.C. Rumen development and blood metabolites of Criollo kids under two different rearing systems. *Livest. Sci.* **2014**, *167*, 171–177. [[CrossRef](#)]
81. Cozzi, G.; Gottardo, F.; Mattiello, S.; Canali, E.; Scanziani, E.; Verga, M.; Andrighetto, I. The provision of solid feeds to veal calves: I. Growth performance, forestomach development, and carcass and meat quality. *J. Anim. Sci.* **2002**, *80*, 357–366. [[CrossRef](#)]
82. Bélanger-Naud, S.; Cinq-Mars, D.; Julien, C.; Arsenaault, J.; Buczinski, S.; Lévesque, J.; Vasseur, E. A survey of dairy goat kid-rearing practices on Canadian farms and their associations with self-reported farm performance. *J. Dairy Sci.* **2021**, *104*, 9999–10009. [[CrossRef](#)]
83. Fall, C.H. Evidence for the intra-uterine programming of adiposity in later life. *Ann. Hum. Biol.* **2011**, *38*, 410–428. [[CrossRef](#)] [[PubMed](#)]
84. D’Occhio, M.J.; Baruselli, P.S.; Campanile, G. Influence of nutrition, body condition, and metabolic status on reproduction in female beef cattle: A review. *Theriogenology* **2019**, *125*, 277–284. [[CrossRef](#)] [[PubMed](#)]
85. Chelikani, P.K.; Ambrose, D.J.; Keisler, D.H.; Kennelly, J.J. Effects of dietary energy and protein density on plasma concentrations of leptin and metabolic hormones in dairy heifers. *J. Dairy Sci.* **2009**, *92*, 1430–1441. [[CrossRef](#)] [[PubMed](#)]
86. Cheng, L.; Cantalapiedra-Hijar, G.; Meale, S.J.; Rugoho, I.; Jonker, A.; Khan, M.A.; Al-Marashdeh, O.; Dewhurst, R.J. Review: Markers and proxies to monitor ruminal function and feed efficiency in young ruminants. *Animal* **2021**, *15*, 100337. [[CrossRef](#)] [[PubMed](#)]
87. Palma, J.M.; Galina, M.A. Effect of Early and Late Weaning on the Growth of Female Kids. *Small Rumin. Res.* **1995**, *18*, 33–38. [[CrossRef](#)]
88. Teke, B.; Akdag, F. The effects of age of lamb and parity of dam and sex and birth type of lamb on suckling behaviours of Karayaka lambs. *Small Rumin. Res.* **2012**, *103*, 176–181. [[CrossRef](#)]
89. Lu, C.D.; Potchoiba, M.J. Milk feeding and weaning of goat kids—A review. *Small Rumin. Res.* **1988**, *1*, 105–112. [[CrossRef](#)]
90. Datt, M.; Bhatেশwar, V.; Rai, D.C. Importance of body weight, age and body condition in weaning of goat kids: A review. *J. Livest. Sci.* **2023**, *14*, 71–77. [[CrossRef](#)]
91. Ergul Ekiz, E.; Yalcintan, H.; Ekiz, B. Haematological stress parameters and behavioural characteristics of dairy type goat kids compared to indigenous breeds during an intensive fattening programme. *Arch. Anim. Breed.* **2020**, *63*, 441–450. [[CrossRef](#)]
92. Delgado-Pertíñez, M.; Guzmán-Guerrero, J.L.; Mena, Y.; Castel, J.M.; González-Redondo, P.; Caravaca, F.P. Influence of kid rearing systems on milk yield, kid growth and cost of Florida dairy goats. *Small Rumin. Res.* **2009**, *81*, 105–111. [[CrossRef](#)]
93. Li, C.; Wang, W.; Liu, T.; Zhang, Q.; Wang, G.; Li, F.; Li, F.; Yue, X.; Li, T. Effect of Early Weaning on the Intestinal Microbiota and Expression of Genes Related to Barrier Function in Lambs. *Front. Microbiol.* **2018**, *9*, 1431. [[CrossRef](#)]
94. Thomsen, L.E.; Knudsen, K.E.; Hedemann, M.S.; Roepstorff, A. The effect of dietary carbohydrates and *Trichuris suis* infection on pig large intestine tissue structure, epithelial cell proliferation and mucin characteristics. *Vet. Parasitol.* **2006**, *142*, 112–122. [[CrossRef](#)]
95. Sarker, M.B.; Alam, M.H.; Saha, B.K.; Amin, M.R.; Moniruzzaman, M. Effects of soybean milk replacer on growth, meat quality, rumen and gonad development of goats. *Small Rumin. Res.* **2015**, *130*, 127–135. [[CrossRef](#)]
96. Urge, M.; Merkel, R.C.; Sahlü, T.; Anmut, G.; Goetsch, A.L. Growth performance by Alpine, Angora, Boer and Spanish wether goats consuming 50 or 75% concentrate diets. *Small Rumin. Res.* **2004**, *55*, 149–158. [[CrossRef](#)]
97. Carballo, O.C.; Khan, M.A.; Knol, F.W.; Lewis, S.J.; Stevens, D.R.; Laven, R.A.; McCoard, S.A. Impact of weaning age on rumen development in artificially reared lambs. *J. Anim. Sci.* **2019**, *97*, 3498–3510. [[CrossRef](#)]
98. Hao, Y.; Guo, C.; Gong, Y.; Sun, X.; Wang, W.; Wang, Y.; Yang, H.; Cao, Z.; Li, S. Rumen Fermentation, Digestive Enzyme Activity, and Bacteria Composition between Pre-Weaning and Post-Weaning Dairy Calves. *Animals* **2021**, *11*, 2527. [[CrossRef](#)]
99. Li, A.; Yang, Y.; Qin, S.; Lv, S.; Jin, T.; Li, K.; Han, Z.; Li, Y. Microbiome analysis reveals gut microbiota alteration of early-weaned Yimeng black goats with the effect of milk replacer and age. *Microb. Cell Fact.* **2021**, *20*, 78. [[CrossRef](#)]
100. Malmuthuge, N.; Liang, G.; Guan, L.L. Regulation of rumen development in neonatal ruminants through microbial metagenomes and host transcriptomes. *Genome Biol.* **2019**, *20*, 172. [[CrossRef](#)]
101. Saro, C.; Hohenester, U.M.; Bernard, M.; Lagree, M.; Martin, C.; Doreau, M.; Boudra, H.; Popova, M.; Morgavi, D.P. Effectiveness of Interventions to Modulate the Rumen Microbiota Composition and Function in Pre-ruminant and Ruminant Lambs. *Front. Microbiol.* **2018**, *9*, 1273. [[CrossRef](#)]
102. Distel, R.A.; Villalba, J.J.; Laborde, H.E. Effects of early experience on voluntary intake of low-quality roughage by sheep. *J. Anim. Sci.* **1994**, *72*, 1191–1195. [[CrossRef](#)]
103. Yeoman, C.J.; Ishaq, S.L.; Bichi, E.; Olivo, S.K.; Lowe, J.; Aldridge, B.M. Biogeographical Differences in the Influence of Maternal Microbial Sources on the Early Successional Development of the Bovine Neonatal Gastrointestinal tract. *Sci. Rep.* **2018**, *8*, 3197. [[CrossRef](#)] [[PubMed](#)]
104. Kelly, D.; Coutts, A.G.P. Development of digestive and immunological function in neonates: Role of early nutrition. *Livest. Prod. Sci.* **2000**, *66*, 161–167. [[CrossRef](#)]
105. Li, C.; Wang, G.; Zhang, Q.; Huang, Y.; Li, F.; Wang, W. Developmental changes of nutrient digestion in young lambs are influenced by weaning and associated with intestinal microbiota. *Anim. Biotechnol.* **2022**; ahead of print. [[CrossRef](#)] [[PubMed](#)]
106. Liu, K.; Zhang, Y.; Yu, Z.; Xu, Q.; Zheng, N.; Zhao, S.; Huang, G.; Wang, J. Ruminal microbiota-host interaction and its effect on nutrient metabolism. *Anim. Nutr.* **2021**, *7*, 49–55. [[CrossRef](#)] [[PubMed](#)]
107. Li, C.; Zhang, Q.; Wang, G.; Niu, X.; Wang, W.; Li, F.; Li, F.; Zhang, Z. The functional development of the rumen is influenced by weaning and associated with ruminal microbiota in lambs. *Anim. Biotechnol.* **2022**, *33*, 612–628. [[CrossRef](#)]

108. Pan, X.; Li, Z.; Li, B.; Zhao, C.; Wang, Y.; Chen, Y.; Jiang, Y. Dynamics of rumen gene expression, microbiome colonization, and their interplay in goats. *BMC Genom.* **2021**, *22*, 288. [[CrossRef](#)]
109. Palma-Hidalgo, J.M.; Yanez-Ruiz, D.R.; Jimenez, E.; Martin-Garcia, A.I.; Belanche, A. Presence of Adult Companion Goats Favors the Rumen Microbial and Functional Development in Artificially Reared Kids. *Front. Vet. Sci.* **2021**, *8*, 706592. [[CrossRef](#)]
110. Torres, A.; Capote, J.; Fresno, M.; Eguiza, A.; Barba, E.; Molina, J.M.; Ruiz, A. Impact of different feeding systems on cost-effectiveness and *Eimeria* spp. infections in Canarian goat kids. *Small Rumin. Res.* **2021**, *204*, 106518. [[CrossRef](#)]
111. Hinch, G.N.; Lynch, J.J.; Elwin, R.L.; Green, G.C. Long-Term Associations between Merino Ewes and Their Offspring. *Appl. Anim. Behav. Sci.* **1990**, *27*, 93–103. [[CrossRef](#)]
112. Tsiplakou, E.; Papadomichelakis, G.; Sparaggis, D.; Sotirakoglou, K.; Georgiadou, M.; Zervas, G. The effect of maternal or artificial milk, age and sex on three muscles fatty acid profile of Damascus breed goat kids. *Livest. Sci.* **2016**, *188*, 142–152. [[CrossRef](#)]
113. Abecia, L.; Ramos-Morales, E.; Martinez-Fernandez, G.; Arco, A.; Martin-Garcia, A.I.; Newbold, C.J.; Yanez-Ruiz, D.R. Feeding management in early life influences microbial colonisation and fermentation in the rumen of newborn goat kids. *Anim. Prod. Sci.* **2014**, *54*, 1449–1454. [[CrossRef](#)]
114. Abecia, L.; Jiménez, E.; Martínez-Fernández, G.; Martín-García, A.I.; Ramos-Morales, E.; Pinloche, E.; Denman, S.E.; Newbold, C.J.; Yáñez-Ruiz, D.R. Natural and artificial feeding management before weaning promote different rumen microbial colonization but not differences in gene expression levels at the rumen epithelium of newborn goats. *PLoS ONE* **2017**, *12*, e0182235. [[CrossRef](#)]
115. Belanche, A.; Yanez-Ruiz, D.R.; Detheridge, A.P.; Griffith, G.W.; Kingston-Smith, A.H.; Newbold, C.J. Maternal versus artificial rearing shapes the rumen microbiome having minor long-term physiological implications. *Environ. Microbiol.* **2019**, *21*, 4360–4377. [[CrossRef](#)] [[PubMed](#)]
116. Guo, J.; Li, P.; Liu, S.; Miao, B.; Zeng, B.; Jiang, Y.; Li, L.; Wang, L.; Chen, Y.; Zhang, H. Characterization of the Rumen Microbiota and Volatile Fatty Acid Profiles of Weaned Goat Kids under Shrub-Grassland Grazing and Indoor Feeding. *Animals* **2020**, *10*, 176. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.