fermentation

Opinion

Impacts of Slow-Release Urea in Ruminant Diets: A Review

Szu-Wei Ma and Antonio P. Faciola *

Department of Animal Sciences, University of Florida, Gainesville, FL 32611, USA; yehmaszuwei@gmail.com
* Correspondence: afaciola@ufl.edu

Abstract: The increasing costs of traditional protein sources, such as soybean meal (SBM), have prompted interest in alternative feeds for ruminants. Non-protein nitrogen (NPN) sources, like urea, offer a cost-effective alternative by enabling rumen microorganisms to convert NPN into microbial protein, which is crucial for ruminant nutrition. However, the rapid hydrolysis of urea in the rumen can result in excessive ammonia (NH_3) production and potential toxicity. Slow-release urea (SRU) has been developed to mitigate these issues by gradually releasing nitrogen, thereby improving nutrient utilization and reducing NH_3 toxicity risks. This review explores SRU's development, types, mechanisms, and benefits, highlighting its potential to enhance ruminal fermentation, microbial protein synthesis, and overall feed efficiency. SRU formulations include polymer-coated urea, lipid-coated urea, calcium-urea, starea, and zeolite-impregnated urea, each designed to control nitrogen release and minimize adverse effects. Studies have demonstrated that SRU can improve microbial nitrogen efficiency and reduce nitrogen losses, although results regarding feed intake, digestibility, and milk yield are mixed. These discrepancies indicate that factors such as SRU type, diet formulation, and animal breed may influence outcomes. Continued research is essential to optimize SRU applications, aiming to enhance ruminant production, economic viability, and environmental stewardship.

Keywords: ammonia nitrogen; nitrogen efficiency; nitrogen utilization; protein nutrition; rumen degradable protein

Citation: Ma, S.-W.; Faciola, A.P. Impacts of Slow-Release Urea in Ruminant Diets: A Review. *Fermentation* **2024**, *10*, 527. https://doi.org/10.3390/fermentation10100527

Academic Editor: Cláudia Braga Pereira Bento

Received: 24 September 2024
Revised: 14 October 2024
Accepted: 15 October 2024
Published: 17 October 2024

1. Introduction

There is growing interest in finding alternatives to plant-based protein sources, particularly soybean meal (SBM), in animal feed due to rising feed costs and environmental concerns, such as land use changes, deforestation, soil erosion, and biodiversity loss [1,2]. For ruminants, the use of non-protein nitrogen (NPN) sources in feed is a feasible alternative to SBM, as rumen microorganisms can convert NPN into microbial protein, which accounts for 50–80% of the protein absorbed in the small intestine of cattle [3,4].

Urea is a commonly used NPN source for partially replacing SBM, but its rapid hydrolysis in the rumen to ammonia (NH_3) can lead to overaccumulation of NH_3 in the rumen and elevated blood NH_3 levels [5]. To address this issue, slow-release urea (SRU) has been developed to release nitrogen more gradually in the rumen, improving nutrient utilization by rumen microorganisms. SRU comes in various forms, including biuret, starea, urea-calcium sulfate, urea-impregnated zeolite, and urea coated with lipid or polymer. This review aims to provide an overview of SRU based on current research, including its development, common types, structure, mode of action, production responses, and potential benefits for ruminants.

2. SRU Development

2.1. NPN Sources for Ruminants

Ruminants, such as cattle, sheep, and goats, play a vital role in global agriculture by producing meat, milk, and other essential products. Their ability to utilize non-edible food sources through rumen microorganisms contributes to a more sustainable food system [6,7].

However, limited availability and rising costs of dietary protein present challenges for ruminant nutrition, with feed expenses accounting for up to 70% of total production costs in the industry [8]. Additionally, the environmental impact of plant-based protein sources like soybean meal (SBM), including land use change, deforestation, and biodiversity loss, has intensified the search for alternative solutions [9].

One promising alternative is the use of NPN, which can be utilized by rumen microorganisms to synthesize microbial protein, providing amino acids for the host animal. NPN, such as urea, NH_3, and biuret, is not a protein but can be degraded in the rumen and converted into microbial protein, serving as a source of rumen-degradable protein (RDP) [10].

2.2. Urea Applications

Urea is a cost-effective and widely used NPN source, offering a more economical alternative to protein feeds like soybean meal due to its great rumen degradability and lower price [11]. Urea is typically recommended at no more than 1% of total dietary dry matter (DM), up to 135 g per cow per day, and no more than 20% of total dietary crude protein (CP) [12,13]. Furthermore, greater urea levels, such as 2% of the diet, have been reported [14]. Despite its benefits, the rapid hydrolysis of urea in the rumen can lead to inefficient nitrogen utilization, resulting in excessive NH_3 production and nitrogen losses through urea excretion [11,15]. Excessive NH_3 concentrations in the rumen can cause NH_3 toxicity if hepatic detoxification is overwhelmed, with blood NH_3 levels exceeding 0.5 mM [10,16].

Cases of NH_3 toxicity may occur under conditions such as improper mixing of total mixed rations (TMRs); errors in diet formulation or segregation of feed ingredients in storages; formation of uneven groups of animals in relation to body size, hierarchy, and feed competition; lack of acclimation to NPN-containing diets; or NPN diets low in energy and protein but high in roughage [17]. Clinical symptoms of urea toxicity can appear within minutes to hours and are often acute, leading to significant mortality if not addressed [18]. Slow-release urea technologies have been developed to address these issues, providing a controlled release of nitrogen that aligns with microbial protein synthesis in the rumen, improving nutrient utilization and reducing the risk of NH_3 toxicity [19].

2.3. Slow-Release Urea Overview

Slow-release urea (SRU) formulations are designed to provide a steady supply of nitrogen by gradually releasing urea over an extended period. These formulations utilize various techniques, such as chemical modifications, condensation, and coatings or encapsulation, to delay urea degradation in the rumen and ensure a consistent nitrogen source for rumen microorganisms [19]. However, the challenge lies in slowing NH_3 release without limiting urea's overall degradation [20].

Common types of SRU for ruminants include the following:

1. Polymer-coated urea: Synthetic polymers (e.g., polyurethane) are used to coat urea, regulating nitrogen diffusion and reducing the rate of urea degradation [11,21,22].
2. Lipid-coated urea: Urea is coated with lipids (e.g., waxes, fats, or oils) to slow its solubility and hydrolysis in the rumen [5].
3. Calcium–urea: A urea–calcium chloride complex designed for controlled release [23].
4. Starea: Extruded urea combined with corn and sulfur, offering a slower release rate [24].
5. Zeolite-impregnated urea: Urea combined with zeolite, a cation exchanger, which retains ammonium ions for gradual release [25,26].

Polymer- and lipid-coated urea are the most studied types. Both have shown potential to improve ruminal fermentation, nutrient utilization, and nitrogen efficiency. However, their effects depend on factors such as coating material, NH_3 release rate, rumen pH, and microbial composition.

3. SRU Mode of Action and Benefits

3.1. Slow Nitrogen Release

As noted, slow-release urea (SRU) formulations control the rate of urea degradation and NH_3 release, providing a slower release compared to regular urea [27]. In an in vitro study by Xin et al. [11], NH_3 concentrations in the polymer-coated urea and soybean meal (SBM) groups declined at 8 h, whereas the feed-grade urea group did not, likely due to bacterial autolysis. This indicates that SRU diets prolong the availability of nitrogen for microbial utilization during ruminal fermentation.

3.2. Nitrogen and Energy Synchronization

Slow-release urea mimics the natural breakdown of protein in the rumen and synchronizes nitrogen release with carbohydrate fermentation, enhancing microbial protein production and reducing nitrogen waste, thereby improving ruminant nutrition efficiency [19]. Inefficiencies in microbial protein synthesis can occur when ruminal NH_3 production is not synchronized with available fermentable energy, leading to nutrient imbalances [28].

3.3. Impact on Microbial Environment

In addition to improved nitrogen utilization, slow-release urea (SRU) offers several benefits. It supports a more favorable microbial environment in the rumen, potentially enhancing fiber digestion, feed efficiency, and overall animal performance by influencing microbial communities. Utilizing the latent energy in potentially digestible neutral detergent fiber may enhance nitrogen use efficiency and microbial protein synthesis. This is because a slower release of nitrogen from urea is expected to improve nitrogen use efficiency since NDF can provide carbons and NH_3 can supply nitrogens, in a form (NH_3) crucial for fibrolytic microorganisms. Guo et al. [29] reported that SRU supplementation positively altered microbial communities, increasing the abundance of feed particle-associated bacteria compared to regular urea. This indicates that SRU may support bacterial growth and thereby improve fiber digestion.

Additionally, slow-release urea (SRU) reduces the risk of metabolic disorders associated with excessive NH_3 production by decreasing peak NH_3 concentrations in the rumen [19].

3.4. Environmental Impact and Feed Cost

Slow-release urea (SRU) offers an environmentally sustainable option for ruminant nutrition by reducing nitrogen losses in urine and manure [15,19]. Economically, SRU can improve the income over feed cost (IOFC) under specific feeding conditions. Economic simulations indicate that, with a milk yield response of 0.5 kg/day per cow from SRU inclusion, the IOFC improves, particularly when corn grain, corn silage, and SRU (Optigen) prices are low and soybean meal and milk prices are high [30].

4. Production Responses

4.1. Ruminal Fermentation

The primary effect of slow-release urea (SRU) in the rumen is its slower release rate of NH_3. Ceconi et al. [31] observed that the urea group (0.6% DM) reached its peak NH_3 concentration 4 h after feeding, decreased to its lowest point around 16 h, and then returned to baseline levels by 24 h. In contrast, the SRU groups (lipid- or polymer-coated, 0.67% DM) maintained intermediate NH_3 levels until 9 h post-feeding. The control group (without urea) remained at low NH_3 levels between 4 and 15 h. These findings are consistent with Ribeiro et al. [32], which reported NH_3 peaks between 1 and 2 h after feeding, with greater levels in the urea group (25.8 g/kg of diet), intermediate levels in the SRU group (30.4 g/kg of diet), and the lowest levels in the control group.

Regarding ruminal pH, Ceconi et al. [31] found no significant differences, while Ribeiro et al. [32] reported significant differences in pH ($p < 0.05$) among treatments, but no interaction between treatment and time. The highest pH values were observed between 1 and 2 h after feeding for the urea group, likely due to faster hydrolysis and NH_3 release.

For ruminal volatile fatty acids (VFAs), Ceconi et al. [31] found no differences in total VFA, branched-chain VFA, acetate, or butyrate molar proportions. Similarly, Taylor-Edwards et al. [22] and Xin et al. [11] reported no differences in total or individual VFA concentrations using in vivo and in vitro methods. However, Ceconi et al. [31] reported a lower acetate-to-propionate ratio in the SRU group compared to the control group (1.08 vs. 1.50), while Holder [33] found a greater acetate-to-propionate ratio in cattle fed Optigen II compared to regular urea (4.25 vs. 4.10). It was suggested that a consistent NH_3 source might favor slow-growing fiber-digesting bacteria. Nonetheless, Ceconi et al. [31] proposed that the lower NH_3 levels in calves fed coated urea might have inhibited fiber-digesting bacteria and reduced the acetate-to-propionate ratio, challenging Holder's [33] findings.

4.2. Microbial Protein Synthesis

Maximizing microbial growth and the uptake of rumen-degradable protein (RDP) by rumen microorganisms is a key objective in optimizing rumen nutrition. Enhancing amino acid (AA) availability to the small intestine while reducing nitrogen (N) losses can significantly improve feed efficiency [19].

A recent study by Guo et al. [29] demonstrated improved microbial nitrogen efficiency with increased SRU supplementation compared to the control group (11.7 vs. 9.5, $p = 0.03$). Conversely, Galo et al. [21] and Alipour et al. [34] reported no significant differences in total microbial protein synthesis when comparing SRU with regular urea in lactating cow diets.

4.3. Feed Intake, Digestibility, and Milk Yield

For dry matter intake (DMI), a study by Xin et al. [11] found that cows fed a polymer-coated urea (PCU) diet (0.6% DM) had approximately 12.8% greater DMI (22.78 vs. 20.19 kg/d) compared to those fed regular urea (0.6% DM). However, other studies reported no significant differences in DMI among treatment groups [22,35].

Regarding nutrient digestibility, SRU is expected to improve digestibility due to sustained nitrogen availability and enhanced microbial utilization. Ribeiro et al. [32] found increased crude protein (CP) digestibility ($p < 0.01$) with NPN treatments compared to a control without urea. Galo et al. [21] also observed greater total tract apparent dry matter (DM) and CP digestibility in cows fed 18% CP with coated urea (CP18+CU) compared to those fed 18% CP without coated urea (CP18-CU). In contrast, Ceconi et al. [31] reported no differences in the digestibility of organic matter (OM), neutral detergent fiber (NDF), CP, or starch among diets with 0% DM urea, 0.6% DM urea, and 0.67% DM Optigen II or NitroShure.

For milk yield, Inostroza et al. [30] found that cows fed a diet with coated urea (114 g/d per cow) had a greater milk yield (+0.5 kg/d per cow, $p < 0.01$) compared to those fed a control diet without coated urea (35.9 vs. 35.4 kg/d). Conversely, Highstreet et al. [5] found no difference in milk yield between cows fed coated urea (113.5 g/d per cow) and those fed regular urea (102.2 g/d per cow). A meta-analysis by Salami et al. [27] also indicated no significant difference in milk yield ($p > 0.05$) between diets with and without polymer-coated SRU. The findings regarding the production responses discussed above are summarized in Table 1.

Table 1. Summary of the effects of slow-release urea supplements on the production responses compared to the control group in the studies discussed.

Study	Inclusion Rate of SRU	Production Responses
Highstreet et al. [5]	In vivo: 113.5 g/d per cow	No differences in milk yield, DMI No differences in total tract digestibility of CP and aNDF Increased milk fat (0.068 kg/d, $p = 0.01$) and protein (0.041 kg/d, $p = 0.01$) in early lactation cows
Xin et al. [11]	In vitro: 1.7% DM In vivo: 0.6% DM	No differences in total or individual VFA concentrations using in vitro methods compared to the control group Greater DMI (22.78 vs. 20.19 kg/d) in in vivo trial
Galo et al. [21]	In vivo: 0.77% DM	No differences in microbial protein production Greater total tract apparent DM and CP digestibility in cows
Taylor-Edwards et al. [22]	In vivo 1: 1.8% DM In vivo 2: 0.6% DM	No differences in total and individual VFA concentrations using in vivo methods No significant differences in DMI in in vivo trial
Salami et al. [27]	Mean: 0.58% DM (meta-analysis)	No significant differences in milk yield ($p > 0.05$) Improved feed efficiency (+3%) and NUE (+4%)
Guo et al. [29]	In vitro: 0.28% or 0.56% DM	Improved microbial nitrogen efficiency with SRU supplementation No differences in fermentation pH and total VFA production, whereas acetate-to-propionate ratio increased
Inostroza et al. [30]	In vivo: 114 g/d per cow	Greater milk yield (+0.5 kg/d per cow, $p < 0.01$) Indicated that changes in IOFC were more positive when the prices of corn and SRU were lower and when the prices of soybean meal and milk were greater
Ceconi et al. [31]	In vivo: 0.67% DM	Maintained intermediate NH_3 levels No significant differences on ruminal pH, total VFA, branched-chain VFA, acetate, or butyrate molar proportions Lower acetate-to-propionate ratio No differences in the digestibility of OM, NDF, CP, or starch
Ribeiro et al. [32]	In vivo: 30.4 g/kg of diet	Intermediate NH_3 levels in the SRU group Significant differences in pH ($p < 0.05$) among treatments, but no interaction between treatment and time Increased CP digestibility ($p < 0.01$) with NPN treatments
Holder [33]	In vivo: 0.87% or 0.97% DM	Reduced rumen NH_3 and plasma urea concentrations Greater acetate-to-propionate ratio in cattle
Alipour et al. [34]	In vitro: 0.5–1.75% DM	SRU levels had a quadratic effect on the disappearance of NDF and ADF, with a plateau at 1% SRU inclusion level in finishing beef diet in vitro No significant differences in total microbial protein synthesis
Chegeni et al. [35]	In vivo: 1.8% DM	No significant differences in DMI in in vivo trial with sheep No significant differences in the pH and total VFA, whereas the acetate-to-propionate ratio tended to be lower

SRU, slow-release urea; DM, dry matter; DMI, dry matter intake; CP, crude protein; aNDF, amylase-treated neutral detergent fiber; VFA, volatile fatty acid; NUE, nitrogen use efficiency; IOFC, income over feed cost; NH_3, ammonia; OM, organic matter; NPN, non-protein nitrogen; The control group refers to those without SRU supplements.

These inconsistencies indicate that factors beyond SRU inclusion rate, such as SRU physical structure, degradable intake protein (DIP) or RDP adequacy [31], dietary CP level [32], diet formulation interactions, forage-to-concentrate ratio [36], and animal breed, may also influence the effects of SRU.

5. Conclusions

In conclusion, slow-release urea offers a promising approach to optimizing dietary protein utilization in ruminant nutrition. By controlling the release of nitrogen, SRU can enhance microbial protein synthesis, can improve fiber digestion, and can reduce nitrogen losses. While previous research has focused on SRU inclusion rates, further investigation is needed into how SRU interacts with different diet formulations. Ongoing research and development will continue to refine slow-release urea, contributing to the sustainable intensification of ruminant production systems. By improving farm economics, animal health, and environmental stewardship, slow-release urea holds significant potential for advancing ruminant production.

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

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors acknowledge the valuable and constructive discussions with postdoctoral researchers, graduate students, and visiting scholars that contributed to the development of this manuscript.

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

References

1. Aide, T.M.; Clark, M.L.; Grau, H.R.; López-Carr, D.; Levy, M.A.; Redo, D.; Bonilla-Moheno, M.; Riner, G.; Andrade-Núñez, M.J.; Muñiz, M. Deforestation and Reforestation of Latin America and the Caribbean (2001–2010). *Biotropica* **2013**, *45*, 262–271. [CrossRef]
2. Rota Graziosi, A.; Gislon, G.; Colombini, S.; Bava, L.; Rapetti, L. Partial Replacement of Soybean Meal with Soybean Silage and Responsible Soybean Meal in Lactating Cows Diet: Part 2, Environmental Impact of Milk Production. *Ital. J. Anim. Sci.* **2022**, *21*, 645–658. [CrossRef]
3. Storm, E.; Brown, D.S.; Ørskov, E.R. The Nutritive Value of Rumen Micro-Organisms in Ruminants. *Br. J. Nutr.* **1983**, *50*, 479–485. [CrossRef]
4. Lu, Z.; Xu, Z.; Shen, Z.; Tian, Y.; Shen, H. Dietary Energy Level Promotes Rumen Microbial Protein Synthesis by Improving the Energy Productivity of the Ruminal Microbiome. *Front. Microbiol.* **2019**, *10*, 847. [CrossRef]
5. Highstreet, A.; Robinson, P.H.; Robison, J.; Garrett, J.G. Response of Holstein Cows to Replacing Urea with with a Slowly Rumen Released Urea in a Diet High in Soluble Crude Protein. *Livest. Sci.* **2010**, *129*, 179–185. [CrossRef]
6. Broderick, G.A. Review: Optimizing Ruminant Conversion of Feed Protein to Human Food Protein. *Animal* **2018**, *12*, 1722–1734. [CrossRef]
7. Myer, P.R.; Clemmons, B.A.; Schneider, L.G.; Ault, T.B. Microbiomes in Ruminant Protein Production and Food Security. *CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* **2019**, *14*, 1–11. [CrossRef]
8. Bach, A. Key Indicators for Measuring Dairy Cow Performance. In *FAO Animal Production and Health Proceedings, Proceedings of the FAO Symposium: Optimization of Feed Use Efficiency in Ruminant Production Systems, Bangkok, Thailand, 27 November 2012*; FAO: Rome, Italy, 2012; pp. 33–44.
9. Grossi, S.; Compiani, R.; Rossi, L.; Dell'anno, M.; Castillo, I.; Sgoifo Rossi, C.A. Effect of Slow-Release Urea Administration on Production Performance, Health Status, Diet Digestibility, and Environmental Sustainability in Lactating Dairy Cows. *Animal* **2021**, *11*, 2405. [CrossRef]
10. Nichols, K.; de Carvalho, I.P.C.; Rauch, R.; Martín-Tereso, J. Review: Unlocking the Limitations of Urea Supply in Ruminant Diets by Considering the Natural Mechanism of Endogenous Urea Secretion. *Animal* **2022**, *16*, 100537. [CrossRef]
11. Xin, H.S.; Schaefer, D.M.; Liu, Q.P.; Axe, D.E.; Meng, Q.X. Effects of Polyurethane Coated Urea Supplement on in Vitro Ruminal Fermentation, Ammonia Release Dynamics and Lactating Performance of Holstein Dairy Cows Fed a Steam-Flaked Corn-Based Diet. *Asian-Australas. J. Anim. Sci.* **2010**, *23*, 491–500. [CrossRef]
12. Kertz, A.F. Urea Feeding to Dairy Cattle: A Historical Perspective and Review. *Prof. Anim. Sci.* **2010**, *26*, 257–272. [CrossRef]
13. EFSA Panel on Additives and Products or Substances used in Animal Feed (FEEDAP). Scientific Opinion on the Safety and Efficacy of Urea for Ruminants. *EFSA J.* **2012**, *10*, 2624. [CrossRef]
14. Barbosa, J.G.; Costa, R.G.; Medeiros, A.N.D.; Queiroga, R.D.C.R.D.E.; Batista, Â.M.V.; Medeiros, G.R.D.; Beltrão Filho, E.M. Use of Different Urea Levels in the Feeding of Alpine Goats. *Rev. Bras. Zootec.* **2012**, *41*, 1713–1719. [CrossRef]
15. Jonker, J.S.; Kohn, R.A.; Erdman, R.A. Using Milk Urea Nitrogen to Predict Nitrogen Excretion and Utilization Efficiency in Lactating Dairy Cows. *J. Dairy Sci.* **1998**, *81*, 2681–2692. [CrossRef]

16. Symonds, H.W.; Mather, D.L.; Collis, K.A. The Maximum Capacity of the Liver of the Adult Dairy Cow to Metabolize Ammonia. *Br. J. Nutr.* **1981**, *46*, 481–486. [CrossRef]
17. Antonelli, A.C.; Torres, G.A.S.; Soares, P.C.; Mori, C.S.; Sucupira, M.C.A.; Ortolani, E.L. Ammonia Poisoning Causes Muscular but Not Liver Damage in Cattle. *Arq. Bras. Med. Veterinária Zootec.* **2007**, *59*, 8–13. [CrossRef]
18. Ortolani, E.L.; Mori, C.S.; Filho, J.A.R. Ammonia Toxicity from Urea in a Brazilian Dairy Goat Flock. *Vet. Hum. Toxicol.* **2000**, *42*, 87–89.
19. Cherdthong, A.; Wanapat, M. Development of Urea Products as Rumen Slow-Release Feed for Ruminant Production: A Review. *Aust. J. Basic Appl. Sci.* **2010**, *4*, 2232–2241.
20. Joysowal, M.; Tyagi, A.K.; Tyagi, N.; Kumar, S.; Keshri, A.; Singh, D. Use of Slow Release Ammonia Products in Ruminant Diet: A Review. *J. Entomol. Zool. Stud.* **2019**, *7*, 882–888.
21. Galo, E.; Emanuele, S.M.; Sniffen, C.J.; White, J.H.; Knapp, J.R. Effects of a Polymer-Coated Urea Product on Nitrogen Metabolism in Lactating Holstein Dairy Cattle. *J. Dairy Sci.* **2003**, *86*, 2154–2162. [CrossRef]
22. Taylor-Edwards, C.C.; Hibbard, G.; Kitts, S.E.; McLeod, K.R.; Axe, D.E.; Vanzant, E.S.; Kristensen, N.B.; Harmon, D.L. Effects of Slow-Release Urea on Ruminal Digesta Characteristics and Growth Performance in Beef Steers. *J. Anim. Sci.* **2009**, *87*, 200–208. [CrossRef]
23. Huntington, G.B.; Harmon, D.L.; Kristensen, N.B.; Hanson, K.C.; Spears, J.W. Effects of a Slow-Release Urea Source on Absorption of Ammonia and Endogenous Production of Urea by Cattle. *Anim. Feed. Sci. Technol.* **2006**, *130*, 225–241. [CrossRef]
24. Kozerski, N.D.; Ítavo, L.C.V.; dos Santos, G.T.; Ítavo, C.C.B.F.; Benchaar, C.; Dias, A.M.; Difante, G.D.S.; Leal, E.S. Extruded Urea-Corn Product Can Partially Replace True Protein Sources in the Diet for Lactating Jersey Cows. *Anim. Feed. Sci. Technol.* **2021**, *282*, 115129. [CrossRef]
25. Mumpton, F.A. Uses of Natural Zeolites in Agriculture and Industry. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 3463–3470. [CrossRef]
26. Kardaya, D.; Sudrajat, D.; Dihansih, E. Efficacy of Dietary Urea-Impregnated Zeolite in Improving Rumen Fermentation Characteristics of Local Lamb. *Media Peternak.* **2012**, *35*, 207. [CrossRef]
27. Salami, S.A.; Moran, C.A.; Warren, H.E.; Taylor-Pickard, J. Meta-Analysis and Sustainability of Feeding Slow-Release Urea in Dairy Production. *PLoS ONE* **2021**, *16*, e0246922. [CrossRef]
28. Sinclair, L.A.; Garnsworthy, P.C.; Newbold, J.R.; Buttery, P.J. Effects of Synchronizing the Rate of Dietary Energy and Nitrogen Release in Diets with a Similar Carbohydrate Composition on Rumen Fermentation and Microbial Protein Synthesis in Sheep. *J. Agric. Sci.* **1995**, *124*, 463–472. [CrossRef]
29. Guo, Y.; Xiao, L.; Jin, L.; Yan, S.; Niu, D.; Yang, W. Effect of Commercial Slow-Release Urea Product on in Vitro Rumen Fermentation and Ruminal Microbial Community Using RUSITEC Technique. *J. Anim. Sci. Biotechnol.* **2022**, *13*, 56. [CrossRef]
30. Inostroza, J.F.; Shaver, R.D.; Cabrera, V.E.; Tricárico, J.M. Effect of Diets Containing a Controlled-Release Urea Product on Milk Yield, Milk Composition, and Milk Component Yields in Commercial Wisconsin Dairy Herds and Economic Implications. *Prof. Anim. Sci.* **2010**, *26*, 175–180. [CrossRef]
31. Ceconi, I.; Ruiz-Moreno, M.J.; Dilorenzo, N.; Dicostanzo, A.; Crawford, G.I. Effect of Slow-Release Urea Inclusion in Diets Containing Modified Corn Distillers Grains on Total Tract Digestibility and Ruminal Fermentation in Feedlot Cattle. *J. Anim. Sci.* **2015**, *93*, 4058–4069. [CrossRef]
32. Ribeiro, S.S.; Vasconcelos, J.T.; Morais, M.G.; Ítavo, C.B.C.F.; Franco, G.L. Effects of Ruminal Infusion of a Slow-Release Polymer-Coated Urea or Conventional Urea on Apparent Nutrient Digestibility, in Situ Degradability, and Rumen Parameters in Cattle Fed Low-Quality Hay. *Anim. Feed. Sci. Technol.* **2011**, *164*, 53–61. [CrossRef]
33. Holder, V.B. The Effects of Slow Release Urea on Nitrogen Metabolism in Cattle. Ph.D. Dissertation, University of Kentucky, Lexington, KY, USA, 2012. Available online: https://uknowledge.uky.edu/animalsci_etds/6 (accessed on 14 October 2024).
34. Alipour, D.; Saleem, A.M.; Sanderson, H.; Brand, T.; Santos, L.V.; Mahmoudi-Abyane, M.; Marami, M.R.; McAllister, T.A. Effect of Combinations of Feed-Grade Urea and Slow-Release Urea in a Finishing Beef Diet on Fermentation in an Artificial Rumen System. *Transl. Anim. Sci.* **2020**, *4*, 839–847. [CrossRef]
35. Chegeni, A.; Li, Y.L.; Deng, K.D.; Jiang, C.G.; Diao, Q.Y. Effect of Dietary Polymer-Coated Urea and Sodium Bentonite on Digestibility, Rumen Fermentation, and Microbial Protein Yield in Sheep Fed High Levels of Corn Stalk. *Livest. Sci.* **2013**, *157*, 141–150. [CrossRef]
36. Salami, S.A.; Devant, M.; Apajalahti, J.; Holder, V.B.; Salomaa, S.; Keegan, J.D.; Moran, C.A. Slow-Release Urea as a Sustainable Alternative to Soybean Meal in Ruminant Nutrition. *Sustainability* **2021**, *13*, 2464. [CrossRef]