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# Global Research Dynamics on Agro-Ecological Zones and Units: Mapping Themes, Thematic Shifts, and Emerging Research Patterns

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## Abstract

*This study presents a comprehensive bibliometric analysis of global research trends in Agro-Ecological Zones (AEZ) and Agro-Ecological Units (AEU) from 2000 to 2024. AEZ and AEU are foundational frameworks for assessing land suitability, crop productivity, and sustainable agricultural practices. Utilizing data from the Scopus and Web of Science databases, a total of 2,406 documents were analysed after deduplication. The study reveals a steady increase in research output, with the number of publications rising from 18 in 2000 to a peak of 228 in 2021, indicating an annual growth rate of 9.83%. These publications were spread across 928 sources, including journals, books, and conference proceedings, with an average of 17.54 citations per document, reflecting strong academic engagement. A total of 8,434 authors contributed to the literature, with a co-authorship pattern averaging 4.07 authors per document. While 135 documents were single-authored, only 121 unique authors accounted for these, suggesting that collaborative research predominates in this field. International collaboration is notable, with 26.23% of publications involving authors from multiple countries. The study identifies key publication trends, leading authors, prominent institutions, and global collaboration networks. The thematic evolution analysis identifies a clear progression in research focus from organism specific, soil, and crop-level studies to integrated, system-wide approaches highlighting a shift toward yield optimization, sustainability, agro-ecological classification, and emerging emphasis on spatial planning, adaptive capacity, and climate-resilient agricultural strategies. This bibliometric review offers key insights into the evolution of AEZ and AEU research, supporting its use in sustainable land-use planning and agricultural development.*

**Keywords:** Agro-Ecological Zones, Agro-Ecological Units, Bibliometric Analysis, Sustainable Agriculture, Agro Ecology, Research Trends

## 1 Introduction

Agroecological zones (AEZs) are geographical areas exhibiting similar climatic conditions that determine their ability to support rainfed agriculture. At a regional scale, AEZs are influenced by latitude, elevation, and temperature, as well as seasonality, and rainfall amounts and distribution during the growing season [8]. Agro-

ecological zones embody complex interactions between agricultural practices and ecological systems, presenting a vibrant and multifaceted landscape essential for sustaining agricultural productivity and mitigating ecological degradation. This paper, aims to comprehensively analyse the vast array of literature related to agro ecological zones (AEZ) through bibliometric techniques. By systematically examining scholarly contributions, this study seeks to map

the existing research landscape and identify trends, gaps, and opportunities for future inquiry.

The framework of agro-ecological zoning allows researchers and practitioners to understand the spatial distribution of different agro-ecosystems and their corresponding attributes such as climate, soil type, and vegetation. The multi-dimensional approach inherent in agro-ecological research recognizes not only the physical and biological characteristics of these zones but also socio-economic factors affecting agricultural production and sustainability practices. The vulnerability of smallholder farmers to climate variability across various agro-ecological zones underscores the necessity of tailored adaptation strategies that can enhance resilience [4]. The implications of appropriate agricultural practices suitable for specific AEZ, which can enhance productivity and ensure the sustainable utilization of natural resources, although the specific details of their findings need further context [3].

Past studies using bibliometric methodologies have underscored critical themes such as the impact of climate variability, agricultural biodiversity, and ecosystem services within AEZ [9]. Scholarly works, including those by Suyunov et al., illustrate the intricate relationships between ecological, geographical aspects, and agricultural practices, reinforcing the need for localized strategies to foster sustainable agro-landscapes [9]. This paper will build upon these foundational insights, utilizing bibliometric analysis to distill knowledge patterns, research productivity, and the evolution of key topics related to agro ecological units.

The significance of agro-ecological zones is also amplified in the context of global challenges such as biodiversity loss and the need for sustainable agricultural solutions. Recent literature has pointed towards the critical role of agro diversity in enhancing nutrient cycles and sustaining production systems, making a clear case for the adoption of agro-ecological practices. This aligns with findings from scholars like Remans et al., who demonstrate the importance of diverse cropping systems in addressing micronutrient deficiencies prevalent in various populations [7].

Past research has demonstrated that the classification and understanding of AEZs provide critical insights that can optimize agricultural outputs and sustain local livelihoods [11]. The relationship between agroecological classifications

and specific agricultural practices, such as crop selection and pest management, underscores the imperative for a thorough understanding of agroecological units. Such knowledge is pivotal for crafting resilient farming systems that can adapt to both current ecological challenges and future uncertainties posed by climate change [10].

This bibliometric analysis will serve as a vital tool in delineating the current research terrain concerning agro-ecological zones, offering insights into the dynamics of publications, citations, and emerging themes. By utilizing systematic review techniques and bibliometric tools, this study aims to not only catalog existing academic contributions but also pave the way for future research directions that address critical challenges faced by agro-ecological systems, thus contributing to sustainable practices that enhance food security and ecological resilience

## 1.1 Need and Significance of the Study

Agro-ecological zones (AEZ) and agro-ecological units (AEU) play a crucial role in sustainable agricultural planning, resource management, and food security. As agricultural landscapes face increasing pressures from climate change, soil degradation, and changing land-use patterns, understanding the dynamics of agro-ecological research becomes essential. Scientific insights into AEZs and AEUs are vital for developing region-specific agricultural strategies, promoting climate-resilient practices, and ensuring sustainable food production. Despite the growing body of research in this field, the evolution of agro-ecological studies, key contributors, research hotspots, and knowledge gaps remain insufficiently explored.

A bibliometric analysis offers a comprehensive and data-driven approach to systematically map the research landscape, track the growth of publications, assess the influence of prominent studies, and uncover emerging themes and research frontiers. This study aims to provide a clear understanding of the global research trends in agro-ecological zones and units, identify collaboration networks, and evaluate the impact of scientific contributions. The insights derived from this analysis will support evidence-based policymaking, encourage interdisciplinary collaboration, and guide future research to address the pressing challenges in agricultural sustainability.

## 1.2 Objectives

- To analyse publication trends and research growth in agro-ecological zones (AEZ) and agro-ecological units (AEU).
- To assess the most influential countries, authors, and documents by evaluating citation patterns, average article citations, and international collaboration networks in the field of agro-ecology.
- To explore thematic evolution and research fronts by examining the development of major research themes over time using thematic maps and keyword analysis.
- To identify emerging and declining research themes using the factorial analysis method (MCA) and assess the evolution of scientific discourse in agro-ecological research.

## 2 Methodology

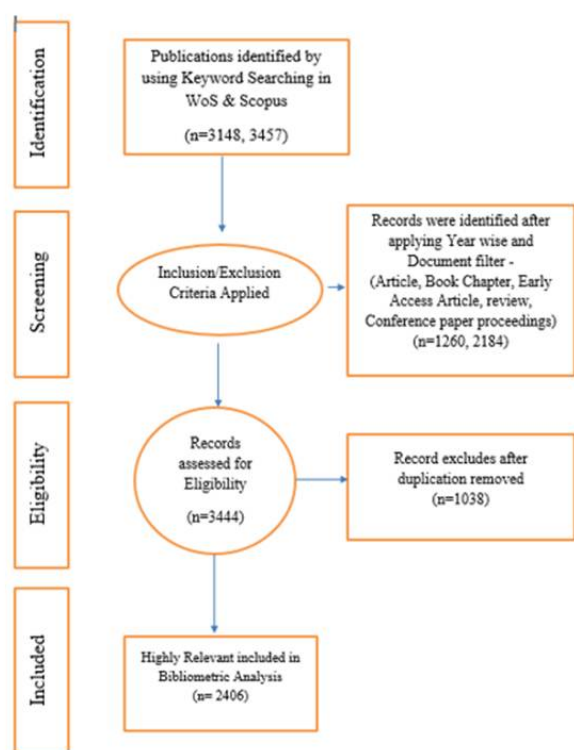


Fig. 1: Methodology flow chart

To systematically map the research landscape of agro-ecological zones (AEZ) and agro-ecological units (AEU), this study employs a bibliometric analysis covering

publications from 2000 to 2024. Bibliometric analysis is a quantitative research method used to evaluate the structure, impact, and trends within a scientific domain through statistical and network-based approaches [1]. By applying quantitative methods, this approach identifies key trends, influential works, and emerging themes in the field.

Relevant scholarly articles, reviews, and conference papers were systematically retrieved from Web of Science and Scopus ensuring a comprehensive and high-impact dataset. The search strategy incorporated a combination of keywords related to agro-ecological zones, agro-ecological units, agricultural sustainability, and climate-resilient agriculture, enabling a precise and targeted analysis of the field's academic contributions.

### 2.1 Data Collection

The study utilized specific keywords to conduct a comprehensive search in academic databases like Web of Science and Scopus. The keywords used for conducting a bibliometric analysis in Web of Science and Scopus include *aeu*, *aez*, *aez model*, *agro-ecological zone*, *agro-ecological zones*, and *agroecological zoning*. The search query has been used for extracting documents from Scopus and Web of Science (WOS) are listed below;

**WOS;** *ts*=(*"AEU OR aez OR aez model OR agro-ecological zone OR agro-ecological zones OR agroecological zoning"*)

**Scopus;** *TITLE-ABS-KEY* ( *aeu OR aez OR "aez model" OR "agro-ecological zone" OR "agro-ecological zones" OR "agroecological zoning"* )

### 2.2 Data Preprocessing

The bibliometric analysis spans from 2000 to 2024, encompassing a total of **2,406 documents** from **928 sources** such as journals, books, and conference proceedings. In terms of document types, the majority of contributions are **articles (2,090)**, followed by **book chapters (96)** and **conference papers (90)**. Other types include **reviews (28)**, **errata (28)**, and a limited number of **books (8)**, **data papers (1)**, and **early access articles (7)**. The presence of **proceedings papers (28)** indicates active participation in academic conferences, contributing to the dynamic discourse in the field. This comprehensive bibliometric overview provides a robust foundation for analysing research trends, identifying knowledge gaps, and understanding the evolving landscape of agro-ecological zones and unit's research.

In bibliometric analysis, merging data from sources like Web of Science and Scopus involves extracting key bibliographic details and removing duplicates using criteria such as DOI and title similarity. In this study, **1,038 duplicate** records were eliminated to ensure a clean and reliable dataset.

### 2.3 Data Analysis

The analysis was conducted using specialized bibliometric tools, Biblioshiny (an R-based bibliometric package) (Aria and Cuccurullo, 2017). The following techniques were applied:

- **Descriptive Analysis:** Examined publication patterns, key journals, leading authors, and citation metrics to understand overall research output.
- **Co-occurrence Analysis:** Analysed keyword relationships to reveal the thematic structure of the research domain through network visualizations.
- **Thematic Mapping:** Classified research themes using a two-dimensional framework based on their relevance and level of development, categorizing them into Basic, Motor, Niche, and Emerging/Declining Themes.
- **Collaboration Network Analysis:** Investigated international research collaborations at the country level to identify major research centers and global partnerships.
- **Thematic Evolution Analysis:** Tracked shifts in research focus over time using Sankey diagrams to illustrate how themes have evolved across different periods.

## 3 Descriptive analysis of a bibliographic data frame

### 3.1 Annual Scientific Production

The analysis of the annual scientific production on agro-ecological zones and units from **2000 to 2024** reveals a significant upward trend in research activity. The number of articles published per year has grown from **18 articles in 2000** to a peak of **228 articles in 2021**, reflecting a growing academic interest in the subject. Notable increases are observed after **2010**, with the annual publication rate consistently exceeding **100 articles from 2014 onwards**. This surge in publications could be attributed to increasing global concerns about agricultural sustainability, food security, and climate change, prompting intensified research in agro-ecological frameworks.

The most significant growth occurred between **2019 and 2021**, where the number of publications rose from **163 to 228 articles**, indicating heightened scholarly attention, possibly driven by international initiatives and policy interest in sustainable agricultural practices. However, a slight decline in publications is evident in **2022 (209 articles)** and **2023 (171 articles)**, which may suggest saturation in specific research areas or shifting academic priorities. The stabilization of publications in **2024 (171 articles)** further supports this observation.

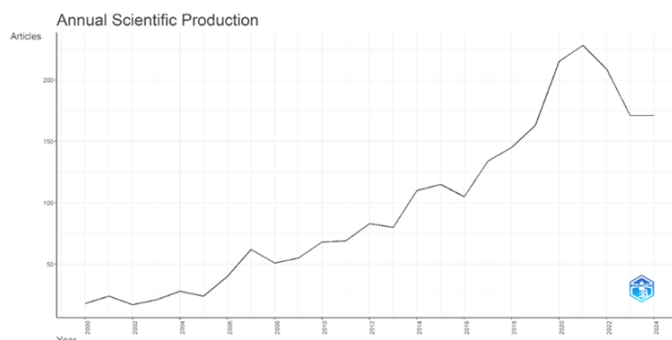


Fig. 2: Annual scientific production

(All figures in this paper, except [Fig. 1], [Fig. 6] has been prepared using biblioshiny (Aria and Cuccurullo, 2017)).

The consistent growth in research output over the past two decades, with an **annual growth rate of 9.83%**, highlights the expanding relevance of agro-ecological studies. This upward trajectory underscores the need for further interdisciplinary collaboration and continued exploration of innovative solutions to agricultural and environmental challenges.

### 3.2 Average Citations Per Year

The citation analysis of research on agro-ecological zones and units from **2000 to 2024** highlights significant variations in citation impact over time. The **Mean Total Citations per Article** shows fluctuations, with notable peaks in **2005 (71.00)** and **2002 (39.94)**, suggesting that articles published during these years had a substantial impact. These spikes may indicate landmark studies or influential publications that have shaped subsequent research. Conversely, the recent years (**2022–2024**) exhibit a declining trend in mean citations, with **2024** having a particularly low **MeanTCperArt of 1.03**, reflecting the limited time available for newer articles to accumulate citations.

The **Mean Total Citations per Year** provides further insight into the citation dynamics. While articles from **2005** maintain the highest citation rate (**3.38 per year**), subsequent years witness a more moderate yet consistent impact. A gradual decline in citation rates is noticeable after **2020**, with the most recent years experiencing lower citation rates, likely due to the recency of publications and the typical lag in citation accrual. The **Citable Years** metric emphasizes the temporal dimension of citation activity.

Articles published in the early 2000s have had over two decades to accumulate citations, resulting in higher cumulative citation counts. In contrast, articles from **2023 and 2024** have had only **3 and 2 years**, respectively, limiting their citation potential. This disparity is a common phenomenon in citation analysis and should be considered when assessing the long-term influence of recent publications. The citation trends underscore the evolving nature of research on agro-ecological zones and units. The initial surge in highly cited articles reflects the establishment of foundational knowledge, while the recent decline may signify emerging research areas that are yet to gain widespread academic recognition.

### 3.3 Most Relevant Sources

The analysis of the most relevant sources in agro-ecological zones and units research from **2000 to 2024** reveals the prominence of specialized journals and multidisciplinary platforms. **"Livestock Research for Rural Development"** emerges as the leading source, contributing **40 articles**, reflecting the significant focus on livestock management within agro-ecological contexts. This indicates the importance of integrating livestock systems into sustainable agricultural practices, especially in rural settings.

**"Sustainability"** follows closely with **34 articles**, underscoring the growing emphasis on sustainable agricultural methods and resource management. Similarly, **"Pakistan Journal of Botany"** (**33 articles**) and **"PLOS ONE"** (**33 articles**) contribute extensively to the field, reflecting the integration of botanical studies and broad interdisciplinary research. The presence of **"Acta Horticulturae"** (**31 articles**) and **"Heliyon"** (**31 articles**) further highlights the importance of horticultural studies and the role of open-access platforms in disseminating agro-ecological research.

Notably, the inclusion of **"AEU - International Journal of Electronics and Communications"** with **29 articles**

suggests the increasing role of technological innovations, such as remote sensing, GIS, and digital communication tools, in monitoring and managing agro-ecological zones. The journals like **"Field Crops Research"** (**27 articles**), **"Agronomy-Basel"** (**26 articles**), and **"Agricultural Systems"** (**24 articles**) emphasize field-based agronomic studies and system-level analyses, which are crucial for understanding crop performance under different agro-ecological conditions.

This diverse set of sources illustrates the interdisciplinary nature of agro-ecological research, integrating agronomy, sustainability science, technological innovation, and environmental management. The prevalence of journals covering sustainability and agricultural systems highlights the continued academic interest in developing resilient and efficient agricultural practices within various ecological contexts.

### 3.4 Core Sources by Bradford's Law

Bradford's Law, proposed by Samuel C. Bradford in 1934, explains how articles on a specific subject are unevenly distributed across scientific journals, with a core set publishing the majority of relevant work. It is commonly used to identify key journals in a field and supports library practices in collection development and information retrieval [2].

The application of **Bradford's Law** to the analysis of agro-ecological zones and units research reveals the core sources contributing to the field. Bradford's Law, which describes the distribution of scientific articles across journals, identifies a small number of highly productive journals forming the **core sources**, while the majority of articles are dispersed across a large number of less frequently publishing journals. As illustrated in the graph [Fig. 3], **"Livestock Research for Rural Development"** ranks as the most prolific source, followed by journals like **"Sustainability," "Pakistan Journal of Botany,"** and **"PLOS ONE."** These journals consistently produce a significant volume of articles, highlighting their central role in advancing knowledge within the domain.

The shaded region in the plot denotes the **core sources**, journals that provide the highest number of relevant articles. Beyond the core, the distribution follows a sharp decline, indicating a large number of journals contributing fewer articles. This pattern reflects the interdisciplinary nature of agro-ecological research, encompassing fields like sustainability, agronomy, livestock management, and

technological applications. The presence of open-access journals like "Heliyon" suggests an emphasis on accessible dissemination of research findings. Understanding the core sources identified by Bradford's Law is essential for researchers aiming to stay updated with the latest developments in agro-ecological research. It also aids in targeting high-impact journals for future publications and forming strategic collaborations within the research community.

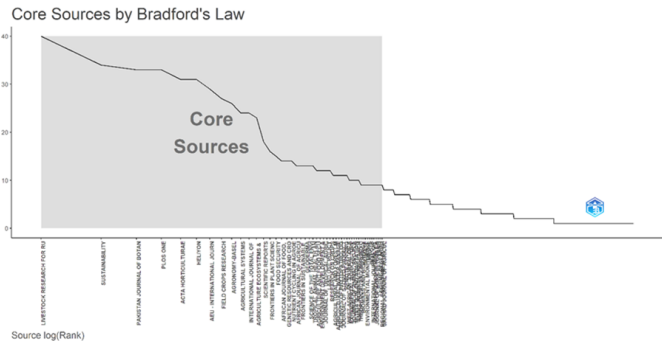


Fig. 3: Core Sources by Bradford Law

3.5 Sources' Local Impact

The evaluation of sources' local impact using key bibliometric indicators such as the **h-index**, **total citations (TC)**, and **number of publications (NP)** provides valuable insights into the influence of journals within the field of agro-ecological zones and unit's research. "Field Crops Research" stands out as a leading source with an **h-index of 19**, **1,234 citations**, and **27 publications** since its initial contribution in **2003**. Its high citation count indicates a significant influence on field-level agricultural studies. Similarly, "Agriculture, Ecosystems & Environment" holds an **h-index of 18** with the highest number of citations (**1,512 citations** from **23 publications**), emphasizing its impact on interdisciplinary research addressing agricultural sustainability and ecosystem management [Table. 1].

"Agricultural Systems" also demonstrates notable influence with an **h-index of 15** and **814 citations** from **24 publications** since **2002**, reflecting its role in advancing agricultural modeling and system-level analysis. On the other hand, "Nutrient Cycling in Agroecosystems" focuses on soil and nutrient management, evident from its **13 publications** and an **h-index of 13** with **466 citations**.

Journals like "PLOS ONE" and "Sustainability" have comparatively lower citation counts (**567** and **385**

**citations**, respectively) despite publishing more articles, suggesting a wider but potentially less concentrated influence. However, their significant number of publications (**33** and **34**, respectively) underscores their role in disseminating diverse research findings in an open-access format. Specialized journals such as "Food Security" and "Livestock Research for Rural Development" also make notable contributions, particularly in addressing food production and livestock management challenges. Furthermore, the presence of "Frontiers in Plant Science" and "Geoderma" highlights the role of plant biology and soil science in agro-ecological research, with both journals demonstrating a growing impact in recent years.

This analysis of local impact emphasizes the interdisciplinary nature of agro-ecological research, with key journals contributing to agricultural productivity, ecosystem management, soil science, and sustainability studies. These insights are valuable for identifying impactful publication venues and understanding the evolving landscape of research in the field.

Table 1: Source Local Impact

| Source                                   | H_In- dex | Total Citation | No of Publication | Publication year Start |
|------------------------------------------|-----------|----------------|-------------------|------------------------|
| FIELD CROPS RESEARCH                     | 19        | 1234           | 27                | 2003                   |
| AGRICULTURE ECOSYSTEMS & ENVIRONMENT     | 18        | 1512           | 23                | 2001                   |
| AGRICULTURAL SYSTEMS                     | 15        | 814            | 24                | 2002                   |
| NUTRIENT CYCLING IN AGROECOSYSTEMS       | 13        | 466            | 14                | 2001                   |
| PLOS ONE                                 | 13        | 567            | 33                | 2013                   |
| FOOD SECURITY                            | 12        | 430            | 15                | 2011                   |
| LIVESTOCK RESEARCH FOR RURAL DEVELOPMENT | 12        | 339            | 40                | 2005                   |
| SUSTAINABILITY                           | 12        | 385            | 34                | 2013                   |
| FRONTIERS IN PLANT SCIENCE               | 11        | 271            | 16                | 2016                   |
| GEODERMA                                 | 11        | 741            | 13                | 2003                   |

Source: The tables ([Table. 1] & [Table. 2]) have been created using Biblioshiny (Aria & Cuccurullo, 2017)

3.6 Sources' Production over Time

The cumulative production of articles by key sources from **2000 to 2024** provides insights into the growth and publication trends in agro-ecological zones and unit's research. "Livestock Research for Rural Development"



has demonstrated consistent growth, maintaining its position as one of the most prolific sources. Its steady increase reflects the ongoing importance of livestock management in agro-ecological research.

"Sustainability" and "PLOS ONE" have shown a significant surge in publications, particularly from **2018 onwards**, indicating the growing emphasis on sustainability-related studies and the preference for open-access platforms. "Pakistan Journal of Botany" also exhibits a consistent upward trend, reflecting its role in regional agro-ecological research, especially in South Asia. Meanwhile, "Heliyon" and "Acta Horticulturae" have shown comparatively slower growth but maintained relevance, particularly in specialized areas of horticultural and interdisciplinary agricultural research. The sharp rise in cumulative publications by "Sustainability" in recent years suggests its increasing influence in addressing agricultural challenges within a sustainability framework.

The trend analysis highlights the diversification of research contributions across both traditional agricultural journals and emerging interdisciplinary platforms. This shift underscores the expanding scope of agro-ecological research, encompassing sustainability, food security, and technological advancements. The growing contribution of open-access journals further suggests a movement towards wider accessibility and dissemination of scientific knowledge.

### 3.7 Most Relevant Authors

The analysis of the most relevant authors in the field of agro-ecological zones and units research from **2000 to 2024** highlights key contributors whose work has significantly influenced the academic discourse. "Islam M." emerges as the most prolific author, with **36 publications**, reflecting a substantial research focus in this domain. The prominence of authors such as "Fischer G." and "Rahman M.", each with **19 articles**, further indicates the presence of established scholars driving research on agro-ecological studies, particularly in regions prone to agricultural challenges.

Authors like "Ahmad I." and "Vanlauwe B." have also made notable contributions, each with **17 publications**, underscoring their role in advancing knowledge on sustainable agricultural practices and soil management. Similarly, "Hossain M.," "Khan M.," and "Kumar S." have contributed **16 articles** each, reflecting their active engagement in research areas like crop management, soil

fertility, and agricultural productivity. The consistent presence of authors from South Asia, particularly "Islam M.," "Rahman M.," and "Hossain M.," suggests a strong regional focus on agro-ecological research in countries like Bangladesh, India, and Pakistan.

The Author, "Wang X." and "Alam M." have significantly contributed, with **16 and 15 publications** respectively, indicating their influence in fields like remote sensing applications and climate adaptation in agro-ecological zones. The collaborative and regionally concentrated nature of this research is evident, with many leading authors contributing to policy-relevant studies addressing agricultural sustainability and food security.

### 3.8 Author Productivity through Lotka's Law

Lotka's Law, introduced by Alfred J. Lotka in 1926 [6], describes the unequal distribution of scientific productivity, where a few authors produce many publications while most contribute only a few. It predicts that the number of authors publishing  $n$  papers is about  $1/n^2$  of those publishing a single paper.

The application of **Lotka's Law** to the field of agro-ecological zones and units research offers valuable insights into author productivity patterns. Lotka's Law posits that the number of authors publishing a large number of articles is exponentially smaller than the number of authors contributing fewer publications. This inverse relationship is evident in the graph [Fig. 4], where a significant proportion of authors have published only one or two articles, while a small number of prolific authors are responsible for a substantial share of the publications.

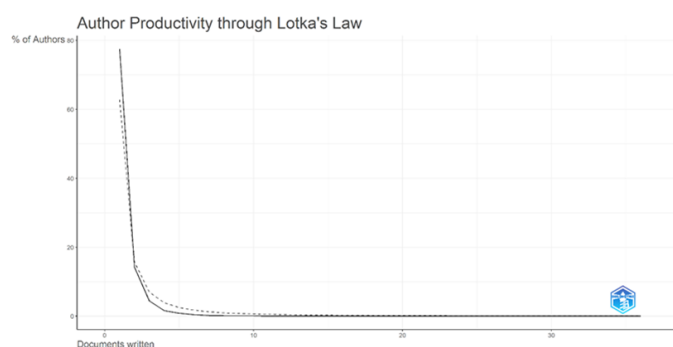


Fig. 4: Lotka Law of Productivity

The steep decline in the curve indicates that a large majority of authors have contributed minimally, aligning with Lotka's predicted distribution. The presence of a few

highly productive authors, such as **Islam M.**, **Fischer G.**, and **Rahman M.**, underscores their central role in driving the discourse on agro-ecological research. These prolific contributors have not only expanded the body of knowledge but also influenced the direction of research through their extensive publications.

The compliance of the observed data with Lotka's Law suggests a typical authorship structure in scientific research. It also highlights the importance of encouraging collaboration and fostering emerging scholars to ensure the continuous growth of the field. Recognizing the contributions of both prolific authors and less frequent contributors is crucial for understanding the diversity of perspectives and advancing interdisciplinary approaches in agro-ecological studies.

### Most Relevant Affiliations

The analysis of the most relevant affiliations in agro-ecological zones and units research from **2000 to 2024** highlights key institutions that have made significant contributions to the field. **CGIAR (Consultative Group on International Agricultural Research)** leads with an impressive **248 articles**, reflecting its pivotal role in global agricultural research, particularly in addressing food security, sustainable farming, and climate resilience.

**The University of Ghana** and **Wageningen University and Research** follow with **95 articles each**, indicating their strong engagement in regional and international agricultural research. Similarly, the **Chinese Academy of Sciences (CAS)** has published **94 articles**, demonstrating China's active participation in advancing agricultural innovation and environmental research.

In Africa, institutions like the **University of Nairobi (92 articles)** and the **International Institute of Tropical Agriculture (IITA)** with **76 articles** have made substantial contributions to agro-ecological research, particularly in tropical and sub-Saharan regions. The **Indian Council of Agricultural Research (ICAR)**, with **70 articles**, has played a crucial role in enhancing agricultural resilience in South Asia through innovative research in agro-ecological zones. Other key contributors include **Makerere University (65 articles)** and the **International Livestock Research Institute (ILRI) (54 articles)**, both of which have significantly impacted livestock management and agricultural sustainability. The **Sokoine University of Agriculture**, with **49 articles**, has also made notable contributions, particularly in the East African context.

These leading affiliations reflect a strong collaborative network across international, regional, and national institutions. Their research efforts have significantly influenced policy development, sustainable agricultural practices, and the adaptation of farming systems to environmental challenges.

### 3.9 Corresponding Author's Countries

The distribution of corresponding authors by country from **2000 to 2024** provides insight into the geographical landscape of agro-ecological zones and unit's research. **China** leads with **174 articles (7.2% of the total)**, reflecting its prominent role in agricultural research and environmental management. A significant portion of these publications (**31.6%**) are **multi-country publications (MCP)**, highlighting China's active participation in international collaborations. Similarly, **India**, contributing **161 articles (6.7%)**, has a high number of **single-country publications (SCP)** (**146 articles**), indicating a strong domestic research focus, particularly in addressing regional agricultural challenges [Fig. 5].

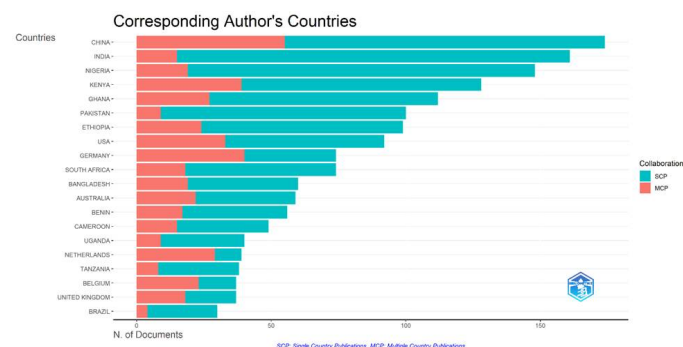


Fig. 5: Corresponding Authors Countries

**Nigeria** and **Kenya** are notable contributors, with **148 (6.2%)** and **128 (5.3%)** articles, respectively. While Nigeria's publications are predominantly single-country studies (**87.2% SCP**), Kenya exhibits a significant proportion of collaborative research (**30.5% MCP**), demonstrating the country's emphasis on cross-border knowledge exchange and regional agricultural resilience. **Ghana** and **Ethiopia** also contribute substantially, with **112** and **99 articles** respectively, showing their growing involvement in agro-ecological research, particularly through international partnerships (**24.1% and 24.2% MCP**).

In the **Global North**, the **USA** accounts for **92 articles (3.8%)**, with a notably high proportion of multi-country

collaborations (35.9% MCP), reflecting its leadership in global agricultural initiatives. **Germany**, with **74 articles (3.1%)**, stands out for its extensive collaboration (54.1% MCP), emphasizing its active role in international research networks. Similarly, **South Africa** has contributed **74 articles**, maintaining a strong collaborative research presence (24.3% MCP).

The prevalence of multi-country publications, particularly from countries like Germany, Kenya, and China, underscores the significance of international cooperation in addressing complex agro-ecological challenges. This collaborative research landscape facilitates the exchange of knowledge, resources, and innovative practices, fostering sustainable agricultural development globally. Recognizing the leading countries in agro-ecological research can inform future collaborative efforts and guide the development of region-specific agricultural policies and practices.

### 3.10 Countries' Scientific Production

The provided graph visualizes **Countries' Production Over Time** in agro-ecological zones and units research from **2000 to 2024**. Notably, **China** leads with a significant increase in research output, particularly after **2018**, indicating a strong focus on agricultural sustainability and technological advancements. **India** follows closely, reflecting its commitment to agro-ecological research as a means to address food security challenges and agricultural sustainability.

**Kenya** and **Nigeria** show steady growth, with a notable rise in publications post-2015. These trends highlight increasing efforts in African nations to apply agro-ecological principles in tackling agricultural challenges. The **USA** has maintained a consistent contribution to the research landscape, often collaborating internationally to provide technological and policy insights.

The sharp increase in research articles from **China** and **India** in recent years may be attributed to government-supported agricultural policies, sustainable farming initiatives, and international research partnerships. Meanwhile, African countries like **Kenya** and **Nigeria** demonstrate the growing recognition of agro-ecological practices to mitigate the impacts of climate change and enhance food security. The upward trajectory in research publications from multiple countries underlines the global relevance of agro-ecological research and its role in ensuring sustainable agricultural development.

### 3.11 Most Cited Countries

The map highlights the **Most Cited Countries** in agro-ecological zones and units research, indicating the significant influence of these countries in the field. **China** leads with **3,981 citations** and an average of **22.9 citations per article**, reflecting the country's substantial research output and impact [Fig. 6]. Despite a lower average citation rate compared to some Western nations, China's contributions are widely recognized in the scientific community.

The **USA** follows closely with **3,481 citations** and an impressive average of **37.8 citations per article**, signifying the high quality and influence of its research. Similarly, **Germany** maintains a strong research presence with **2,686 citations** and an average of **36.3 citations per article**, indicating well-received publications, often in collaboration with international institutions. **Austria** stands out with the highest average citation rate of **126.2 citations per article**, suggesting highly impactful research, possibly in specialized or interdisciplinary areas. **Belgium** also demonstrates a strong research influence, with an average of **45.1 citations per article**, highlighting its contributions to agro-ecological studies, often through EU-funded collaborative research.

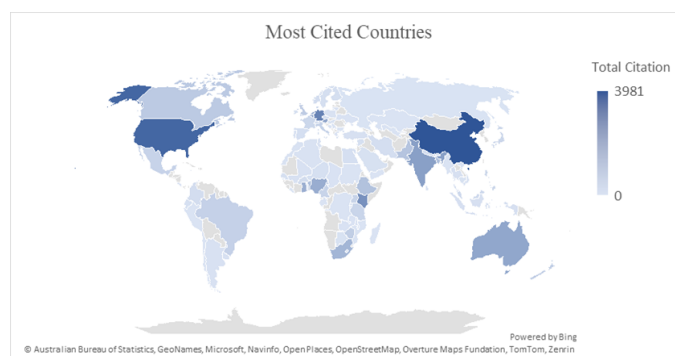


Fig. 6: Most Cited Countries [Source: Created by the Investigator using Microsoft Excel]

African countries, including **Kenya (2,290 citations)**, **Nigeria (1,518 citations)**, and **Ghana (1,477 citations)**, show increasing visibility in the research landscape. While their average citation rates are relatively lower, these countries are making significant contributions to practical agro-ecological applications, often addressing region-specific agricultural challenges. The data emphasizes the global collaborative nature of agro-ecological research,

with both developed and developing countries contributing to advancements in sustainable agriculture.

**Table 2: Most Cited Documents**

| Paper                                                                   | DOI                             | Total Citation (TC) | TC per Year |
|-------------------------------------------------------------------------|---------------------------------|---------------------|-------------|
| FISCHER G, 2005, PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B      | 10.1098/rstb.2005.1744          | 595                 | 28.33       |
| TEIXEIRA E, 2013, AGRICULTURAL AND FOREST METEOROLOGY                   | 10.1016/j.agrformet.2011.09.002 | 513                 | 39.46       |
| FISCHER G, 2007, TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE            | 10.1016/j.techfore.2006.05.021  | 451                 | 23.74       |
| ARSHAD M, 2002, AGRICULTURE, ECOSYSTEMS & ENVIRONMENT                   | 10.1016/S0167-8809(01)00252-3   | 409                 | 17.04       |
| ABID M, 2015, EARTH SYSTEM DYNAMICS                                     | 10.5194/esd-6-225-2015          | 371                 | 33.73       |
| TELUGUNTALA P, 2018, ISPRS JOURNAL OF PHOTOGRAMMETRY AND REMOTE SENSING | 10.1016/j.isprsjprs.2018.07.017 | 364                 | 45.50       |
| XIONG J, 2017, ISPRS JOURNAL OF PHOTOGRAMMETRY AND REMOTE SENSING       | 10.1016/j.isprsjprs.2017.01.019 | 349                 | 38.78       |
| TUONG T, 2005, PLANT PRODUCTION SCIENCE                                 | 10.1626/pps.8.231               | 299                 | 14.24       |
| SEJIAN V, 2018, ANIMAL                                                  | 10.1017/S1751731118001945       | 295                 | 36.88       |
| LAMBIN E, 2013, GLOBAL ENVIRONMENTAL CHANGE                             | 10.1016/j.gloenvcha.2013.05.005 | 245                 | 18.85       |

*Photogrammetry and Remote Sensing*, received **349 citations (38.78 citations per year)**, emphasizing

### 3.12 Most Global Cited Documents

The **Most Globally Cited Documents** in agro-ecological zones and units research provide insights into the key contributions that have significantly influenced the field [Table. 2]. The most cited paper is by **Fischer G (2005)**, published in *Philosophical Transactions of the Royal Society B*, with **595 total citations** and an average of **28.33 citations per year**. This study likely addressed major advancements in agro-ecological modelling and climate impact assessments, making it a foundational reference in the field. Another highly influential work is by **Teixeira E (2013)**, published in *Agricultural and Forest Meteorology*, accumulating **513 citations** at a rate of **39.46 citations per year**. This paper likely contributed to understanding the interactions between climate change and agricultural productivity, emphasizing meteorological factors.

**Fischer G (2007)** appears again with a publication in *Technological Forecasting and Social Change*, achieving **451 citations (23.74 citations per year)**, reflecting the importance of technological forecasting in agro-ecological research. Similarly, **Arshad M (2002)** in *Agriculture, Ecosystems & Environment* has received **409 citations (17.04 citations per year)**, indicating the paper's impact on environmental management in agricultural systems.

The works of **Abid M (2015)** in *Earth System Dynamics* (**371 citations, 33.73 citations per year**) and **Teluguntla P (2018)** in *ISPRS Journal of Photogrammetry and Remote Sensing* (**364 citations, 45.50 citations per year**) further illustrate the growing influence of geospatial technologies and earth system models in agro-ecological research. Notably, **Xiong J (2017)**, also published in *ISPRS Journal of*

advancements in remote sensing applications for agricultural monitoring.

The contributions by **Tuong T (2005)** in *Plant Production Science* (**299 citations, 14.24 citations per year**), **Sejian V (2018)** in *Animal* (**295 citations, 36.88 citations per year**), and **Lambin E (2013)** in *Global Environmental Change* (**245 citations, 18.85 citations per year**) further highlight interdisciplinary research in plant productivity, livestock management, and environmental change.

### 3.13 Most Frequent Words

The most frequent words in the bibliometric analysis reflect key themes and areas of focus within agro-ecological zones and unit's research. **Agriculture (126)** emerges as the dominant subject, emphasizing the importance of understanding agricultural practices, sustainability, and productivity in specific ecological regions. The frequent occurrence of **yield (113)** indicates a significant focus on crop productivity and the factors influencing it, such as soil quality, water availability, and management practices. **Agro-ecological zones (98)** and **agroecology (93)** are central to this discourse, highlighting the need for region-specific agricultural planning that aligns with ecological conditions. The emphasis on **maize (90)** suggests its prominence as a staple crop studied for its adaptability and resilience across diverse ecological zones.

The frequent appearance of **management (87)** underscores the critical role of effective agricultural and resource management strategies, including soil conservation, water

management, and sustainable land use. **Systems (84)** is another recurring term, indicating the analysis of various agricultural systems like mixed farming and crop rotation to optimize productivity. The word **growth (80)** often pertains to both the biological growth of crops and the broader agricultural expansion across regions. **Productivity (76)** remains a key focus, with researchers aiming to identify ways to enhance agricultural output sustainably. Lastly, the notable presence of **climate-change (72)** reflects growing concerns over its impact on agriculture, driving research towards adaptive strategies and resilience-building measures. These frequent words collectively illustrate the research community's dedication to addressing agricultural productivity, sustainability, and the challenges posed by climate change.

### 3.14 Co-occurrence Network

The co-occurrence network map visualizes the intellectual structure of agro-ecological research through the interconnectedness of frequently occurring keywords. This network, structured into three distinct clusters, reveals the thematic density and collaborative orientation of the domain. Each node represents a keyword, while the size of the node indicates its frequency, and the edges denote the strength of co-occurrence between terms [Fig. 7].

The **blue cluster**, prominently featuring keywords such as “agriculture,” “agro-ecological zones,” “agroecology,” “maize,” and “productivity,” represents the core thematic domain of agro-ecological research. These terms are heavily interlinked, reflecting a high degree of conceptual coherence around agricultural systems, zonation, and crop productivity. The recurrence of geographically and climatologically relevant keywords like “rainfall,” “drought,” “sub-Saharan Africa,” and “climate change” within this cluster underlines the regional and environmental dimensions of agricultural sustainability and resilience studies.

The **green cluster** emphasizes systemic and adaptive dimensions, with “yield,” “management,” “systems,” “climate-change,” “adaptation,” “temperature,” and “variability” forming the backbone of this network. This grouping suggests a strong focus on modeling and managing agricultural outputs under shifting climatic conditions. The presence of terms like “diversity,” “quality,” and “impact” points to the increasing interest in outcome evaluation and performance optimization in agro-ecological practices, revealing the integration of environmental dynamics with agronomic efficiency.

The **red cluster**, on the other hand, centers around “article,” “animals,” “animal,” and geographically specific keywords such as “Ethiopia,” “Kenya,” and “prevalence.” This cluster appears more peripheral and thematically distinct, likely representing a subset of literature dealing with animal production, gender-specific studies (“male,” “female”), and livestock prevalence in localized settings. Its relatively weaker linkages with the main thematic hubs suggest a semi-independent research strand within agro-ecological scholarship, potentially overlapping with veterinary and public health dimensions.

Collectively, the co-occurrence network underscores the centrality of agriculture, agroecology, and productivity in the research landscape, while also highlighting the role of climate-related variables, adaptive management systems, and localized animal studies as significant but thematically distinct elements. This visualization not only maps the knowledge domains but also hints at potential interdisciplinary integration opportunities, especially between crop-based and livestock-based agro-ecological research streams.

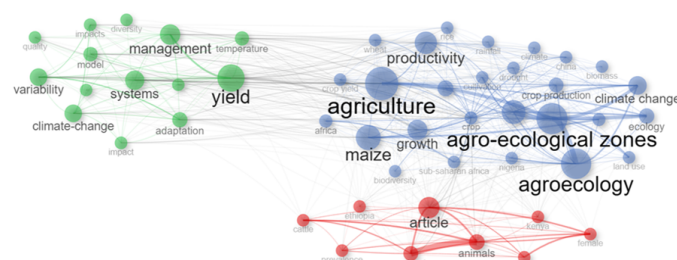


Fig. 7: Co Occurrence Network

### 3.15 Thematic Map

The thematic map presented in this study visually classifies research themes related to agro-ecological zones (AEZ) and agro-ecological units (AEU) based on two dimensions: centrality (relevance degree) and density (development degree). These two axes facilitate a strategic analysis of the intellectual structure of the domain by categorizing themes into four quadrants, each representing a specific stage of thematic development [Fig. 8].

In the **upper-right quadrant**, identified as the *Motor Themes* section, are highly central and well-developed topics that drive the field forward. The presence of terms such as “agro-ecological zones” and “maize” in this quadrant highlights their pivotal role in current research,

indicating that they are both conceptually important and methodologically mature. This signifies that AEZ research is actively linked to practical agricultural concerns, particularly with staple crops like maize, reflecting their global relevance in sustainable agricultural systems.

The **lower-right quadrant**, representing *Basic and Transversal Themes*, includes clusters like “production,” “soil,” “analysis,” and topics associated with “climate change” and “farmers.” These themes are highly central but have lower density, implying they are foundational to the research field but not yet fully developed in terms of depth and internal cohesion. Their central positioning suggests that these themes underpin multiple research areas, serving as building blocks for further inquiry, particularly in linking agro-ecological classifications with socio-environmental variables like climate adaptation and farmer-centered studies.

In contrast, the **upper-left quadrant**, denoting *Niche Themes*, contains terms such as “indigenous,” “uganda,” “species,” and an isolated cluster of editorial correction terms like “erratum.” These themes are characterized by high density but low centrality, implying that they are specialized areas with concentrated research interest but limited interaction with broader themes. The inclusion of region-specific and species-level studies in this quadrant suggests the presence of localized but methodologically strong subfields that could potentially integrate with mainstream AEZ research through cross-disciplinary efforts.

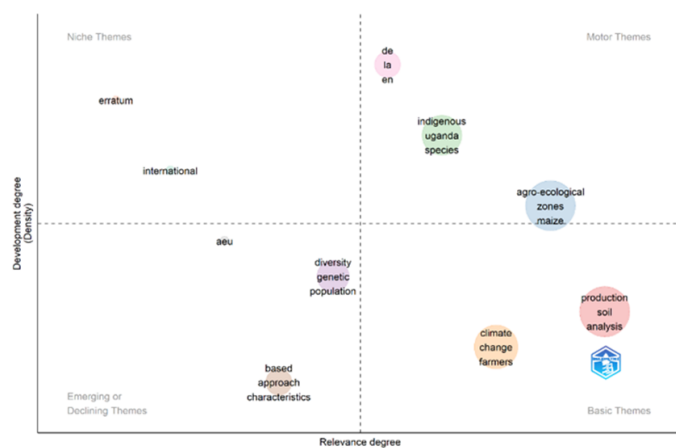


Fig. 8: Thematic Map

The **lower-left quadrant**, which encompasses *Emerging or Declining Themes*, features terms such as “aeu,” “based,”

“approach,” and “characteristics.” These topics currently exhibit both low centrality and low density, suggesting that research into agro-ecological units (AEU) is either in its nascent stages or has experienced a decline in scholarly attention. The positioning of AEU in this quadrant is particularly insightful, as it underscores a research gap and an opportunity for deeper investigation and methodological innovation, especially given the increasing relevance of spatially fine-tuned agricultural zoning systems in climate-resilient farming. The thematic map effectively illustrates the structure and dynamics of AEZ and AEU research, indicating which areas are thriving, foundational, emerging, or in need of revitalization. This analysis serves as a strategic tool for guiding future investigations and policy-relevant studies in agro-ecological classification.

### 3.16 Thematic Evolution

The thematic evolution diagram provides a longitudinal view of the shifting research focus within agro-ecological studies across four distinct time periods: 2000–2006, 2007–2012, 2013–2018, and 2019–2024. By visualizing the flow of keywords over time, the diagram captures how foundational topics matured, merged, or gave rise to new research directions, indicating the dynamic evolution of scholarly inquiry in this field [Fig. 9].

In the earliest phase (2000–2006), the research landscape was characterized by a strong emphasis on specific elements such as “**zea mays**,” “**land use**,” “**diversity**,” “**model**,” “**organic matter**,” and “**fungi**.” These keywords point toward foundational explorations into crop-specific studies, soil-plant interactions, and ecological modeling, often rooted in the biophysical assessment of agricultural systems. Notably, the presence of terms like “*aspergillus flavus*,” “barley,” and “bacteria (microorganisms)” suggests a microbiological and organism-specific focus, underlining early interests in crop-pathogen dynamics and agro-biodiversity.

Transitioning to the period of 2007–2012, the thematic scope expands and begins to consolidate around broader agricultural and ecological issues. Keywords such as “**yield**,” “**variability**,” “**adoption**,” “**impacts**,” “**agroecology**,” and “**sustainability**” emerge, indicating a growing preoccupation with productivity, climate variability, and sustainable farming practices. The inclusion of species like “*gallus gallus*” and “*phaseolus vulgaris*” reflects continuity in organism-specific research, while also hinting at diversification into livestock and legume crops.

The emergence of “Asia,” “farmers,” and “climate change” during this phase suggests regional contextualization and a shift toward understanding socio-ecological systems.

From 2013 to 2018, the thematic structure shows a clear clustering around “**animals**,” “**agriculture**,” “**yield**,” and “**mycotoxins**.” This period marks a transition into more integrated agricultural systems research, where livestock and crop production are studied in tandem, and yield optimization remains a central concern. The appearance of “mycotoxins” indicates a health and safety dimension, showing the expanding purview of agro-ecological studies into food quality and contamination risks.

In the most recent phase (2019–2024) illustrates a thematic narrowing and refinement around two core topics: “**yield**” and “**agro-ecological zones**.” This suggests a consolidation of research into large-scale, systems-level understanding of agro-ecological zoning and its implications for agricultural output. The prominence of these themes in the current phase indicates a mature research agenda where spatial frameworks (AEZs) are increasingly applied for guiding policy, planning, and sustainable agricultural development.

The thematic evolution diagram underscores a clear trajectory from organism-specific, soil and crop-level studies toward integrated, system-wide approaches emphasizing yield optimization, sustainability, and agro-ecological classification. It reflects the intellectual maturation of the field and points to future research that is likely to focus on spatial planning, adaptive capacity, and climate-resilient agricultural strategies.

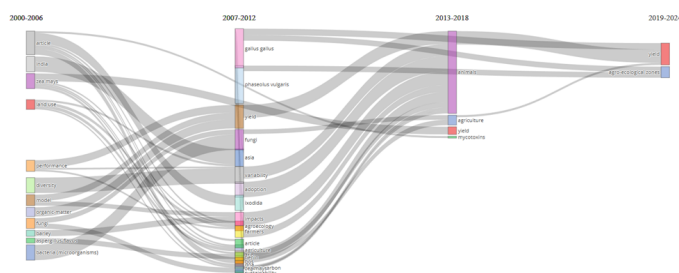


Fig. 9: Sankey Diagram of thematic evolution

### 3.17 Factorial Analysis

The factorial diagram (Conceptual Structure Map using MCA—Multiple Correspondence Analysis) visually represents the conceptual organization of keywords within the literature on agro-ecological zones and related topics. This diagram enables the identification of core thematic

clusters and their spatial relationships, helping to reveal the underlying intellectual structure and key domains of research focus.

In the Digram [Fig. 10], keywords are plotted based on their co-occurrence in the literature, where proximity indicates thematic similarity or shared research contexts. The keywords are enclosed within a polygon, capturing the conceptual diversity across the research landscape. The axes (Dim 1 and Dim 2) represent latent dimensions extracted from the dataset that explain the maximum variance in thematic distribution.

The **left region** of the diagram is dominated by terms such as “climate change,” “crops,” “ecology,” “cultivation,” “agroecology,” and “agro-ecological zones.” These closely clustered terms suggest a strong research orientation toward understanding how agro-ecological frameworks interact with ecological principles and climate variability to influence crop systems. This cluster represents a well-established body of research that integrates biophysical and climatic parameters in agro-ecological assessment and land-use planning.

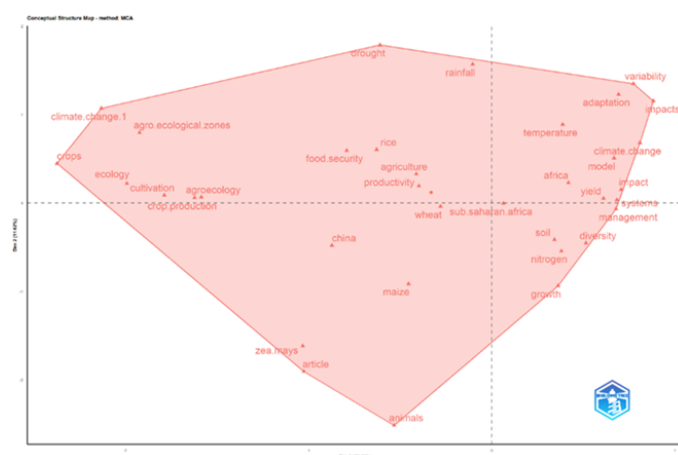
Toward the **upper-central and top-right areas**, terms such as “drought,” “rainfall,” “temperature,” “adaptation,” “variability,” and “climate change” converge, indicating a distinct research focus on climate-related stressors and their management within agricultural systems. This thematic grouping reflects growing scholarly attention on the resilience and adaptability of agro-ecological systems to climate extremes, particularly in vulnerable regions like Sub-Saharan Africa.

The **right region** features keywords like “yield,” “soil,” “nitrogen,” “diversity,” “growth,” “management,” and “systems,” which signify an emphasis on agricultural productivity and soil-plant dynamics. This suggests a techno-centric or agronomic focus within the literature, often addressing optimization of inputs, nutrient cycling, and system efficiency under varying ecological conditions.

In the **lower portion**, terms such as “zea mays,” “maize,” “china,” and “animals” appear more isolated. These may represent either specialized case studies or narrower thematic domains that are somewhat disconnected from the central research clusters. For example, “zea mays” and “maize” denote crop-specific studies, which, while significant, may not be widely integrated across broader conceptual discussions.

The keywords such as “sub-Saharan Africa,” “Africa,” and “food security” span the central axis, suggesting their cross-cutting relevance across multiple research clusters. Their placement near the center implies that these topics are pivotal in bridging agro-ecological research with development priorities, policy-making, and sustainable food systems.

The factorial diagram provides a holistic view of the conceptual structure underpinning AEZ and AEU research. It highlights thematic convergence around climate change, ecological productivity, and adaptive strategies, while also pointing to emerging or peripheral topics that warrant further interdisciplinary exploration.



**Fig. 10: Factorial Diagram**

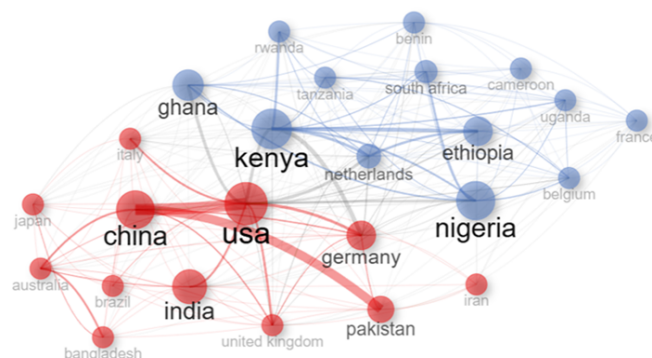
### 3.18 Collaboration by Countries

This **Collaboration Network by Countries** visualizes the research collaborations between various countries. The size of each node represents the prominence or volume of research output from a particular country, while the thickness of the connecting lines (edges) indicates the strength of collaboration [Fig. 11].

In this network, **USA**, **China**, and **Kenya** are central hubs with extensive connections, highlighting their dominant role in global research collaboration. The red cluster, consisting of countries like **India**, **Pakistan**, and **Brazil**, suggests strong partnerships primarily with **China** and **USA**. On the other hand, the blue cluster includes countries like **Nigeria**, **Ethiopia**, and **Ghana**,

## References

demonstrating regional collaboration across African nations. Countries like **Germany** and **Netherlands** act as bridging nodes, connecting different regional clusters. This visualization effectively showcases the global distribution of research collaboration, with clear patterns of regional partnerships and international scientific exchange.



**Fig. 11: Collaboration Network**

## 4 Conclusion

This bibliometric analysis underscores the dynamic, collaborative, and globally relevant nature of research on Agro-Ecological Zones (AEZs) and Agro-Ecological Units (AEUs). With contributions from over 8,400 authors and a notable international co-authorship rate of 26.23%, the field reflects a strong foundation of global engagement, particularly from leading research hubs such as China, the USA, and Germany. The steady annual growth rate of 9.83% and an average of 17.54 citations per document demonstrate both increasing scholarly interest and academic impact. Thematic evolution analysis reveals a clear shift from organism-specific and crop-level studies to integrated, system-wide approaches focused on yield optimization, sustainability, and agro-ecological classification. Emerging research priorities include spatial planning, adaptive capacity, and climate-resilient agricultural strategies, indicating the intellectual maturation of the field. Moving forward, enhanced interdisciplinary collaboration and strategic integration of geospatial and climate-adaptive approaches will be vital to advancing agro-ecological research and informing policy frameworks aimed at sustainable agriculture and global food security.

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