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Review Article

Sustainable helminth control in ruminants using plant secondary metabolites: A systematic and bibliometric review

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Abstract

Gastrointestinal helminthiasis continues to be one of the major constraints limiting the productivity of ruminant livestock throughout the world, especially in the tropics and subtropics, leading to economic and welfare impacts. Frequent use of commercial anthelmintics has increased cases of drug resistance, raising fears about adverse effects on the environment and contamination of animal-based products. Plant secondary metabolites (PSMs) have increasingly emerged as an environmentally friendly alternative for controlling helminths. In this study, bibliometrics was combined with a systematic review conducted following the PRISMA protocol to assess the global research dynamics and anthelmintic activity of PSMs on ruminants. In total, 176 publications from 2015 to 2025 underwent bibliometric analysis, whereas 117 eligible publications were considered for the systematic review. The findings indicate that there is a positive trend towards publication volume with a peak in 2019 and then stabilisation in subsequent years. The keyword analysis indicated that three main thematic areas exist: parasitology and field studies, bioactivity assessment, and phytochemistry. The results indicate that PSMs possess considerable anthelmintic potential via various pathways, such as the interference with the parasite, inhibition of egg hatching, larval development, and host-parasite interaction. Nevertheless, an evident discrepancy between in vitro experiments and in vivo/field trials has been highlighted, emphasizing an essential limitation of transferring the experimental results into practice. Therefore, the current work presents a valuable compilation of global research trends and knowledge gaps, underlining the necessity for a standardized approach, as well as in vivo/field validation, which would facilitate sustainable management of helminths using plant resources.

Keywords: Gastrointestinal nematodes, Ruminants, Plant secondary metabolites, Anthelmintic activity, Sustainable parasite control, Anthelmintic resistance

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Introduction

Parasitism continues to be one of the biggest parasitological threats to ruminant livestock production globally. Helminths like *Haemonchus contortus, Trichostrongylus* spp., and *Ostertagia ostertagi* lead to economic losses due to reduced growth rate, low milk production, poor fertility, and, in some instances, death (Nolinda et al., 2024; Rehman and Abidi, 2022; Salem et al., 2025; Strydom et al., 2023). The estimated global cost attributed to GINs is billions of US dollars per year and mainly affects small-scale farmers and extensive grazing farms operating under tropical and subtropical environments (Ma et al., 2025; Strydom et al., 2023). In addition to its adverse effects on livestock production, helminthiasis also harms animal welfare and the sustainability of livestock farming ((Podpečan et al., 2023). Besides, anthelmintic resistance is increasingly becoming prevalent, making parasite management difficult (Fissiha and Kinde, 2021; Kapo et al., 2022).

Over many years, the use of chemical anthelmintics has been the mainstay of helminth management in ruminants. Unfortunately, this has resulted in the fast development of resistance against anthelmintics that are now prevalent among various groups of drugs, such as benzimidazoles, imidazothiazoles, and macrocyclic lactones (Fissiha and Kinde, 2021; Kaplan and Vidyashankar, 2012; Sauermann et al., 2024). This problem is more pronounced in small ruminants but is also emerging in cattle (Borges et al., 2024; Ehnert et al., 2025; Kelleher et al., 2020). Moreover, the issue of drug residues in meat and milk, environmental pollution, and consumer desire for free-from drug livestock products has encouraged looking for other options.

Plant secondary metabolites (PSMs) have recently gained recognition as a potential means for sustainable parasite control. The biological properties of PSMs include condensed tannins, saponins, flavonoids, alkaloids, phenols, and essential oils that affect various biological functions, such as direct anthelmintic activity by affecting parasites' development and indirect host immunity modulation (Rodríguez-Hernández et al., 2023). These molecules are natural, biodegradable, and may be incorporated in feed systems using forage materials, extracts from plants, or feed supplements. The use of PSMs in IPM strategies may aid in the reduction of dependence on pharmaceuticals and promote the well-being of livestock (Hoste et al., 2022; Rodríguez-Hernández et al., 2023).

There is a considerable extensive of studies suggesting that plant secondary metabolites (PSMs), especially condensed tannins, can be used to enhance the resistance of animals to parasitic diseases (Mueller-Harvey et al., 2019; Rodríguez-Hernández et al., 2023). In addition, the study of the relationship between different PSMs and their implementation into grazing management practices and animal nutrition is becoming increasingly popular (Bricarello et al., 2023; Charlier et al., 2024). Nevertheless, due to the diversity of scientific areas where these aspects are being studied, the current research lacks a comprehensive analysis of trends in the field (Ahmed et al., 2023).

Bibliometric analysis provides a strong tool for charting the development, structure, and limitations within the body of knowledge of any scientific field. Through the use of statistical measures to analyze publication trends, important scholars and organizations, collaborations, and themes, bibliometrics provides a scientific perspective on how the field developed and potential directions for future study (Donthu et al., 2021). In spite of the rise in the number of studies on PSM in helminth management in ruminants, no bibliometric analysis has ever been carried out in the past 20 years.

Currently, most reviews have tended to focus on providing a summary of the biological activities and mechanisms of PSMs among various plant species or groups of compounds and regions (Ahmed et al., 2023; Rodríguez-Hernández et al., 2023). Nevertheless, there is a dearth of studies that provide an overall review of the current state of science regarding the PSMs used for controlling helminths in ruminants through mapping their scientific knowledge structures and identifying the research trends. The use of bibliometric methods presents a chance to fill this gap and provide the needed information on research trends, collaboration networks, and emerging themes in the field under discussion. As such, this study presents a bibliometric review of the global scientific literature on the PSMs used for controlling helminths in ruminants during the period 2004 to 2023 using VOSViewer. Therefore, the purpose of the present study is to conduct a bibliometric analysis of the literature pertaining to the use of PSMs for control of helminths in ruminants during the past two decades. Such an analysis would include examination of publication trends per year, leading countries, institutes, and authors, as well as highly cited articles and clusters of themes, among others. Not only will such an analysis contribute towards strengthening the current knowledge base, but it will also provide insights into potential directions of future research and policy formulation in this field.

Material and Methods

Data source and literature retrieval
The source material for the bibliography that was used in this study was obtained from the Scopus database. Scopus is among the largest sources of peer-reviewed literature on scientific topics available today. Scopus was chosen because of its wide coverage across scientific fields and the high quality of its indexing of scientific literature. The use of a single source database also ensures the consistency of data. A search of the literature was carried out in the month of January 2026, and only articles published between 2015 and 2025 were chosen for this study, as it would help to identify the recent advancements in research regarding the possible anthelmintic action of secondary metabolites in plants against ruminants. Articles in languages other than English, research papers, and review articles were included in the search process.

Search strategy
A systematic search of the literature was performed using key terms associated with tannins, anthelmintic effects, and ruminants. The search was done using the TITLE-ABS-KEY search query on the Scopus database. The search query is: TITLE-ABS-KEY ("condensed tannins" OR tannin) AND TITLE-ABS-KEY (anthelmintic OR helminth OR nematode OR "*H. contortus*") AND TITLE-ABS-KEY (ruminant OR sheep OR goat OR cattle). In order to make sure that the literature was relevant and up-to-date, the search was restricted to papers published between 2015 and 2025.

In the present study, the systematic review methodology was used in accordance with the principles outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The PRISMA framework acted as a guide for the identification, screening, selection, and inclusion of the articles that were pertinent to the use of tannin-based compounds for the management of parasites in ruminants. The process of systematic review involved four principal steps, which included the identification of the record from the database, duplication of the record, title and abstract screening, and eligibility assessment of the full text.

Bibliometric analysis
The subsequent analysis was carried out using bibliometric methods in order to investigate the research field and identify key trends in scientific papers dealing with secondary metabolites in plants with anthelmintic activity. Data was collected via Scopus database and exported in CSV format for bibliometric analysis using VOSviewer version 1.6.20. Software VOSviewer was used to create and visualize bibliometric maps based on keyword co-occurrences and clusters in order to identify popular research areas and ideas in the literature base. This process included analyzing author keywords extracted from all database entries comprising 176 papers. A criterion of keyword frequency of at least 10 appearances was used, which resulted in 71 keywords being analyzed. The creation of the visualization map involved keyword co-occurrences where node size represents keyword frequency, whereas link thickness represents the relationship intensity between keywords. Clusters were created using an internal clustering function offered by VOSviewer software, where keywords can be grouped into various themes. A thesaurus file was applied in VOSviewer.

Systematic review procedure (PRISMA)
Inclusion of studies in this review adhered to PRISMA standards. In the first round, all the articles obtained from the search of the databases were screened by title and abstract according to their eligibility for the use of tannins as anthelmintics in the control of parasites in ruminants. Those that did not fulfil the set inclusion criteria were omitted at this point. The rest of the articles were further subjected to full-text assessment according to some predetermined criteria, such as relevance to the topic under discussion. The screening process adopted is demonstrated in Figure 1 below.

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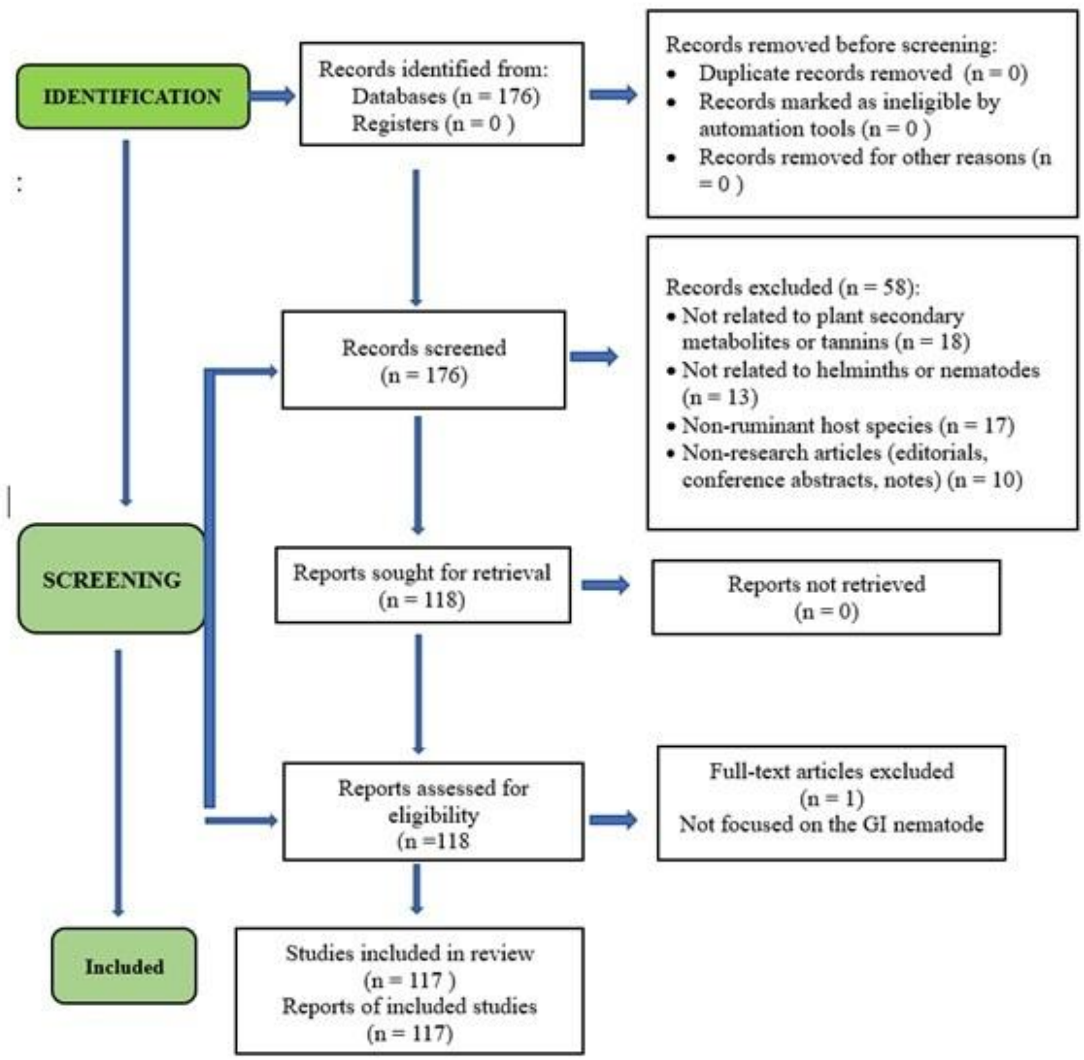

Figure-1. PRISMA flow diagram illustrating the literature selection process for studies included in the systematic review.

Data extraction
Bibliographic data pertinent to the studies identified were collected for both qualitative and bibliometric analysis. Data collected included: authors' names, year of publication, title of the article, keywords, number of citations, affiliation of the author(s), and references. The collected data were then exported to an Excel spreadsheet using Scopus.

Bibliometric analysis
The bibliometric analysis was conducted on the entire dataset retrieved from the Scopus database after applying the publication-year filter. In contrast, the systematic review involved further screening of titles and abstracts to identify studies specifically related to tannin-based anthelmintic applications in ruminants. A thesaurus file was applied in VOSviewer to standardise terminology, merge synonymous keywords (e.g., singular and plural forms), and exclude non-informative terms in order to improve the clarity of the network visualisation. The minimum occurrence threshold for keywords was determined to identify the most relevant terms for network visualisation.
Several types of bibliometric analyses were performed, including: annual publication trends, to assess the development of research on tannin-based

anthelmintics over time, keyword co-occurrence analysis, to identify major research themes and clusters within the literature, co-authorship networks, to explore collaboration patterns among researchers, country collaboration analysis, to identify leading countries contributing to this research field, citation analysis, to identify influential studies and authors.

The keyword co-occurrence analysis was used to generate network visualisations, in which nodes represent keywords and links indicate their co-occurrence relationships in the literature. Clusters identified in the network represent major thematic areas in tannin-based anthelmintic research.

Results

The bibliometric study gives a general picture of the scientific research field of secondary metabolites from plants that could have potential anthelmintic properties for controlling helminths in ruminants. This study analyses various elements of this field, such as the number of publications in this field, the most active countries, the most productive authors, collaborations between scientists in this field, and the thematic structure of this scientific research. All this information helps understand the development of scientific work in this field and scientific trends.

Publication trend per year

Bibliometric analysis based on publications obtained from Scopus for the period 2015 to 2025 there is a positive trend in relation to studies regarding secondary metabolites extracted from plants for helminthic treatment in ruminants, albeit with slight variations over time (Figure 2). This can be observed through the increased number of publications throughout the early years of the period being discussed, reaching a peak during 2019.

It is important to note that an initial rise in the production rate of publications from 2015 through 2018 can be explained by an increased interest in plant secondary metabolites as new sources of anthelmintic treatment for animals. In this period, most studies were conducted as in vitro screens of the influence of plant extracts on various stages of development of the gastrointestinal nematodes, which included egg hatching inhibition, larval development, and larvae exsheathment (Castañeda-Ramírez et al., 2017; Oliveira et al., 2022; Zabré et al., 2017). As a rule, researchers have tried to determine the effectiveness of certain phenolic compounds as natural anthelmintics (Hajaji et al., 2018).

The peak seen in about 2019 may be linked to the increasing availability of data from experiments and studies on the bioactivity and modes of action of secondary metabolites of plants. It was characterized by many studies conducted in vitro using parasite life cycle stages, while in vivo studies have been growing in number along with nutritional approaches using tannin-rich forages and feed supplements from plants to control parasites (Kadigi et al., 2024).

A different pattern can be seen in studies published after 2020. The focus is no longer limited to laboratory-based screening, although in vitro work is still frequently used. In many cases, it is combined with phytochemical profiling and occasional mechanistic observations, with attempts to better approximate field conditions, particularly in relation to ongoing anthelmintic resistance. At the same time, more studies begin to include in vivo elements, such as feeding trials, to examine how plant-derived compounds perform under practical production settings. These approaches are mainly directed at understanding their effects on animal health, physiological responses, and overall productivity (Nolinda et al., 2024; Rehman and Abidi, 2022).

Nevertheless, regardless of the progress noted above, studies conducted during this period have shown that there remain difficulties in moving from in vitro efficacy to real-world success in the field. Specifically, some researchers indicate that the results produced by certain studies related to the use of plants against parasites might not always be consistent or applicable in real-world scenarios, in addition to possible conflicts between antiparasitic efficiency and the performance of animals (Bordes et al., 2024; Shepherd et al., 2024).

The marginal drop in the number of publications during the last two years (2024-2025) should not raise any concerns, as it is probably caused by the partial coverage of recently published articles in indexing systems rather than any reduction in the research work. As for the general tendency, it can be regarded as an example of the development and evolution of this sphere of science in the direction of practical integration and sustainability.

Taken collectively, these temporal patterns reveal not only the development in methodologies for research, but also a change in the geographic location and collaborative practices of science, as discussed further below.

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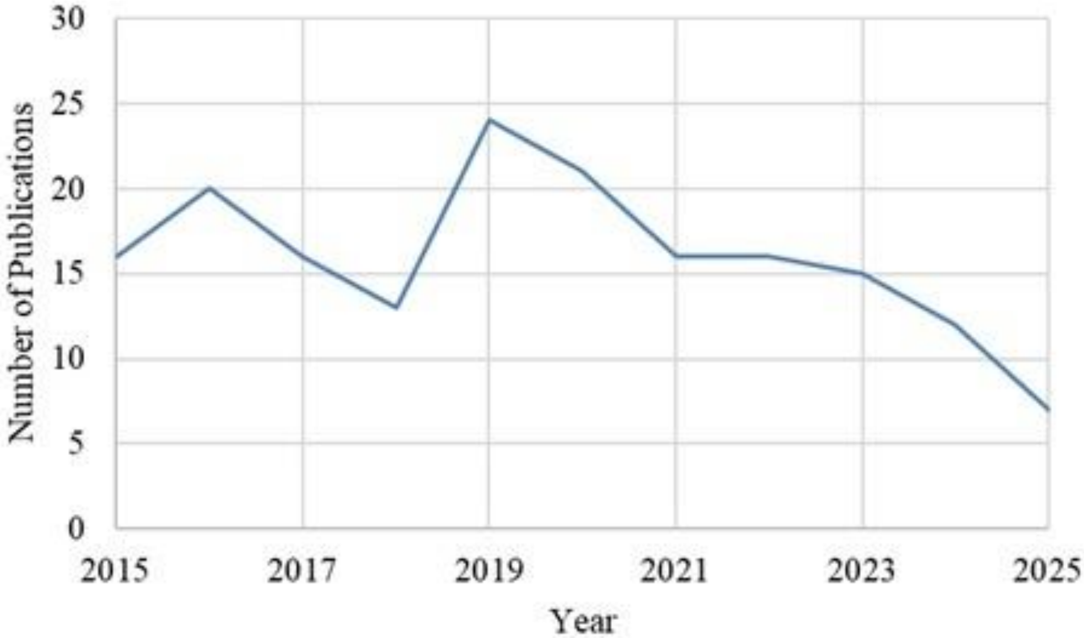

Figure-2. Annual publication trend of research on plant-derived secondary metabolites for helminth control in ruminants (2015–2025).

Leading countries/authors

Based on the temporal patterns observed, the bibliometric analysis also provides additional information about the geographical and institutional distribution of scientific activity in the field. In addition to the temporal trends associated with publications, the bibliometric analysis also offers information regarding the geographical and institutional distribution of research on secondary metabolites obtained from plants for helminth control in ruminants. As shown in the international collaboration network (Figure 3), research activity is spread around different regions, and there are some countries acting as hubs in the global network. Notably, some countries, like Mexico, the USA, and France, act as central nodes. Indeed, many studies performed in Mexico have provided extensive information on the use of plants rich in tannins as well as ethnoveterinary practices for the management of gastrointestinal nematodes in ruminants (e.g., (Olmedo-Juárez et al., 2017). Likewise, research work in the USA has mainly addressed the integration of plant-based metabolites within feeding programs and evaluated their potential impact on parasite control and animal performance (Min et al., 2019). On the other hand, French research efforts have been essential for comprehending the importance of secondary metabolites in sustainable parasite management and their interaction with grazing systems (e.g., (Hoste et al., 2015). The broad distribution of the number of publications among different regions points to the international significance of studies aimed at developing sustainable parasite control mechanisms. This is explained by the prevalence of gastrointestinal helminth infections that influence the performance of livestock in terms of meat productivity. It can be supposed that more research was conducted in the regions where livestock is influenced by infections with gastrointestinal nematodes, which makes its production lower in tropical and subtropical environments due to the favourable conditions for parasites' transmission. The wide use of anthelmintics in such countries results in the rapid development of resistance to drugs, which increases interest in studying plant extracts with bioactive properties. As can be seen in Figure 3, the intensity of links among countries suggests their high involvement in the process of collaboration.

While the geographical distribution of research highlights where scientific activity is concentrated, it does not fully capture the field's thematic structure. Therefore, a keyword co-occurrence analysis was conducted to identify the main research themes and emerging topics.

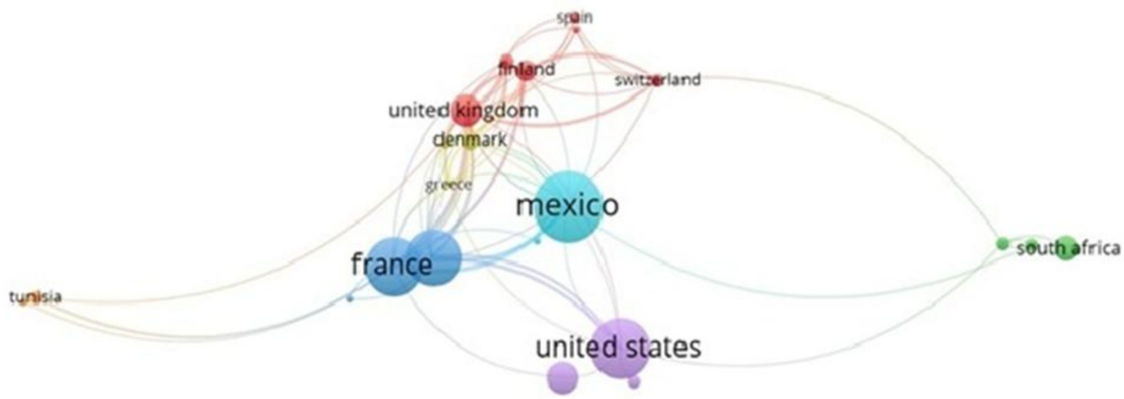

Figure-3. An international collaboration network of countries publishing research on plant-derived secondary metabolites for helminth control in ruminants (VOSviewer).

Keyword co-occurrence analysis

To further explore the intellectual structure of the research field, a keyword co-occurrence analysis was performed using VOSviewer. This approach allows the identification of major thematic clusters and provides insights into how different research areas are interconnected.

Keyword co-occurrence analysis was conducted using VOSviewer to identify the main thematic structures in the literature on plant secondary metabolites for helminth control in ruminants. The analysis was based on 176 articles published between 2015 and 2025 retrieved from the Scopus database. Of these, 65 keywords met the minimum occurrence threshold and were included in the network visualisation. The resulting network map revealed three major clusters representing the dominant research themes in this field (Figure 4).

The first cluster (in red) can be linked mainly to parasitological and field-related topics. The following terms can be found in this group: sheep, goat, faeces, number of parasite eggs, nematode infection, and haemonchosis. This suggests that the analysis is heavily concentrated on the evaluation of infection processes, host-parasite relationships, and the efficacy of treatment procedures conducted in real-world situations. Diagnostic markers, like faecal egg counts, provide additional evidence that conventional parasitological techniques play an important role in parasite quantification.

The second cluster (green) is concerned with experimental and bioactivity-driven studies. The defining features of this grouping include such keywords as plant extract, anthelmintic activity, in vitro studies, and *H. contortus*, as well as phytochemicals, including alkaloid and saponin. It can be noted that the use of such keywords indicates the presence of considerable amounts of literature on the topic of laboratory screening for anthelmintic properties.

The third cluster (blue) relates to phytochemical investigation and chemical characterization. The keywords in this cluster include chemistry, proanthocyanidin, tannin derivative, and drug action. The third cluster captures the theme of research concerned with the chemical makeup of substances derived from plants as well as the biological processes involved in their functioning.

Overall, the network clearly depicts a strong association between studies of parasite infection in livestock and plant metabolites that have anthelmintic properties. The inclusion of the concepts ‘tannin’, ‘sheep’, ‘nematode’, and ‘anthelmintic activity’ in the central nodes confirms the fact that most studies involve assessing whether these plants can be an alternative source for anthelmintic drugs rather than traditional anthelmintic compounds.

Furthermore, this framework highlights the multidisciplinary approach involved in this field of study. The association between parasitology-related keywords, including ‘sheep’, ‘nematode’, and

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'parasite egg count', and plant metabolites-related keywords, such as 'tannin', 'alkaloid', and 'saponin', confirms the increasing convergence between parasitology and phytochemistry.

Furthermore, there is an evident correlation between the *H. contortus* and parasitology keywords, along with those used experimentally. This is expected as the nematode is famous for its economic impact as one of the costliest nematodes affecting small ruminants. In conclusion, the above-mentioned results are indicative of the validity of the idea to combine the research on plant-derived secondary metabolites with parasitology-related information to provide an empirical basis for the development of more environmentally sustainable approaches to controlling the parasites.

Conclusively, it is evident that the field of study experiences rapid shifts, with particular attention to bioactive substances derived from plants within experimental or laboratory settings. However, it should be noted that while being useful in highlighting tendencies and progress of topics, these innovations do not take into account the biological complexity and constraints associated with managing GINs of ruminants. Therefore, it is essential to understand the epidemiological and transmission dynamics of these parasites to highlight their significance in parasite control programs.

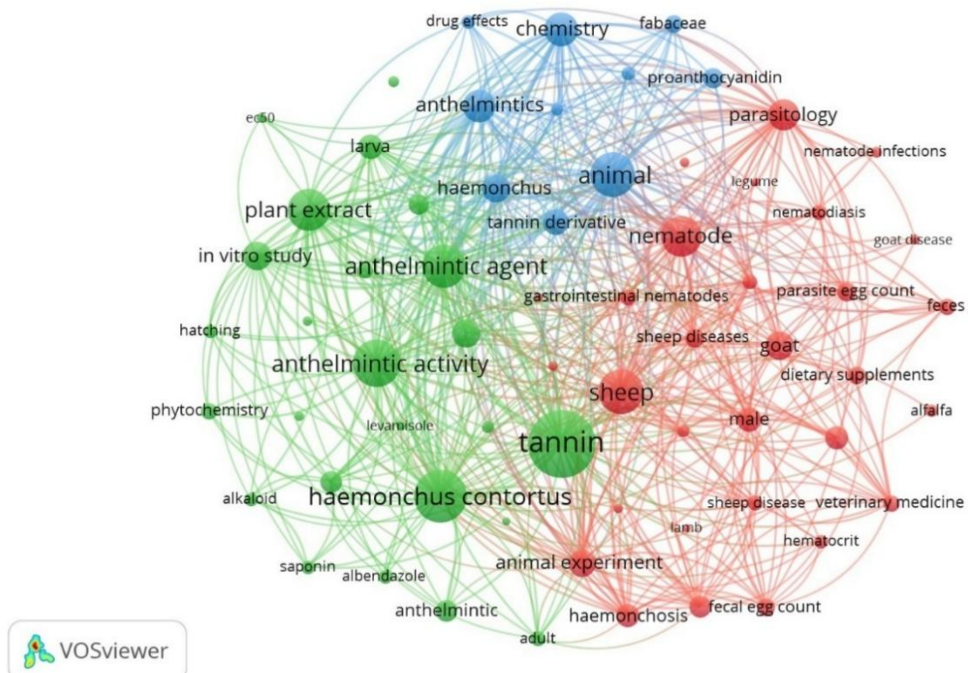

Figure-4. Keyword co-occurrence network illustrating thematic relationships among publications on plant secondary metabolites for helminth control in ruminants published between 2015 and 2025. Larger nodes indicate higher keyword occurrence frequencies, whereas connecting lines represent co-occurrence relationships between terms.

Epidemiology and control challenges of gastrointestinal nematodes in ruminants

GINs are considered among the most significant parasites in livestock, particularly ruminants, on an international scale. These parasites infect the abomasum and intestines of cattle, sheep, and goats, causing conditions such as parasitic gastroenteritis and other problems that result in economic losses for livestock grazing operations. Mixed infections by different types of nematodes are often observed in ruminants (Bricarello et al., 2023; Charlier et al., 2020).

The nematodes that cause economic damage among ruminants include *Haemonchus, Trichostrongylus, Ostertagia* (also known as Teladorsagia), Cooperia, and Nematodirus. All these nematodes are classified under the Trichostrongylidae family, which is home to

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many of the most common and pathogenic nematodes in grazing livestock around the world (Vineer et al., 2020).

Lifecycle and transmission dynamics

Life cycles for GI nematodes generally involve direct development with a parasitic phase in the host animal and a free-living phase outside the host in the environment. Eggs are excreted through feces and develop into infective third-stage larvae (L3), which invade pastures and become ingested by grazing livestock. This lifecycle allows for constant transmission in grazing environments where livestock come into contact with L3 nematodes on a consistent basis (Solomon et al., 2024; Taylor et al., 2016).

The parasites have been observed to include a particularly pathogenic nematode species named *H. contortus*, owing to its tendency to feed on blood and prolific reproduction rate. The parasite can lead to serious conditions such as anaemia, loss of productivity, and financial costs associated with treating the infections. These parasites have, therefore, been identified as among the major limiting factors in small ruminant farming systems globally (Ma et al., 2025).

Epidemiology and factors influencing infection

The epidemiology of gastrointestinal nematode infections in ruminants is influenced by the complex interplay of several environmental and biological factors. The interaction of these various factors affects the prevalence and transmission of the disease in grazing-based farming systems.

The environmental factors, such as temperature, humidity, and rainfall, significantly affect the growth and survival of the larvae outside the body. Warmer and humid climatic conditions positively impact the growth and survival of larvae and increase the chances of infection of the host animal. Therefore, seasonal variations of infection can be seen, where infection pressure is high in seasons when larvae develop optimally (Solomon et al., 2024).

Variations in infection intensity can also be attributed to host factors. Young animals tend to be more susceptible owing to their underdeveloped immunity, and poor nutrition is also capable of affecting host immunity against infection. Genetically, there exists variability between breeds, where some are more resistant to nematode infections than others (Cunha et al., 2024; Hayward, 2022; Onzima et al., 2017).

Management of livestock is also an important determinant of disease transmission dynamics. Grazing and overstocking may lead to contamination of pastures by infective larvae and thus promote transmission of infections through recurrent infections. However, enhanced methods of grazing, such as pasture rotation, have been recommended for reducing infection transmission (Malik et al., 2023; Taylor et al., 2016).

These epidemiological factors interacting together bring out the difficulties in managing gastrointestinal nematodes within ruminants. These include those factors that make continued transmission and re-infection easy, thus leading to the survival of parasites, and hence greater dependence on control methods and the increased chance of drug resistance.

Global distribution and economic impact

Gastrointestinal nematodes are commonly found within the ruminant farming enterprises in most parts of the world, and they are one of the key constraints for ruminant production. In various regions of the world, the worms lead to significant production losses due to lower growth rate, low milk yield, and inefficiency in utilizing their food sources. The worms are more common in grazing-based farming enterprises.

These parasites are known to include *H. contortus* as one of the economically significant parasites in sheep and goats all over the world. According to meta-analysis studies, the global prevalence rate of *H. contortus* infections in ruminants is predicted to be greater than 35% (Ma et al., 2025).

The costs associated with gastrointestinal nematode infestations are not limited to losses of production, but include those related to treatments and management of parasitism. Therefore, these infestations pose significant problems for the sustainable production of ruminants around the world.

Current control strategies and emerging anthelmintic resistance

Resistance to anthelmintics has emerged as one of the most pressing issues in controlling parasites in ruminants globally, with rising incidents reported among various types of nematodes (Rehman and Abidi, 2022; Vineer et al., 2020). Gastrointestinal nematode parasites have classically been controlled using chemotherapeutic agents like benzimidazoles, macrocyclic lactones, and levamisole. However, the over-reliance and extensive application of these drugs have resulted in an increasing number of parasite resistance (Mavundela et al., 2025).

Resistance is especially notable in *H. contortus*, which has become famous for being one of the most resistant parasitic nematodes of small ruminants. This growing resistance to common drugs makes the conventional methods of managing parasites increasingly ineffective (Beleckė et al., 2025; Burke and Miller, 2020).

This has led to increasing emphasis on the development of alternative parasitic control methods that would minimize the need for artificial drugs. Such methods include effective grazing techniques, selective treatments, selection of parasite-resistant breeds, and bioactive compounds from plants. The increasing difficulty of managing gastrointestinal worm infestations due to the rising instances of drug resistance has led to this paradigm shift in control methods.

Recent bibliometric data from the period of 2015 to 2025 also attest to this trend, showing that plant secondary metabolites remain among the most rapidly expanding topics in the field of helminth control. The keywords "tannin," "plant extract," and "*H. contortus*" appear together quite often in scientific literature. This shows that there is increasing scientific interest in the use of plants in the development of effective anthelmintic drugs. Plant-derived molecules like tannins, saponins, and alkaloids have received widespread attention because of their unique ability to inhibit parasitic infection while improving animal performance.

Plant secondary metabolites (PSMs): Classification and bioactivity

From the results gathered from the bibliometric trends and epidemiology of gastrointestinal nematode parasitism above, it has become clear that PSMs could be used in sustainable parasite management. While bibliometric analysis gives an insight into the growing trend of research in this field and the major themes involved, there must be adequate information regarding the nature, bioactivities, and modes of action of PSMs. After employing the PRISMA guideline for a comprehensive search of the available literature, a total of 117 studies has been included in the present study. From the results gathered from these sources, it becomes clear that the potential application of PSMs in managing gastrointestinal nematodes is. In conclusion, the results mentioned above validate the significance of the involvement of PSMs in current parasite control schemes and the potential application of these natural products as alternatives to synthetic anthelmintics.

Major classes of plant secondary metabolites with anthelmintic activity

Tannins, especially condensed tannins, remain some of the best-researched plant secondary metabolites for their anti-helminthic properties. These compounds exert their effect through the binding of proteins present in the cuticle of the nematodes and in the intestinal tract of parasites, preventing their nutrition and hindering their growth. As shown by PRISMA-based selected articles, tannin-containing plants, including Acacia, Leucaena, and Lotus species, have been found to display notable decreases in fecal egg count and larval growth. In addition, the presence of tannin can be seen in the co-occurrence network as one of the most cited and central keywords.

Apart from tannins, another significant category of compounds includes saponins, which hold anthelmintic potential. The glycosides affect parasite cell membranes directly, thus making the cell membranes more permeable and eventually killing the parasites. According to PRISMA-based findings, the larvacidal effects of plants rich in saponins have been observed, especially in vitro studies (Hoste et al., 2015). In terms of bibliometric analysis, saponins often coincide with the keywords plant extracts, in vitro experiments, and anthelmintic properties, emphasizing the significance of saponins in experimental screening investigations. Despite this fact, there is an inadequate number of publications related to saponins concerning in vivo experiments.

Another class of secondary metabolites in plants with pharmacological properties is alkaloids. The parasitic-paralyzing effect of these metabolites is usually ascribed to the disruption of neuromuscular communication in the parasites. Even though there have been promising results in the laboratory, there is some PRISMA evidence to suggest that the use of these compounds is limited because of their high toxicity and low safety margins (Katiki et al., 2017). Indeed, as demonstrated through bibliometric studies, alkaloids are not as common as tannins and saponins.

Flavonoids, which have been well-known due to their antioxidant, anti-inflammatory, and immunomodulatory properties, can be attributed to parasitic control because of several ways of action. First of all, their antiparasitic properties lie in enzyme inhibition and interference with the parasite's physiology. Second, flavonoids might increase the host's immunity and work together with other phytochemicals, which would improve their parasitic control performance (Ma et al., 2025). From a bibliometric point of view, flavonoids correlate with key terms related to the host's response and biological activity.

In the same way, essential oils containing terpenoids display wide-ranging antiparasitic properties, with the methods involved including cell membrane damage, disruption of parasitic movement, and disruption of energy metabolism. According to the PRISMA study results, plant essential oils, specifically those of Artemisia and Thymus, show considerable promise in terms of in vitro treatment. Nevertheless, the application of essential oils under practical settings is constrained by their unstable nature, volatility, and composition differences (Bricarello et al., 2023). The bibliometric analysis highlights that, despite increasing research interest, essential oils have primarily been linked to in vitro studies.

Insights from bibliometric and PRISMA analysis

The combination of bibliometric and systematic approaches reveals a general picture of trends in recent research in the area of helminth control through the use of plants. In terms of the bibliometric approach, the largest part of studies is devoted to the in vitro study owing to the closeness of the in vitro keyword and such key terms as plant extract and anthelmintic activity. This result is confirmed by the results obtained during the PRISMA study, since the number of papers dealing with in vitro studies constitutes a considerable share of the total number of 117 papers analyzed in the course of the work. The absence of large-scale in vivo and field studies serves as one of the major obstacles to the practical implementation of theoretical results.

Limitations and research gaps

Although there is a wealth of positive prospects associated with their use, there remain several significant problems that hinder the use of secondary metabolites in plants for helminth control. The first problem relates to the inconsistency of phytochemicals owing to changes in the environment and extraction procedures. Another challenge relates to the absence of standardisation in the extraction and dosing process. Finally, issues relating to safety and palatability may arise. A multi-disciplinary approach involving the study of phytochemistry, parasitology, and animal nutrition needs to be adopted to resolve these issues. Future research should therefore focus on formulating plant secondary metabolites for consistent dosing.

Anthelmintic efficacy of plant secondary metabolites

Anthelmintic activity of plant secondary metabolites (PSM) is an area widely researched through both in vitro and in vivo methods. From the systematic review following PRISMA guidelines, 117 papers selected indicate sufficient data backing the possibility of exploiting PSMs as a viable means of gastrointestinal nematode management in ruminants. Simultaneously, bibliometric analysis demonstrates that terms such as "in vitro", "plant extracts", and "anthelmintic activity" are highly associated, showing that efficacy assessment still constitutes the core of ongoing research. Nevertheless, study distribution shows a disparity in that the number of laboratory experiments far outweighs in vivo and field-based experiments (Kaplan and Vidyashankar, 2012; Vineer et al., 2020).

In vitro anthelmintic activity

In vitro testing methods are the most frequently utilized technique in evaluating the efficacy of PSMs against helminth parasites, based on the selected studies according to PRISMA criteria. Common methods are EHA (egg hatch assays) as well as LDA (larval development assays), providing a fast way to determine potential antiparasitic activity. The vast majority of selected studies have shown effective inhibition of plant extracts against gastrointestinal nematodes. In particular, there is strong evidence for their ovicidal and larvicidal activity against nematodes at different stages of development, such as egg hatching and larval development (Brito et al., 2017; Fomum and Nsahlai, 2017; Gaudin et al., 2016; Jamous et al., 2017; Mondal et al., 2015; Morais-Costa et al., 2016).

In vivo anthelmintic efficacy

Recent studies continue to lend additional support to these results, with the extracts and active compounds from various plants being found to possess high levels of in vitro efficiency (Belga et al., 2024; Cortes-Morales et al., 2023; Jasso-Díaz et al., 2022; Kpabi et al., 2022; Mahachi et al., 2023; Maurer et al., 2022; Ndaong et al., 2022; Sireesha et al., 2023). Moreover, ethnoveterinary plants tested in various areas have shown to produce equal efficacy in terms of their anthelmintic activity, thus underlining the universal importance of using plants for parasite treatment (Athanasiadou et al., 2021; Costes-Thiré et al., 2018; Mata-Padrino et al., 2019).

Comparative analysis: In vitro vs In vivo findings

In a comparative analysis of the 117 PRISMA-selected studies, the existence of an in vitro effectiveness vs. in vivo effectiveness contradiction is apparent throughout. In this regard, the effectiveness of PSMs has been proven through in vitro experiments, where the effectiveness of such compounds is usually high since the inhibition of egg hatchability and larvae development is observed in many of the studies selected for inclusion in this paper (Brito et al., 2017; Fomum and Nsahlai, 2017; Gaudin et al., 2016; Jamous et al., 2017; Kpabi et al., 2022; Mondal et al., 2015; Morais-Costa et al., 2016; Ndaong et al., 2022). The comparison of in vivo studies shows a reduced effectiveness compared to in vitro experiments. This means that while PSMs prove their effectiveness by completely inhibiting the reproduction of parasites, their effectiveness in vivo is much lower, as seen from various studies (Athanasiadou et al., 2021; Cortes-Morales et al., 2023; Mahachi et al., 2023; Pramu et al., 2025; Shepherd et al., 2024).

This difference has always been attributed to biological and methodological causes. The rumen conditions might affect the bioactivity of these phytochemicals before reaching the targeted parasitic species, thus making them less effective. Moreover, their interaction with the dietary content and variation in the physiological conditions of hosts significantly affects the results (Costes-Thiré et al., 2018; Mata-Padrino et al., 2019; Maurer et al., 2022). In addition, variations in the design of the experiments, such as different plant species used and extraction methods applied, significantly impact their efficacy (Belga et al., 2024; Jasso-Díaz et al., 2022; Sireesha et al., 2023). Therefore, from the literature reviewed, it is clear that whereas in vitro experiments are critical in testing the initial efficacy of these phytochemicals, they are inadequate predictors of field effectiveness.

Advantages and limitations of plant secondary metabolites in helminth control

The use of plant secondary metabolites (PSMs) for sustainable alternatives to synthetic anthelmintics has been receiving more attention in ruminants. Based on the data collected from 117 PRISMA articles, PSMs exhibit benefits in terms of sustainability, bioactivity, and their potential application in livestock farming systems. Nevertheless, their practical application is limited due to inconsistency in performance, standardization, and practicality issues (Hoste et al., 2015; Katiki et al., 2017; Maurer et al., 2022).

Environmental and sustainability benefits

The primary strengths of PSMs include the fact that they are friendly to the environment, unlike other anthelmintic drugs. Plant-based products do not negatively affect the environment, and they have fewer side effects compared to chemically synthesized products since they reduce the amount of residues formed in livestock products (Aïssa et al., 2023; Hoste et al., 2015; Katiki et al., 2017). Moreover, the utilization of PSM is an environmentally friendly approach to fighting parasites since it could be applied to sustainable parasite control programs and in organic systems of production (Costes-Thiré et al., 2018; Mata-Padrino et al., 2019). Reducing reliance on chemically produced drugs could help reduce the resistance to anthelmintic drugs, which is more frequent in ruminants (Desrues et al., 2017; Maurer et al., 2022). However, the availability of plant resources predisposes sustainability linked with PSM utilization, and it is an unexplored topic.

Biological and functional advantages

The biological mechanisms responsible for the efficiency of PSMs as anthelmintics include several modes of action of substances like tannins, saponins, flavonoids, and alkaloids. These biological molecules affect parasites in many ways by interfering with metabolic activities, inhibiting feeding, and affecting reproduction (Kakimori et al., 2019; Kanojiya et al., 2015; Khan et al., 2019). Numerous studies prove that, besides reducing parasitic loads, PSMs increase host resistance to infection by strengthening immune functions in infected organisms (Brito et al., 2017; Cortes-Morales et al., 2023; Ndaong et al., 2022). This additional function makes PSMs superior to classical drugs that target parasites without affecting host defence. However, it is essential to note that the

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biological effectiveness of PSMs depends considerably on their chemical structure, which differs among various plant species and depends on specific environmental factors (Jasso-Díaz et al., 2022; Sireesha et al., 2023).

Limitations and practical constraints

However, some limitations could limit the practical applications of the use of PSMs. The first limitation is that there are no standardized uses of plants in the preparation of supplements for livestock, especially in terms of composition, method of extraction, and dosage (Acevedo-Ramírez et al., 2020; Corona-Palazuelos et al., 2016; Hajaji et al., 2018). Moreover, the taste and toxicity of some active compounds found in PSMs could reduce feed intake and productivity of animals at higher dosages (Akkari et al., 2016; Wahyuni et al., 2019). Another problem with PSMs is that the effectiveness of the supplement would be affected by ruminal metabolism and dietary components when used on farms, thus reducing its efficacy Mata-Padrino et al., 2019; Maurer et al., 2022). Lastly, the small number of field tests limits the applicability of results from laboratory and small-scale experiments to actual production environments (Mwangi et al., 2024; Singh et al., 2015).

Integration into livestock health management

Successful implementation of PSMs will depend on their use in comprehensive schemes of livestock health management. A number of works have shown that the use of anthelmintic plants could be used in targeted selective therapy programs to minimize dependence on wide-scale drug use (Hoste et al., 2015; Rojo-Rubio et al., 2019). Moreover, PSMs could be used in combination with pasture management methods, such as rotational grazing, to limit parasitic infection (Quijada et al., 2015; Rivaroli et al., 2019). The importance of integrating ethnoveterinary practice in this process and farmer involvement has also been stressed in literature (Buyi et al., 2024; Indrati et al., 2019). In practical terms, creating standardized preparations is necessary for successful commercialization (Adebayo et al., 2019; Esteban-Ballesteros et al., 2019).

Trade-offs and implementation challenges

One notable point about the effectiveness of PSMs in controlling helminths, as found from the synthesis of literature, is the presence of trade-offs in the process of application in the real world. Although PSMs exhibit excellent anthelmintic properties in laboratory settings, their effectiveness is hard to implement in practice (Acevedo-Ramírez et al., 2020; Katiki et al., 2017; Saric et al., 2015). Some research suggests that PSMs effective in vitro turn out to be moderately effective when applied in vivo (Hoste et al., 2015; Mahachi et al., 2023; Mwangi et al., 2024). This observation could be attributed to different biological and environmental factors affecting the effectiveness of PSMs in the process of implementation in the real world (Desrues et al., 2017; Khan et al., 2019). Moreover, scalability issues persist. Even though experimental research indicates positive outcomes, the implementation in commercial enterprises demands standardised formulations, quality consistency, and efficient administration channels (Belga et al., 2024; Cortes-Morales et al., 2023; Maurer et al., 2022). Consequently, the potential of employing PSMs for parasite suppression will rely upon an integrated strategy that includes both plant-based treatment and proper livestock management. In several cases, PSMs were found to decrease the number of parasitic organisms while simultaneously increasing the resilience of hosts and improving their immune responses (Brito et al., 2018; Cortes-Morales et al., 2023; Ndaong et al., 2022). In this regard, such a dual mechanism can be considered an essential advantage over conventional treatments that do not have this effect. Nonetheless, the effectiveness of PSMs relies heavily on their chemical composition, which significantly varies from one plant species to another depending on environmental conditions and extraction procedures (Jasso-Díaz et al., 2022; Sireesha et al., 2023).

Limitations and practical constraints

Though promising, however, PSMs still face a number of barriers to implementation. Lack of standardization of the extracts, in terms of variations in the components, methodology, and dosage of the plant material, was pointed out as one of the key barriers that were noted throughout the review of literature (Acevedo-Ramírez et al., 2020; Corona-Palazuelos et al., 2016; Hajaji et al., 2018). Moreover, palatability and toxicity may influence the feed intake and productivity of livestock in response to higher concentrations of certain compounds (Akkari et al., 2016; Wahyuni et al., 2019). Additionally, the effectiveness of the supplements could be compromised by rumen metabolism and interactions with diet compositions (Mata-Padrino et al., 2019; Maurer et al., 2022). Limited research in vivo further complicates translating results into practice (Mwangi et al., 2024; Singh et al., 2015).

Although the use of PSMs offers several advantages, there are certain barriers that can limit their successful application. Firstly, according to several of the reviewed articles, one of the key issues affecting the application of plant extracts relates to the inconsistency in terms of phytochemical composition, extraction procedures, and doses of plant materials (Acevedo-Ramírez et al., 2020; Corona-Palazuelos et al., 2016; Hajaji et al., 2018). Secondly, taste and possible toxic effects on animals might negatively impact feed intake and performance, especially when high concentrations of specific compounds are used (Akkari et al., 2016; Wahyuni et al., 2019). Moreover, their effect can be compromised by rumen metabolism and other factors depending on diet compositions in real-life conditions (Mata-Padrino et al., 2019; Maurer et al., 2022). Lastly, the rather small number of large-scale experiments conducted on animals hinders the transferability of the results to real-world commercial applications (Mwangi et al., 2024; Singh et al., 2015).

Integration into livestock health management

The effectiveness of PSMs is influenced by their incorporation into livestock health management programs. Various research works indicate that there is a potential possibility of using plant-derived anthelmintics within the context of targeted selective treatment (TST), minimizing the use of indiscriminate use of drugs (Hoste et al., 2015; Rojo-Rubio et al., 2019). Moreover, PSMs may also be used together with pasture management programs like rotational grazing, which help minimize parasite infections (Quijada et al., 2015; Rivaroli et al., 2019). Finally, the involvement of ethnoveterinary practices in the treatment process has also been pointed out as an important element influencing the success of using plants in animal health management (Buyi et al., 2024; Indrati et al., 2019). As far as practicality is concerned, there is a need to develop standardized plant-based medicines in order to facilitate their widespread use and marketing (Adebayo et al., 2019; Esteban-Ballesteros et al., 2019).

Future perspectives and research needs

Although there is a growing scientific support in the use of PSMs in the control of helminths, a number of knowledge gaps still exist. Such gaps need to be filled to make sure that what is learned in the laboratory can be successfully used in the real world to control the parasites in ruminants. This discussion on the 117 articles identified by the PRISMA guidelines offers a guideline on the prioritization of future studies.

Bridging the gap between In vitro and In vivo studies

Another commonality that has emerged from this literature review is the difference between efficacy observed in laboratory settings and performance in field settings among PSMs. Although many publications have documented potent antiparasitic effects in laboratory settings, such performance is variable under field conditions (Acevedo-Ramírez et al., 2020; Corona-Palazuelos et al., 2016; Katiki et al., 2017; Saric et al., 2015). It is further observed that laboratory studies showing potential promise against parasites do not ensure success in field settings for managing parasites in commercial production systems (Bordes et al., 2024; Hoste et al., 2015; Mwangi et al., 2024; Singh et al., 2015). Therefore, future investigations on plant-based antiparasitic need to include laboratory studies followed by animal trials and finally field trials under actual production settings.

Standardisation of plant-based anthelmintic products

One of the major limitations observed within the scope of the provided data is associated with the lack of standardization of plant-derived drugs. The researchers have shown that the differences concerning specific types of plants, their chemical composition, methods of extraction, and doses can largely affect their efficacy (Belga et al., 2024; Hajaji et al., 2018; Jasso-Díaz et al., 2022; Kakimori et al., 2019; Sireesha et al., 2023). Furthermore, researchers were able to identify bioactivity variations of a specific plant depending on the region where they were extracted (Cabardo and Portugaliza, 2017; Kanojiya et al., 2015; Khan et al., 2019). Future studies should be directed toward standardizing plant extraction and their doses.

Mechanistic studies and bioactive compound identification

According to bibliometrics, there is a limited number of research studies conducted on the mechanisms of action of PSMs as opposed to studies investigating the effectiveness of PSMs. The disparity indicates that there is a major gap in terms of knowledge concerning how PSMs interact with parasites. Despite some research identifying bioactive components such as tannins, alkaloids, and flavonoids that impart anthelmintic activity (Cortes-Morales et al., 2023; Kakimori et al., 2019; Khan et al., 2019; Maurer et al., 2022), there is room for further exploration in the mechanisms of action. Therefore, future studies need to utilize advanced approaches in identifying the active components and the mechanisms involved in their action.

Integration into sustainable livestock systems

The successful implementation of PSMs depends on their integration into broader livestock health management strategies. Evidence suggests that plant-based anthelmintics can be incorporated into targeted selective treatment (TST) programmes and grazing management systems to reduce parasite transmission and drug reliance (Quijada et al., 2015; Rivaroli et al., 2019; Rojo-Rubio et al., 2019). Furthermore, ethnoveterinary approaches play an important role, particularly in smallholder systems where plant-based treatments are already widely utilised (Aissa et al., 2016; Buyi et al., 2024; Indrati et al., 2019).

Future research should therefore explore integrated parasite management strategies that combine plant-based treatments with pasture management, host resistance, and broader One Health approaches. Such integration is essential to enhance sustainability, resilience, and long-term effectiveness in ruminant production systems.

Large-scale validation and commercial development

Although there have been promising findings through many scientific experiments, there has yet to be success in the implementation of the findings in real-world practices. Field-based experiments produced inconclusive outcomes, indicating that further study should be done under different production systems (Bordes et al., 2024; Mahachi et al., 2023; Mwangi et al., 2024). The inconsistencies indicate the need for more field trials and efficacy tests to be done in order to validate the efficacy of the botanicals under different circumstances. In addition, a cost-benefit analysis needs to be undertaken to determine whether the application of PSM in livestock businesses would be economically feasible.

Policy support and regulatory frameworks

The development and use of anthelmintics from plants require proper regulation. Currently, there are no guidelines on the regulations needed for these plant-derived drugs. Research will be necessary in the future to provide guidelines based on safety and toxicity assessment and to ensure that these guidelines are integrated into national parasite control programs. It is necessary to have such regulatory support for this purpose because it is important for the proper use of anthelmintics obtained from plants.

Conclusion

The present work gives an integrated review of the current state of research related to PSMs used in helminth infection control in ruminants. The outcomes of the bibliometric study suggest that there is a well-established and expanding body of research, globally spread, which puts a significant focus on experimental and laboratory studies, specifically dealing with plant extracts and biologically active substances like tannins, saponins, and flavonoids. This review also reiterates that PSMs have shown considerable anthelmintic activity due to several reasons, such as alteration in the physiological processes of the parasites, inhibition of their nutrition and development, and regulation of interactions between the host and the parasite. Of all these PSMs, tannins continue to be the most researched and successful, although there are other categories of PSMs that can show considerable bioactivity. Nevertheless, the results point out an important gap between the success of these compounds in vitro versus in vivo and also the need for larger-scale validation of their use in the field. In general, the plant secondary metabolites serve as a promising source for anthelmintics due to their sustainable use in comparison with the conventional drugs, especially under rising drug resistance. In the future, studies on this topic need to focus more on integration and translation, where laboratory experiments can be combined with practical use. Improvements in this direction will significantly contribute to implementing the plant-based parasite control methods in ruminants.

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Contribution of Authors

Wahyuwardani S, Yulistiani D, Praharani L, Widiastuti R, Sawitri DH & Hidayat C: Conceived the review, designed the review methodology, performed literature screening and data extraction and drafted the manuscript.
Tresia GE, Saputra F, Rakhmani SIW & Fanindi A: Contributed to manuscript writing, reviewed the manuscript, and provided supervision, guidance and critical comments.
Pasaribu T, Asmarasari SA, Kusumaningrum DA & Sutedi E: Analyzed and interpreted the bibliometric data and critically revised the draft for intellectual content.
Rohaeni ES, Kostaman T & Hariyadi TZP: Performed literature screening, data validation, manuscript preparation and manuscript review.

All authors read and approved the final draft of the manuscript.

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