Iranian Society of Animal Science

Journal of Livestock Science and Technologies

Shahid Bahonar University of Kerman

ISSN: 2322-3553 (Print) ISSN: 2322-374X (Online)

Paper type: Original Research

From rumen fermentation to productivity: a bibliometric synthesis of nanotechnology in small ruminant nutrition

Elias Ibrahimi Khoram Abadi

Department of Animal Sciences, Faculty of Agriculture and Animal Science, University of Torbat-e Jam, Torbat-e Jam, Iran

*Corresponding author,
E-mail address:
el.ebrahimi@tjamcaas.ac.ir

Received: 15 Oct 2025,
Received in revised form: 14 Nov 2025,
Accepted: 29 Nov 2025,
Published online: 30 Nov 2025,

ORCID
Elias Ibrahimi Khoram Abadi
0000-0002-9977-2822

Abstract Conventional dietary supplements in livestock often face challenges of poor bioavailability and environmental impact, limiting their sustainable use. Nanotechnology-based approaches present innovative solutions by improving nutrient efficiency and enhancing productivity in small ruminant. The present investigation offers a rigorous bibliometric examination of the worldwide scholarly discourse surrounding nanoparticle-mediated nutritional interventions in small ruminant species, particularly sheep and goats. Leveraging a structured analytic framework, this study scrutinized publication data amassed between 2010 and 2025 from the databases Science Direct, Google Scholar, and Dimensions. Data curation and refinement, performed via Publish or Perish and standardized into CSV format, enabled a robust keyword co-occurrence analysis using VOSviewer, thereby ensuring methodological rigor and reproducibility, with acknowledgment that results may be shaped by database scope, English-language bias, and keyword-selection thresholds inherent to co-occurrence mapping. Findings disclose an appreciable escalation in the volume of pertinent literature since 2017, with discernible spikes in scientific productivity concentrated in 2021 and 2023. The bibliometric mapping identified pivotal thematic nodes, namely nanotechnology, nanoparticles, livestock, sheep, digestibility, and bioavailability. Concurrently, emerging research frontiers such as selenium and zinc nanoparticles, rumen physiology, heat stress responses, toxicity, and nano-enabled drug delivery have gained greater visibility in recent scholarly output. Temporal analyses of keyword co-occurrence patterns demonstrated a field-wide evolution, transitioning from foundational inquiries into ruminal fermentation and in vitro digestibility toward sophisticated applications aimed at enhancing feed efficiency, safety, and overall efficacy. Notably, highly cited studies have consistently highlighted the superior bioavailability of nano-form selenium and zinc, which may serve as benchmarks for innovation in the domain. Parallel to these advancements, there is increasing scholarly attention on the assessment of biological safety, metabolic fate, and the ecological ramifications of nanoparticle use in animal nutrition. In summary, emerging evidence highlights that low-dose nano-selenium and nano-zinc can improve rumen function, antioxidant status, and growth in small ruminant, while reducing mineral excretion, when implemented through extension-guided dosing, verified suppliers, and phased farm-scale trials providing practical guidance for farmers and feed producers.

Keywords: bibliometric mapping, feed additives, nanoparticles, performance

Introduction

Although traditional feed additives have long supported core nutritional goals, their long-term use is increasingly scrutinized due to limited efficacy, questionable cost-effectiveness, and environmental sustainability concerns. Against this backdrop, the advent of nanotechnology, which enables the manipulation of matter at the nanoscale, offers new approaches to the development of feed additives (Tona, 2017; Placha et al., 2022a, 2022b). Among these, nanoparticles (NPs) have garnered particular attention for

their unique physicochemical properties, enabling targeted delivery and improved bioavailability in animals (Dubey et al., 2017; Abdel-Rahman et al., 2022).

Small ruminant, as a key component of livestock systems, play an essential role in sustaining agricultural livelihoods in developing regions by supplying food, fiber, and other vital resources (Adams et al., 2014; Adams et al., 2021). Their adaptability to diverse environmental conditions enhances their significance for farmers aiming to maximize productivity and profitability (Lebbie, 2004; Joy et al., 2021). However, the literature consistently highlights persistent challenges confronting small ruminant systems, including seasonal feed shortages, suboptimal yields in meat and milk, disease prevalence, and the multifaceted impacts of climate change (Nuvey et al., 2022a; Nuvey et al., 2022b; Leal et al., 2020; Lhermie et al., 2022; Teshome and Sori, 2021). Further compounding these issues are limitations associated with conventional feed additives, whose low bioavailability frequently impairs nutrient absorption and animal performance (Scott et al., 2018; Matuszewski et al., 2020; Alagawany and Abd El-Hack, 2021; Gorniak et al., 2022). In response, emerging research has increasingly investigated nanotechnological interventions as promising avenues to improve health outcomes and enhance the productive efficiency of small ruminant populations (Michalak et al., 2022).

Recent empirical investigations have demonstrated that the incorporation of nano-based feed additives into the diets of s small ruminant, frequently leads to favorable outcomes in milk yield and other performance indicators (Gelaye, 2024). Nanominerals, in particular, have shown potential for suppressing pathogenic microorganisms present in feed, modulating rumen fermentation dynamics, and addressing reproductive challenges within sheep (Chen et al., 2011; Mohamed et al., 2015; Corbo et al., 2016; Mohamed et al., 2017; Kojouri et al., 2020) and goat (Shi et al., 2011a; El-Nile et al., 2023) populations.

Although nanoparticles have emerged as promising feed additives in small ruminant nutrition, their adoption on a wider scale remains constrained by several critical factors. Chief among these are the verification of nanoparticle safety for animals and consumers alike, the evaluation of potential long-term ecological effects, and the development of cost-effective, scalable production methods (Almeida et al., 2023; Hassan et al., 2018). Bibliometric analysis, as a robust quantitative methodology, integrates statistical techniques, data mining, and mathematical modelling to systematically trace publication trajectories, citation dynamics, and intellectual structure within a research domain. This method has gained considerable traction across diverse scientific disciplines for mapping research trends and identifying emerging areas of inquiry (Favaro-Trindade et al., 2021). Leveraging bibliometric tools, the current study provides a comprehensive overview of the evolving landscape, principal research themes, and knowledge gaps related to nano-enabled strategies in small ruminant nutrition. The findings facilitate informed decision-making for stakeholders ranging from academic researchers and industry practitioners to policymakers and consumers while highlighting key avenues for future investigation in this rapidly advancing field (Abdelwahab et al., 2023).

Therefore, this study aims to systematically map and analyze publication trends, citation networks, and the intellectual structure of research on the use of nanoparticles as feed additives in small ruminant nutrition, using bibliometric methods. By identifying key research themes and gaps, this analysis supports evidence-based decision-making and advances the sustainable application of nano-enabled feed additives.

Materials and methods

Databases and search strategy

This study presents a systematic bibliometric analysis aimed at elucidating research developments concerning the application of nanotechnology in the nutrition of small ruminant, specifically sheep and goats, from 2000 to 2025. Data were sourced from three prominent electronic databases ScienceDirect, Google Scholar, and Dimensions to ensure broad coverage and methodological rigor. The literature search targeted peer-reviewed English-language articles, employing carefully structured search strategies tailored to each database (Mansoori, 2018; Orimoloye et al., 2020).

For ScienceDirect, a Boolean search combination ("nanoparticle*" OR "nano-additive*" OR "nanotechnology") AND ("sheep" OR "goat") AND ("nutrition" OR "diet" OR "feed") was applied across article titles, abstracts, and keywords to capture all relevant publications systematically. A parallel approach was utilized in Google Scholar through the advanced search interface, followed by manual screening to ascertain topical relevance and eliminate non-pertinent records. In the Dimensions database, search queries were refined using relevant keywords and further filtered to restrict the results to research articles within the agricultural, veterinary, and food science domains, published in English over the defined period (Idamokoro and Hosu, 2022). Initially, 170 records were retrieved from ScienceDirect, Google Scholar, and Dimensions; after de-duplication and full-text eligibility assessment, 109 articles met the inclusion criteria for analysis [inclusion: peer - reviewed English - language journal articles on nanotechnology-based nutritional interventions in sheep/goats; exclusion: duplicates; non-article document types; non-English; out-of-window dates; studies outside small ruminant nutrition or not involving nanotechnology] (Luo et al., 2025).

Data extraction and processing

References were systematically collected from ScienceDirect and Dimensions by exporting records in Reference Manager (RIS) format. For data retrieval from Google Scholar, the "Export as.RIS" feature available in

the Publish or Perish software was employed to facilitate consistent file formatting. All RIS files were merged and processed using Publish or Perish (version 8), enabling the extraction and standardization of bibliometric metadata. The unified dataset encompassed essential bibliographic fields, including article titles, author names, publication years, author-defined keywords, abstracts, and source journal titles. To enhance interoperability with prevalent bibliometric analysis tools, the curated and standardized dataset was exported in comma-separated values (CSV) format, thereby supporting subsequent analytical procedures such as citation analysis and research mapping.

Bibliometric analysis and keyword co-occurrence

VOSviewer (version 1.6.20) was utilized to perform a comprehensive keyword co-occurrence analysis. The dataset comprised exclusively of author-supplied keywords, which served as the principal analytical units. Keyword frequencies were calculated using the complete counting approach to ensure systematic quantification. To improve analytical robustness and reduce the influence of infrequent terms, only those keywords appearing in at least two publications were retained for further examination. Based on this selection, a co-occurrence network map was generated, wherein each node corresponds to a unique keyword, links denote their co-occurrence within the same article, and clusters represent groups of thematically interconnected terms. The Total Link Strength (TLS) indicator was employed to measure the degree of association between pairs of keywords, thereby offering insights into the underlying conceptual structure and thematic organization of the research domain, within a methodological framework widely adopted in contemporary bibliometric analyses (Ghassemi Nejad et al., 2023; Luo et al., 2025).

Figure 1. Bibliometric analysis of nanotechnolgy in small ruminant nutrition flowchart

Data interpretation

Bibliometric mapping was conducted using VOSviewer, which enabled the visualization of keyword clusters and their interrelationships. Quantitative analysis of cluster structures, including the frequency and strength of keyword co-occurrences, was performed systematically in Microsoft Excel. This methodological framework allowed for the comprehensive identification of prevailing research themes, emerging trends, and underexplored areas within the field of nanoparticle applications in small ruminant nutrition, thereby providing a nuanced understanding of the intellectual landscape and thematic evolution in this domain (Ghassemi Nejad et al., 2023) (Figure 1). However, the present study is subject to several limitations regarding database selection and language constraints. Data were exclusively retrieved from ScienceDirect, Google Scholar, and Dimensions, with inclusion restricted to peer-reviewed articles published in English; this strategy may have led to an underrepresentation of non-English literature and research primarily indexed in platforms such as Web of Science or Scopus. Furthermore, the selection of

keywords and implementation of frequency thresholds within VOSviewer likely influenced cluster composition and the overall strength of linkages; specifically, the exclusion of low-frequency or emerging terms and the disproportionate emphasis on prevalent terms and synonyms may have introduced bias into the thematic structure (Lou et al., 2025). Additional methodological choices including the defined time frame, the restriction to original research articles and reviews, and the removal of duplicate records further impacted publication counts and temporal distribution, potentially resulting in minor inconsistencies across sections and reduced comparability with other bibliometric analyses (Michalak et al., 2022; Gelyae, 2024).

Results

Publications' annual growth rate in nanoparticle applications for small ruminant nutrition

Over the 15-year interval from 2010 to 2025, the temporal overview provided in Figure 2 elucidates the evolving scholarly engagement with the application of nanoparticles in the nutrition of small ruminant. The bibliometric assessment indicates a cumulative output of 109 publications during this period. The early years (2010–2016) were characterized by modest and consistent publication activity, with annual outputs ranging narrowly between 2 and 4 articles and no substantial escalation identified. However, a pivotal shift emerged from 2017 onward; the yearly average publication rate escalated significantly to 15 articles in the concluding five-year segment, exemplifying an intensification of research endeavors. Peaks in publication numbers were particularly evident in 2021 and 2023, each registering 18 published studies.

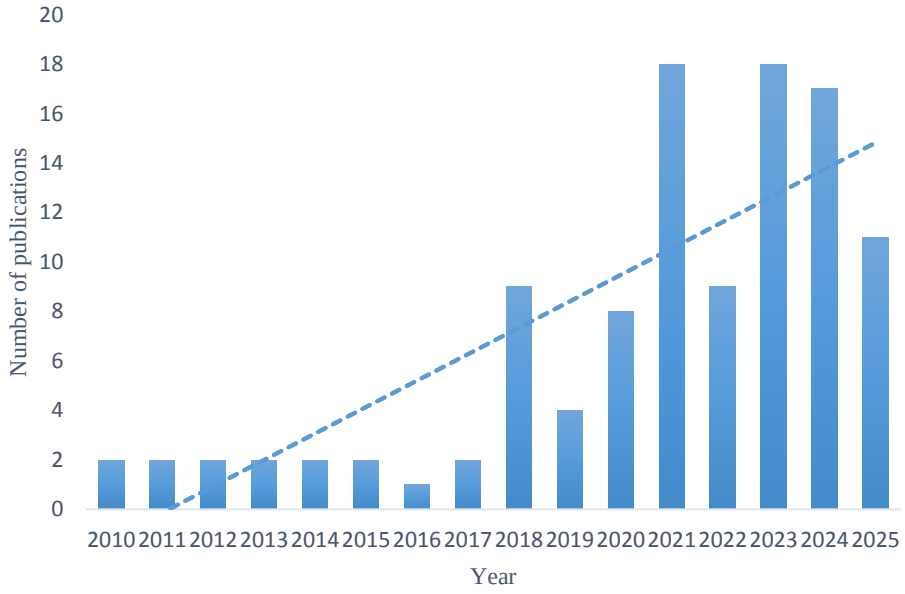

Figure 2. Annual publication trends in small ruminant nanoparticle applications

Distribution of research output by journals and publishers in nanoparticle applications for small ruminant nutrition

Figure 3 delineates the scholarly output of the fifteen most productive journals with respect to research on nanoparticle utilization in the nutrition of small ruminant over the period 2010–2025. These journals were selected strictly by article volume within the curated dataset, with ties resolved by total local citation score (TLCS); Journal Impact Factor and JCR quartile are reported descriptively and were not used as selection criteria. The analysis underscores the pivotal role that eminent and prolific journals and publishing houses have played in shaping this domain. In particular, journals such as Animals (MDPI, JCR Q1), Animal Feed Science and Technology, and Animal Nutrition (both Elsevier, JCR Q1) have established themselves as principal platforms for the dissemination of pioneering research in this specialized field. Furthermore, outlets including Annals of Animal Science (De Gruyter, JCR Q2), BMC Veterinary Research (BioMed Central, JCR Q1), and Biological Trace Element Research (Springer, JCR Q2) have made significant contributions to the propagation and enrichment of scientific knowledge regarding nanoparticle applications in small ruminant diets.

The pronounced scholarly impact of major publishing houses such as Elsevier and Springer warrants particular mention; these organizations have collectively accounted for the majority of outputs in this sphere

during the study's temporal window, which attests to their scientific standing and sustained commitment to both animal nutrition and nanotechnology research. Additionally, research outputs from university-affiliated and national institutions exemplified by the Egyptian Journal of Nutrition and Feeds and the Arab Universities Journal of Agricultural Sciences highlight the dynamic and geographically diverse nature of scholarly participation that is driving advances in this rapidly progressing field.

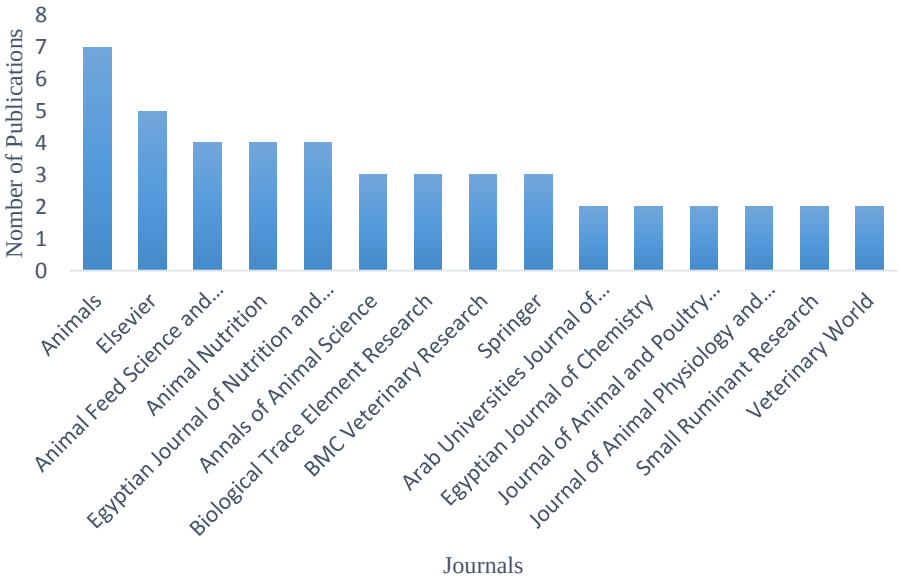

Figure 3. Journals and publishers in nanoparticle applications for small ruminant nutrition

Intellectual structure and research network in nanoparticle applications for small ruminant nutrition

Figure 4 offers a comprehensive visualization of the intellectual landscape and interconnections within the application of nanoparticles in the nutrition of small ruminant domain, delineating how various research themes and concepts are interrelated. Each node within this network is represented by a circle whose size reflects the frequency with which the associated topic appears in the literature, at the same time its color denotes the historical period during which that topic was initially prominent. The network encompasses 293 nodes connected by 959 links, resulting in a network density of 1016. The interlinking lines indicate thematic associations, with their coloration corresponding to the era when these scholarly linkages were first established (Cheng, 2006; Ghassemi Nejad et al., 2023). Analysis of the network structure highlights that pivotal concepts such as nanotechnology, nanoparticles, livestock, sheep, animal nutrition, digestibility, and bioavailability emerged as focal points within the application of nanoparticles in the nutrition of small ruminant research throughout the period under study (Figure 5).

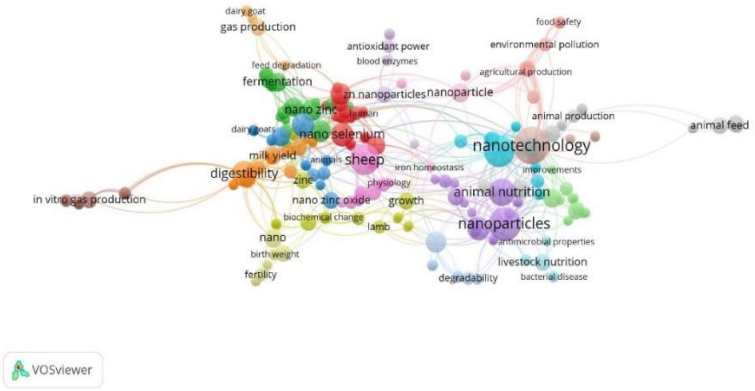

Figure 4. Intellectual landscape and collaborative network in nanoparticle applications for small ruminant nutrition

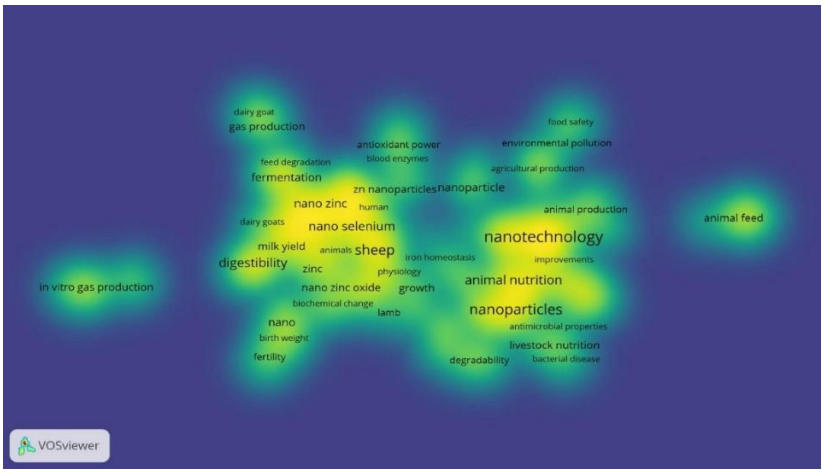

Figure 5. Intellectual and collaborative structure in nanoparticle applications for small ruminant nutrition

Figure 6 displays a temporally stratified keyword co-occurrence network, where the horizontal layout progresses chronologically from earlier studies on the left to more contemporary investigations on the right. In this visualization, the color gradient serves as a temporal indicator: nodes shown in deeper blue and green tones represent publications from earlier years, while yellow indicates the most recent research. This spatial and chromatic arrangement of clusters and linkages facilitates a nuanced comprehension of how scholarly interests have evolved during the analyzed period. The temporal dynamics evident in the prevalence of specific keywords underscore the shifting priorities within the research community. Initially, as denoted by blue-colored nodes, the dominant thematic areas centered on core scientific topics, particularly those relating to digestive physiology and microbial fermentation. Terms such as “rumen fermentation” and “feed digestibility” featured prominently, laying the conceptual groundwork for subsequent research trajectories. Subsequently, during an intermediate phase characterized by green and turquoise hues, the bibliometric landscape diversified to encompass broader, application-oriented subjects. This period witnessed an increased focus on keywords like “zinc,” “nano selenium,” “animal nutrition,” “sheep,” and “growth performance,” suggesting a methodological pivot toward practical and physiological implications. The appearance of “gas production” as a recurrent term further reflects a widening of investigational scope during this stage. In the most recent interval indicated by yellow shades, scholarly discourse has gravitated towards innovative themes, particularly the integration of nanotechnology within the nutritional management of small ruminant. Recent literature increasingly prioritizes concerns about food safety, environmental impact, antimicrobial effectiveness, and improved animal productivity, signaling a broader paradigm shift in the research directions of this field. The intellectual-structure maps were generated from author-defined keywords using a minimum occurrence criterion, which may exclude low-frequency or emerging terms and influence the resulting clusters; accordingly, the maps should be viewed as indicative rather than exhaustive. Future work could incorporate Keywords Plus or controlled vocabularies, compare databases, and vary the co-occurrence threshold to assess robustness (Idamokoro and Hosu, 2022; Gelyae, 2024; Lou et al., 2025).

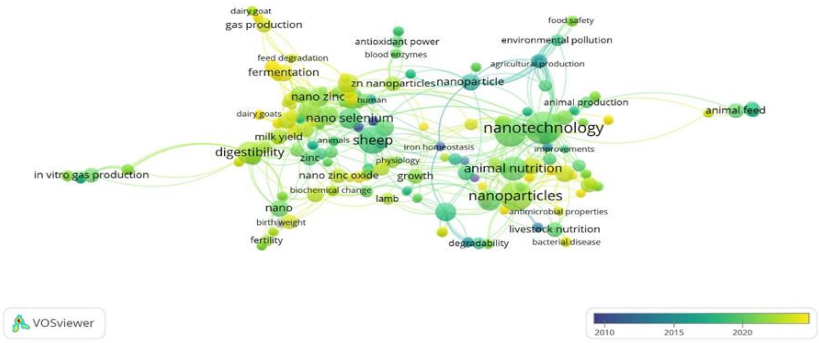

Figure 6. Temporal keyword co-occurrence mapping in nanoparticle applications for small ruminant nutrition

Figure 6 displays a temporally stratified keyword co-occurrence network, where the horizontal layout progresses chronologically from earlier studies on the left to more contemporary investigations on the right. In this visualization, the color gradient serves as a temporal indicator: nodes shown in deeper blue and green tones represent publications from earlier years, while yellow indicates the most recent research. This spatial and chromatic arrangement of clusters and linkages facilitates a nuanced comprehension of how scholarly interests have evolved during the analyzed period. The temporal dynamics evident in the prevalence of specific keywords underscore the shifting priorities within the research community. Initially, as denoted by blue-colored nodes, the dominant thematic areas centered on core scientific topics, particularly those relating to digestive physiology and microbial fermentation. Terms such as “rumen fermentation” and “feed digestibility” featured prominently, laying the conceptual groundwork for subsequent research trajectories. Subsequently, during an intermediate phase characterized by green and turquoise hues, the bibliometric landscape diversified to encompass broader, application-oriented subjects. This period witnessed an increased focus on keywords like “zinc,” “nano selenium,” “animal nutrition,” “sheep,” and “growth performance,” suggesting a methodological pivot toward practical and physiological implications. The appearance of “gas production” as a recurrent term further reflects a widening of investigational scope during this stage. In the most recent interval indicated by yellow shades, scholarly discourse has gravitated towards innovative themes, particularly the integration of nanotechnology within the nutritional management of small ruminant. Recent literature increasingly prioritizes concerns about food safety, environmental impact, antimicrobial effectiveness, and improved animal productivity, signaling a broader paradigm shift in the research directions of this field. The intellectual-structure maps were generated from author-defined keywords using a minimum occurrence criterion, which may exclude low-frequency or emerging terms and influence the resulting clusters; accordingly, the maps should be viewed as indicative rather than exhaustive. Future work could incorporate Keywords Plus or controlled vocabularies, compare databases, and vary the co-occurrence threshold to assess robustness (Idamokoro and Hosu, 2022; Gelyae, 2024; Lou et al., 2025).

Analysis of keyword co-occurrence within the literature addressing nanoparticle applications in small ruminant nutrition reveals pronounced prominence for both "nanotechnology" and "nanoparticles," recording 15 and 12 occurrences, respectively, with mean publication years of 2020.133 and 2021.417 (Table 1). This distribution signifies a substantive and recent surge of scholarly attention toward nanotechnological interventions within this domain. Following closely in frequency are the terms "livestock" (11 occurrences; average year: 2020.091) and "sheep" (10 occurrences; average year: 2018.7), reflecting a continued research focus on both species-specific objectives and core nutritional parameters, particularly the optimization of digestibility and nutrient bioavailability. It is noteworthy that, in recent years, keywords relating to nano-minerals such as "nano-zinc" (average year: 2021; 5 occurrences) have emerged with greater frequency, suggesting a shift toward investigating the potential of nano-element supplementation for advancing growth metrics and improving animal health indices. Collectively, these bibliometric trends indicate a discernible progression within the field: scholarly inquiries have moved beyond generalized topics, such as "nutrition" (average publication year: 2017.7), to embrace increasingly nuanced research foci, exemplified by themes like "rumen" (mean publication year: 2022.6) and "in vitro gas production." This evolution underscores an expanding research agenda that aligns with the broader objectives of enhancing productive efficiency and physiological outcomes in small ruminant.

Table 1. Frequent keyword co-occurrences in small ruminant nanoparticle applications

Keywords	Years	Counts
nanotechnology	2020.133	15
nanoparticles	2021.417	12
livestock	2020.091	11
sheep	2018.7	10
animal nutrition	2020	8
digestibility	2021.714	7
bioavailability	2020	6
nano selenium	2019.167	6
selenium nanoparticles	2021.333	6
nano zinc	2021	5
performance	2020.8	5
rumen	2022.6	5
selenium	2018.2	5
animal health	2022.75	4
fermentation	2023.5	4
goats	2021.5	4
growth performance	2019.5	4
nano	2020	4
nanominerals	2022.5	4
nanoparticle	2016.25	4
nutrition	2017.75	4
zinc oxide nanoparticles	2022.75	4
animal feed	2019.667	3
drug delivery	2022	3
ewes	2020	3
gas production	2023	3
growth	2021	3
heat stress	2022.333	3
in vitro gas production	2020	3
lambs	2023.333	3
livestock nutrition	2019.667	3
milk yield	2021.667	3
nano zinc oxide	2022.333	3
organic selenium	2022.333	3
ruminants	2018.667	3
toxicity	2020.667	3
weight gain	2022.333	3
zinc	2019.333	3
zinc nanoparticles	2024	3
zinc oxide	2023	3

Citation-burst keywords in nanoparticle applications for small ruminant nutrition

Figure 7 delineates the chronological progression of key thematic areas related to the deployment of nanoparticles within the nutritional management of small ruminant. In this graphical representation, the band width indicates the relative frequency of keyword citations across predefined time segments, while the gradual color shift from gray to red illustrates the rising scholarly interest. The persistence of uninterrupted bands is emblematic of the sustained relevance of specific research topics, In contrast, the migration and reorganization of keyword clusters over time illustrate the dynamic evolution of scientific priorities within this domain.

Throughout the period under review, keywords such as nanotechnology, nanoparticles, livestock, sheep, digestibility, animal nutrition, bioavailability, selenium nanoparticles, nano selenium, and rumen assume particular salience, manifesting as prominent, consistently broad, and vividly colored bands. This recurring pattern underscores the central role of advances in nanotechnology, particularly the use of selenium and zinc-based nanoparticles, in nutritional research targeted at small ruminant species. A substantial proportion of these studies seek to potentiate nutrient bioavailability, enhance digestive efficiency, optimize ruminal function, and promote key productivity indices, notably growth rates and weight gain in sheep and goats.

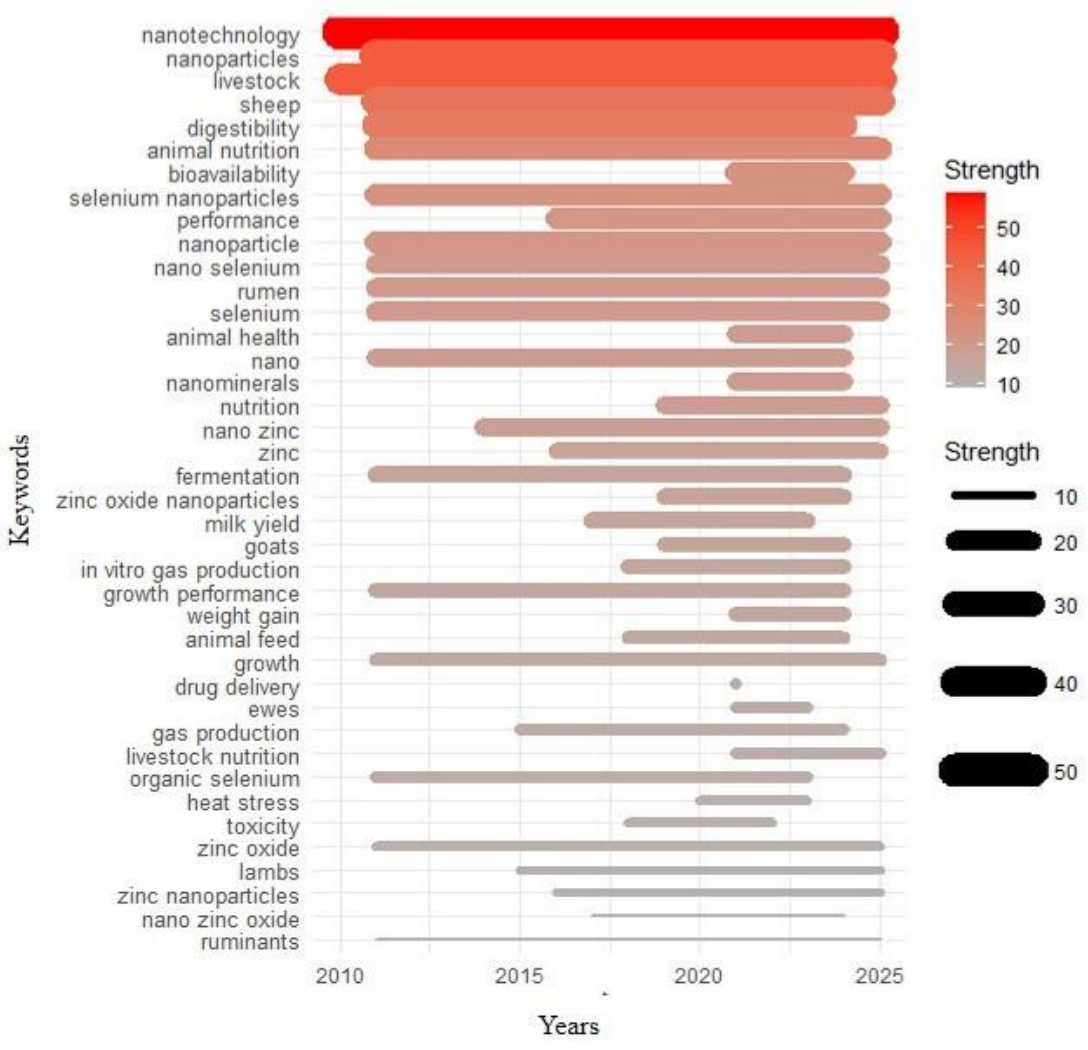

Figure 7. Temporal dynamics of keyword intensity in small ruminant nanoparticle applications

The temporal segmentation elucidated by Figure 7 reveals distinct phases in the maturation of this research field. The initial stage, extending through the mid-2010s, was characterized primarily by foundational investigations focusing on digestibility, in vitro gas production, fermentation, and rumen function. These efforts contributed significantly to elucidating the interactions between ruminal microbiota and administered nanoparticles, as well as their subsequent implications for fermentation processes. By contrast, the 2016–2020 period marks a notable inflection point, with scholarly attention increasingly devoted to terms such as

selenium nanoparticles, zinc oxide, nano zinc, organic selenium, and animal feed. This shift signals a transition from primarily mechanistic inquiries toward applied research focused on nutritional efficacy and feed utilization. Beyond 2020, a marked diversification in research foci emerges, as reflected by the prominence of terms addressing health, immune response/animal health, performance, growth performance, weight gain, milk yield, heat stress, toxicity, and drug delivery. In the contemporary literature, investigations now span considerations of efficacy and safety, dosage optimization, and direct assessment of nanoparticle impacts on productivity in small ruminant, thereby evidencing the maturation and broadening of the field's scope. Furthermore, the intensification of red-hued bands in more recent years signals burgeoning interest in topics such as mitigation of heat stress, enhancement of antioxidant status via selenium and zinc nanoparticles, fine-tuning of trace mineral bioavailability with concurrent reductions in environmental excretion, and the innovation of targeted delivery modalities designed to circumvent rumen-mediated degradation. Equally prominent are emergent lines of inquiry into comprehensive toxicity profiling, long-term safety, bioaccumulation in tissues, and detailed analyses of growth and lactational performance in sheep and goat models.

Influential references and network linkages in nanoparticle applications for small ruminant nutrition

Table 2 presents the most influential sources about the application of nanoparticles in the nutrition of small ruminant, ranked according to citation count. Among these, Mohd Yusof et al. (2019) stands out as the most highly cited work, with 689 citations, indicating its considerable impact on the field. The publications by Swain et al. (2016) and Shi et al. (2011b) follow, with 398 and 285 citations, respectively. Additionally, the inclusion of highly cited articles such as Ferrari et al. (2023), Michalak et al. (2022), and Malyugina et al. (2021), which have been published between 2018 and 2023, highlights the growing significance and contemporary relevance of research in this area. Figure 8 effectively delineates the intricate interplay among three principal analytical categories: countries, keywords, and authors through a tripartite flow diagram. In this representation, the vertical magnitude of each rectangle within a given section quantitatively reflects the proportion of pertinent studies or the frequency of established interconnections. Simultaneously, the breadth of the bands linking these sections signifies the strength of collaborative efforts and the extent of co-authored outputs. Furthermore, color-coding of the connecting streams is used to distinguish specific keywords. This approach enables a clear visualization of hematic progressions, as topics are traced from their keyword origins through national research landscapes to individual scholarly contributors.

Table 2. Top-cited references in small ruminant nanoparticle applications

Cited references	Years	Count
Mohd Yusof et al.	2019	689
Swain et al.	2016	398
Shi et al.	2011b	285
Shi et al.	2011a	172
Abdelnour et al.	2021	127
Sadeghian et al.	2012	126
Romero-Pérez et al.	2010	102
Kuzma	2010	92
Bunglavan et al.	2014	89
Kojouri et al.	2012	77
El Sabry et al.	2018	70
Michalak et al.	2022	68
Raje et al.	2018	68
Ferrari et al.	2023	67
Malyugina et al.	2021	58
Rajendran	2013	57
Tona	2018	54
De Silva et al.	2021	51
Kachuee et al.	2019	51
Hashem & Gonzalez-Bulnes	2021	47
El Sabry et al.	2021	45
Thulasi et al.	2013	45
Ducournau et al.	2020	45
El-Nile et al.	2021	44
Mehrazar et al.	2015	44
Ramachandraiah et al.	2018	41
Bąkowski et al.	2018	41
Hosseini-Vardanjani et al.	2020	34
Soltan et al.	2021	31
Bhagat & Singh	2022	28
Mekonnen	2021	28
Sarker et al.	2018	25
Riazi et al.	2019	25
Geetha et al.	2020	25
Ibrahim & Mohamed	2018	24
Alijani et al.	2020	24
Pieszka et al.	2019	23
Kojouri et al.	2020	23
Swain et al.	2021	20

As evidenced in Figure 8, Egypt, India, and Iran emerge as the most prominent contributors, as indicated by the dominant size of their respective rectangles, thereby underscoring their position as principal sources of scholarly production within this field. Directly succeeding these key nations are Nigeria and Poland, which, while occupying a secondary echelon, nonetheless demonstrate a substantial scholarly presence. Several additional countries, including the Czech Republic, Indonesia, Australia, Hungary, Portugal, and the United States, are characterized by lower overall frequencies yet maintain a discernible level of engagement, contributing meaningfully to the field's thematic diversity. A detailed examination of the principal nations reveals that broadly encompassing terms such as "nanoparticles," "animal nutrition," and "livestock" are recurrently co-linked with more specialized descriptors, notably "zinc" and "selenium," suggesting nuanced thematic intersections.

From a thematic mapping perspective, the keywords "nanoparticles," "sheep," and "zinc" exhibit the densest connectivity, signifying their pivotal roles in linking countries and authors and highlighting their centrality to the research domain. Additionally, terms emphasizing functional outcomes, including "performance,"

"bioavailability," and "digestibility," are prevalent throughout the examined literature. These findings indicate sustained scholarly attention to production metrics and nutrient assimilation processes. While "sheep" represent the more frequently encountered species-specific term, the presence of "goats" as a notable keyword implies the existence of a significant albeit comparatively less extensive body of research.

In the dimension of authorship, it is notable that researchers such as Swain et al. (2016, 2021), Mohamed et al. (2015), Ali et al. (2023), and Kojouri et al. (2012, 2020) are associated with the most prominent rectangles and the most extensive network connections. This pattern may be interpreted to reflect their substantial and focused contributions to the application of zinc and selenium nanoparticles, particularly in relation to animal nutrition, metabolic pathways, and enhancements in small ruminant productivity.

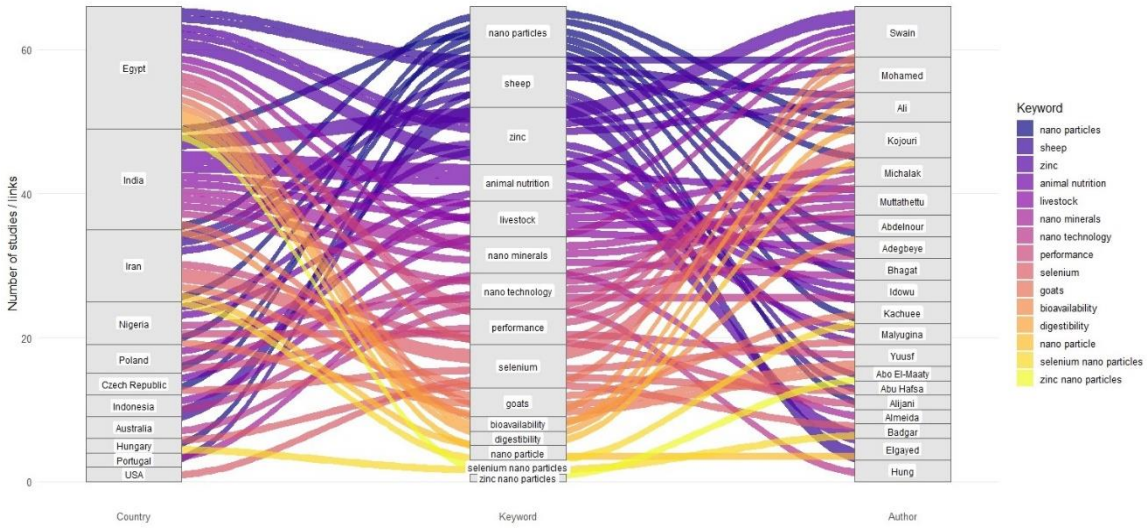

Figure 8. Three-field plot: authors-countries-keywords in small ruminant nanoparticle applications

Discussion

Despite certain limitations, including the selection of databases and the heterogeneity of methodologies and indicators employed, this study constitutes the first comprehensive bibliometric analysis of nanoparticle applications in small ruminant nutrition. It is essential to acknowledge several inherent limitations associated with bibliometric co-occurrence analysis to ensure accurate interpretation of the findings. First, the selection of databases specifically ScienceDirect, Google Scholar, and Dimensions may generate datasets that differ substantially from those sourced from Web of Science or Scopus. These differences can affect citation metrics, co-occurrence networks, and the relative prominence attributed to specific journals or countries. Second, language bias is prevalent, as the majority of research concerning the application of nanotechnology in animal sciences is published in English, potentially resulting in the underrepresentation of non-English studies and regional journals. Third, lexical bias may arise due to reliance on author-assigned keywords and the implementation of thresholding procedures, which can influence the construction of co-occurrence maps. Finally, the temporal range of the data can introduce distortions in thematic evolution, given that limited publication volume in early periods may lead to underweighting or exclusion of certain years during analysis (Idamokoro and Hosu, 2022; Michalak, 2022; Lou et al., 2025). The primary objective of this research is to elucidate foundational studies and their thematic focus, assess evolutionary trends in the literature, identify neglected research domains, and delineate emerging and prominent topics within the application of nanoparticles to small ruminant nutrition.

As depicted in Figure 2, scholarly activity in this domain has increased substantially since 2017, with publication peaks observed in 2021 and 2023. This pronounced upward trajectory reflects the growing recognition of nanotechnology's transformative potential to enhance nutritional efficiency, animal health, and productivity in small ruminant. Current evidence suggests that nanoparticles, particularly nanominerals such as selenium, zinc, and copper, play multifaceted roles in small ruminant nutrition. These nanominerals demonstrate significantly greater bioavailability compared to their conventional counterparts, thereby facilitating improved nutrient absorption and mitigating environmental excretion (Dumlu, 2024; Michalak et al., 2022). For example, nano-selenium has been shown to enhance ruminal fermentation, augment antioxidant capacity, and improve reproductive performance,

thereby addressing critical challenges encountered in small ruminant husbandry (Sisterami et al., 2024).

However, despite these promising advancements, the implementation of nanoparticles in small ruminant diets is accompanied by several challenges. Notably, risks associated with nanoparticle accumulation in biological tissues and potential environmental contamination necessitate rigorous safety assessments (Michalak et al., 2022). Moreover, the ethical application of nanoparticles in livestock nutrition, coupled with the establishment of robust regulatory frameworks, is imperative to ensure the sustainable and responsible integration of nanotechnology within animal agriculture (Parveen et al., 2024). Continued research efforts addressing these issues seem to be contributing to the sustained increase in scholarly output concerning nanoparticle applications in small ruminant nutrition.

Over the past fifteen years, the findings of this investigation indicate that preeminent academic journals and influential publishing entities have exerted a substantial impact on the evolution of research concerning the integration of nanoparticles within the field of small ruminant nutrition. Journals of noteworthy prominence such as Animals, Animal Feed Science and Technology, Animal Nutrition, Annals of Animal Science, BMC Veterinary Research, and Biological Trace Element Research distinguished by commendable impact factors and rigorous evaluative standards, have served as essential conduits for the dissemination of cutting-edge research in this domain. Publishing scholarly work in high-caliber outlets not only enhances the scientific rigor and visibility of emerging literature but also aids in identifying and analyzing prevailing and emerging trends, especially in journals with strong indexing and significant scholarly influence.

The spectrum of journals contributing to this literature ranging from those specializing in ruminant nutrition and physiology (e.g., Animals, Animal Feed Science and Technology, Animal Nutrition, and Annals of Animal Science), to dedicated veterinary science periodicals (BMC Veterinary Research), as well as journals focusing on trace element research (Biological Trace Element Research) effectively illustrates the inherently interdisciplinary character of scholarship on nanoparticles in small ruminant nutrition. This multidisciplinary trajectory encompasses diverse thematic areas, including but not limited to elemental biochemistry, biosafety assessment, nutrient bioavailability, dietary efficacy, and broader impacts on animal health and welfare. Moreover, the inclusion of publications that prioritize research on micronutrients and trace elements highlights the growing importance of elucidating dose response dynamics, assessing nanoparticle bioavailability, and evaluating environmental outcomes resulting from their use in ruminant feeding regimens.

Major international publishers such as Elsevier, Springer, MDPI, and BioMed Central have proven instrumental in advancing this field by providing well-established platforms that ensure both the accessibility and discoverability of scientific outputs. These publishers also play a pivotal role in promoting methodological rigor and fostering the adoption of standardized reporting practices. Concurrently, the engagement of journals affiliated with academic institutions and regional scientific bodies, such as the Egyptian Journal of Nutrition and Feeds and the Arab Universities Journal of Agricultural Sciences, reflects the vibrant geographical diversification and contextual richness of contributions in this area. Such outlets often report data from diverse agro-ecological environments and production systems, thereby enhancing the relevance, scope, and practical use of current research on nanoparticle applications in small ruminant nutrition.

A systematic bibliometric evaluation of the intellectual landscape and collaborative networks regarding nanoparticle utilization in small ruminant nutrition elucidates emergent research trajectories and illustrates the discipline's interdisciplinary connectivity. Nanoparticles distinguished by their markedly high specific surface area exhibit enhanced surface reactivity, superior catalytic efficiency, and improved absorptive potential when compared to traditional, larger-scale particulate forms. These nanomaterials also possess an array of exceptional physicochemical and biological properties, encompassing increased mechanical robustness, greater solubility, elevated electrical and thermal conductivities, and advanced optical as well as catalytic capabilities (Alhashmi Alamer and Beyari, 2022; Khan and Hossain, 2022). Importantly, such distinctive attributes, most notably the enlarged specific surface area, substantially augment the efficacy of nanoparticles as dietary supplements within ruminant nutrition science. Empirical findings indicate that the incorporation of nanoparticles into feed formulations contributes to enhanced nutrient assimilation, fortifies immunological responses, and supports the overall growth and developmental processes in livestock (Hatab et al., 2022; Hussain et al., 2023). The diminutive scale of these nano-supplements not only enhances nutritional efficiency by improving digestive dynamics but also facilitates targeted nutrient delivery to specific biological tissues, thereby fostering animal health and optimizing productive outcomes. Moreover, research has associated the strategic deployment of nano-additives with heightened nutrient bioavailability, which translates into measurable improvements in growth indices, feed conversion ratios, and comprehensive health parameters among ruminant (Sharif et al., 2021). The environmental consequences of the widespread use of conventional inorganic mineral supplements, which are often poorly bioavailable and frequently overused as growth promoters, underscore the urgent need for more sustainable and effective alternatives. In this regard, the advent of nanoscale feed additives emerges as a compelling solution. Notably, Michalak et al. (2022) demonstrated that metal-based nanoparticles, such as those composed of zinc, silver, copper, gold, selenium, and calcium, exhibit pronounced bioavailability and absorption advantages, rendering them promising

substitutes for conventional mineral sources in ruminant diet formulations.

To facilitate the practical implementation of dietary nano-supplements in ruminant nutrition and support the progression from laboratory research to on-farm applications, a coordinated and structured interdisciplinary collaboration is essential. Specifically, animal scientists must establish standardized phenotypic criteria and on-farm efficiency metrics. Nanotechnologists should focus on the development and rigorous evaluation of safe, scalable nano formulations suitable for commercial deployment. Furthermore, specialists in environmental science and food safety are required to investigate the environmental fate, transfer mechanisms, bioaccumulation, residue profiles, and ecological impacts of orally administered nano-supplements under authentic agricultural conditions (Idamokoro and Hosu, 2022; Michalak, 2022; Gelyae, 2024).

Building upon these collaborative efforts, sector-wide initiatives within livestock production can encourage active engagement throughout the value chain. Such participation will accelerate the adoption of advanced technologies at the farm level while safeguarding and enhancing the sustainability of animal production systems. The findings of this study substantiate this approach by demonstrating the expansion of multi-author collaboration networks in meat and livestock nanotechnology, alongside the emergence of interdisciplinary connections identified through our bibliometric analysis.

Temporal mapping of keyword co-occurrence helps scholars gain a clearer and more comprehensive understanding of the intellectual trajectory of research on nanoparticle applications in small ruminant nutrition. Temporal stratification of scholarly output in this domain reveals a discernible shift in research emphasis: the field has progressed from initial investigations focused on the physiological impacts of nanoparticles particularly their role in modulating digestive processes and rumen microbial dynamics toward more integrative and application-oriented studies. Network analyses tracking the progression of keywords corroborate this trend, illustrating that scholarly attention has gradually broadened; early efforts were confined mainly to internal physiological mechanisms, whereas recent work increasingly addresses issues situated at the intersection of systemic health, biosecurity, and environmental sustainability. This evolution not only attests to the field's maturation but also reflects an enhanced recognition of nanotechnology's potential to address multifaceted challenges within small ruminant nutrition. Furthermore, by elucidating both historic trends and emergent themes, temporal analysis of keyword co-occurrence proves instrumental in identifying prospective avenues for inquiry, such as the adoption of precision nutrition paradigms, the development of environmentally sustainable (green) nanotechnologies, and rigorous risk assessment protocols for nano-additives in livestock alimentation. The demonstrated higher bioavailability of selenium and zinc nano-minerals substantiates a paradigm shift toward lower-dose nano-supplementation in animal nutrition. This approach supports the maintenance of optimal animal performance while simultaneously minimizing mineral excretion and mitigating environmental impact, as evidenced across diverse livestock species. The accumulation of such findings underscores the urgent need for well-defined dosage standards, rigorous labeling requirements, and comprehensive safety monitoring protocols for nano-additives. Furthermore, it is imperative to implement farm-scale validation studies and robust toxicological assessments to facilitate the responsible integration of nano-minerals into livestock production systems (Idamokoro and Hosu, 2022; Michalak, 2022).

In the present bibliometric investigation, forty distinct keywords were identified as demonstrating the most pronounced citation bursts throughout the surveyed timeframe. Within scientific literature, keywords fulfill an indispensable role by encapsulating core research themes, fostering the generation of novel scientific insights, enhancing the efficiency of information retrieval, and revealing the intricate interrelationships among subdomains within a broader disciplinary context (Ghassemi Nejad et al., 2023). Traditionally, authors select keywords during manuscript submission to succinctly capture the pivotal concepts under investigation in their scholarly works. Additionally, bibliographic platforms such as the Web of Science algorithmically assign supplementary indexing terms referred to as keywords plus by analyzing recurrent terminology and phraseology in the titles of cited references (Tripathi et al., 2018). The strategic integration of both author-designated keywords and keywords plus contributes to a more nuanced and comprehensive mapping of intellectual structures, article content areas, and thematic linkages within the field (Ghassemi Nejad et al., 2023). The results of this analysis indicate that terms such as "nanotechnology," "nanoparticles," "livestock," "sheep," "digestibility," "animal nutrition," "bioavailability," "selenium nanoparticles," "nano selenium," and "rumen" manifested remarkably enduring citation bursts. This sustained pattern suggests a marked and growing scholarly focus on these topics, underlining their increasing significance and evolving influence within the academic community (Ghassemi Nejad et al., 2023; Tripathi et al., 2018; Zhang et al., 2016).

Table 2 presents the principal sources that have the most significant influence on the scholarly discourse surrounding the use of nanoparticles in small ruminant nutrition, organized by citation frequency. Analysis of the three-field plot provides nuanced insights into the heterogeneity of research foci within this discipline, revealing that authors' thematic priorities are notably shaped by their respective disciplinary orientations and national affiliations, which in turn drive shifts in scientific trends and agendas across different countries

(Ghassemi Nejad et al., 2023). Egypt is particularly distinguished as the preeminent contributor to this research area, attaining top rankings in metrics such as publication volume, research funding, institutional engagement, and lead authorship. Within Egypt, the Agricultural Research Center and the National Research Centre have emerged as the foremost institutions in terms of scholarly output, at the same time, Ain Shams University and Cairo University have also substantially bolstered the landscape of scientific productivity. On an individual scale, Partha Sarathi Swain of Odisha University of Agriculture and Technology (India) stands out as the most prolific author in terms of publication count, In contrast, Hidayat Mohd Yusof from Universiti Putra Malaysia commands the highest citation frequency, thereby underscoring the significant scholarly impact of his contributions within the global research community (Ghassemi Nejad et al., 2023).

Conclusions

Research on nanoparticle supplementation in small ruminant nutrition has grown rapidly, evolving from foundational studies on physiology and fermentation to focused investigations on functional improvements such as digestive efficiency, nutrient absorption, production, and herd welfare. Nano-selenium and nano-zinc have emerged as key minerals in this field, with contributions from countries like Egypt, India, and Iran disseminated through leading journals. Despite promising results, translating these findings into routine practice requires standardized protocols, farm-scale trials, safety assessments, and precise delivery systems. When these prerequisites are met, low-dose, validated nano-minerals can effectively enhance rumen function, antioxidant capacity, and growth performance while minimizing mineral excretion, provided implementation is guided by extension services, verified suppliers, and phased trials. Overall, careful integration of nanoparticles offers a pathway to optimize nutrition, safeguard animal health, and reduce ecological impact in small ruminant systems.

Conflict of interest

The author declares no conflicts of interest.

Acknowledgements

We thank the University of Torbat-e Jam for providing the financial and technical supports for this project.

References

Abdelnour, S.A., Alagawany, M., Hashem, N.M., Farag, M.R., Alghamdi, E.S., Hassan, F.U., 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, 1916.

Abdel-Rahman, H.G., Alian, H.A., Mahmoud, M., 2022. Impacts of dietary supplementation with nano-iron and methionine on growth, blood chemistry, liver biomarkers, and tissue histology of heat-stressed broiler chickens. *Tropical Animal Health and Production* 54, 126.

Abdelwahab, S.I., Taha, M.M.E., Moni, S.S., Alsayegh, A.A., 2023. Bibliometric mapping of solid lipid nanoparticles research (2012–2022) using VOSviewer. *Medicine in Novel Technology and Devices* 17, 100217.

Adams, F., Ohene-Yankyera, K., 2014. Socio-economic characteristics of subsistent small ruminant farmers in three regions of northern Ghana. *Asian Journal of Applied Science and Engineering* 3, 351-364.

Adams, F., Ohene-Yankyera, K., Aidoo, R., Wongnaa, C.A., 2021. Economic benefits of livestock management in Ghana. *Agricultural and Food Economics* 9, 1-17.

Alagawany, M., Abd El-Hack, M.E., 2021. Natural feed additives used in the poultry industry. Bentham Science Publishers, Singapore.

Alijani, K., Rezaei, J., Rouzbehan, Y., 2020. Effect of nano-ZnO, compared to ZnO and Zn-methionine, on performance, nutrient status, rumen fermentation, blood enzymes, ferric reducing antioxidant power and immunoglobulin G in sheep. *Animal Feed Science and Technology* 267, 114532.

Alhashmi Alamer, F.A., Beyari, R.F., 2022. Overview of the influence of silver, gold, and titanium nanoparticles on the physical properties of PEDOT: PSS-coated cotton fabrics. *Nanomaterials* 12, 1609.

Ali, M., El-Sheikh, H.A., Ahmed, B., Nayel, U., 2023. Efficiency of nano zinc supplementation on growth performance, digestibility, rumen parameters, blood biochemistry and immunity status of Barki sheep. *Menoufia Journal of Animal and Poultry and Fish Production* 7, 37-46.

Almeida, C.F., Faria, M., Carvalho, J., Pinho, E., 2024. Contribution of nanotechnology to greater efficiency in animal nutrition and production. *Journal of Animal Physiology and Animal Nutrition* 108, 1430-1452.

Bąkowski, M., Kiczorowska, B., Samolińska, W., Klebaniuk, R., Lipiec, A., 2018. Silver and zinc nanoparticles in animal nutrition – a review. *Annals of Animal Science* 18, 879-898.

Bhagat, S., Singh, S., 2022. Nanominerals in nutrition: recent developments, present burning issues and future perspectives. *Food Research International* 160, 111703.

Bunglavan, S.J., Garg, A.K., Dass, R.S., Shrivastava, S., 2014. Use of nanoparticles as feed additives to improve digestion and absorption in livestock. *Livestock Research International* 2, 36-47.

Chen, J., Wei, W., ZhiSheng, W., 2011. Effect of nano-zinc oxide supplementation on rumen fermentation in vitro. *Chinese Journal of Animal Nutrition* 23, 1415-1421.

Cheng, B., 2006. Using social network analyses to investigate potential bias in editorial peer review in core journals of comparative/international education. Ph.D. dissertation, Brigham Young University, Provo, UT, USA.

Corbo, C., Molinaro, R., Parodi, A., Toledano Furman, N.E., Salvatore, F., Tasciotti, E., 2016. The impact of nanoparticle protein corona on cytotoxicity, immunotoxicity and target drug delivery. *Nanomedicine* 11, 81-100.

De Silva, C., Nawawi, N.M., Abd Karim, M.M., Abd Gani, S., Masarudin, M.J., Gunasekaran, B., Ahmad, S.A., 2021. The mechanistic action of biosynthesised silver nanoparticles and its application in aquaculture and livestock industries. *Animals* 11, 2097.

Dubey, M., Singh, V., Pandey, R.K., Chaubey, A.K., 2017. Effect of feed additives on nutrient intake and feed efficiency of lactating crossbred cows. *International Journal of Current Microbiology and Applied Sciences*. 6(2), 752-758.

Ducournau, C., Moiré, N., Carpentier, R., Cantin, P., Herkt, C., Lantier, I., Dimier-Poisson, I., 2020. Effective nanoparticle-based nasal vaccine against latent and congenital toxoplasmosis in sheep. *Frontiers in Immunology* 11, 2183.

Dumlu, B., 2024. Importance of nano-sized feed additives in animal nutrition. *Journal of Agricultural Production* 5, 55-72.

El-Nile, A., Elazab, M., El-Zaiat, H., El-Azrak, K.E.D., Elkomy, A., Sallam, S., Soltan, Y., 2021. In vitro and in vivo assessment of dietary supplementation of both natural or nano-zeolite in goat diets: effects on ruminal fermentation and nutrients digestibility. *Animals* 11, 2215.

El Sabry, M.I., McMillin, K.W., Sabliov, C.M., 2018. Nanotechnology considerations for poultry and livestock production systems – a review. *Annals of Animal Science* 18, 319.

El Sabry, M.I., Stino, F.K., El-Ghany, W.A.A., 2021. Copper: benefits and risks for poultry, livestock, and fish production. *Tropical Animal Health and Production* 53, 487.

Favaro-Trindade, C.S., de Matos Junior, F.E., Okuro, P.K., Dias-Ferreira, J., Cano, A., Severino, P., Zielińska, A., Souto, E.B., 2021. Encapsulation of Active Pharmaceutical Ingredients in Lipid Micro/Nanoparticles for Oral Administration by Spray-Cooling. *Pharmaceutics* 13, 1186.

Ferrari, L., Cattaneo, D.M., Abbate, R., Manoni, M., Ottoboni, M., Luciano, A., Pinotti, L., 2023. Advances in selenium supplementation: from selenium-enriched yeast to potential selenium-enriched insects, and selenium nanoparticles. *Animal Nutrition* 14, 193-203.

Geetha, K., Chellapandian, M., Arulnathan, N., Ramanathan, A., 2020. Nano zinc oxide – an alternate zinc supplement for livestock. *Veterinary World* 13, 121.

Gelaye, Y., 2024. Application of nanotechnology in animal nutrition: bibliographic review. *Animal Husbandry and Veterinary Science* 10, 2290308.

Ghassemi Nejad, J., Vakili, R., Sobhani, E., Sangari, M., Mokhtarpour, A., Hosseini Ghafari, S.A., 2023. Worldwide research trends for chelates in animal science: a bibliometric analysis. *Animals* 13, 2374.

Gorniak, W., Popiela, E., Szuba-Trznadel, A., Konkol, D., Korczyński, M., 2022. Smart feed additives for livestock. In: Chojnacka, K., Saeid, A. (Eds), smart agrochemicals for sustainable agriculture, Vol. 5. Academic press, New York, pp. 103-138.

Hashem, N.M., Gonzalez-Bulnes, A., 2021. Nanotechnology and reproductive management of farm animals: challenges and advances. *Animals* 11, 1932.

Hassan, Y.I., Lahaye, L., Gong, M.M., Peng, J., Gong, J., Liu, S., Gay, C.G., Yang, C., 2018. Innovative drugs, chemicals, and enzymes within the animal production chain. *Veterinary Research* 49, 71.

Hatab, M.H., Rashad, E., Saleh, H.M., El-Sayed, E.R., Abu Taleb, A.M., 2022. Effects of dietary supplementation of myco-fabricated zinc oxide nanoparticles on performance, histological changes, and tissues Zn concentration in broiler chicks. *Scientific Reports* 12, 18791.

Hosseini-Vardanjani, S.F., Rezaei, J., Karimi-Dehkordi, S., Rouzbehan, Y., 2020. Effect of feeding nano-ZnO on performance, rumen fermentation, leukocytes, antioxidant capacity, blood serum enzymes and minerals of ewes. *Small Ruminant Research* 191, 106170.

Hussain, S.M., Naeem, E., Ali, S., Adrees, M., Riaz, D., Paray, B.A., Naeem, A., 2023. Evaluation of growth, nutrient absorption, body composition and blood indices under dietary exposure of iron oxide nanoparticles in common carp (Cyprinus carpio). *Journal of Animal Physiology and Animal Nutrition* 108, 366-373.

Ibrahim, E.M., Mohamed, M.Y., 2018. Effect of different dietary selenium sources supplementation on nutrient digestibility, productive performance and some serum biochemical indices in sheep. *Egyptian Journal of Nutrition and Feeds* 21, 53-64.

Idamokoro, E.M., Hosu, Y.S., 2022. Global research trends on the use of nanotechnology to boost meat production: a scientometric analysis. *Frontiers in Research Metrics and Analytics* 6, 793853.

Joy, A., Dunshea, F.R., Leury, B.J., Clarke, I.J., Digiacomo, K., Chauhan, S.S., 2020. Resilience of small ruminant to climate change and increased environmental temperature: a review. *Animals* 10, 867.

Kachuee, R., Abdi-Benemar, H., Mansoori, Y., Sánchez-Aparicio, P., Seifdavati, J., Elghandour, M.M., Salem, A.Z., 2019. Effects of sodium selenite, L-selenomethionine, and selenium nanoparticles during late pregnancy on selenium, zinc, copper, and iron concentrations in Khalkhali goats and their kids. *Biological Trace Element Research* 191, 389-402.

Khan, S., Hossain, M.K., 2022. Classification and properties of nanoparticles. In: Rangappa, S.M., Parameswaranpillai, J., Seydibeyoglu, M.O. (Eds), Nanoparticle-based polymer composites, pp. 15-54.

Kojouri, G.A., Arbabi, F., Mohebbi, A., 2020. The effects of selenium nanoparticles (SeNPs) on oxidant and antioxidant activities and neonatal lamb weight gain pattern. *Comparative Clinical Pathology* 29, 369-374.

Kojouri, G.A., Jahanabadi, S., Shakibaie, M., Ahadi, A.M., Shahverdi, A.R., 2012. Effect of selenium supplementation with sodium selenite and selenium nanoparticles on iron homeostasis and transferrin gene expression in sheep: a preliminary study. *Research in Veterinary Science* 93, 275-278.

Kuzma, J., 2010. Nanotechnology in animal production—upstream assessment of applications. *Livestock Science* 130, 14-24.

Lebbie, S.H.B., 2004. Goats under household conditions. *Small Ruminant Research* 51, 131-136.

Lhermie, G., Pica-Ciamarra, U., Newman, S., Raboisson, D., Waret-Szkuta, A., 2022. Impact of peste des petits ruminants for sub-Saharan African farmers: a bioeconomic household production model. *Transboundary and Emerging Diseases* 69, 185-193.

Luo, X., Li, J., Guo, S., Yu, H., Zeng, X., Zhou, Z., Shangguan, Y., He, M., Ouyang, Y., Chen, K., Chen, Z., Qin, Y., 2025. Analysis of research status and trends on nano-agricultural application: a bibliometric study. *Frontiers in Plant Science* 16, 1530629.

Malyugina, S., Skalickova, S., Skladanka, J., Slama, P., Horky, P., 2021. Biogenic selenium nanoparticles in animal nutrition: a review. *Agriculture* 11, 1244.

Matuszewski, A., Łukasiewicz, M., Niemiec, J., 2020. Calcium and phosphorus and their nanoparticle forms in poultry nutrition. *World's Poultry Science Journal* 76, 328-345.

Mehrazar, E., Rahaie, M., Rahaie, S., 2015. Application of nanoparticles for pesticides, herbicides, fertilisers and animals feed management. *International Journal of Nanoparticles* 8, 1-19.

Mekonnen, G., 2021. Review on application of nanotechnology in animal health and production. *Journal of Nanomedicine & Nanotechnology* 12, 559.

Michalak, I., Dziergowska, K., Alagawany, M., Farag, M.R., El-Shall, N.A., Tuli, H.S., Dhama, K., 2022. The effect of metal-containing nanoparticles on the health, performance and production of livestock animals and poultry. *Veterinary Quarterly* 42, 68-94.

Mohamed, A., Mohamed, M., Abd-El-Ghany, F., Mahgoup, A., 2015. Influence of some trace minerals in form of nanoparticles as feed additives on lambs' performance. *Journal of Animal and Poultry Production* 6, 693-703.

Mohamed, M.Y., Ibrahim, E.M.M., Abd El-Mola, A.M., 2017. Effect of selenium yeast and/or vitamin E supplemented rations on some physiological responses of post-lambing Ossimi ewes under two different housing systems. *Egyptian Journal of Nutrition and Feeds* 20, 361-378.

Mohd Yusof, H., Mohamad, R., Zaidan, U.H., Abdul Rahman, N.A., 2019. Microbial synthesis of zinc oxide nanoparticles and their potential application as an antimicrobial agent and a feed supplement in animal industry: a review. *Journal of Animal Science and Biotechnology* 10, 57.

Nuvey, F.S., Nortey, P.A., Addo, K.K., Addo-Lartey, A., Kreppel, K., Houngbedji, C.A., Dzansi, G., Bonfoh, B., 2022a. Farm-related determinants of food insecurity among livestock dependent households in two agrarian districts with varying rainfall patterns in Ghana. *Frontiers in Sustainable Food Systems* 6, 743600.

Nuvey, F.S., Arkoazi, J., Hattendorf, J., Mensah, G.I., Addo, K.K., Fink, G., Zinsstag, J., Bonfoh, B., 2022b. Effectiveness and profitability of preventive veterinary interventions in controlling infectious diseases of ruminant livestock in sub-Saharan Africa: a scoping review. *BMC Veterinary Research* 18, 332.

Pieszka, M., Bederska-Łojewska, D., Szczurek, P., Pieszka, M., 2019. The membrane interactions of nano-silica and its potential application in animal nutrition. *Animals* 9, 1041.

Placha, I., Gai, F., Simonová, M.P., 2022a. Editorial: Natural feed additives in animal nutrition-Their potential as functional feed. *Frontiers in Veterinary Science* 9, 1062724.

Placha, I., Simonová, M.P., Lauková, A., 2022b. Natural feed additives and novel approaches for healthy rabbit breeding. *Animals* 12, 2111.

Ramachandraiah, K., Choi, M.J., Hong, G.P., 2018. Micro- and nano-scaled materials for strategy-based applications in innovative livestock products: a review. *Trends in Food Science & Technology* 71, 25-35.

Raje, K., Ojha, S., Mishra, A., Munde, V.K., Rawat, C., Chaudhary, S.K., 2018. Impact of supplementation of mineral nanoparticles on growth performance and health status of animals: a review. *Journal of Entomology and Zoology Studies* 6, 1690-1694.

Rajendran, D., Thulasi, A., Jash, S., Selvaraju, S., Rao, S.B.N., 2013. Synthesis and application of nano

minerals in livestock industry. In: animal nutrition and reproductive physiology (recent concepts). Satish serial publishing house, Delhi, pp. 517-530.

Riazi, H., Rezaei, J., Rouzbehan, Y., 2019. Effects of supplementary nano-ZnO on in vitro ruminal fermentation, methane release, antioxidants, and microbial biomass. *Turkish Journal of Veterinary and Animal Sciences* 43, 737-746.

Romero-Pérez, A., García-García, E., Zavaleta-Mancera, A., Ramírez-Bribiesca, J.E., Revilla-Vázquez, A., Hernández-Calva, L.M., Cruz-Monterrosa, R.G., 2010. Designing and evaluation of sodium selenite nanoparticles in vitro to improve selenium absorption in ruminants. *Veterinary Research Communications* 34, 71-79.

Sadeghian, S., Kojouri, G.A., Mohebbi, A., 2012. Nanoparticles of selenium as species with stronger physiological effects in sheep in comparison with sodium selenite. *Biological Trace Element Research* 146, 302-308.

Sarker, N.C., Keomanivong, F., Borhan, M.D., Rahman, S., Swanson, K., 2018. In vitro evaluation of nano zinc oxide (nZnO) on mitigation of gaseous emissions. *Journal of Animal Science and Technology* 60, 27.

Scott, A., Vadalasetty, K.P., Chwalibog, A., Sawosz, E., 2018. Copper nanoparticles as an alternative feed additive in poultry diet: a review. *Nanotechnology Reviews* 7, 69-93.

Sharif, M., Rahman, M.A., Ahmed, B., Abbas, R.Z., Hassan, F., 2021. Copper nanoparticles as growth promoter, antioxidant and anti-bacterial agents in poultry nutrition: prospects and future implications. *Biological Trace Element Research* 199, 3825-3836.

Shi, L., Xun, W., Yue, W., Zhang, C., Ren, Y., Liu, Q., Shi, L., 2011a. Effect of elemental nano-selenium on feed digestibility, rumen fermentation, and purine derivatives in sheep. *Animal Feed Science and Technology* 163, 136-142.

Shi, L., Xun, W., Yue, W., Zhang, C., Ren, Y., Shi, L., Wang, Q., Yang, R., Lei, F., 2011b. Effect of sodium selenite, Se-yeast and nanoelemental selenium on growth performance, Se concentration and antioxidant status in growing male goats. *Small Ruminant Research* 96, 49-52.

Soltan, Y., Morsy, A., Hashem, N., Elazab, M., Sultan, M., Marey, H., Sallam, S., 2021. Modified nano-montmorillonite and monensin modulate in vitro ruminal fermentation, nutrient degradability, and methanogenesis differently. *Animals* 11, 3005.

Swain, P.S., Rao, S.B., Rajendran, D., Dominic, G., Selvaraju, S., 2016. Nano zinc, an alternative to conventional zinc as animal feed supplement: a review. *Animal Nutrition* 2, 134-141.

Swain, P.S., Rao, S.B.N., Rajendran, D., Krishnamoorthy, P., Mondal, S., Pal, D., Selvaraju, S., 2021. Nano zinc supplementation in goat (Capra hircus) ration improves immunity, serum zinc profile and IGF-1 hormones without affecting thyroid hormones. *Journal of Animal Physiology and Animal Nutrition* 105, 621-629.

Teshome, D., Sori, T., 2021. Contagious caprine pleuropneumonia: a review. *Journal of Veterinary Medicine and Animal Health* 13, 132-143.

Tona, G.O., 2017. Current and future improvements in livestock nutrition and feed resources. In: Yücel, B., Taşkin, T. (Eds.), animal husbandry and nutrition, pp. 147-169.

Tripathi, M., Kumar, S., Sonker, S.K., Babbar, P., 2018. Occurrence of author keywords and keywords plus in social sciences and humanities research: a preliminary study. COLLNET *Journal of Scientometrics and Information Management* 12, 215-232.

Thulasi, A., Rajendran, D., Jash, S., Selvaraju, S., Jose, V.L., Velusamy, S., Mathivanan, S., 2013. Nanobiotechnology in animal nutrition. In: animal nutrition and reproductive physiology (recent concepts), pp. 499-516.

Zhang, J., Yu, Q., Zheng, F., Long, C., Lu, Z., Duan, Z., 2016. Comparing keywords plus of wos and author keywords: a case study of patient adherence research. *Journal of the Association for Information Science and Technology* 67, 967-972.