TJNN Thai Journal of Nanoscience and Nanotechnology

Smart Tannin Nanoparticles: A Novel Approach to Overcome Rumen Anti-Nutritional Barriers in Ruminant Nutrition

Rezki Amalyadi*

Faculty of Animal Science, Department of Animal Science, University of Mataram, West Nusa Tenggara, 83115, Indonesia

Received: 10 September 2025, Revised: 30 October 2025, Accepted: 1 December 2025

Abstract

Ruminant livestock production in semi-arid regions faces persistent challenges, including seasonal feed shortages, variable nutrient quality, and environmental issues such as methane emissions. These constraints impact animal productivity, health, and sustainability. Tannins, a group of plant-derived polyphenols, have garnered attention for their potential to improve protein utilization and reduce enteric methane emissions. However, at high concentrations, tannins exert anti-nutritional effects—reducing feed intake, nutrient digestibility, and altering rumen microbial balance—thus limiting their practical utility in ruminant diets. Recent advancements in nanotechnology offer an innovative strategy to address these limitations through the formulation of tannin nanoparticles. These smart delivery systems have the potential to enhance the bioavailability, stability, and targeted release of tannins in the gastrointestinal tract, enabling controlled interactions with rumen microbes and dietary macromolecules based on principles demonstrated in other biological systems. This review explores the current state of knowledge regarding the dualistic role of tannins, the principles and safety of nanotechnology in animal feed, and the comparative impacts of conventional tannins and nano-tannin applications on rumen fermentation, methane mitigation, nutrient metabolism, and animal performance. While tannin nanoparticles show promise in improving ruminant nutrition and environmental sustainability, several research gaps remain. These include the need for standardized nanoparticle formulations, comprehensive long-term safety evaluations, and clear regulatory frameworks for their use in livestock systems. Addressing these challenges is crucial for enabling the responsible and effective integration of nanotechnology into future ruminant feeding strategies, particularly in resource-limited and climate-vulnerable regions. Most evidence on nano-tannin applications in ruminants remains theoretical or from in vitro studies, highlighting the need for comprehensive in vivo validation.

Keywords: Tannins, Nanotechnology, Ruminant nutrition, Methane mitigation, Feed efficiency

1. Introduction

In semi-arid regions, the productivity of ruminants is limited by the seasonal growth of grasses and the fluctuating quality of feed [1]. Additionally, digestive disorders due to inadequate nutritional management can lead to significant economic losses [2]. Ruminant livestock contribute to greenhouse gas emissions, particularly methane, which poses a challenge to global food sustainability [3]. The increasing global population demands more animal protein, putting pressure on the Earth's resources and contributing to climate change [4], [5]. Tannins, a group of plant secondary metabolites, have both beneficial and detrimental effects on ruminant nutrition: positive effects, at low concentrations, tannins can reduce methane emissions, improve rumen-bypass protein synthesis, and enhance the fatty acid composition in ruminant products [6], [7]. They also have bacteriostatic, anti-inflammatory, and antioxidant properties; and negative effects, high levels of tannins can be anti-nutritional, reducing feed intake and fiber digestibility [8], [9]. The complexity of tannins makes it challenging to remove their antinutritional effects without losing nutritive value [10].

Nanotechnology can improve the stability and bioavailability of feed ingredients, leading to higher-quality and safer products [11]. Nanoencapsulation technologies, such as nano-propolis, enhance the absorption and effectiveness of natural supplements [12]. Nanotechnology applications in

Corresponding Author: rezkiamalyadi@staff.unram.ac.id

veterinary medicine and animal health can address global challenges related to disease control and food security [12], [13]. Nanotechnology has the potential to reduce the environmental impact of ruminant production by improving feed efficiency and reducing greenhouse gas emissions [14]. The review aims to analyze the global challenges in ruminant nutrition and explore potential solutions to improve feed quality, animal health, and environmental sustainability; evaluate the role and limitations of tannins in ruminant feed, focusing on their beneficial and detrimental effects; investigate the promise of nanotechnology in feed science, highlighting its potential to revolutionize ruminant nutrition and production; and provide a comprehensive overview of current research and developments in ruminant nutrition, aiming to enhance sustainable productivity and food security.

Scope and Methodology

This comprehensive narrative review synthesizes current knowledge on tannins and nanotechnology in ruminant nutrition. Given the emerging nature of nano-tannin applications and limited in vivo ruminant studies, we adopted a narrative approach to integrate evidence from related fields (in vitro rumen studies, nanoparticle characterization, conventional tannin research) and identify research directions. Literature was identified through PubMed, Web of Science, and Google Scholar (2000-2025) using search terms including tannins, nanoparticles, ruminant nutrition, and methane mitigation.

Tannins in Ruminant Nutrition

Tannins are classified into two main types hydrolyzable tannins (HT) and condensed tannins (CT) [15]. Hydrolyzable tannins (HT), these are esters of phenolic acids (e.g. gallic acid) with a carbohydrate core [16]. Condensed tannins (CT), these are polymers of flavan-3-ols, lacking a carbohydrate core. Chemical properties, tannins are polyphenolic compounds with high molecular weight, capable of forming complexes with proteins, carbohydrates, and metal ions [17], [18]. Beneficial effects of tannins: protein protection, tannins can protect dietary proteins from degradation in the rumen, leading to increased protein availability in the intestines [19]; methane reduction, tannins have been shown to reduce methane emissions from ruminants, contributing to lower greenhouse gas emissions [20], [21]; and nutrient utilization, improved nutrient utilization, including better nitrogen retention and reduced nitrogen excretion, has been observed with tannin supplementation [22], [23].

High concentrations of tannins can inhibit the digestibility of nutrients by forming complexes with proteins and carbohydrates, making them less available for absorption [24], [25]. Tannins can suppress rumen microbial populations, including bacteria, protozoa, and fungi, which can negatively impact rumen fermentation and nutrient digestion [26], [27]. The beneficial effects of tannins are dose-dependent. Low to moderate doses (e.g. <1% to ~3% of diet dry matter) are generally beneficial, while higher doses can be detrimental [7], [28]. Achieving the right balance is crucial. Over-supplementation can lead to reduced feed intake, lower nutrient digestibility, and adverse effects on animal performance [29]. The effects of tannins can vary based on their chemical structure, the type of tannin, the diet composition, and the animal species [30].

Table 1. Characteristics, Benefits, and Limitations of Tannins in Ruminant Diets

Aspect	Details
Types of Tannins	Hydrolyzable (HT) and Condensed (CT)
Chemical Nature	Polyphenolic compounds, high molecular weight, form complexes with macromolecules
Beneficial Effects	Protein protection, methane reduction, improved nutrient utilization
Anti-Nutritional Effects	Digestibility inhibition, microbial suppression
Dose-Dependent Response	Optimal at low to moderate doses, detrimental at high doses
Balance Challenges	Variability based on structure, type, diet, and species
Optimal Dose Range	1-3% of diet DM for beneficial effects; >3-5% risk of anti-nutritional effects (species and tannin-type dependent)

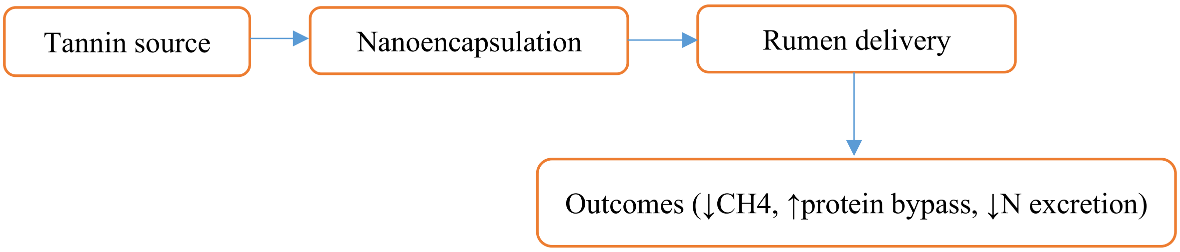

Fig. 1. Conceptual Framework

Nanotechnology in Animal Feed

Nanotechnology involves the manipulation of materials at the nanoscale (1-100 nm) to create new materials and devices with unique properties [31], [32]. Nanoparticle delivery in animal feed utilizes these small particles to enhance nutrient absorption and bioavailability by passing through biological barriers more efficiently [11], [33]. Nanoparticles can be designed to deliver nutrients directly to specific organs or tissues, improving the efficiency of nutrient utilization [34], [35]. Nanoformulations can provide a sustained release of nutrients, ensuring a steady supply over time and reducing the frequency of feed administration [36]. Nanoparticles enhance the bioavailability of nutrients, allowing for lower doses and reducing waste [34], [35]. Types of nanocarriers used in livestock feed, lipid-based nanocarriers, these include liposomes and nanoemulsions, which are effective in encapsulating hydrophobic nutrients and improving their solubility and absorption [36]. Polymeric nanocarriers, made from biodegradable polymers, these carriers can protect nutrients from degradation and release them in a controlled manner [37]. Inorganic nanocarriers, examples include nano-minerals like nano-selenium and nano-zinc, which enhance nutrient bioavailability and have additional health benefits such as antioxidant activity [38].

The potential toxicity of nanoparticles at the cellular level is a significant concern. Studies have shown that nanoparticles like silicon oxide, titanium oxide, and zinc oxide can exhibit toxic effects [39], [40]. Regulatory bodies such as the european food safety authority (efsa) and the United States food and drug administration (fda) have established guidelines for the safety assessment of nanomaterials in food and feed [41]. These guidelines include physicochemical characterization, exposure assessment, and hazard identification [42], [43]. Comprehensive risk assessments are necessary to evaluate the long-term effects of nanoparticles on animal health, human health, and the environment. This includes studies on reproductive and developmental toxicity, immunotoxicity, and allergenicity [44].

Table 2. Overview of Nanotechnology Principles, Advantages, and Safety Considerations

Aspect	Details
Definition	Manipulation of materials at the nanoscale (1-100 nm) [31], [32]
Principles	Enhanced nutrient absorption and bioavailability [11], [33], [35]
Advantages	Targeted delivery, controlled release, improved bioavailability [34], [36]
Types of Nanocarriers	Lipid-based, polymeric, inorganic [37]
Safety Concerns	Potential toxicity at cellular level [39], [40], [42]
Regulatory Frameworks	EFSA, FDA guidelines for safety assessment [41]
Risk Assessment	Studies on toxicity, immunotoxicity, allergenicity [44]

Tannin Nanoparticles: Formulation and Characterization

Green synthesis, tannins can be used as reducing and capping agents in the green synthesis of nanoparticles. This method is eco-friendly and cost-effective, utilizing plant extracts rich in tannins to reduce metal ions and stabilize the nanoparticles [45], [46]. Film dispersion method, this method involves the preparation of tannin-loaded nanoparticles, such as those decorated with FA-PEG, through film dispersion [47]. Solvothermal method, tannins can be used to modify magnetic nanoparticles via a solvothermal method, enhancing their properties for specific applications [48]. Size and morphology, nanoparticles synthesized using tannins typically range from 15-166.8 nm in size, with spherical and uniform shapes confirmed by techniques like TEM, SEM, and DLS [49], [50]. Charge and stability, zeta potential measurements indicate good stability, with values such as -28.48 mv for tannin-capped silver nanoparticles [51]. Stability is also confirmed by minimal changes in size and encapsulation efficiency over time 7. Release profile, encapsulation efficiency and controlled release profiles are crucial. For instance, tannin-modified nanoparticles show a high encapsulation efficiency (up to 92.11%) and controlled release under simulated conditions [52].

The advantages of nano-encapsulated tannins over free tannins in ruminant systems are hypothesized to stem from several mechanisms: (1) Protection from premature degradation – nanoencapsulation may protect tannins from rapid degradation by rumen microbes, allowing controlled release in targeted regions; (2) Modulated protein binding - encapsulation may prevent excessive tannin-protein complexation in the rumen while maintaining beneficial effects post-ruminally; (3) Enhanced stability - nanoformulations may improve chemical stability during feed processing and storage; and (4) Improved bioavailability - smaller particle size may enhance absorption of bioactive compounds."

Tannin nanoparticles exhibit stability and controlled release in varying pH environments, which is essential for their interaction with the rumen environment. For example, kafirin microparticles encapsulating tannins showed significant antioxidant release under simulated gastric conditions [53]. The stability and degradation of tannin nanoparticles can be influenced by their composition and the presence of stabilizing agents like glycine betaine, which enhances thermal stability [54]. Tannin nanoparticles have shown significant antimicrobial, antioxidant, and anticancer activities in vitro. For instance, tannin-capped silver nanoparticles exhibited strong antibacterial and antioxidant properties [55]. In vivo studies demonstrate the potential of tannin nanoparticles for therapeutic applications. For example, tannin-modified silver nanoparticles showed promising results in reducing liver enzyme levels and inflammation in mice models [56], [57]. Additionally, tannin nanoparticles have been used for drug delivery, showing improved bioavailability and stability of encapsulated compounds [52].

Table 3. Physicochemical and Functional Properties of Tannin Nanoparticles

Aspect	Details
Encapsulation Methods	Green synthesis, film dispersion, solvothermal method
Size and Morphology	15-166.8 nm, spherical and uniform shapes
Charge and Stability	Zeta potential: -28.48 mV, stable over time
Release Profile	High encapsulation efficiency (up to 92.11%), controlled release
pH Sensitivity and Degradation	Stable in varying pH, enhanced thermal stability with glycine betaine
In Vitro Dynamics	Significant antimicrobial, antioxidant, and anticancer activities
In Vivo Dynamics	Reduced liver enzyme levels, inflammation, improved bioavailability and stability of drugs

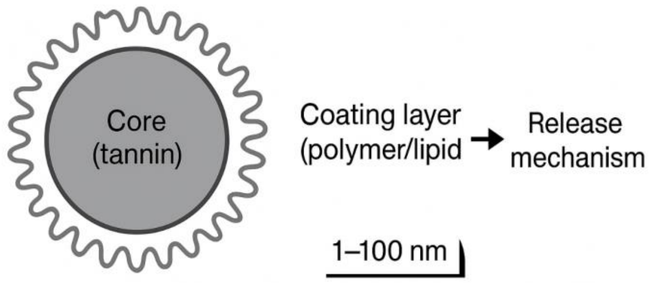

Fig. 2. Nanoparticle Structure

Effects of Tannin Nanoparticles on Rumen Fermentation

Tannins have been shown to significantly reduce methane production in the rumen. This effect is primarily due to the suppression of methanogenesis, which is a key process in methane production [58]. Tannins can decrease the population of certain rumen microbes, such as Butyrivibrio fibrisolvens, which are involved in fiber degradation [59]. Additionally, tannins can alter the microbial protein synthesis, with varying effects depending on the type of tannin and the plant source [60], [61]. Increased levels of tannins in the diet have been consistently shown to lower methane emissions [22], [62]. This reduction is beneficial for mitigating greenhouse gas emissions from ruminants. Tannins can improve nitrogen utilization by reducing rumen protein degradation, thus increasing the proportion of feed protein reaching the lower digestive tract for enzymatic digestion [15], [61]. However, high levels of tannins can decrease nitrogen utilization efficiency, leading to more nitrogen being excreted in feces [22].

Tannins can inhibit fiber degradation by binding to proteins and protecting plant cell walls from microbial digestion [25]. This effect can slow down the digestibility of forages, which may be beneficial in certain feeding strategies. The impact of tannins on nutrient digestibility is dose-dependent. Lower levels of tannins may have minimal effects, while higher levels can significantly reduce the digestibility of dry matter and crude protein [61]. The type of tannin also plays a role, with hydrolyzable tannins (HT) being more favorable for maintaining nutrient intake and digestibility compared to condensed tannins (CT) [22]. Traditional tannin applications have shown similar effects on rumen fermentation, methane production, and nutrient digestibility as tannin nanoparticles [59], [62]. However, the use of nanoparticles may offer more controlled and targeted delivery, potentially enhancing the efficiency of tannin utilization. Nanoparticles can improve the bioavailability and stability of tannins, protecting them from degradation during digestion and ensuring more consistent effects on rumen fermentation [60], [63]. This targeted approach may lead to better modulation of microbial populations and fermentation processes.

Table 4. Comparative Effects of Tannin Nanoparticles and Conventional Tannins: Evidence from Ruminant and Related Studies

Aspect	Tannin Nanoparticles	Conventional Tannin Application
Methane Emission	Significant reduction [59], [62]	Significant reduction [22], [58]
Nitrogen Utilization	Improved, but can decrease at high levels [61]	Improved, but can decrease at high levels [22]
Fiber Degradation	Inhibited [61]	Inhibited [25]
Nutrient Digestibility	Dose-dependent reduction [25]	Dose-dependent reduction [61]
Microbial Population	Altered, reduced specific microbes [59]	Altered, reduced specific microbes [64]
Bioavailability and Stability	Enhanced [60], [63]	Variable [22], [59]

*Most nano-tannin data derived from in vitro rumen studies or extrapolated from nanoparticle studies in other biological systems

Animal Performance and Health Outcomes

Growth performance and feed efficiency are influenced by various factors including diet composition, genetic factors, and management practices. For instance, pharmacological supplementation of trace minerals like zinc (Zn) and copper (Cu) can enhance growth and feed efficiency in pigs [65]. Additionally, feed efficiency measures such as feed conversion ratio (FCR) and residual feed intake (RFI) are critical for evaluating animal performance [66]. Factors such as bedding, group composition, and ambient temperature significantly affect feed intake in pigs [67]. In cattle, dominance can influence feed intake, with more dominant animals having higher dry matter intakes [68].

Supplementation with rumen-protected amino acids (RPAA) like methionine and lysine can improve nitrogen balance and average daily gain (ADG) in buffalo calves, demonstrating a protein-sparing effect [69]. Similarly, supplementation of RPAA in dairy cows can enhance milk production and overall performance [70], [71]. The form in which amino acids are provided (free vs. protein-bound) affects their postprandial plasma appearance and metabolic responses, impacting protein deposition and growth performance [72], [73], [74]. The rumen epithelium plays a crucial role in nutrient absorption and maintaining barrier function. High concentrate diets can lead to imbalances in cellular metabolism and immune responses, potentially causing epithelial damage and systemic inflammation [75], [76], [77].

Subacute ruminal acidosis (SARA) can alter rumen fermentation patterns and epithelial integrity, leading to health issues [78], [79]. Dysbiosis in the rumen can increase permeability, allowing harmful substances to enter the bloodstream and cause systemic inflammation [80], [81]. Antioxidants play a vital role in mitigating oxidative stress, which can affect animal health. The balance between reactive oxygen species (ROS) and antioxidants is crucial for maintaining health, especially under stress conditions [82], [83], [84]. The use of antimicrobials in animal production is a double-edged sword. While they improve health and growth, their overuse can lead to antimicrobial resistance, posing a significant public health threat [85], [86], [87], [88], [89].

Sustainability and Future Applications

Livestock production is a significant contributor to greenhouse gas (GHG) emissions, accounting for about 14.5% of global emissions [90]. Strategies to mitigate these emissions include improving feed efficiency, changing animal diets, and adopting sustainable farming practices [91]. Precision Livestock Farming (PLF) technologies can help by optimizing resource use and reducing emissions through better management practices [92], [93]. Precision nutrition (PN), a component of PLF, involves supplying the right amount of feed with suitable composition to individual animals, which can reduce nitrogen excretion and improve feed efficiency [94]. The use of natural feed additives such as essential oils, polyphenols, and saponins has been explored as alternatives to synthetic additives. These natural additives can improve animal health and production while ensuring food safety [95]. Probiotics and phytobiotics are also promising alternatives to antibiotics, enhancing gut health and immunity [96], [97]. The ban on antibiotic growth promoters has led to the development of alternative feed additives. Probiotics and plant-based additives have shown potential in maintaining animal health and performance without the use of antibiotics [98].

PLF involves the use of sensors, algorithms, and data analytics to monitor and manage livestock. These technologies can improve animal health, welfare, and productivity by providing real-time data for decision-making [99]. PLF can also help in precision grazing, optimizing pasture use and reducing overgrazing [100], [101]. PN systems within PLF can tailor feed supply to individual animals, improving nutrient utilization and reducing waste. The high cost of PLF technologies and the need for customization in extensive farming systems pose significant barriers to widespread adoption [102]. Small ruminant farms, often located in remote areas, face additional challenges due to poor technological infrastructure and higher costs of miniaturized sensors [103]. Successful implementation of PLF requires adequate training for farmers and integration into existing farm management systems [99]. There is also a need for more research to understand the full impact of PLF technologies on animal health and production [104].

Challenges and Research Gaps

There is a significant gap in long-term in vivo studies on the effects of nanoparticles (NPs) in livestock. Most studies focus on short-term impacts, leaving long-term consequences largely unexplored [105], [106]. This lack of data hinders a comprehensive understanding of chronic exposure and its potential risks. The toxicity and accumulation of NPs in livestock and their environments pose substantial risks. Studies have shown that NPs can accumulate in various tissues, leading to potential health hazards. For instance, iron oxide NPs have been found to cross the placental barrier and accumulate in fetal tissues, causing increased fetal deaths [107]. Similarly, Cu and ZnO NPs have been shown to accumulate in aquatic organisms, indicating potential risks for livestock consuming contaminated water [108], [109]. The combined toxicity of NPs with other pollutants, such as pesticides, further exacerbates these risks.

There is a lack of standardization in the formulation and dosage of NPs used in livestock. This variability can lead to inconsistent results and difficulties in comparing studies. The need for standardized protocols is critical to ensure reproducibility and reliability of research findings [110], [111]. Without standardization, it is challenging to determine safe and effective dosages for different applications. Regulatory frameworks for the use of NPs in livestock are still evolving. The potential risks associated with NPs necessitate stringent regulations to ensure safety. However, the current regulatory landscape is fragmented and lacks comprehensive guidelines [110]. Additionally, consumer acceptance of NP-based products in livestock is uncertain. Public concerns about the safety and ethical implications of using NPs in food production need to be addressed through transparent communication and robust safety assessments [111].

Table 5. Priority Research Gaps and Proposed Solutions

Research Gap	Current Status	Proposed Approaches
Formulation standardization	Multiple methods exist; no standard protocols	Develop consensus protocols for synthesis, characterization, and quality control
In vivo ruminant data	Limited to in vitro or short-term studies	Conduct dose-response studies in sheep/cattle across lactation/growth cycles
Safety assessment	Mostly acute toxicity data	Long-term feeding trials (>6 months) with tissue residue analysis
Mechanism validation	Hypothetical based on other systems	Rumen-cannulated studies with temporal sampling
Cost-effectiveness	Unknown for commercial scale	Techno-economic analysis and pilot production
Regulatory pathway	Unclear in most jurisdictions	Engage with regulatory bodies early in development

4. Conclusion

The use of tannins and nanotechnology offers a promising strategy to address key nutritional, environmental, and health challenges in ruminant production, particularly in semi-arid regions. Tannins, when used at optimal levels, can improve nitrogen utilization and reduce methane emissions, although their anti-nutritional effects at high concentrations require careful management. Nanotechnology, especially through the formulation of tannin nanoparticles, enhances the stability, bioavailability, and targeted delivery of bioactive compounds. These advances may enable more efficient rumen modulation, improved animal performance, and reduced environmental impact. However, concerns over nanoparticle toxicity, regulatory uncertainties, and the lack of long-term in vivo data highlight the need for more standardized, transparent, and safety-focused research. Integration with Precision Livestock Farming (PLF) and natural feed strategies can further enhance sustainability. Future efforts must focus on bridging knowledge gaps and ensuring responsible innovation to fully leverage smart tannin nanoparticles for sustainable ruminant nutrition.

References

[1] Mlambo, V., & Mapiye, C. (2015). Towards household food and nutrition security in semi-arid areas: What role for condensed tannin-rich ruminant feedstuffs? *Food Research International, 76*, 953–961. DOI: 10.1016/j.foodres.2015.04.011.

[2] Reddy, B. S., Sivajothi, S., Raghavi, D. N., & Karthik, P. (2020). Clinical physiology of digestive disorders in ruminants. In *Fundamentals of Veterinary Pathophysiology* (pp. 103–118). CRC Press.

[3] Davis, T. C., & White, R. R. (2020). Breeding animals to feed people: The many roles of animal reproduction in ensuring global food security. *Theriogenology, 150*, 27–33. DOI: 10.1016/j.theriogenology.2020.01.033.

[4] Rivero, M. J., López-Villalobos, N., Evans, A., Berndt, A., Cartmill, A., Neal, A. L., McLaren, A., Farruggia, A., Mignolet, C., & Chadwick, D. R. (2021). Key traits for ruminant livestock across diverse production systems in the context of climate change: Perspectives from a global platform of research farms. *Reproduction, Fertility and Development, 33*(2), 1–19. DOI: 10.1071/RD20206.

[5] Garcia-Oliveira, P., Fraga-Corral, M., Carpena, M., Prieto, M. A., & Simal-Gandara, J. (2022). Approaches for sustainable food production and consumption systems. In *Future foods* (pp. 23–38). Elsevier. DOI: 10.1016/B978-0-323-91001-9.00014-9.

[6] Wang, Y., Yu, S., Zhao, Y., & Jiang, L. (2023). *Research progress on tannins regulated rumen biohydrogenation in ruminants*. [Manuscript in preparation/Technical Report].

[7] Liang, Z., Zhang, J., Zheng, J., & Ding, X. (2020). Tannin: Biological function and its advances in research on ruminant nutrition. *Journal of Animal Science and Biotechnology*.

[8] Adejoro, F. A., Hassen, A., & Akanmu, A. M. (2019). Effect of lipid-encapsulated acacia tannin extract on feed intake, nutrient digestibility and methane emission in sheep. *Animals, 9*(11), 863. DOI: 10.3390/ani9110863.

[9] Decandia, M., Cabiddu, A., & Molle, G. (2011). Effect of tannins on the nutrition, grazing or browsing management and environmental impact of small ruminants fed Mediterranean pastures. *Tannins: Types, Foods Containing, and Nutrition* (pp. 83–112). Nova Science Publishers.

[10] Bhat, T. K., Kannan, A., Singh, B., & Sharma, O. P. (2013). Value addition of feed and fodder by alleviating the antinutritional effects of tannins. *Agricultural Research, 2*(3), 189–206. DOI: 10.1007/s40003-013-0066-y.

[11] Almeida, C. F., Faria, M., Carvalho, J., & E. Pinho. (2024). Contribution of nanotechnology to greater efficiency in animal nutrition and production. *Journal of Animal Physiology and Animal Nutrition, 108*(5), 1430–1452. DOI: 10.1111/jpn.13941.

[12] Tatli Seven, P., Seven, I., Gul Baykalir, B., Iflazoglu Mutlu, S., & Salem, A. Z. M. (2018). Nanotechnology and nano-propolis in animal production and health: An overview. *Italian Journal of Animal Science, 17*(4), 921–930. DOI: 10.1080/1828051X.2018.1448011.

[13] El-Sayed, A., & Kamel, M. (2020). Advanced applications of nanotechnology in veterinary medicine. *Environmental Science and Pollution Research, 27*, 19073–19086. DOI: 10.1007/s11356-018-3913-y.

[14] Wijesekara, W. L. I., Gokila, S., Gomathi, T., Prasad, S., Deepa, M., & Sudha, P. N. (2023). Bio-nanotechnology in agriculture: New opportunities and future prospects. In *Nanobiomaterials* (pp. 314–322). CRC Press.

[15] Fonseca, N. V. B., Cardoso, A. da S., Bahia, A. S. R. de S., Messana, J. D., Vicente, E. F., & Reis, R. A. (2023). Additive tannins in ruminant nutrition: An alternative to achieve sustainability in animal production. *Sustainability, 15*(5), 4162. DOI: 10.3390/su15054162.

[16] Besharati, M., Maggiolino, A., Palangi, V., Kaya, A., Jabbar, M., Eseceli, H., De Palo, P., & Lorenzo, J. M. (2022). Tannin in ruminant nutrition. *Molecules, 27*(23), 8273. DOI: 10.3390/molecules27238273.

[17] Patra, A. K., & Saxena, J. (2011). Exploitation of dietary tannins to improve rumen metabolism and ruminant nutrition. *Journal of the Science of Food and Agriculture, 91*(1), 24–37. DOI: 10.1002/jsfa.4151.

[18] Zhang, J., Ge, Z., Liu, R., Zhong, Q., & Sun, Z. (2024). Tannin species and dose effects in ruminant production. *Acta Agrestia Sinica, 32*(8), 2337.

[19] Oliveira, S. G., & Berchielli, T. T. (2007). Potentiality of tannins used in forages conservation and ruminant nutrition: A review. *Semina: Ciências Agrárias, 28*(4), 731-740.

[20] Manoni, M., Terranova, M., Amelchanka, S., Pinotti, L., Silacci, P., & Tretola, M. (2023). Effect of ellagic and gallic acid on the mitigation of methane production and ammonia formation in an in vitro model of short-term rumen fermentation. *Animal Feed Science and Technology, 305*, 115791. DOI: 10.1016/j.anifeedsci.2023.115791.

[21] Espinoza-Velasco, B., & Mella, M. R. (2021). Vegetable tannins, ruminal microbiota and ruminant metabolism interaction. *Tropical and Subtropical Agroecosystems, 25*(1). DOI: 10.56369/tsaes.3969.

[22] Yanza, Y. R., Fitri, A., Ramdani, D., Jayanegara, A., & Samsudin, A. A. (2021). The utilisation of tannin extract as a dietary additive in ruminant nutrition: A meta-analysis. *Animals, 11*(11), 3317. DOI: 10.3390/ani11113317.

[23] Aguerre, M. J., Capozzolo, M. C., Lencioni, P., Cabral, C., & Wattiaux, M. A. (2016). Effect of quebracho-chestnut tannin extracts at 2 dietary crude protein levels on performance, rumen fermentation, and nitrogen partitioning in dairy cows. *Journal of Dairy Science, 99*(6), 4476–4486. DOI: 10.3168/jds.2015-10618.

[24] Martínez, T. F., McAllister, T. A., Wang, Y., & Reuter, T. (2006). Effects of tannic acid and quebracho tannins on in vitro ruminal fermentation of wheat and corn grain. *Journal of the Science of Food and Agriculture, 86*(8), 1244–1256. DOI: 10.1002/jsfa.2535.

[25] Martínez, T. F., Moyano, F. J., Diaz, M., Barroso, F. G., & Alarcón, F. J. (2004). Ruminal degradation of tannin-treated legume meals. *Journal of the Science of Food and Agriculture, 84*(14), 1979–1987. DOI: 10.1002/jsfa.1821.

[26] Goel, G., Puniya, A. K., Aguilar, C. N., & Singh, K. (2005). Interaction of gut microflora with tannins in feeds. *Naturwissenschaften, 92*(11), 497–503. DOI: 10.1007/s00114-005-0041-5.

[27] Smith, A. H., Zoetendal, E., & Mackie, R. I. (2005). Bacterial mechanisms to overcome inhibitory effects of dietary tannins. *Microbial Ecology, 50*(2), 197–205. DOI: 10.1007/s00248-005-0147-6.

[28] Rennó, F. P., Gandra, J. R., Freitas, J. E., Verdurico, L. C., Barletta, R. V., Vilela, F. G., & Mingoti, R. D. (2025). Low levels of condensed tannins enhance lactation performance in dairy cows. *Animal Feed Science and Technology, 325*, 116349.

[29] Rahmatillah, R. S., Ramdani, D., Hernaman, I., Jayanegara, A., & Hidayatik, N. (2024). Evaluation of the effects of green tea extract as a dietary supplement in sheep on gas production, volatile fatty acids, and digestibility. *Veterinary World, 17*(10), 2204–2212. DOI: 10.14202/vetworld.2024.2204-2212.

[30] Mueller-Harvey, I., Bee, G., Dohme-Meier, F., Hoste, H., Karonen, M., Kölliker, R., Lüscher, A., Niderkorn, V., Pellikaan, W. F., Salminen, J.-P., Thill, J., & Waghorn, G. C. (2019). Benefits of condensed tannins in forage legumes fed to ruminants: Importance of structure, concentration, and diet composition. *Crop Science, 59*(3), 861–885. DOI: 10.2135/cropsci2018.09.0555.

[31] Riviere, J. E. (2012). Nanoscale feed ingredients and animal and human health. In *Animal Feed Contamination* (pp. 540–553). Elsevier. DOI: 10.1533/9780857093615.4.540.

[32] Maurya, P. K., & Singh, S. (2019). *Nanotechnology in modern animal biotechnology: Concepts and applications*. Elsevier Academic Press.

[33] Alagawany, M., Abdelnour, S. A., Farag, M. R., Elnesr, S. S., & El Kholy, M. S. (2020). Nutritional applications of nanotechnology in poultry with special references to minerals. In *Natural Feed Additives Used in the Poultry Industry* (pp. 262–284). Bentham Science Publishers.

[34] Gelaye, Y. (2024). Application of nanotechnology in animal nutrition: Bibliographic review. *Cogent Food & Agriculture, 10*(1), 2290308. DOI: 10.1080/23311932.2024.2290308.

[35] Abdelnour, S. A., Alagawany, M., Hashem, N. M., Farag, M. R., Alghamdi, E. S., Hassan, F. U., Bilal, R. M., Elnesr, S. S., Dawood, M. A. O., Nagadi, S. A., Elwan, H. A. M., ALmasoudi, A. G., & Attia, Y. A. (2021). Nanominerals: Fabrication methods, benefits and hazards, and

their applications in ruminants with special reference to selenium and zinc nanoparticles. *Animals, 11*(7), 1916. DOI: 10.3390/ani11071916.

[36] Gressler, S., Hipfinger, C., Part, F., Pavlicek, A., Zafiu, C., & Giese, B. (2025). A systematic review of nanocarriers used in medicine and beyond—definition and categorization framework. *Journal of Nanobiotechnology, 23*(1), 90. DOI: 10.1186/s12951-025-00911-1.

[37] AL-Hamdany, E. K., & Al-hbiti, T. Y. (2020). Nanonephrology in veterinary medicine: A branch of nanomedicine for renal diseases in animals. *Journal of Applied Veterinary Sciences, 5*(4), 17–24. DOI: 10.21608/javs.2020.116666.

[38] Muttathettu, V. A., & Anitha, P. (2023). Biological prospects and potential of nanoparticles in animal nutrition. In *Applications of Multifunctional Nanomaterials* (pp. 525–541). Elsevier. DOI: 10.1016/B978-0-323-95514-0.00007-0.

[39] Gurunathan, K. (2022). Application of nanoparticles for quality and safety enhancement of foods of animal origin. In *Nanotechnology in Agriculture and Environmental Science* (pp. 227–260). CRC Press.

[40] Granados-Chinchilla, F., Maldonado, E. A. L., & Solangi, A. R. (2023). Safety issues and regulatory challenges of nanoproducts in food. In *Nanobiotechnology for Sustainable Food Management* (pp. 340–359). CRC Press.

[41] Amenta, V., Aschberger, K., Arena, M., Bouwmeester, H., Botelho Moniz, F., Brandhoff, P., Gottardo, S., Janer, G., Peters, R. J., Pesudo, L. Q., Rocker, W., Schoonjans, R., Vettori, M. V., Weigel, S., & Peters, R. J. (2015). Regulatory aspects of nanotechnology in the agri/feed/food sector in EU and non-EU countries. *Regulatory Toxicology and Pharmacology, 73*(1), 463–476. DOI: 10.1016/j.yrtph.2015.08.001.

[42] EFSA Scientific Committee, More, S. J., Bampidis, V., Benford, D., Bragard, C., Halldorsson, T. I., Hernández-Jerez, A. F., Hougaard Bennekou, S., Koutsoumanis, K. P., Machera, K., Naegeli, H., Nielsen, S. S., Schlatter, J. R., Schrenk, D., Silano, V., Turck, D., Younes, M., Castenmiller, J., Chaudhry, Q., . . . Schoonjans, R. (2021). Guidance on risk assessment of nanomaterials to be applied in the food and feed chain: Human and animal health. *EFSA Journal, 19*(8), e06768. DOI: 10.2903/j.efsa.2021.6768.

[43] EFSA Scientific Committee, Hardy, A., Benford, D., Halldorsson, T., Jeger, M. J., Machera, K. H., Mutshinda, S., Naegeli, H., Noteborn, H. P., Schlatter, J. R., Solecki, R., Turck, D., Younes, M., Chaudhry, Q., Cubadda, F., Gottardo, S., Niemann, B., Peters, R., Weigel, S., & Schoonjans, R. (2018). Guidance on risk assessment of the application of nanoscience and nanotechnologies in the food and feed chain: Part 1, human and animal health. *EFSA Journal, 16*(7), e05327. DOI: 10.2903/j.efsa.2018.5327.

[44] Chau, C. F., Wu, S. H., & Yen, G. C. (2007). The development of regulations for food nanotechnology. *Trends in Food Science & Technology, 18*(5), 269–280. DOI: 10.1016/j.tifs. 2007.02.010.

[45] Kshtriya, V., Koshti, B., & Gour, N. (2021). Green synthesized nanoparticles: Classification, synthesis, characterization, and applications. In *Comprehensive Analytical Chemistry* (Vol. 94, pp. 173–222). Elsevier. DOI: 10.1016/bs.coac.2020.12.006.

[46] Biswas, I., Mitra, D., Das, S., Sarkar, D., & Das Mohapatra, P. K. (2024). Enhanced antibacterial effect of natural tannin stabilized silver nano particles against human pathogens: A target toward FtsZ proteins. *Journal of Trace Elements and Minerals, 10*, 100200. DOI: 10.1016/j.jtemin.2024.100200.

[47] Houng, S. (2009). *Synthesis and characterization of folate-PEG-conjugated polysaccharide nanoparticles for potential use as a targeted DNA carrier* [Doctoral dissertation, University of Kentucky].

[48] Atacan, K., Çakıroğlu, B., & Özacar, M. (2017). Efficient protein digestion using immobilized trypsin onto tannin modified Fe3O4 magnetic nanoparticles. *Colloids and Surfaces B: Biointerfaces, 156*, 9–18. DOI: 10.1016/j.colsurfb.2017.05.006.

[49] Yadava, Y. P., Raju, V., Chathoth, A. M., Vasu, A. E., Vijayaraghavan, R., & Surendran, A. K. (2025). Characterization and antifungal potential of green-synthesized copper nanoparticles using waste leaf biomass. *Chemical Papers*, 1–15. DOI: 10.1007/s11696-024-03829-x.

[50] Raja, P. B., Rahim, A. A., Qureshi, A. K., & Awang, K. (2014). Green synthesis of silver nanoparticles using tannins. *Journal of Sol-Gel Science and Technology, 32*, 408–413. DOI: 10.1007/s10854-014-2172-y.

[51] Saratale, R. G., Saratale, G. D., Ahn, S., & Shin, H. S. (2021). Grape pomace extracted tannin for green synthesis of silver nanoparticles: Assessment of their antidiabetic, antioxidant potential and antimicrobial activity. *Polymers, 13*(24), 4355. DOI: 10.3390/polym13244355.

[52] Gu, Q., Lu, G., Han, J., McClements, D. J., Ma, C., Liu, X., & Liu, F. (2025). Design, fabrication, and performance evaluation of curcumin-loaded nanoparticles based on zein, hyaluronic acid, and tannic acid. *International Journal of Biological Macromolecules, 309*, 142884. DOI: 10.1016/j.ijbiomac.2025.142884.

[53] Taylor, J., Taylor, J. R. N., Belton, P. S., & Minnaar, A. (2009). Kafirin microparticle encapsulation of catechin and sorghum condensed tannins. *Journal of Agricultural and Food Chemistry, 57*(16), 7523–7528. DOI: 10.1021/jf901508m.

[54] Cabrera-Barjas, G., Del-Valle, C., Nesic, A., Castro, J. I., Ortiz, P., Valdés, O., & Zuniga, H. (2024). Condensed tannins from Pinus radiata bark: Extraction and their nanoparticles preparation in water by green method. *International Journal of Biological Macromolecules, 278*, 134598. DOI: 10.1016/j.ijbiomac.2024.134598.

[55] Pawar, A. P., Naktode, S. S., & Mungole, A. J. (2023). Green synthesis of silver nanoparticles from whole plant extract analyzed for characterization, antioxidant, and antibacterial properties. *Physics and Chemistry of Solid State, 24*(4), 640–649. DOI: 10.15330/pcss.24.4.640-649.

[56] Tavakoli, S., Rafiee, M., Ghorbanpour, M., & Pourmortazavi, S. M. (2020). Excess iron ion reduction in a thalassemia model using silver nanoparticles modified by the tannin fraction of *Myrtus communis* extract. *Nanomedicine Research Journal, 5*(4), 355–363. DOI: 10.22034/nmrj.2020.04.008.

[57] Tavakoli, S., Rafiee, M., Ghorbanpour, M., & Pourmortazavi, S. M. (2020). Sub-chronic intraperitoneal toxicity assessments of modified silver nanoparticles capped with *Myrtus communis*-derived hydrolysable tannins in mice. *Nanomedicine Research Journal, 5*(3), 288–297. DOI: 10.22034/nmrj.2020.03.009.

[58] Hess, H. D., Tiemann, T. T., Noto, F., Carulla, J. E., & Kreuzer, M. (2004). Effects of tannins in *Calliandra calothyrsus* and supplemental molasses on ruminal fermentation in vitro. *Journal of Animal and Feed Sciences, 13*(1), 95–98. DOI: 10.22358/jafs/67344/2004.

[59] Makmur, M., Zain, M., Sholikin, M. M., Suharlina, S., & Jayanegara, A. (2022). Modulatory effects of dietary tannins on polyunsaturated fatty acid biohydrogenation in the rumen: A meta-analysis. *Heliyon, 8*(7), e09968. DOI: 10.1016/j.heliyon.2022.e09968.

[60] Madureira, A. R., Pereira, A., Castro, P. M., & Pintado, M. M. (2016). Fermentation of bioactive solid lipid nanoparticles by human gut microflora. *Food & Function, 7*(1), 516–529. DOI: 10.1039/C5FO01141C.

[61] Getachew, G., Pittroff, W., Putnam, D. H., Dandekar, A., Goyal, S., & DePeters, E. J. (2008). The influence of addition of gallic acid, tannic acid, or quebracho tannins to alfalfa hay on in vitro rumen fermentation and microbial protein synthesis. *Animal Feed Science and Technology, 140*(3–4), 444–461. DOI: 10.1016/j.anifeedsci.2007.04.002.

[62] Wanapat, M., Mapato, C., Pilajun, R., & Guyader, J. (2012). Effects of plants containing secondary compounds and plant oils on rumen fermentation and ecology. *Tropical Animal Health and Production, 44*(3), 399–405. DOI: 10.1007/s11250-011-9925-2.

[63] Costa, J. R., Madureira, A. R., Castro, P. M., & Pintado, M. (2021). Polymeric nanoparticles as oral delivery systems for a grape pomace extract towards the improvement of biological activities. *Materials Science and Engineering: C, 119*, 111551. DOI: 10.1016/j.msec.2020.111551.

[64] Rodríguez, R., De la Fuente, G., Gómez, S., & Fondevila, M. (2013). Biological effect of tannins from different vegetal origin on microbial and fermentation traits in vitro. *Animal Production Science, 54*(8), 1039–1046. DOI: 10.1071/AN12345.

[65] Shannon, M. C., & Hill, G. M. (2019). Trace mineral supplementation for the intestinal health of young monogastric animals. *Frontiers in Veterinary Science, 6*, 73. DOI: 10.3389/fvets.2019.00073.

[66] Young, J. M., & Dekbers, J. C. M. (2012). The genetic and biological basis of residual feed intake as a measure of feed efficiency. In *Feed Efficiency in Swine* (pp. 153–166). Wageningen Academic.

[67] Douglas, S. L., Edwards, S. A., Kyriazakis, I., & Wellock, I. J. (2015). Animal and management factors influencing grower and finisher pig performance and efficiency in European systems: A meta-analysis. *Animal, 9*(7), 1210–1220. DOI: 10.1017/S1751731115 000670.

[68] Haskell, M. J., Simm, G., Turner, S. P., & Roehe, R. (2019). Relationships between feeding behaviour, activity, dominance and feed efficiency in finishing beef steers. *Applied Animal Behaviour Science, 210*, 9–15. DOI: 10.1016/j.applanim.2018.10.007.

[69] Gami, R., Patel, A. K., Gami, S., & Singh, P. (2017). Protein sparing effect of dietary rumen protected lysine plus methionine in growing Murrah buffaloes. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 87*(4), 885–891. DOI: 10.1007/ s40011-015-0644-9.

[70] Robinson, P. H., Swanepoel, N., Shinzato, I., & Juchem, S. O. (2010). Effects of feeding a ruminally protected lysine product to lactating dairy cows. *Animal Feed Science and Technology, 161*(3–4), 75–84. DOI: 10.1016/j.anifeedsci.2010.08.003.

[71] Leal Yepes, F., Nydam, D. V., Mann, S., Duplessis, M., Schuh-von Graevenitz, K., Webb, L. A., Sadri, H., Sauerwein, H., De Koster, J., Nelli, R. K., Strieder-Barboza, C., Contreras, G. A., & Overton, T. R. (2021). Hepatic effects of rumen-protected branched-chain amino acids in dairy cows. *Journal of Dairy Science, 104*(9), 10324–10337. DOI: 10.3168/jds.2021-20359.

[72] Eugenio, F. A., Remus, A., Hauschild, L., Gaillard, C., & Pomar, C. (2022). Feeding intact proteins, peptides, or free amino acids to monogastric farm animals. *Amino Acids, 54*(2), 157–168. DOI: 10.1007/s00726-021-03068-1.

[73] Morales, A., Htoo, J. K., Valenzuela, E. J., Buenabad, L., & Cervantes, M. (2020). Serum concentration of free amino acids in pigs. *Animal Feed Science and Technology, 267*, 114552. DOI: 10.1016/j.anifeedsci.2020.114552.

[74] van den Borne, J. J. G. C., Schierbeek, H., van der Aa, A., Gerrits, W. J. J., & van Keulen, P. (2012). Asynchronous supply of indispensable amino acids reduces protein deposition in milk-fed calves. *The Journal of Nutrition, 142*(12), 2075–2082. DOI: 10.3945/jn.112.165316.

[75] Khiaosa-Ard, R., & Zebeli, Q. (2014). Cattle's variation in rumen ecology and metabolism and its contributions to feed efficiency. *Livestock Science, 162*, 66–75. DOI: 10.1016/j.livsci. 2014.01.005.

[76] Baaske, L., Brede, S., Seyboldt, C., & Leonhard-Marek, S. (2020). Ruminal epithelium: A checkpoint for cattle health. *Journal of Dairy Research, 87*(3), 322–329. DOI: 10.1017/ S0022029920000302.

[77] Lu, Z., Lian, H., Zhang, G., Yan, Z., Ma, S., & Shen, Z. (2018). High-concentrate diet-induced change of cellular metabolism leads to decreases of immunity and imbalance of cellular activities in rumen epithelium. *Cellular Physiology and Biochemistry, 45*(5), 2145–2157. DOI: 10.1159/000487889.

[78] Lian, H., Zhang, C., Liu, Y., Li, W., Fu, T., Gao, T., & Zhang, L. (2022). In vitro gene expression responses of bovine rumen epithelial cells to different pH stresses. *Animals, 12*(19), 2621. DOI: 10.3390/ani12192621.

[79] Jiang, Y., Zhao, S., Sun, P., Wang, J., & Wang, Y. (2021). Effects of subacute ruminal acidosis on rumen physiological function and substance absorption and transportation of ruminants. *Chinese Journal of Animal Science, 57*(11), 31–37.

[80] Garcia, M., Greco, L. F., & Santos, J. E. P. (2017). Invited review: Ruminal microbes, microbial products, and systemic inflammation. *The Professional Animal Scientist, 33*(6), 635–650. DOI: 10.15232/pas.2017-01653.

[81] Schmitz-Esser, S. (2021). The rumen epithelial microbiota: Possible gatekeepers of the rumen epithelium and its potential contributions to epithelial barrier function and animal health and performance. *Meat and Muscle Biology, 4*(2), 1–11. DOI: 10.22175/mmb.9596.

[82] Debrincat, S., Boardman, W., & Shaughnessy, P. (2014). Effects of overnight captivity on antioxidant capacity and clinical chemistry of wild southern hairy-nosed wombats (*Lasiorhinus latifrons*). *Journal of Zoo and Wildlife Medicine, 45*(3), 469–475. DOI: 10.1638/2013-0281.1.

[83] Kumar, N., Sharma, S., & Kumar, S. (2020). Antioxidants: Responses and importance in plant defense system. In *Sustainable Agriculture in the Era of Climate Change* (pp. 153–176). Springer.
[84] Costantini, D., Monaghan, P., & Metcalfe, N. B. (2010). From molecules to living systems: Historical and contemporary issues in oxidative stress and antioxidant ecology. *Functional Ecology, 24*(5), 950–959. DOI: 10.1111/j.1365-2435.2010.01739.x.
[85] Weese, J. S., Giguère, S., Guardabassi, L., Morley, P. S., Papich, M. G., Ricciuto, D. R., & Sykes, J. E. (2022). Governance processes and challenges for reservation of antimicrobials exclusively for human use and restriction of antimicrobial use in animals. *The Journal of Law, Medicine & Ethics, 50*(S2), 55–63. DOI: 10.1017/jme.2022.55.
[86] Vincent, F. (2008). Chromatographic analysis of banned antibacterial growth promoters in animal feed. *Journal of Separation Science, 31*(11), 2091–2112. DOI: 10.1002/jssc.200700633.
[87] McEwen, S. A., & Collignon, P. J. (2018). Antimicrobial resistance: A one health perspective. *Microbiology Spectrum, 6*(2). DOI: 10.1128/microbiolspec.ARBA-0009-2017.
[88] Pokharel, S., Raut, S., & Adhikari, B. (2020). Antimicrobial use in food animals and human health: Time to implement 'One Health' approach. *Antimicrobial Resistance & Infection Control, 9*(1), 1–5. DOI: 10.1186/s13756-020-00744-1.
[89] Rushton, J. (2015). Anti-microbial use in animals: How to assess the trade-offs. *Zoonoses and Public Health, 62*(S1), 10–21. DOI: 10.1111/zph.12167.
[90] Shahin, K. I., Belahsen, M., El Hami, A., & El Hami, N. (2023). Multi-objective decision support tool for sustainable livestock farming. *2023 8th International Conference on Smart and Sustainable Technologies (SpliTech)*. DOI: 10.23919/SpliTech58164.2023.10263154.
[91] Ovani, V., & Jayanegara, A. (2025). Achieving net-zero emission through greenhouse gases emissions reduction in animal production. *Sustainable Production and Consumption*. Elsevier.
[92] Papakonstantinou, G. I., Gelasakis, A. I., & Banos, G. (2024). Precision livestock farming technology: Applications and challenges of animal welfare and climate change. *Agriculture, 14*(4), 620. DOI: 10.3390/agriculture14040620.
[93] Antonik, I., Mazurak, O., & Zhuravel, V. (2025). Global environmental challenges in livestock farming: Solutions and sustainable development. *BIO Web of Conferences, 98*, 02012. DOI: 10.1051/bioconf/20259802012.
[94] Pomar, C., & Remus, A. (2023). Fundamentals, limitations and pitfalls on the development and application of precision nutrition techniques for precision livestock farming. *Animal, 17*(S1), 100763. DOI: 10.1016/j.animal.2023.100763.
[95] Ramdani, D., Yanza, Y. R., Fitri, A., Samsudin, A. A., & Jayanegara, A. (2023). Roles of essential oils, polyphenols, and saponins of medicinal plants as natural additives and anthelmintics in ruminant diets: A systematic review. *Animals, 13*(4), 767. DOI: 10.3390/ani13040767.
[96] Bagno, O. A., Shevchenko, S. A., Shevchenko, A. I., Prokhorov, O. N., & Bagno, V. D. (2018). Use of phytobiotics in farm animal feeding. *Agricultural Biology, 53*(4), 687–697. DOI: 10.15389/agrobiology.2018.4.687eng.
[97] Molina, A. (2019). Probiotics and their mechanism of action in animal feed. *Agronomía Mesoamericana, 30*(2), 601–611. DOI: 10.15517/am.v30i2.36035.
[98] Candinegara, T. (2020). Challenges of using feed additives in Indonesia. *IOP Conference Series: Earth and Environmental Science, 425*, 012001. DOI: 10.1088/1755-1315/425/1/012001.
[99] Vranken, E., & Berckmans, D. (2017). Precision livestock farming for pigs. *Animal Frontiers, 7*(1), 32–37. DOI: 10.2527/af.2017-0101.
[100] Aquilani, C., Confessore, A., Bozzi, R., Sirtori, F., & Pugliese, C. (2022). Precision Livestock Farming technologies in pasture-based livestock systems. *Animal, 16*(1), 100429. DOI: 10.1016/j.animal.2021.100429.
[101] Laca, E. A. (2009). Precision livestock production: Tools and concepts. *Revista Brasileira de Zootecnia, 38*, 123–132.
[102] Bernabucci, G., Biffani, S., Pugliese, C., Aquilani, C., & Vitali, A. (2025). Precision livestock farming: An overview on the application in extensive systems. *Italian Journal of Animal Science, 24*(1), 859–884. DOI: 10.1080/1828051X.2025.2339214.

[103] Paolino, R., Vitali, A., Aquilani, C., Pugliese, C., & Bernabucci, G. (2025). May the extensive farming system of small ruminants be smart? *Agriculture, 15*(9), 929. DOI: 10.3390/agriculture 15090929.
[104] Kleen, J. L., & Guatteo, R. (2023). Precision livestock farming: What does it contain and what are the perspectives? *Animals, 13*(5), 779. DOI: 10.3390/ani13050779.
[105] Ryabova, Y. V., Kudryavtsev, A. A., Skalny, A. V., & Nikonov, I. N. (2024). Toxicological effects of selenium nanoparticles in laboratory animals: A review. *Journal of Applied Toxicology, 44*(1), 4–16. DOI: 10.1002/jat.4472.
[106] Zhu, X., Zhou, J., & Cai, Z. (2010). Toxicity and bioaccumulation of TiO2 nanoparticle aggregates in *Daphnia magna*. *Chemosphere, 78*(3), 209–215. DOI: 10.1016/j.chemosphere. 2009.11.013.
[107] Di Bona, K. R., Xu, Y., Ramirez, P. A., DeLancey, J., Mamudu, A., Khaing, C. P., Lauer, C., & Rasco, J. F. (2014). Surface charge and dosage dependent potential developmental toxicity and biodistribution of iron oxide nanoparticles in pregnant CD-1 mice. *Reproductive Toxicology, 50*, 36–42. DOI: 10.1016/j.reprotox.2014.09.002.
[108] Shahzad, K., Khan, M. N., Jabeen, F., Asghar, M. S., & Chaudhry, A. S. (2017). Bioaccumulation of metal oxide nanoparticles in tilapia. *Punjab University Journal of Zoology, 32*(2), 237–243.
[109] Xiao, Y., Peijnenburg, W. J. G. M., Chen, G., & Vijver, M. G. (2015). Toxicity and accumulation of Cu and ZnO nanoparticles in *Daphnia magna*. *Environmental Science & Technology, 49*(7), 4657–4664. DOI: 10.1021/es505768x.
[110] Srivastava, S., & Srivastava, S. (2023). Bioregulation of nanobiotechnology-based livestock products. In *Nanobiotechnology for Sustainable Bioresources and Environmental Management*. Elsevier.
[111] Srivastava, S. (2023). Ethical issues regarding the use of nanobiotechnology-based products. In *Nanobiotechnology for Sustainable Bioresources and Environmental Management*. Elsevier.