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WASTE AGRICULTURE MATERIAL IN ANIMAL FEED TREND EVALUATION: A BIBLIOMETRIC ANALYSIS

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Abstract:

The worldwide demand for sustainable livestock production has generated heightened interest in employing agricultural waste materials as alternative feed sources with the objective of improving resource efficiency and reducing environmental impact. Notwithstanding increasing research, a thorough assessment of publication trends, principal themes, and significant contributors in this domain remains insufficiently examined. This study performs a bibliometric analysis entitled "Waste Agriculture Material in Animal Feed Trend Evaluation," utilising Scopus Analyser and VOSviewer software to analyse 1,287 documents published from 2004 to 2024 systematically. The analysis reveals a notable increase in research output, especially after 2018, propelled by increased global awareness of sustainable practices and the circular economy. Prominent themes identified in the keyword analysis encompass "agriculture," "circular economy," "sustainability," and "bioconversion," underscoring the emphasis on waste valorisation and nutrient recovery in animal feed. The co-authorship analysis indicates robust international collaborations, with significant contributions from the United States, China, India, and European nations, highlighting the global character of

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this research domain. Prominent authors such as Tomberlin, Oenema, and Godbout have significantly influenced the research trajectory on novel feed alternatives. The findings highlight the growing importance of incorporating waste management strategies into animal nutrition to tackle issues concerning food security, environmental sustainability, and livestock efficiency. The results provide significant insights for future research, highlighting the necessity for the ongoing investigation into advanced bioconversion technologies and sustainable feeding practices to enhance the utilisation of agricultural by-products in animal feed systems.

Keywords:

Waste, Agriculture, Feed, Bibliometric Analysis

Introduction

The increasing production of agri-food commodities has led to the generation of substantial volumes of waste and by-products, contributing significantly to environmental pollution. These wastes, rich in bioactive compounds such as polyphenols, dietary fibres, oils, essential vitamins, and minerals, present an under-exploited resource that can be effectively managed and valorised. One promising strategy is the development of nutritious, low-cost, and sustainable animal feed from these agri-food wastes. This approach aligns with the concepts of the EU circular economy and green biorefinery, promoting sustainability by reducing waste and providing an alternative animal protein source (Ajila *et al.*, 2012; Malenica *et al.*, 2022; Martin *et al.*, 2016). Various types of food losses and wastes, including vegetable by-products and biodegradable municipal solid waste, have been found to be nutritionally viable and safe for use in animal feed, provided they undergo appropriate processing to meet safety standards (García *et al.*, 2005; Iskakov & Sugirbay, 2023; Rajeh *et al.*, 2020).

The valorisation of food waste into animal feed not only addresses waste management and food security challenges but also reduces the environmental burden associated with conventional feed production. Technologies such as solid substrate fermentation, ensiling, and high solid or slurry processes have been developed to enrich the nutrient content of these wastes, making them suitable for animal consumption (Ajila *et al.*, 2012; Chen *et al.*, 2015). Additionally, using food waste as animal feed contributes to the circular economy by creating a closed-loop system that minimises using natural resources and environmental pollution 8. However, it is crucial to ensure the quality and safety of the feed through rigorous testing and compliance with regulatory standards to prevent the presence of harmful contaminants (Iskakov & Sugirbay, 2023), (Shlyamina *et al.*, 2020).

Overall, the utilisation of agricultural and food industry wastes as animal feed presents a sustainable solution that benefits both the environment and the agricultural sector.

Literature Review

The utilisation of agricultural waste in animal feed has garnered heightened interest owing to its capacity to improve environmental sustainability and promote a circular economy. A significant trend is the utilisation of humic acids (HAs) sourced from natural carbonaceous materials such as lignite and peat, which are treated using advanced techniques, including catalytic oxidation and microbial activation. HAs have demonstrated the potential to enhance soil health and animal feed supplements by supplying nutrient-dense and bioactive constituents

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(Sarlaki *et al.*, 2024). These materials function as synergistic intermediaries between soil and plants, facilitating improved nutrition and growth in livestock feed. Nevertheless, the protracted natural humification process and elevated production expenses continue to pose substantial obstacles. Consequently, subsequent research should concentrate on refining extraction methodologies to diminish expenses and enhance yield efficiency. A promising domain is the utilisation of insect-based feeds, particularly those incorporating black soldier fly (BSF) larvae. BSF larvae effectively transform organic waste into nutrient-rich biomass appropriate for animal feed. Research indicates that BSF larvae can convert organic waste into valuable feed components, thereby mitigating agricultural waste (Gerba & Smith Jr., 2005; Oro *et al.*, 2013). This method has garnered favourable consumer responses and provides a sustainable substitute for traditional animal feed. Notwithstanding its benefits, challenges such as substrate quality and consumer acceptance persist as significant obstacles. Subsequent research should examine these obstacles by investigating the metabolic functions of intestinal microbes in BSF larvae and their influence on nutrient synthesis.

The integration of microalgae cultivated in non-toxic wastewater into animal feed is an emerging trend, emphasising the utilisation of this biomass (Ivanova *et al.*, 2024). Microalgae exhibit potential as a sustainable feed component owing to their elevated protein levels and the inclusion of essential amino acids and fatty acids. Utilising wastewater as a growth medium not only mitigates waste management challenges but also increases the economic viability of anaerobic digestion facilities. However, the risk of contamination and the necessity for rigorous selection of suitable wastewater sources present considerable challenges. Consequently, forthcoming research must emphasise the establishment of standardised protocols for wastewater treatment to guarantee its safe and effective application in feed production. The livestock sector is increasingly concerned about microplastic contamination in animal feed, which has been identified in feed materials and livestock products (Glorio Patrucco *et al.*, 2024). The significant prevalence of microplastics, especially in feed stored with plastic materials, underscores the necessity for efficient detection and mitigation strategies. Despite recent progress in establishing protocols for microplastic extraction from animal feeds, the lack of standardised regulations jeopardises both animal and human health. Additional research is required to formulate comprehensive guidelines for microplastic detection in feed products and to investigate potential strategies for reducing contamination during feed storage and handling.

The generation of single-cell protein (SCP) from agricultural byproducts constitutes a novel strategy for mitigating protein shortages in animal feed. The utilisation of microbial cell biomass grown on substrates, such as wheat bran and dairy waste, demonstrates promise for generating nutrient-dense feed additives with elevated fermentative and probiotic properties (Ualieva *et al.*, 2024). Co-cultures of yeast and lactic acid bacteria (LAB) have proven particularly efficacious in augmenting protein content and delivering probiotic advantages. Nonetheless, the scalability of this technology and its economic viability remain ambiguous. Subsequent research should investigate economical cultivation methods and evaluate the enduring impacts of SCP incorporation in animal feed. Concerns have arisen regarding glyphosate residues in manure-based fertilisers utilised in animal feed production, particularly regarding their potential adverse effects on feed quality and safety. Glyphosate, a commonly utilised herbicide, has been identified in multiple phases of the agricultural cycle, encompassing feed, faeces, and fertilisers (Birge *et al.*, 2024). Glyphosate residues in feed are associated with diminished crop yield and quality, along with possible health hazards for livestock. The absence of standardised testing for pesticide residues in recycled fertilisers

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requires additional research to determine safe usage guidelines and avert contamination. Cooperative initiatives between regulatory bodies and fertiliser manufacturers are essential for resolving this issue.

Recent studies have emphasised the potential of bioconversion processes utilising agricultural waste, such as composting and vermicomposting, to generate nutrient-dense feed additives. These processes mitigate environmental impacts while improving feed nutrient composition (Chuma *et al.*, 2024). Vermicomposting, specifically, has demonstrated exceptional efficacy in enhancing plant growth and yield. Notwithstanding the advantages, the extensive implementation of these technologies is constrained by infrastructural obstacles and the necessity for more thorough waste management strategies. Incorporating agricultural waste into animal feed production offers substantial prospects for enhancing sustainable livestock practices. Nonetheless, numerous challenges must be tackled, such as optimising processing methods, guaranteeing feed safety, and surmounting economic obstacles. Subsequent research must concentrate on creating economical and scalable solutions alongside formulating regulatory frameworks to guarantee the safe and efficient utilisation of waste materials in animal feed. Moreover, comprehensive studies are required to assess the long-term impacts of these alternative feed sources on animal health and productivity.

Research Question

a. What are the research trends in waste agriculture in animal feed studies according to the year of publication?
b. Who and how many related publications have been published?
c. Who are the top 10 authors based on citation by research?
d. What are the popular keywords related to the study?
e. What are co-authorship countries' collaboration?

Methodology

Bibliometrics means the combination, management, and investigation of bibliographic information obtained from publications that are scientific in nature (Alves *et al.*, 2021; Assyakur & Rosa, 2022; Verbeek *et al.*, 2002) along with general descriptive statistics, such as publishing journals, publication year, and main author classification (Wu & Wu, 2017). It also comprises complex techniques, such as document co-citation analysis. A successful literature review necessitates an iterative process involving the identification of appropriate keywords, a literature search, and a thorough analysis to build a comprehensive bibliography and yield dependable results (Fahimnia *et al.*, 2015). In light of this, the study sought to focus on top-tier publications, as they offer valuable insights into the theoretical perspectives shaping the evolution of the research domain. To ensure data reliability, the study relied on the SCOPUS database for data collection (Al-Khoury *et al.*, 2022; di Stefano *et al.*, 2010; Khiste & Paithankar, 2017). Moreover, to ensure the inclusion of high-quality publications, only articles published in rigorously peer-reviewed academic journals were considered, with a deliberate exclusion of books and lecture notes (Gu *et al.*, 2019). Notably, Elsevier's Scopus, known for its extensive coverage, facilitated the collection of publications spanning from 2004 to December 2024 for subsequent analysis.

Data Search Strategy

The advanced search string in Scopus is an effective instrument that enables researchers to formulate intricate and exact search queries to retrieve specific information from the vast

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Scopus database. This functionality is particularly advantageous for performing systematic literature reviews, bibliometric analyses, and comprehensive subject investigations. The advanced search interface facilitates the application of Boolean operators, field codes, wildcards, proximity operators, and nested queries, enhancing the search process. Tables 1 and 2 show the search string and the selection criterion is searching.

Table 1: The Search String.

SCOPUS	TITLE-ABS-KEY (agriculture AND waste AND feed) AND PUBYEAR > 2003 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "AGRI")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p")).

Table 2: The Selection Criterion is Searching.

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2004–2024	< 2004
Literature type	Journal (Article) and Proceeding	Book, Review

Data Analysis

VOSviewer is an accessible bibliometric software created by Nees Jan van Eck and Ludo Waltman at Leiden University, Netherlands (van Eck & Waltman, 2010, 2017). The tool is extensively employed for visualising and analysing scientific literature, specialising in creating intuitive network visualisations, clustering related items, and generating density maps. Its adaptability facilitates the analysis of co-authorship, co-citation, and keyword co-occurrence networks, offering researchers an in-depth comprehension of research environments. The interactive interface, along with ongoing updates, facilitates efficient and dynamic exploration of extensive datasets. VOSviewer's capacity to calculate metrics and tailor visualisations and its compatibility with diverse bibliometric data sources render it an invaluable tool for researchers pursuing insights into intricate research fields.

A notable feature of VOSviewer is its ability to convert complex bibliometric datasets into visually interpretable maps and charts. The software specialises in network visualisation, effectively clustering related items, analysing keyword co-occurrence patterns, and producing density maps. Researchers gain advantages from its intuitive interface, allowing beginners and seasoned users to navigate research environments effectively. VOSviewer's ongoing advancement guarantees its position as a leader in bibliometric analysis, providing significant insights via metric calculations and customisable visual representations. VOSviewer's adaptability to various bibliometric data types, including co-authorship and citation networks, establishes it as a versatile and essential tool for researchers pursuing profound understanding and significant insights within their fields.

Datasets containing publication year, title, author name, journal, citation, and keywords in PlainText format were obtained from the Scopus database, covering the period from 2004 to December 2024. The datasets were subsequently analysed utilising VOSviewer software version 1.6.20. This software enabled the analysis and creation of maps using VOS clustering and mapping techniques. VOSViewer provides an alternative to the Multidimensional Scaling

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(MDS) method by positioning items in low-dimensional spaces, ensuring that the distance between any two items accurately represents their relatedness and similarity (van Eck & Waltman, 2010). In this regard, VOSViewer exhibits a resemblance to the MDS methodology (Appio *et al.*, 2014). In contrast to MDS, which focuses on calculating similarity metrics such as cosine and Jaccard indices, VOS employs a more appropriate method for normalising co-occurrence frequencies, specifically, the association strength (ASij), calculated as (Van Eck & Waltman, 2007):

$$\mathrm{AS}_{ij} = \frac{C_{ij}}{w_i w_j}$$

It is "proportional to the ratio of the observed number of co-occurrences of i and j to the expected number of co-occurrences of i and j, assuming that the co-occurrences of i and j are statistically independent" (Van Eck & Waltman, 2007).

Results And Findings

What Are The Research Trends In Waste Agriculture In Animal Feed Studies According To The Year Of Publication?

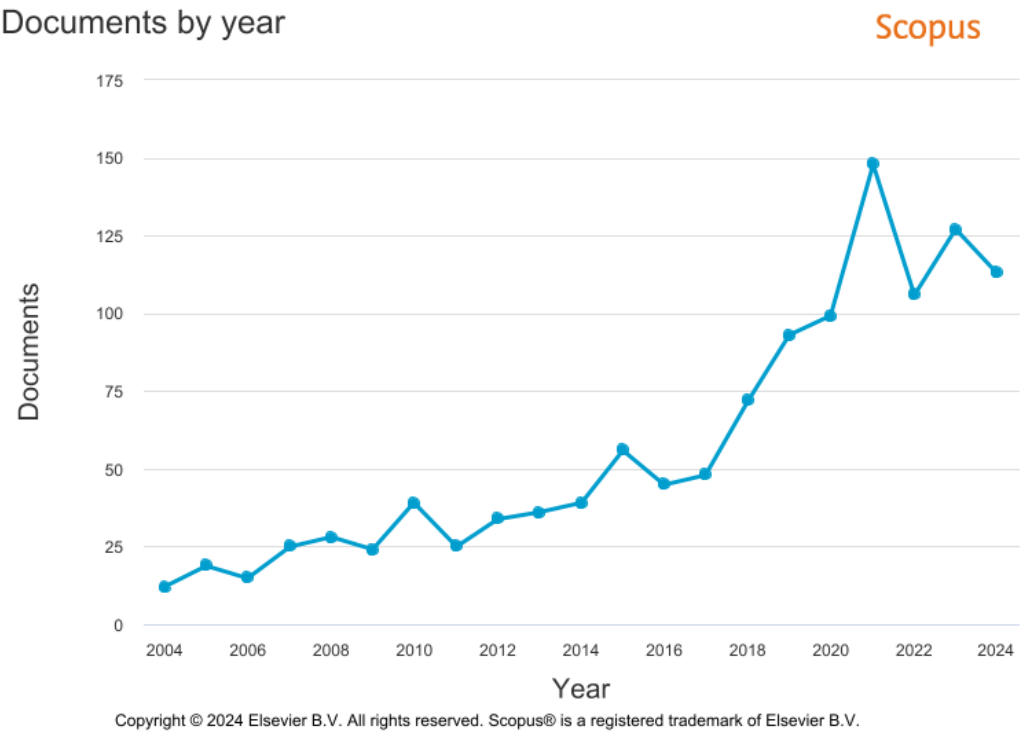

Figure 1: Plotting Document Publication By Years.

The trend analysis of publications concerning "Waste Agricultural Material in Animal Feed" from 2004 to 2024, as illustrated in the figure, demonstrates a distinct upward trend in research interest and academic output. From 2004 to 2015, the rise in publications was incremental, characterised by a steady annual increase in document counts, reflecting initial exploratory research in this field. This period signifies a burgeoning interest as researchers commenced

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investigations into the viability and advantages of utilising agricultural waste materials in animal feed within the framework of sustainable agricultural practices. The variation noted between 2010 and 2016 indicates sporadic focus, likely attributable to the exploratory character of research and the constraints of data availability or technology during that period.

A notable increase in publication volume is evident after 2018, reaching a zenith in 2021 with an output of approximately 175 documents. This increase is likely due to enhanced global awareness of sustainability, the circular economy, and the growing pressure to minimise waste in agricultural systems. The surge in publications during this period corresponds with global trends in tackling food security and sustainable feed solutions. Subsequent to this peak, a modest decline is observed in the ensuing years, potentially indicating a stabilisation phase wherein research transitions from preliminary exploration to comprehensive analysis and application. Notwithstanding the decline post-2021, the total publication count continues to exceed that of previous years, signifying persistent interest and ongoing research endeavours in the optimisation of waste material utilisation in animal feed. This trend highlights the increasing significance of innovative feed alternatives in mitigating environmental impact and improving the efficiency of livestock production systems.

Who And How Many Related Publications Have Been Published?

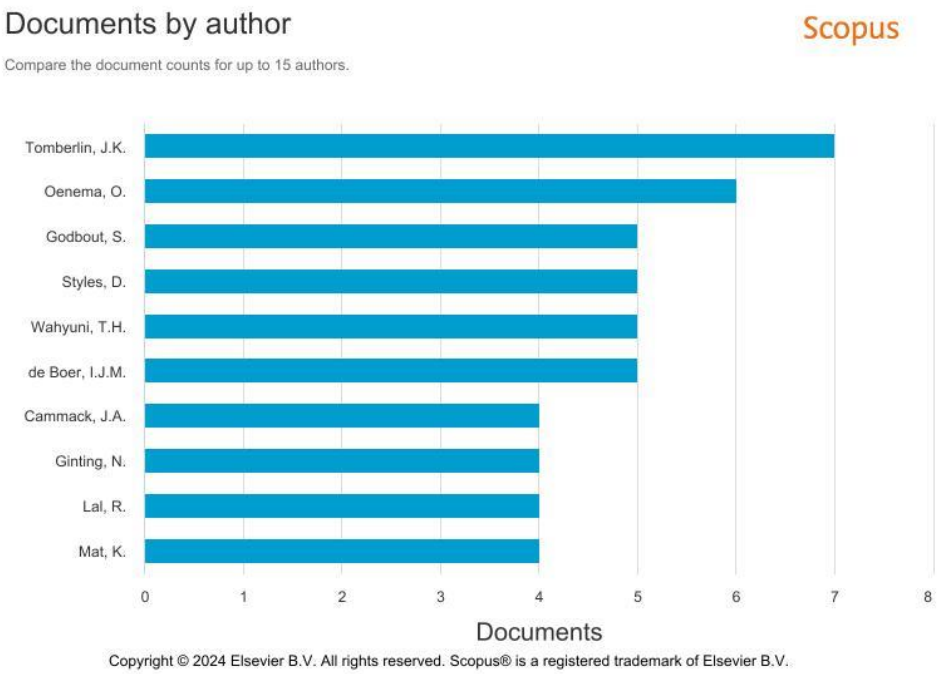

Figure 2: Plotting The Authors's Name And Publication's Number.

The graph illustrating documents by an author from 2004 to 2024 indicates a significant concentration of research contributions in the domain of agricultural waste utilisation in animal feed. Tomberlin, J.K. stands out as the most prolific author with seven publications, demonstrating a robust research emphasis on innovative feed solutions, potentially utilising insect-based feeds such as Black Soldier Fly larvae, which correspond with sustainability initiatives in feed production. His research probably focuses on the environmental advantages

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of transforming organic waste into high-protein feed sources, a burgeoning field of interest owing to its capacity to diminish agricultural waste and improve feed efficiency.

Tomberlin, J.K., Oenema, O., And Goudbout, S. each have six publications, indicating substantial contributions, presumably centred on nutrient management and sustainable livestock production systems. Their work may involve assessing the viability of incorporating agricultural residues, including crop by-products and organic waste, into animal feed formulations. The participation of these authors indicates an increasing focus on circular economy principles in agriculture, wherein waste materials are transformed into valuable inputs for feed production, thereby diminishing environmental impacts and improving resource efficiency.

Other notable researchers, including Styles, D., and Wahyuni, T.H., each with five publications, seem to offer varied viewpoints, likely addressing environmental impact assessments and the socio-economic consequences of utilising waste materials in feeding practices. The inclusion of a varied group of authors, such as Boumans and Miranda, signifies an interdisciplinary methodology in this research domain, integrating knowledge from animal nutrition, environmental science, and agricultural policy. This expertise underscores the collaborative essence of the research, focussing on practical applications in feed formulation and overarching sustainability objectives. The contributions from various authors emphasise the increasing agreement on the necessity of reassessing conventional feed resources in favour of more sustainable, waste-derived alternatives, indicating a significant shift in the research focuses over the two decades analysed.

Table 3: Details On The Number Of Documents Published By Authors And Their Percentage.

Author Name	Number of Documents	Percentage (%)
Tomberlin, J.K.	7	0.582
Oenema, O.	6	0.499
Godbout, S.	5	0.416
Styles, D.	5	0.416
Wahyuni, T.H.	5	0.416
de Boer, I.J.M.	5	0.416
Cammack, J.A.	4	0.333
Ginting, N.	4	0.333
Lal, R.	4	0.333
Mat, K.	4	0.333

The examination of publication data identifies prominent authors who have significantly contributed to the domain of "Waste Agricultural Material in Animal Feed." Tomberlin, J.K. is the most prolific author, having published seven documents, constituting 0.582% of the total publications. Tomberlin's steady output indicates a robust emphasis on pioneering research, potentially in domains such as insect-derived feed alternatives and sustainable waste management methodologies. This leadership role demonstrates a profound commitment to investigating alternative feed sources, especially utilising waste streams, in accordance with emerging trends in circular economy practices within the livestock sector.

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Oenema, O. follows Tomberlin as another notable contributor, with six documents (0.499%). Oenema's research will likely focus on nutrient management and sustainable practices in agricultural systems, emphasising the optimisation of waste materials for animal nutrition while reducing environmental impacts. Notable authors, including Goudbout, S., Styles, D., Wahyuni, T.H., and de Boer, I.J.M. each produced five publications (0.416%), reflecting their shared emphasis on incorporating agricultural by-products into animal feed formulations. The inclusion of these authors highlights an interdisciplinary methodology, integrating knowledge from environmental science, agricultural engineering, and animal nutrition to tackle the challenges related to waste valorisation in animal feed production.

The secondary group of authors, comprising Cammack, J.A., Ginting, N., Lal, R., And Mat, K., have each produced four documents, accounting for 0.333% of the overall total. This cohort of researchers significantly contributes to the enhancement of the knowledge base, likely concentrating on particular facets of waste utilisation, including feed safety, nutrient recycling, and the economic viability of integrating waste materials into feed products. The contributions from this varied group of authors illustrate the collaborative and dynamic characteristics of the research field, focussing on optimising feed resources, diminishing dependence on traditional feed ingredients, and improving the overall sustainability of animal production systems. The allocation of publications among these prominent authors reflects a comprehensive and dynamic research environment motivated by a collective interest in innovative, sustainable animal feed solutions.

Who Are The Top 10 Authors Based On Citation By Research?

Table 4: List Of Top 10 Most Cited Authorship.

Authors	Title	Year	Journal	Cited by
(Sarmah *et al.*, 2006)	A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (VAs) in the environment	2006	Chemosphere	2920
(Jayathilakan *et al.*, 2012)	Utilisation of byproducts and waste materials from meat, poultry and fish processing industries: A review	2012	Journal of Food Science and Technology	721
(Chee-Sanford *et al.*, 2009)	Fate and transport of antibiotic residues and antibiotic resistance genes following land application of manure waste	2009	Journal of Environmental Quality	707

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(Mcewen & Collignon, 2018)	Antimicrobial resistance: A one health perspective	2018	Microbiology Spectrum	692
(Oro *et al.*, 2013)	Ecological and evolutionary implications of food subsidies from humans	2013	Ecology Letters	587
Nguyen T.T.X.; Tomberlin J.K.; Vanlaerhoven S.	The ability of Black Soldier Fly (Diptera: Stratiomyidae) Larvae to Recycle Food Waste	2015	Environmental Entomology	394
(Primavera, 2006)	Overcoming the impacts of aquaculture on the coastal zone	2006	Ocean and Coastal Management	391
(Gerba & Smith Jr., 2005)	Sources of pathogenic microorganisms and their fate during land application of wastes	2005	Journal of Environmental Quality	382
(Kim *et al.*, 2011)	Occurrence and environmental fate of veterinary antibiotics in the terrestrial environment	2011	Water, Air, and Soil Pollution	370
(Zhou *et al.*, 2013)	Excretion masses and environmental occurrence of antibiotics in typical swine and dairy cattle farms in China	2013	Science of the Total Environment	367

The table of the most cited documents on "Waste Agricultural Material in Animal Feed" from 2004 to 2024 reveals key publications that have significantly influenced the research landscape. The top-cited paper by Sarmah *et al.* (2006), with 2,920 citations, discusses the global implications of pharmaceuticals in agricultural waste, focusing on their use, exposure, and environmental impacts. This work highlights concerns about pharmaceutical residues entering the food chain through waste-derived animal feed, bringing attention to the potential risks associated with using agricultural waste materials. The extensive citations reflect the growing awareness and need for research on the safety and environmental implications of reusing waste in feed, particularly in the context of emerging contaminants.

The second most cited document, authored by Jayathilakan *et al.* (2012) with 721 citations, examines the utilisation of by-products and waste materials from the food industry for animal feed. This research is fundamental in demonstrating the feasibility of converting various food processing wastes into valuable feed ingredients, emphasising economic benefits and waste reduction. The high citation count indicates its impact on subsequent studies that explore alternative protein sources and sustainable feed practices. The focus on using food industry by-products aligns with current trends in reducing feed costs and supporting circular economy principles in agriculture.

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Chee-Sanford *et al.* (2009) follow closely with 707 citations, investigating the fate and transport of antibiotic residues from agricultural waste used in animal feed. This study highlights the risks of antimicrobial resistance arising from the presence of antibiotics in waste-derived feed ingredients. The concern for antibiotic residues reflects broader issues in public health, as the continued use of waste materials in feed has implications for the development of resistant bacterial strains. The significant citation count underscores the importance of addressing antimicrobial resistance in the context of sustainable feed production, marking it as a critical area for future research and regulatory considerations.

What Are The Popular Keywords Related To The Study?

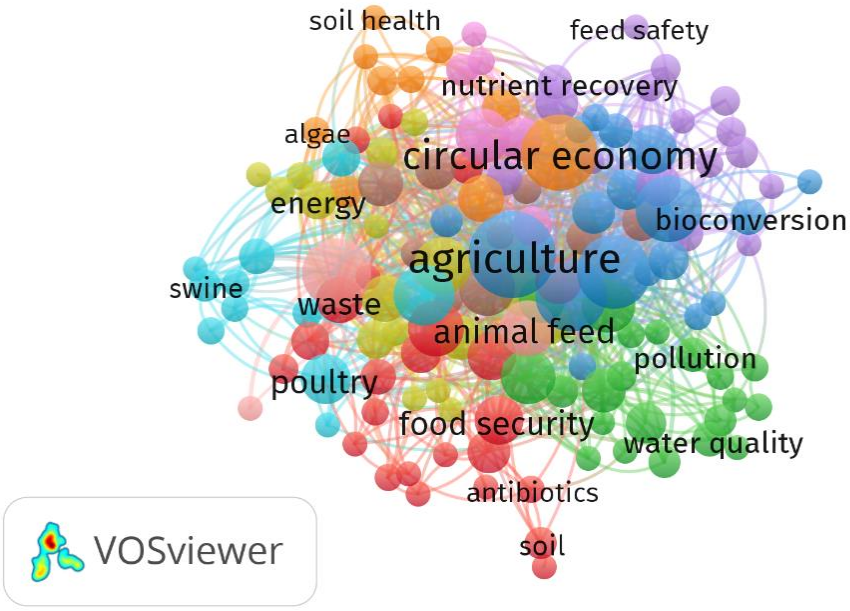

Figure 3: Network Visualisation Map Of Keywords' Co-Occurrence.

The examination of the VOSviewer-generated keyword data for the "Waste Agricultural Material in Animal Feed" study reveals several significant themes and prevalent keywords, elucidating the focal points of contemporary research. The predominant keyword is "agriculture," appearing 58 times and possessing a total link strength of 101, signifying its pivotal importance in the domain. The prevalence of "circular economy" (44 occurrences, 76 link strength) and "sustainability" (42 occurrences, 73 link strength) indicates a significant focus on developing sustainable agricultural systems via the effective use of waste materials. These terms indicate the increasing interest in incorporating waste products into the feed industry to improve resource efficiency and minimise the environmental impact of agricultural practices.

The keyword data indicates notable interest in particular waste management processes and biological transformations, including "anaerobic digestion" (37 occurrences, 70 link strength) and "composting" (16 occurrences, 25 link strength). These methods are frequently examined for their capacity to transform organic waste into valuable products, including biofertilisers or energy sources like biogas. The recurrent use of terms such as "biogas," "biomass," and "biochar" highlights the significance of bioconversion technologies in enhancing the value of

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waste materials. The term "black soldier fly" (18 occurrences, 40 link strength) is prominent. It indicates an increasing trend in insect farming for waste management and animal feed production, underscoring its viability as a sustainable protein source.

Finally, the analysis highlights the environmental and ecological factors related to using waste materials in animal feed. Terms such as "climate change," "greenhouse gas," and "life cycle assessment" illustrate the emphasis on assessing the environmental effects of incorporating waste-derived feed. The prominence of "food waste" (39 instances, 59 link strength) and "waste management" (34 instances, 59 link strength) signifies persistent endeavours to rectify inefficiencies within the food system and advocate for waste minimisation. Collectively, these keywords represent a multidisciplinary research domain addressing the technical, economic, and environmental challenges associated with utilising agricultural residues in animal feed, with the objective of promoting more resilient and sustainable food systems.

What Are Co-Authorship Countries' Collaboration?

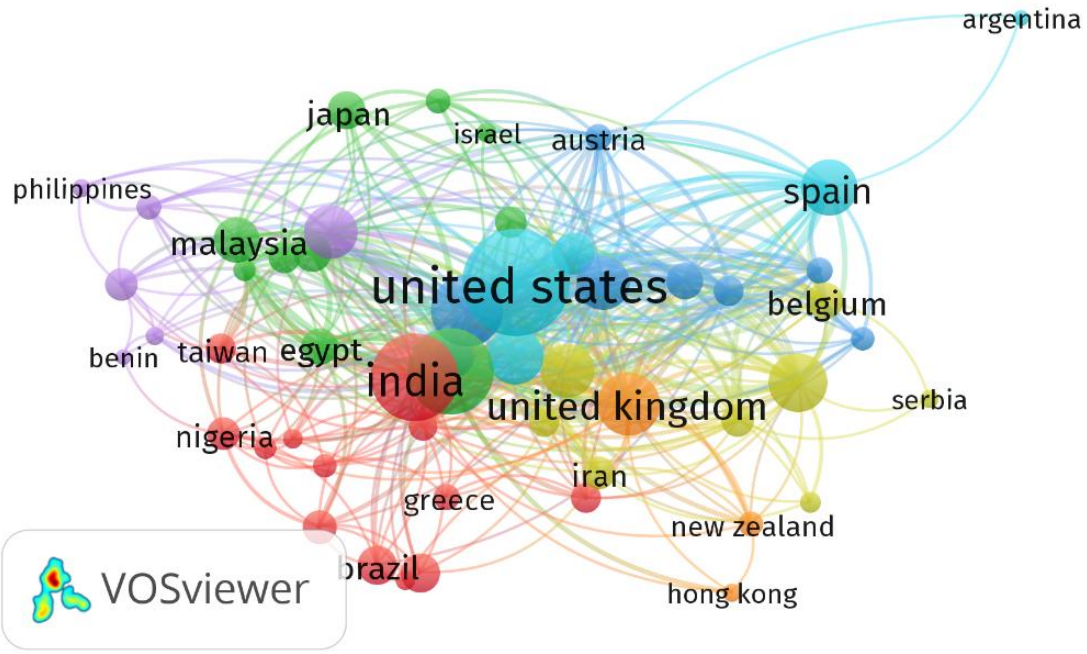

Figure 4: Countries Whose Authors Collaborate On Waste Agriculture In Animal Feed.

The table presenting co-authorship data from the VOSviewer analysis provides an extensive overview of the primary countries involved in research on "Waste Agricultural Material in Animal Feed." The United States possesses 206 documents, 12,111 citations, and a total link strength of 129, underscoring its preeminent position and extensive collaborative network. This robust performance indicates a well-developed research infrastructure and a considerable emphasis on sustainable feed practices and waste management. The elevated citation count signifies that research from the United States exerts considerable influence, directing the trajectory of global research.

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China and India rank as significant contributors, producing 131 and 137 documents, respectively, demonstrating robust research output and notable citation impact (China with 5,004 citations and India with 4,351 citations). China's elevated total link strength (116) indicates its vigorous international partnerships, especially in bioconversion and nutrient recycling within animal feed. India, exhibiting a link strength of 52, showcases a robust network centred on waste valorisation and alternative protein sources. It is propelled by its extensive agricultural sector and the necessity for sustainable livestock feed solutions. The participation of these nations underscores the increasing significance of tackling agricultural waste issues in swiftly advancing economies.

Countries in Europe, such as Germany, the United Kingdom, and Italy, are significant contributors, exhibiting considerable outputs in documents, citations, and collaboration link strength. The United Kingdom possesses 69 documents and 7,238 citations, exhibiting a substantial link strength of 103, which signifies robust research connections both within Europe and globally. Australia, with 51 documents and 3,559 citations, demonstrates significant involvement in sustainable feed research, presumably emphasising environmental considerations and bioconversion technologies. The data emphasises the international scope of this research domain, with engagement from both developed and developing countries, illustrating the collective interest in enhancing agricultural sustainability and maximising the utilisation of waste materials in animal feed production.

Conclusion

The assessment of research trends in "Waste Agricultural Material in Animal Feed" from 2004 to 2024 indicates a notable increase in academic interest, particularly after 2018. The initial phase observed a steady rise in publications, reflecting the exploratory character of early research. The significant increase in academic output around 2021 can be ascribed to heightened awareness of sustainable practices and circular economy models, indicating a global emphasis on waste reduction in agriculture. Despite a minor decrease in publications after this peak, the total volume remains substantial, indicating a persistent interest and continued investigation into optimising agricultural by-products in animal feed. This trend underscores the significance of innovative feed alternatives as a crucial strategy to improve resource efficiency and reduce environmental impact in livestock production. Notable authors have substantially influenced the research field through significant publications addressing the safety, economic feasibility, and environmental consequences of repurposing agricultural waste for animal feed. Elevated citation counts for pivotal studies highlight the necessity of addressing issues like pharmaceutical residues and antimicrobial resistance in waste-derived feed ingredients, reinforcing the imperative for comprehensive safety assessments. The emphasis on converting food industry by-products into valuable feed components corresponds with contemporary trends in sustainable feeding practices and circular economy principles. The analysis demonstrates an interdisciplinary and collaborative approach in this domain, seeking to promote sustainable agricultural systems through efficient waste management and feed innovations.

The bibliometric analysis of "Waste Agricultural Material in Animal Feed" reveals a strong emphasis on sustainability, efficient resource use, and waste valorisation, as evidenced by the prevalent keywords identified through VOSviewer. The dominant themes, including "circular economy," "sustainability," and "agriculture," highlight the focus on integrating waste products into feed systems to enhance environmental performance. Key processes such as "anaerobic

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digestion" and "composting" are frequently studied for their potential to convert organic waste into useful products, indicating a growing trend toward bioconversion technologies. The prominence of terms like "biogas," "biochar," and "black soldier fly" underscores the innovative approaches being explored to utilise waste materials effectively while addressing broader ecological concerns like climate change and greenhouse gas emissions. The analysis of co-authorship collaborations highlights the significant global engagement in this research area, with leading contributions from the United States, China, and India, underscoring the importance of agricultural waste management in developed and developing economies. The strong citation impact from these countries points to influential research outputs that are shaping the field, particularly in areas like bioconversion and nutrient recovery. European nations, including Germany, the United Kingdom, and Italy, also play a key role, contributing substantial research and demonstrating extensive international collaborations. The participation of countries across different regions reflects a collective effort to tackle sustainability challenges, focusing on innovative waste management strategies and alternative feed solutions, which are crucial for advancing sustainable agriculture and optimising livestock production systems.

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