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Bibliometric analysis of biopesticide research trends in Africa

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Abstract: The rapid growth of the global population raises concerns about the ability of production systems to meet food security challenges. In addition to climate uncertainties, pests and diseases are exerting increasing pressure on agricultural yields and the quality of harvests. To address these biological threats, biopesticides have gained increasing attention in recent decades as sustainable and promising alternatives to synthetic pesticides. However, there are notable disparities between countries or regions in terms of research and the adoption of these products. Therefore, this study uses a bibliometric approach to examine scientific literature and provide insights into the current landscape and future trends of biopesticides research in Africa from 1929 to 2024. The results indicated a steady increase in scientific production over the last three decades (1990-2024), with an annual growth rate of 4.92%. The most significant surge occurred between 2015 and 2024, with an average growth rate of 18.35%. South Africa stands out as the most active country in biopesticide research publications, followed by significant contributions from Kenya, Egypt, Nigeria, and Benin. The presence of non-African countries such as the United States, Australia, and the United Kingdom among the key contributors highlights collaborative efforts in this field. The temporal analysis indicated that research focus has shifted to emerging pest control, biopesticide commercialization, and risk assessment of biocontrol agents. While the prospects for biopesticide research in Africa are promising, further efforts are needed to strengthen local capacities, foster partnerships, and promote research initiatives across the continent.

Keywords: Agriculture, Bibliometrix, Biological control, Research collaboration, Scientific production, Sustainability, VOSviewer.

Introduction

United Nations demographic projections predict that the global population will reach 8.5 billion by 2030, 9.7 billion by 2050, and 11.2 billion by 2100 (United Nations, 2015). To meet the rising demand for food by 2050, experts estimate that the agricultural sector will need to boost production by 70% to 100% (Silva, 2018). Meanwhile, the growing impacts of climate change, especially soil degradation and water shortages, pose significant challenges to achieving this goal. Nevertheless, boosting crop productivity face numerous plant health challenges that can reduce yields or affect product quality. In fact, the FAO reports that plant pests and diseases are exerting continuous pressure on production systems, causing annual losses of over 40% in global agricultural output (Kubiak et al., 2022).

Since the mid-twentieth century, chemical pesticides have been a key component of agricultural practices aimed at controlling pests, diseases and weeds. However, their excessive use has led to a number of issues, such as negative effects on the environment and non-target organisms, increased resistance in pests and diseases, and adverse consequences for human health (Mahmood et al., 2016). Therefore, there is a rising demand for pesticide-free foods and a growing recognition of the need to shift from traditional crop protection methods to more sustainable alternatives (Azenzem et al., 2024). In this context, biopesticides are gaining global popularity and hold significant potential in reducing yield losses while safeguarding both the environment and human health. Biopesticides are natural products used to manage agricultural pests and can be derived from a variety of living organisms, including bacteria, viruses, fungi, nematodes, and plants (Oguh et al., 2019). They provide significant advantages over conventional chemical pesticides, thanks to their eco-friendly properties, target specificity, and rapid decomposition without leaving harmful residues. Moreover, they can serve as a vital component of Integrated Pest Management (IPM) programs, helping to minimize the use of traditional biocides.

Biopesticides fall into three main categories: biochemical pesticides (such as pheromones, hormones, botanical pesticides, and emerging molecular biopesticides, including RNAi-based products); microbiological pesticides (including microorganisms); and macrobiological pesticides (like entomopathogenic nematodes and beneficial insects) (Daraban et al., 2023; Fletcher et al., 2020). They function as insecticides, fungicides, nematicides, antifeedants, attractants, and growth regulators. In terms of volume, biopesticides account for 2.5% of the total pesticide market (Soyel et al., 2022). Their market is expanding rapidly, with projections to grow from USD 6.54 billion in 2022 to USD 14.39 billion by 2030, at a compound annual growth rate (CAGR) of 10.34% (Marrone et al., 2023). However, this positive trend should be considered within the wider context of the pesticide market, which is growing at an even faster pace, increasing from a value of USD 104.7 billion in 2021 to an estimated USD 291.4 billion by 2030, with a compound annual growth rate (CAGR) of 12.1%. This highlights the uncertainties surrounding predictions that biopesticide production will match conventional pesticides in market size by the late 2040s to early 2050s (Umetsu and Shirai, 2020). While several factors contribute to the flexibility of these projections, the notable variability in adoption rates, especially in regions like Africa and Southeast Asia, plays a significant role.

Africa accounted for 5% of global pesticide use between 2013 and 2022. During this period, fungicides and bactericides represented 33% of total pesticide use, herbicides 31%, and insecticides 28%. The continent applied the lowest levels of pesticides per cultivated area between 1990 and 2022 (0.45 kg/ha) (FAO, 2024). Although little is known about the adoption rates of biopesticides in Africa, the continent is still in its early stages and accounts for only 3% of the global biopesticide market (Olson, 2015).

However, several countries are making progress by setting standards for biopesticide development and use. For example, seven of the 31 products registered in South Africa are produced in this country mainly from Beauveria bassiana (Hatting et al., 2019). According to FAO (2024), insecticidal biopesticides represented a median share of 1% of total insecticides in Africa, based on data from seven countries over the period 2013 to 2022. Furthermore, research activities could boost adoption rates and contribute to the broader and more sustainable use of biopesticides across Africa. In fact, research on biological control agents closely drives the future growth of the biopesticide market (Chakraborty et al., 2023).

Biopesticide research is a fast-growing field, with a 71.24% increase in the number of studies published worldwide between 2011 and 2021 (Hernandez-Tenorio et al., 2022). However, significant disparities exist between countries and regions in terms of research output (Narandžić et al., 2025). While several analyses have explored biopesticide-related research worldwide and in specific regions, the scientific productivity and collaborative networks of African researchers in this field remain unclear. This study uses bibliometric approach to examine the scientific literature, seeking to understand the current landscape and future prospects of this topic in Africa. To our knowledge, this is the first bibliometric study to assess trends in biopesticide research on the African continent. It aims to uncover publication trends, identify the most active countries and institutions, highlight key contributors, examine collaborative networks, and explore emerging areas for future research. The outcome of this investigation will provide valuable information to researchers, policy-makers and stakeholders seeking to improve the sustainability and resilience of agricultural systems in the region through green alternatives for crop protection.

Materials and Methods

Bibliometric approaches are mathematical and statistical techniques used to analyze large volumes of scientific data. Their primary objective is to classify and quantify interactions between various entities, such as journals, publications, authors, institutions, and countries. These methods provide a visual representation of key topics, recent advancements, and existing gaps within a specific field, helping to assess the development and impact of research. We performed a bibliometric analysis on March 5, 2025, using several search queries to explore trends in biopesticide and biocontrol research across Africa.

Data source

This investigation utilized data from the Scopus scientific database, provided by Elsevier. As one of the largest repositories for scientific journal article citations and abstracts, Scopus is renowned for its extensive collection of peer-reviewed literature across various disciplines, including agriculture. The database is highly valued for its reliability, advanced citation analysis tools, and stringent indexing standards.

Search strategy

To retrieve the scientific literature on biopesticides produced in Africa, we used a search string that combined terms related to biopesticides with the names of African countries. The key terms used were "biopesticide", "botanical insecticide", "Biological pesticide", "biofungicide", "microbial pesticide", "biocontrol agent", "Biological control agent", "bacterial pesticide", "Natural pesticide", "Bioinsecticide", "fungal biopesticide",

"microbial-derived pesticide", "biocontrol", and " Biological control". We used the Boolean operator "OR" to expand the search and retrieve relevant studies in this field based on their titles. The bibliometric analysis covers articles published in the Scopus database up to December 31, 2024. No additional time restrictions were imposed in order to track the evolution of research over time. All document types were included in the search. The results were then refined by excluding publications not related to the continent, even if they contained terms such as “Niger” (e.g. Aspergillus niger) or “Mali” (e.g. Botrytis mali). This process reduced the search results from 717 to 671 publications (Figure 1).

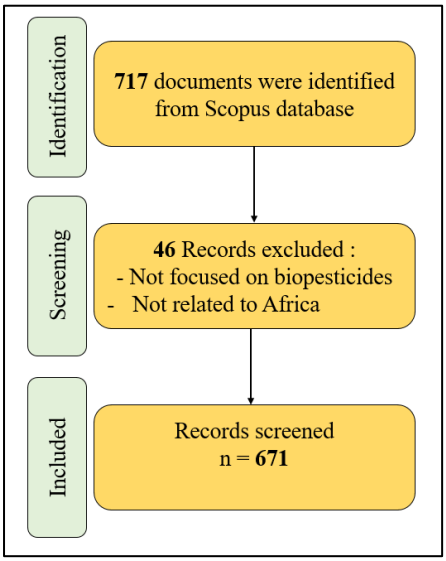

Figure 1. Flow-chart showing the selection process of articles included in the study

Data analysis

After downloading the bibliographic data from the Scopus database, we proceeded with the analysis using two tools: Bibliometrix and VOSviewer. Bibliometrix (University of Naples Federico II, Naples, Italy), an R package, provides a comprehensive set of tools for conducting detailed bibliometric analyses (Aria and Cuccurullo, 2017). It allowed us to calculate bibliometric parameters and map the network. To generate additional visualizations we employed VOSviewer (version 1.6.20, 2023, University of Leiden, Netherlands) (Van Eck and Waltman, 2010). This software has proven effective for such analyses by utilizing the VOS (Visualization of Similarities) mapping technique. VOSviewer offers valuable insights into the evolution of research topics and collaboration models by analyzing co-authorship, co-occurrence, citation patterns, bibliographic coupling, and co-citation (Effendi et al., 2021).

Results

Publications output

The Scopus database included 671 eligible documents published between 1929 and 2024 on the specified topic. 571 were research articles, representing 85% of the total number of documents. Other document types include reviews (63), conference papers (16), book chapters (8), notes (6), erratum (3), short surveys (2), and editorials (2). Their average citation rate is 19.18, indicating a high level of academic impact and recognition.

On average, each document has 3.85 co-authors, with a remarkable international co-authorship rate of 35.62%. This reflects the collaborative efforts of African researchers and the international nature of their research. Furthermore, the large number of keywords highlights the wide range of themes explored in the field. Table 1 summarizes bibliographical data on biopesticide research in Africa.

Table 1. Key indicators of the bibliometric analysis.

DESCRIPTION	COUNT
Timespan	1929 - 2024
Documents	671
Sources (Journals, Books, etc)	219
Keywords Plus (ID)	2 281
Author's Keywords (DE)	1771
Authors	1665
Authors of single-authored docs	71
Single-authored docs	104
Co-Authors per Doc	3.85
International co-authorships %	35.62
Average citations per document	19.18
References	24808
Annual Growth Rate %	3.99
Document Average Age	15.6

It is worth to note that English (97.8%) is the dominant language for biopesticide research in Africa, which is consistent with the global trend in scientific publications. French, with 13 documents (1.9%), is the second most widespread language. Its presence may be due to historical influences and collaboration with French institutions.

With regard to the distribution of research publications on biopesticides in Africa by field of study. “Agricultural and Biological Sciences” leads with 65.2% of the publications, followed by Environmental Science at 12.5%. “Medicine and Immunology” and “Microbiology” each contribute 3.9%, while areas like “Biochemistry, Genetics and Molecular Biology” (3.2%), “Earth and Planetary Sciences (2.4%), and Pharmacology”, “Toxicology and Pharmaceutics” (1.9%) have smaller shares. This highlights a strong focus on agricultural sciences and a more limited involvement from other disciplines in biopesticide research in Africa.

Annual publication growth

The results reveal an interesting trend in the published literature on biopesticides in Africa over the years (Figure 2). They show gradual growth, with more marked increases at certain periods. The annual growth rate from 1929 to 2024 was 3.99%. In the early years (1929-1950s), the number of publications on this subject in Africa was very limited, with only a few documents published per decade. There was a slight increase in publications from the 1960s through the 1980s. This period indicates a slow but steady growth in research efforts in Africa. From the 1990s onward, a significant increase in research output on biopesticides in Africa became apparent. The 1990s saw a shift toward more consistent annual publications (e.g., 29 papers in 1991 and 10 in 1995). The most striking growth in publications occurred from 2010 onward, with the number of published documents reaching significant levels. The most prominent surge occurred between 2020

and 2021, with 53 publications in 2021. The period from 2011 to 2024 shows substantial growth, with numbers consistently ranging between 21 and 53 publications per year.

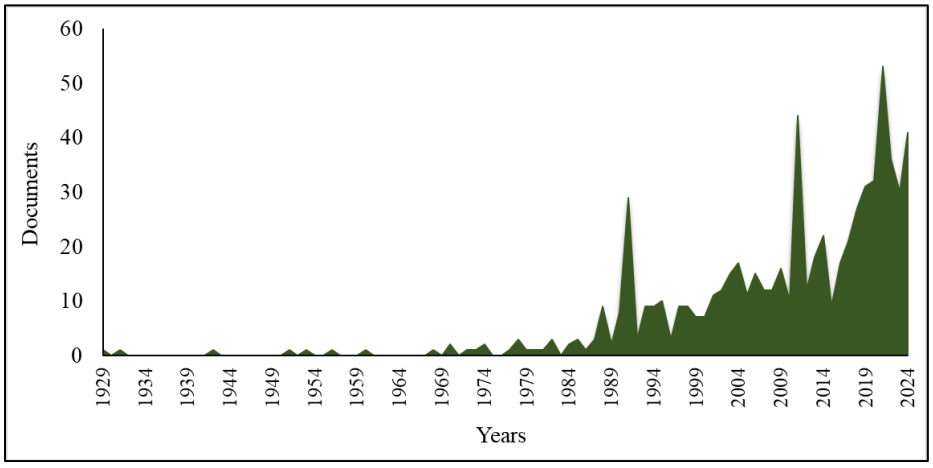

Figure 2. Evolution of scientific research on biopesticides in Africa (1929–2024)

Most relevant sources and institutions

Table 2 displays the top 10 most productive journals and the leading institutions in biopesticide research across Africa from 1929 to 2024. Among the 219 journals that published on the topic, "African Entomology" leads with the highest number of documents (93). The second source is "Biological Control", with 63 papers, followed by "Biocontrol Science and Technology" with 51 publications. On the other hand, the bibliometric analysis identified "Biological Control" as the most influential journal, with the highest h-index (24), g-index (39), and m-index (0.686). "African Entomology" was found to be the second most referenced journal, with an h index of 20.

Table 2 reveals the dominance of South African institutions, with Plant Protection Research Institute (120 publications), Rhodes University (89 publications), and Agricultural Research Council (78 publications) leading the way. In addition, two international research institutions, the International Institute of Tropical Agriculture (IITA), headquartered in Nigeria and the International Centre for Insect Physiology and Ecology (ICIPE), based in Kenya, are making important contributions to this field. Furthermore, the presence of the National Research Center of Egypt (15 publications) in the top 10 reflects the emergence of research on this subject across the continent.

Table 2. Top 10 most productive sources and relevant institutions

RANK	JOURNALS	DOCUMENTS	CITATIONS	H INDEX	INSTITUTIONS	DOCUMENTS
1	African Entomology	93	1645	20	Plant Protection Research Institute - South Africa	120
2	Biological Control	63	1695	24	Rhodes University - South Africa	89
3	Biocontrol Science and Technology	51	489	14	Agricultural Research Council - South Africa	78
4	Biocontrol	37	527	14	University of Kwazulu-Natal - South Africa	53
5	Agriculture, Ecosystems and	23	937	18	University of Cape Town - South Africa	51

6	Environment Bulletin of Entomological research	19	403	9	International Institute of Tropical Agriculture (IITA) - Nigeria	45
7	Entomophaga	15	226	8	International Centre of Insect Physiology and Ecology (ICIPE) - Kenya	44
8	Egyptian Journal of Biological Pest Control	14	174	7	University of the Witwatersrand - South Africa	27
9	International Journal of Pest Management	12	150	6	Commonwealth Scientific and Industrial Research Organisation - South Africa	16
10	Crop Protection	11	231	7	National Research Centre - Egypt	15

Countries contributing to publications on biopesticides in Africa

The bibliometric analysis examined scientific output according to the countries of the corresponding authors. Table 3 provides an overview of the contributions from various countries to biopesticide research in the African continent, ranking them according to the number of publications. South Africa leads the way in terms of volume of articles published and overall citation impact. However, countries like Kenya, Nigeria, Germany, the United Kingdom and the USA demonstrate strong citation per article, indicating that their research is highly influential despite fewer publications.

Table 3. Leading countries of corresponding authors contributing to biopesticide research in Africa

RANK	COUNTRY	DOCUMENTS	PERCENTAGE (%)	TOTAL CITATIONS	AVERAGE CITATION PER ITEM
1	South Africa	206	30,7	3940	19,13
2	Kenya	34	5,1	714	21,00
3	Egypt	25	3,7	308	12,32
4	Benin	16	2,4	251	15,69
5	Nigeria	16	2,4	372	23,25
6	USA	16	2,4	548	34,25
7	Australia	13	1,9	186	14,31
8	United kingdom	13	1,9	277	21,31
9	Germany	10	1,5	301	30,10
10	Morocco	10	1,5	131	13,10
11	Algeria	9	1,3	65	7,22
12	France	8	1,2	29	3,63
13	Tunisia	8	1,2	91	11,38

The Figure 3 shows the number of biopesticide research publications from various African countries between 1929 and 2024. The data reveals clear patterns in the level of research activity across the continent. South Africa is the leading country with 206 publications, accounting for a significant portion of the total research output on

biopesticides in Africa. Other countries, such as Kenya, Egypt, Nigeria, and Benin, also demonstrate notable involvement in biopesticide research. However, many African nations still show limited research activity in this field, indicating the need for further development and investment in agricultural research across the continent.

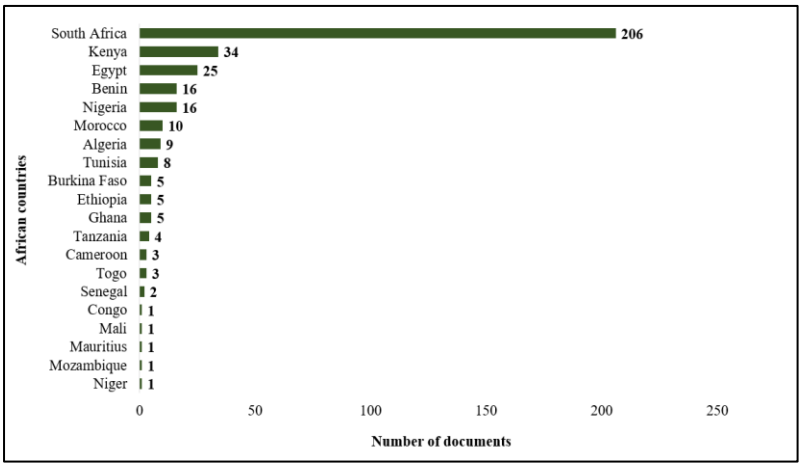

Figure 3. African countries of corresponding authors contributing to biopesticide research in Africa

International collaboration patterns in biopesticide research in Africa

Table 4 shows the balance between single-country and multiple-country publications in biopesticide research across leading countries of corresponding authors. South Africa leads in single-country publications (173) but has only 16% of its research in collaboration. Countries like Kenya (70.6%), Nigeria (75%), and the USA (81.3%) have high percentages of international collaboration, highlighting strong global partnerships. In contrast, some other countries like Morocco, Algeria and Tunisia exhibit lower collaboration rates, indicating more national-focused research.

Table 4. Distribution of inter-country (MCP) and intra-country (SCP) collaborations by corresponding authors' countries.

COUNTRY	DOCUMENTS	SINGLE-COUNTRY PUBLICATION	MULTIPLE-COUNTRY PUBLICATION (MCP)	MCP %
SOUTH AFRICA	206	173	33	16
KENYA	34	10	24	70,6
EGYPT	25	21	4	16
BENIN	16	7	9	56,3
NIGERIA	16	4	12	75
USA	16	3	13	81,3
AUSTRALIA	13	3	10	76,9

UNITED KINGDOM	13	4	9	69,2
GERMANY	10	3	7	70
MOROCCO	10	10	0	0
ALGERIA	9	6	3	33,3
FRANCE	8	2	6	75
TUNISIA	8	6	2	25

The Figure 4 highlights a broad network of international collaborations on biopesticide research, with Kenya, South Africa, and Nigeria as central hubs in Africa. These countries frequently collaborate with global partners, particularly from the United Kingdom, USA, China, Germany, Australia and France.

Figure 4. Collaborations on biopesticide research in Africa: co-authorship strength indicated by line thickness. (Source: Bibliometrix).

We employed VOSviewer software to better display bibliographic coupling among countries regarding biopesticides in Africa. From 1929 to 2024, research articles on this topic were published across 85 countries. After setting the minimum number of documents at five, 38 met the benchmark. Five clusters were identified based on collaborations among the 38 leading countries (Figure 5). Countries in **Cluster 1** (red) exhibit a broad range of collaborations, especially between European and African nations. The most notable contributors are United Kingdom, Egypt, and Benin, reflecting significant scholarly engagement and citation impact. Other European countries such as France, Belgium, and Switzerland collaborate closely with African nations, indicating strong international partnerships. The data reveals varied collaboration levels, with Egypt and Benin standing out as key players, while Algeria, Morocco, and Tunisia show moderate involvement. **Cluster 2** (green) features significant collaboration between Nigeria, United States, and China, which are major contributors to the research output. Nigeria emerges as a central country in biopesticide research in Africa, with an impressive number of documents and citations. The United States and China, both with high citation counts, indicate that African nations are drawing substantial research influence from these global powerhouses. Other countries in this cluster, such as Ghana

and Tanzania, demonstrate strong regional cooperation. In **Cluster 3** (blue), South Africa leads with a significantly higher number of citations and documents, showing its central role in biopesticide research within Africa. Its collaboration with countries like Australia suggests a strong international network. **Cluster 4 (yellow)** features countries such as Germany, India, and Kenya. Kenya stands out with the highest number of documents and citations in this cluster, reflecting its growing role as a hub for biopesticide research in Africa. Its collaboration with global leaders in research such as Germany and India, suggests a robust exchange of knowledge, technology, and funding. **Cluster 5** (purple) represents Uganda, with a modest number of publications on the subject but notable citations and 21 collaborative links with other countries.

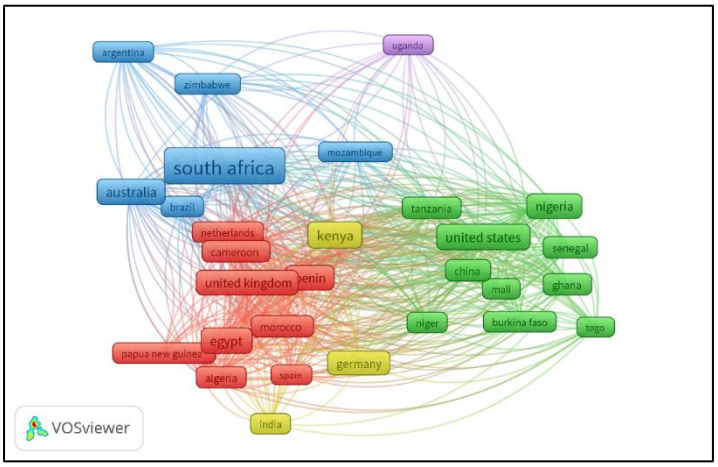

Figure 5. Network visualization diagram based on Co-authorship of countries

Overlay visualization (Figure 6) in VOSviewer is ideal for mapping temporal trends and publication patterns between countries, allowing us to observe how biopesticide research in Africa has evolved in different countries and how international collaborations have developed over time. The data reveals that India, Germany, Papua New Guinea, Benin, Uganda, and Zimbabwe had significant publication activity around 2005, with many of their key contributions appearing in this period. This indicates that while biopesticide research in Africa has attracted some interest in the past in these countries, this interest has not continued at the same pace or intensity in recent years. In contrast, countries like Cameroon, China, Senegal, Burkina Faso, Algeria, Spain, Morocco, Switzerland, Tanzania, and Niger have seen a notable increase in their research output around 2020, indicating a more recent surge in biopesticide-related publications. Contributors from countries such as South Africa, Kenya, Egypt, Nigeria, Australia, Argentina, the UK and the USA have maintained stable growth since 2011.

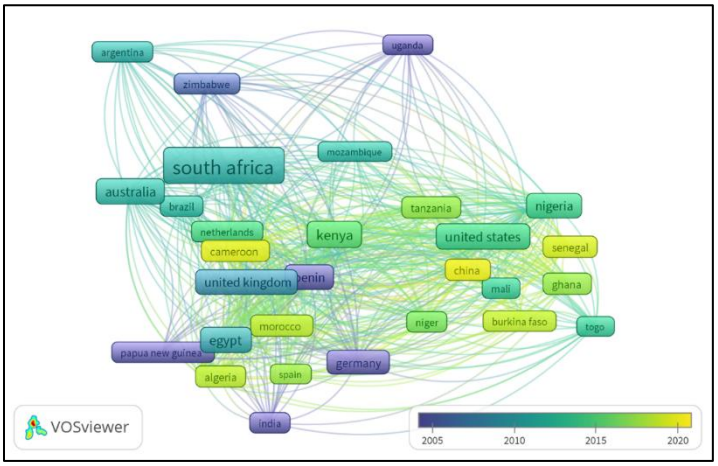

Figure 6. Co-authorship network of leading biopesticide research countries in Africa, by average year of publication.

Highly cited publications

Table 5 highlights the most influential publicaions on biopesticides and biological control in Africa. The top-ranked document by Bandyopadhyay et al. (2016) garnered 238 citations at an average of 23.8 citations per year. The authors discuss how Aflasafe, a biocontrol product made from non-toxic strains of Aspergillus, helps reduce aflatoxin contamination in crops by over 80% in sub-Saharan Africa. They also highlight challenges like climate change and market concerns in expanding its use. Another highly cited study by Stevenson et al. (2017) reviews the potential of botanical insecticides for pest management in Africa, emphasizing their growing importance due to regulatory changes and environmental concerns. Its relevance lies in highlighting the untapped potential of indigenous plant species for pest control, while proposing strategies to fill research gaps and promote commercialization for the benefit of African agriculture. The other highly cited publications in the top ten cover various biocontrol strategies in Africa, including aflatoxin reduction, malaria control, the use of nematodes and parasitoids to control pests, as well as biocontrol of invasive aquatic plants and diseases in crops like sorghum and tomato. These studies are significant due to their contributions to sustainable pest management strategies and their broad interdisciplinary appeal. The data shows also that biocontrol strategies in Africa have garnered increasing attention over the years, reflecting a growing interest in sustainable practices.

Table 5. Top 10 highly cited publications related to biopesticide in Africa

RANK	AUTHORS	TITLE	JOURNAL	YEAR	TC	TC/YEAR
1	Bandyopadhyay et al. (2016)	Biological control of aflatoxins in Africa: current status and potential challenges in the face of climate change	World Mycotoxin Journal	2016	238	23,80
2	Stevenson et al. (2017)	Pesticidal plants in Africa: A global vision of new biological control products from local uses	Industrial Crops and Products	2017	180	20,00
3	Wu and Khlangwiset (2010)	Health economic impacts and cost-effectiveness of aflatoxin-reduction strategies in Africa: case studies in biocontrol and post-harvest interventions.	Food additives and contaminants	2010	177	11,06
4	James et al. (2018)	Pathway to deployment of gene drive mosquitoes as a potential biocontrol tool for elimination of malaria in sub-Saharan Africa: recommendations of a scientific working group.	The American journal of tropical medicine and hygiene	2018	156	19,50
5	Malan et al. (2011)	Isolation and identification of entomopathogenic nematodes from citrus orchards in South Africa and their biocontrol potential against false codling moth	Journal of invertebrate pathology	2011	151	10,07
6	Coetzee et al. (2011)	A review of the biological control programmes on Eichhornia crassipes (C. mart.) solms (Pontederiaceae), Salvinia molesta DS Mitch.(Salviniaceae), Pistia stratiotes L.(Araceae), Myriophyllum aquaticum (vell.) verdc.(Haloragaceae) and Azolla filiculoides Lam.(Azollaceae) in South Africa	African Entomology	2011	139	9,27
7	Spradbery and Kirk (1978)	Aspects of the ecology of siricid woodwasps (Hymenoptera: Siricidae) in Europe, North Africa and Turkey with special reference to the biological control of Sirex noctilio F. in Australia	Bulletin of Entomological Research	1978	127	2,65
8	Kenis et al. (2019)	Telenomus remus, a candidate parasitoid for the biological control of Spodoptera frugiperda in Africa, is already present on the continent	Insects	2019	124	17,71
9	Idris et al. (2007)	Screening rhizobacteria for biological control of Fusarium root and crown rot of sorghum in Ethiopia.	Biological control	2007	124	6,53
10	Lemessa and Zeller (2007)	Screening rhizobacteria for biological control of Ralstonia solanacearum in Ethiopia.	Biological control	2007	121	6,37

Keyword co-occurrence analysis

Term co-occurrence analysis identifies the relationships between keywords in a selected set of publications, reveals thematic clusters, and highlights the key topics within a research area. Figure 7 reveals that "Biological control" is the most prominent theme, appearing 198 times, followed by "South Africa" with 131 occurrences. "Biological control agent" closely follows with 80 mentions. Other frequently occurring keywords in the top 10 include "coleoptera", "Africa", "weed control", "biological pest control", "hexapoda", "lepidoptera", and "curculionidae."

Figure 7. Word cloud of the most frequently used keywords in biopesticide research in Africa

Figure 8 illustrates the keyword co-occurrence network in biopesticide research in Africa. With a minimum occurrence threshold of 20, 42 keywords were selected from a total of 3,505. The analysis revealed four clusters, consisting of 656 links and a total link strength of 4,009. Clusters 1, 2, 3, and 4 include 16, 13, 9, and 4 keywords respectively. **Cluster 1** (Red) focuses on the broad themes of biological control and pest management strategies, with key keywords like biocontrol, biological control agent, biological pest control, and biopesticide. This cluster also emphasizes agricultural challenges in Africa, specifically in countries like Kenya and Nigeria, highlighting the importance of fungi, maize, and pest control in improving sustainable farming practices. **Cluster 2** (Green) highlights the biological control of weeds and pests, with a strong emphasis on insect orders like Coleoptera and Lepidoptera, as well as plant species like *Lantana camara*. It underscores the ecological aspects of biocontrol, particularly in Sub-Saharan Africa, focusing on insect-host relationships and specificity. **Cluster 3** (Blue): This cluster reflects biocontrol strategies in South Africa and Australia, focusing on invasive species, weed management, and the role of beetles and other insects in biocontrol. Keywords like "weed biocontrol" and "biological control" suggest an emphasis on managing invasive plant species through natural pest control methods. **Cluster 4** (Yellow) delves into the role of parasitism and parasitoids, with a particular focus on insect orders like *Hemiptera* and *Hymenoptera*. This cluster emphasizes the potential of parasitoids in natural pest control, underscoring their ecological importance in regulating pest populations and promoting sustainable agriculture.

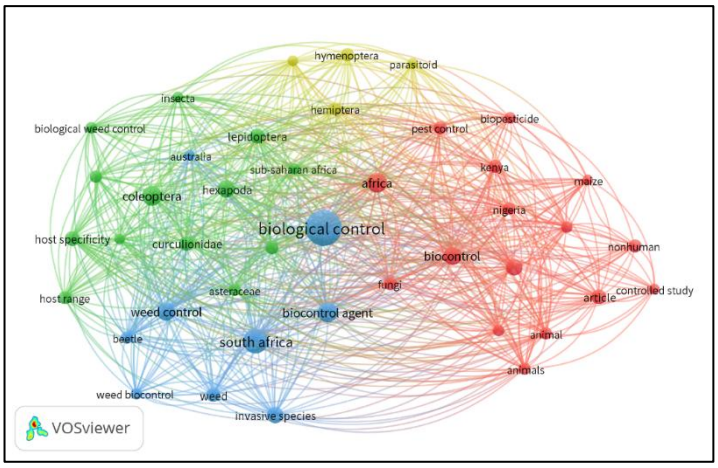

Figure 8. Network visualization diagram of keywords.

Temporal shifts in research focus

Figure 9 reveals several trends and shifts in biopesticide research in Africa over time. In the early years (1990s to early 2000s), research focused mainly on specific pest species that had a significant impact on key crops. The most notable pests were *Phenacoccus manihoti* (cassava mealybug) and *Rastrococcus invadens* (mango mealybug), both of which posed a major threat to crops such as cassava and mango. These pests were at the heart of early biopesticide research, reflecting a direct concern for crop protection. The frequency of terms such as “manioc” and “mango” during this period underlines the importance attached by the continent to the control of pests of high-value crops, important to the African agricultural economy.

In addition, the appearance of the term Prosopis (a plant potentially usable for biocontrol) indicates a growing interest in the use of natural resources in pest management. This period also saw the introduction of biological control, marking the beginning of the recognition of biocontrol as an alternative pest management strategy in Africa.

As the research moved into the late 2000s, there was a noticeable shift towards addressing the growing problem of invasive species and weeds. The term "biological weed control" saw an increase in frequency, and the research expanded to include various invasive plants like *Lantana camara* and bugweed. This evolution reflects a broader understanding of ecological balance, as researchers look at the impact of invasive species not only on agriculture, but also on ecosystems in general. The introduction of terms such as "host range," "host specificity," and "weed biocontrol" in the 2000s and 2010s illustrates the growing need for targeted, sustainable solutions in managing weeds and invasive species. Research has evolved to ensure that biocontrol agents are pest-specific and do not harm non-target species, indicating the development of more refined biocontrol strategies.

By the 2010s, biocontrol research had shifted to a more integrated approach. The increased frequency of terms like "biocontrol," "weed biocontrol," and "integrated pest management" suggests that researchers were now considering a broader, more holistic approach to pest and weed management, moving beyond single-species solutions to more complex, multi-faceted strategies. In this period, there was a notable rise in research on "biopesticides," as the industry began focusing more on practical applications. The growing presence of "biopesticides" and "biocontrol" alongside terms like "natural enemies," "parasitoids," and "biodiversity" reflects the ongoing effort to integrate

biopesticides into larger pest management systems. Additionally, terms like "risk assessment" and "post-release evaluation" that emerged in the 2020s highlight an increasing focus on the safety, effectiveness, and environmental impact of biocontrol agents.

In the most recent period (2020s), there is a clear trend towards the commercialization of biopesticides and an emphasis on their long-term impact and effectiveness. The rise of terms such as "biopesticide" and "biocontrol" reflects the growing market for these products. Research now includes post-release evaluations of biocontrol agents to ensure they continue to be effective and safe in the field. The increase in research on "*Spodoptera frugiperda*" (fall armyworm) and "*Aspergillus flavus*" (a fungal toxin) indicates a continued focus on addressing new and emerging pest threats, particularly those impacting staple crops like maize.

The appearance of terms like "aflatoxin" and "biodiversity" in recent years further suggests that biopesticide research is becoming increasingly intertwined with broader concerns such as food safety and ecological sustainability. The growing focus on integrated pest management (IPM) and risk assessment reflects a trend toward ensuring that biopesticides contribute to sustainable agriculture without negatively affecting ecosystems.

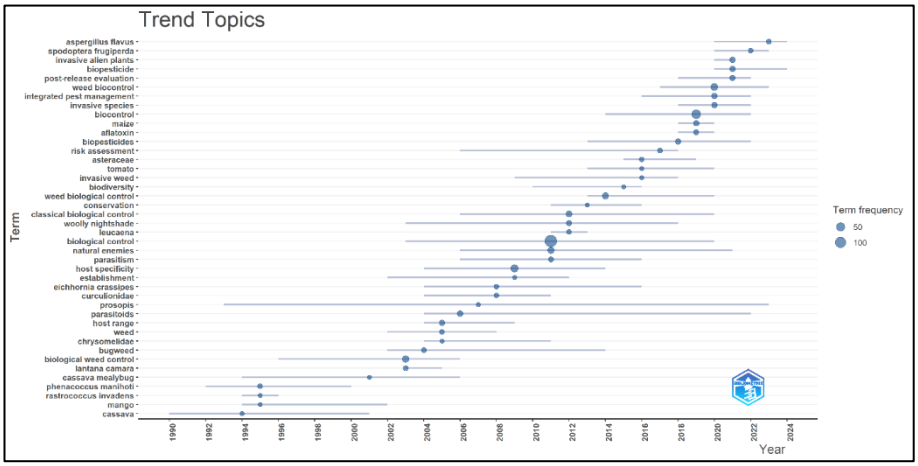

Figure 9. Visual representation of trends in biopesticide research in Africa over time through keywords using Bibliometrix.

Discussion

The steady increase in publications from 1990 to 2024 reflects the growing recognition of biopesticides as a sustainable solution for agriculture in Africa, driven by the global shift towards alternatives to chemical pesticides (Kumar et al., 2021; Šunjka and Mechora, 2022). Notably, the period between 2015 and 2024 experienced an even more pronounced surge in publications, with an average annual growth rate of 18.35%. This surge may be attributed to intensified international research collaborations, targeted funding for sustainable pest management, and stronger national policies promoting biopesticide adoption across the continent. These trends are consistent with other studies, such as Narandžić et al. (2025), which have also highlighted the increasing importance of biocontrol agents and biopesticides worldwide as key elements of modern pest management strategies. The rising interest is reflected both in scientific research exploring novel biocontrol agents and in the expansion of the global biopesticide market.

Analysis of biopesticide research activities in Africa revealed clear regional leaders, with South Africa at the forefront, contributing significantly to the body of literature on the subject. Our results are consistent with earlier studies that highlight South Africa and Kenya as leaders in biopesticide development and use (Akutse et a., 2020). South Africa's leadership in this area can be attributed to the strength of its agricultural sector, its specialist research institutions and its longstanding emphasis on integrated pest management (IPM) and biocontrol solutions. The presence of key research institutions such as the Agricultural Research Council (ARC) and several universities reinforce the country's leadership in advancing biopesticide research. In addition, the growth of biopesticide research and development in South Africa has been strongly supported by initiatives like the launch of the National Bioeconomy Strategy, the creation of the South African Bioproducts Organisation (SABO), and the introduction of updated biopesticide registration guidelines in 2015. Over the past decade, this support has led to substantial progress, including the registration of more than 30 biopesticides, including seven manufactured locally (Hatting et al., 2019). Countries, such as Kenya, Egypt, Nigeria and Benin, are also making valuable contributions to biopesticide research, reflecting the growing interest in sustainable pest management solutions across the continent. Nevertheless, many other African nations still exhibit limited activity in this area. This disparity can be attributed to various factors, such as inadequate research infrastructure, limited financial resources, and the absence of strong policy support. Other contributing factors include outdated or underdeveloped regulatory frameworks, a significant knowledge gap, challenges in market access and commercialization, and a lack of effective collaborations, both among African countries and with international partners.

In the present study, non-African countries such as the United States, Australia, the United Kingdom, Germany, and France are among the top contributors, demonstrating their support for biopesticide research efforts in Africa. Through funding initiatives, collaborative research, and expertise sharing, these countries contribute to building the capacity of African researchers and institutions. By fostering partnerships between research institutions, governments, industry stakeholders, and international organizations, countries can leverage their respective strengths and build a stronger and more innovative biopesticide research landscape. An analysis of collaboration patterns in biopesticide research among African countries reveals that international partnerships play an important role in advancing research and development in this field. Our findings align with existing literature, highlighting the essential role of collaboration in advancing biopesticide research (Ndolo et al., 2019). Our bibliometric investigation underline numerous collaborations between African countries themselves and with those from other continents, particularly Europe, Asia, and North America. Southern Africa leads in collaboration with non-African countries, particularly through South Africa, which has extensive research partnerships with Australia, the UK, and the USA. East Africa, led by Kenya, is actively engaging with global partners such as China, the UK, the USA and the EU. West Africa demonstrates significant partnerships, particularly through Benin and Nigeria, with frequent collaborations with countries such as China, France and the United States. In North Africa, Egypt and Morocco are leading countries in biopesticide research and benefit from collaborations with countries in Europe and the Middle East. A complex mix of factors influences these collaborations, including historical ties, linguistic commonalities, economic interests, shared agricultural challenges, and similarities in agroclimatic conditions (e.g., comparable latitudes and climates).

The keyword co-occurrence analysis conducted in this study provided a comprehensive overview of the central themes and key research areas in biopesticide research across Africa. Our findings emphasize the dominant role of biological control in this field and highlight South Africa's significant contribution to biopesticide research on

the continent. Additionally, the analysis underscores the importance of biocontrol agents as specific organisms (such as bacteria, fungi, or insects) used in biological pest control methods. The frequent references to specific insect orders and weed control underscore the wide-ranging scope of biopesticide research in Africa, reflecting a focus not only on particular insect groups but also on a holistic approach to managing biotic constraints across different ecological levels. This multidimensional aspect of biopesticide research is further highlighted by the identification of four distinct keyword clusters. In fact, the clusters focus on a broad range of topics, including biological control of weeds and pests, invasive species, and parasitism and parasitoids. This echoes the findings of existing literature pointing the multifaceted nature of research on biopesticides (Krismawati et al., 2024; Ragasruthi et al., 2024; Ikhwani et al., 2024).

This study underscored that biopesticide research in Africa has significantly evolved over time. In the 1990s, the focus was primarily on tackling specific pest species that severely affected key crops like cassava and mango mealybugs, with methods relying on natural substances and indigenous practices. Today, the emphasis has shifted towards the commercialization of biopesticides, with a growing focus on the safety, effectiveness, and environmental impact of biocontrol agents. Although biopesticides offer significant environmental and health benefits over conventional chemical pesticides, different risks may be associated with their use (Daraban et al., 2023). In fact, they encompass a wide range of products, including microbial agents (such as bacteria, fungi, and viruses), plant extracts, and natural substances, each with its own distinct risk profile. Risk assessments, supported by scientific data, guide national decisions on licensing, initial registration, and re-registration. Once a biopesticide passes risk assessment and regulatory approval, it enters the commercialization phase. However, in developing regions with limited resources, comprehensive environmental impact assessments are particularly scarce. Some researchers argue that the approval process for biopesticides constitutes a major barrier to their commercialization, with high registration fees and lengthy submission procedures further complicating the process of bringing these products to market (Damalas and Koutroubas, 2018).

Although biopesticides are often expected to require lower development costs and less extensive data packages than conventional chemical pesticides, the reality of regulatory approval can still present substantial hurdles. For comparison, the development of conventional chemical pesticides can exceed USD 250 million and take more than 10 years, involving extensive toxicological and environmental testing (Chio and Li, 2022). Along the same lines, the registration of microbial biopesticides in the European Union may take up to 10–11.5 years for low-risk products such as nucleopolyhedroviruses, approximately 45% longer than in the United States (Frederiks and Wesseler, 2019). These regulatory processes, often modeled after chemical pesticide frameworks, result in disproportionately high costs and delays, stifling investment and innovation, particularly for small and medium-sized enterprises (Malek et al., 2026). Consequently, despite the lower upfront development costs, the commercialization of biopesticides can be delayed and constrained, especially in regions without dedicated regulatory pathways or streamlined approval mechanisms.

Our temporal analysis highlighted that there remains a continued focus on addressing emerging pest threats, particularly those affecting staple crops. Climate change and the growing scale of global trade are expected to heighten the prevalence of pests and diseases, promoting the spread of new invasive pests into regions that were previously unaffected (Azenzem and Eddomairi, 2025). For example, the fall armyworm (Spodoptera frugiperda), originally from the Americas, has recently spread across much of Africa, posing a significant threat to food security by damaging cereal crops (Fan et al.,

2020). Insecticides are a key part of current pest management strategies. However, researchers in various African countries, including Ethiopia, Kenya, Tanzania, Senegal, Ivory Coast, Benin, Niger, and Ghana, are exploring the potential of parasitoids and predators as biological control agents (Agboyi et al., 2020).

Biopesticide research in Africa is promising due to the growing need to explore and develop new biopesticides derived from natural sources, including native plants, fungi, bacteria, viruses, and beneficial insects. The ecological, economic, and social benefits associated with these solutions make this a strategic area for the future of agriculture on the continent. In the digital era, the integration of artificial intelligence (AI) and the Internet of Things (IoT) in research could improve the development, application, and commercialization of biopesticides in this region. Nevertheless, advancing biopesticide research in Africa will require building scientific and technical capacity, investing in research, encouraging international and regional collaborations, and implementing supportive policies. Through these efforts, African countries will be able to establish a robust biopesticide industry that promotes sustainable agriculture, strengthens food security, and drives economic growth across the continent.

Conclusion

This study provided an outlook of the scientific production in biopesticide research across Africa from 1929 to 2024, based on an analysis of records in the Scopus database. Using bibliometric methods, it highlighted the most influential institutions, sources, countries, documents, and research themes in this field. The last three decades has seen a growing trend in scientific production, underlining the rising recognition of the potential benefits of biopesticides across the continent. South Africa stands out as the most active country in biopesticide research publications, with significant contributions from countries such as Kenya, Egypt, Nigeria, and Benin. Notably, non-African countries like the USA, Australia, and the UK are also among the top contributors. Researchers from these nations are working alongside their African counterparts to foster the growth and development of biopesticide research across the continent. This work outlined the fact that biopesticide research in Africa has evolved considerably over time. It now focuses on the control of emerging threats and the commercialization of biopesticides, with growing interest in the safety, efficacy and environmental impact of biocontrol agents. This area of research holds great promise, due to the benefits of these biological solutions, the continuous emergence of new crops threats, and the use of innovative technologies and research tools. However, efforts should focus on strengthening local capacities, promoting partnerships and encouraging research initiatives on this subject in all African countries.

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