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PRECISION AGRICULTURE IN HILLY REGIONS: A BIBLIOMETRIC ASSESSMENT OF GLOBAL RESEARCH TRENDS

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ABSTRACT

Mountain farming sustains rural livelihoods but faces challenges from steep terrain, soil erosion, and climate change. Precision Agriculture (PA), using digital tools and remote sensing, offers solutions but remains underexplored in mountain contexts compared to large-scale flatland farming. This study presents a bibliometric analysis of PA research in hilly regions using *Web of Science* data time span of (2000–2025). The analysis carried out with 42,548 records appeared in search initially and 2111 paper globally on mountain and Precision agriculture has been considered for screening and 490 publications were reviewed and considered for the analysis, since the these were the only article fulfilling the study objective and direction. Results show steady growth peaking in 2021, with Ethiopia and China as leading contributors. Core journals such as *Land Degradation & Development* and *Remote Sensing* dominate the field. Keyword analysis reveals three clusters: environmental conservation, technological integration, and socio-economic adoption. However, gaps persist in cost–benefit assessments, adoption studies, and mountain-specific policy frameworks. Overall, PA shows strong potential for sustainable mountain farming, but greater focus on terrain-sensitive, smallholder-centered innovations is needed.

To address this gap and to understand the dynamics of PA, the paper the present study conducts a bibliometric analysis of PA related to mountain farming drawing on Web of science data from 2000-2025.

Keywords: Precision Agriculture; Mountain Farming; Bibliometric Analysis; Sustainable Agriculture; Remote Sensing; Technological Adoption; Smallholder Farmers; Environmental Conservation; Digital Farming; Climate Change Adaptation

1. INTRODUCTION

Agriculture in mountain regions possess unique challenges due to steep slopes, heterogeneous microclimates, fragmented landholdings, and limited mechanization opportunities (Sharma et al., 2022). These constraints severely limit mechanization and productivity, especially in regions like the Himalayas, Andes, and Ethiopian Highlands. Real-world case examples such as UAV-based slope monitoring in Italian hillside vineyards, digital soil mapping in the Ethiopian highlands, and remote-sensing approaches used in Nepal's terraced fields demonstrate that precision agriculture (PA) can mitigate terrain-induced limitations when appropriately adapted. . In recent decades, Precision Agriculture (PA) has emerged as a transformative approach to optimize resource use, enhance productivity, and ensure environmental sustainability. PA integrates geospatial technologies, sensors, GPS and decision-support systems to enable site-specific management of crops, soils, weather and water (Gebbers & Adamchuk, 2010). While most research has traditionally focused on plains and large-scale farms, there is growing recognition of PA's potential in mountain agriculture, especially in the context of climate change, fragile ecosystems, and smallholder dominance region (Odeh et al., 2019).

Bibliometric analyses play a Pivotal role in synthesizing the scientific landscape of emerging research domains in the field of Precision agriculture. By mapping publication trends, key authors, research clusters, and thematic evolutions, bibliometric studies help identify knowledge gaps and future research directions (Donthu et al., 2021). Applying bibliometric methods to PA in mountain contexts is timely, as it allows the systematic assessment of research outputs addressing terrain-specific challenges such as slope heterogeneity, soil variability, and crop management in high-altitude environments (Tsyplenkov et al., 2020). Thus, this study aims to conduct a bibliometric analysis of precision agriculture in mountain regions, synthesizing insights from Web of Science journals to highlight the evolution, hotspots, and implications of this niche yet significant field of the time span of year 2000-2025.

2. LITERATURE REVIEW

2.1. Precision Agriculture: A Global Context

Precision agriculture has been widely researched as a tool to enhance input efficiency and farm profitability. Global reviews indicate that PA adoption has been driven by advances in remote sensing, variable rate technology, and data analytics, especially in large mechanized farms in the U.S., Europe, and Australia (Mulla, 2013; Lowenberg-DeBoer & Erickson, 2019). However, the literature also suggests significant barriers to adoption in developing and mountainous regions, including high costs, limited awareness, and infrastructural constraints (Shirsath et al., 2020).

2.2. Mountain Agriculture and Terrain-Specific Challenges

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Mountain regions, such as the Himalayas, Andes, and Alpine zones, are characterized by steep gradients, irregular fields, and fragile soils, complicating mechanized farming practices (Sharma et al., 2022). Conventional PA technologies, designed for flat and uniform fields, require adaptation to these conditions. Studies have highlighted how UAV-based remote sensing and terrain-adjusted algorithms enable better monitoring of slope agriculture (Matese et al., 2015). For instance, UAV-based vineyard mapping has proven effective in precision viticulture across hilly Mediterranean terrains (Matese & Di Gennaro, 2018).

2.3. Technological Applications in Mountain Precision Agriculture

Recent studies underscore the role of UAVs, drones, and LiDAR technologies in overcoming terrain constraints. UAV-based canopy mapping has been successfully applied in hillside vineyards, improving irrigation and nutrient management (Comba et al., 2020). Similarly, site-specific soil variability studies in mountain farms demonstrate that spatial decision support systems can significantly enhance crop performance and input efficiency (Zhang et al., 2025). Moreover, break-even analyses of UAV sprayers emphasize their particular suitability for steep and mountainous landscapes (Yuan et al., 2025).

2.4. Knowledge Gaps and Research Clusters

Bibliometric reviews suggest that most precision agriculture studies still focus on plains, with only a small proportion addressing mountains or hilly terrains (Tsyplenkov et al., 2020). The Web of Science dataset filtered for “mountain,” “slope,” and “Himalaya” shows that research clusters concentrate around UAVs, remote sensing, and precision viticulture, while topics such as socio-economic adoption, cost-benefit analysis, and policy support in mountain regions remain underexplored. Scopus and PubMed databases similarly highlight that mountain-focused PA research is emerging but fragmented, often case-specific to viticulture or experimental farms rather than broader regional applications (Matese & Di Gennaro, 2018; Yuan et al., 2025).

2.5. Relevance to Sustainable Mountain Development

The integration of PA in mountain regions aligns with the goals of sustainable mountain development by enhancing productivity, reducing environmental risks, and ensuring resource efficiency. Case studies from the Himalayas and Andes demonstrate how terrain-aware PA tools can address soil erosion, optimize water use, and increase farmer resilience to climate change (Odeh et al., 2019; Sharma et al., 2022). However, systematic bibliometric analyses are essential to map research progress and propose strategies for scaling these innovations in fragile ecosystems.

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3. RESEARCH QUESTIONS AND OBJECTIVES

This study is guided by two key research questions: **(RQ1)** How has research on precision agriculture (PA) in mountain regions grown and evolved globally? and **(RQ2)** Who are the primary contributors such as journals, authors, institutions, and countries driving advancements in this field?

To address these questions, the study pursues three specific objectives. First, it aims to quantify the growth, geographic distribution, and Citation in mountain precision agriculture (MPA) research. Second, it seeks to identify the leading journals, influential authors, and seminal publications that have shaped the development of MPA. Finally, the study endeavors to map thematic research clusters and uncover existing knowledge gaps, thereby providing insights to guide future research directions in precision agriculture within mountainous contexts.

4. METHODOLOGY

4.1 Data Source and Search Strategy

Bibliographic records were retrieved from the Web of Science Core Collection for the years **2000–2025**. Boolean combinations of PA-related keywords and mountain-related terms were used. The search initially returned **42,548 records**.

4.2 Data Cleaning and Filtering in RStudio

To ensure transparency, the filtering process is now explained step-by-step:

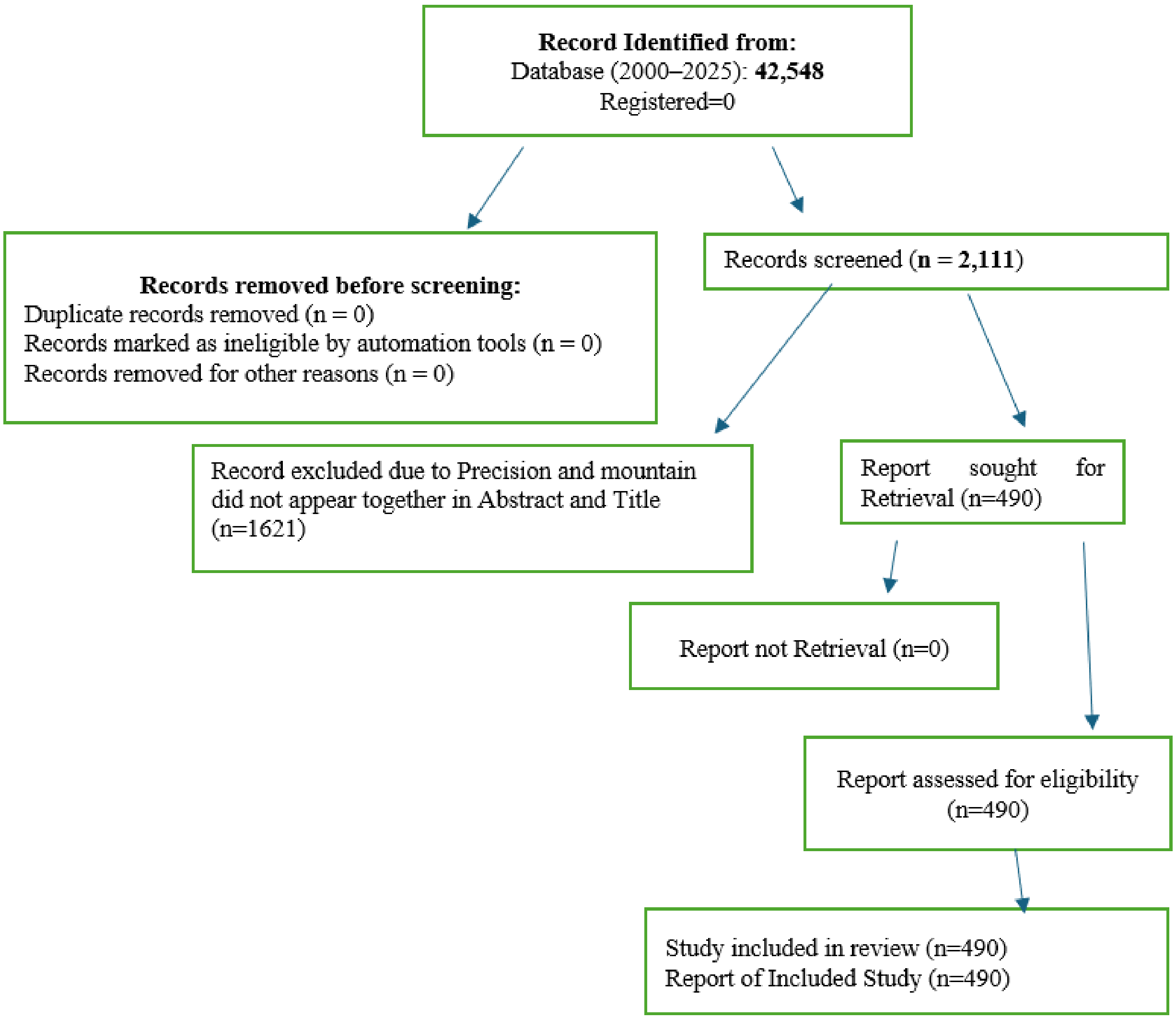
1. **Keyword Matching:** Precision-related terms (e.g., "precision agriculture", "smart farming", "VRT") and mountain terms ("mountain", "Himalaya", "slope", "upland", etc.) were merged using regex filters in R.
2. **Co-occurrence Requirement:**
   Only studies where **both sets of terms appeared in the *title or abstract*** were retained. This removed articles that discussed PA but not mountains, or mountains but not PA.
3. **Exclusion Criteria:**
   Non-English records
   Book reviews, editorials
   Records unrelated to PA applications
   Studies where relevant terms appeared only in author keywords but not the main text
4. **Final Inclusion:**
   1. Initial download: **42,548 records**
   2. After keyword filtering: **2,111 records**

3. After co-occurrence and eligibility screening: **490 studies**

4.3 PRISMA Flow

The PRISMA diagram now succinctly represents each stage without repeated text.

This study uses the R studio for the data merging, cleaning and plotting the map and diagram and Vos viewer also used to fulfil the research objective and findings.



In line with the PRISMA 2020 guidelines for systematic reviews (Page et al., 2021), a total of 42,548 records were initially retrieved from the Web of Science database. To ensure the relevance of the material, only peer-reviewed journal articles, review papers, and conference proceedings

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published in English were considered. Studies were included if they explicitly referred to precision agriculture or related terms in combination with mountain, hilly terrain, or Himalayan contexts within the title or abstract. Conversely, studies were excluded if they referred only to precision agriculture without reference to mountain contexts, or to mountain agriculture without mention of precision technologies. In particular, articles in which the terms “precision” and “mountain” did not co-occur in the title or abstract were excluded (n = 1,621). Non-research documents such as editorials, book reviews, and non-English publications were also omitted. Following this screening process, 2,111 articles were initially shortlisted, and after applying the co-occurrence filter, 490 studies were retained for final review. This approach ensured a focused synthesis of research at the intersection of precision agriculture and mountain farming (Snyder, 2019; Xiao & Watson, 2019).

4.4. Tools and Analysis

Data cleaning and merging were performed in RStudio, while VOSviewer was used for mapping co-authorship, keyword networks, and thematic clusters. Descriptive statistics captured growth trends, citation metrics, and journal distribution.

5. RESULT AND DISCUSSION

5.1 Descriptive Overview

The following table provide comprehensive details on the published studies on Precision Agriculture in mountain region from Web of Sciences database

Table 1: Main Information of Published Studies

Descriptions	**Value**
Timespan	2000 - 2025
Sources (Journals, Books, etc)	10
Documents	490
Annual Growth Rate %	6.65
Document Average Age	7.27
Average citations per doc	27.71
Average citations per year per doc	3.17
References	24611
Author Keywords (DE)	235
Keywords Plus (DI)	480

Sources: Self constructed and compiled

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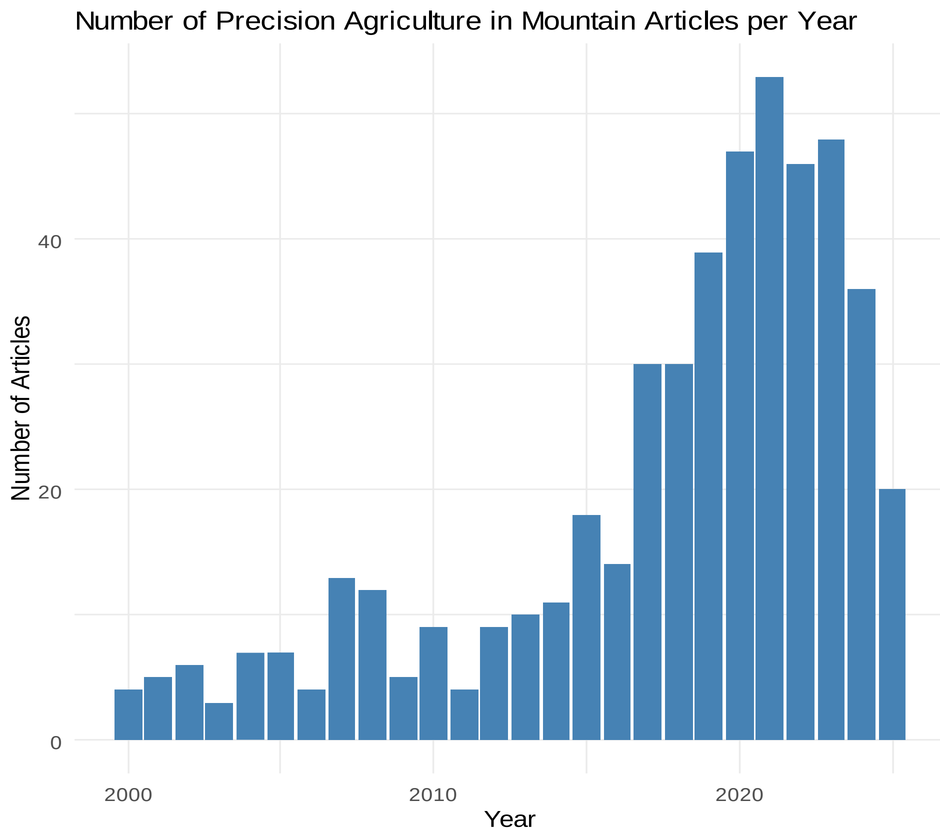
5.2 Tracking the Growth and Global Footprint of Mountain Precision Agriculture Research

Below diagram indicates the growth of article on Precision agriculture in mountain region with the time span of 2000-2025

Fig. 1: Number of Articles (Timespan, 2000-2025)



*Sources***:** Self Constructed and Compiled

The figure shows that journal publications on mountain-specific precision agriculture were very limited in the early 2000s but gradually increased over time, reaching their highest point in the 2020s, with 2021 marking the year of maximum publications. Following this peak, a slight decline in publication numbers is observed. The annual growth rate of articles stands at 7.27%, which is relatively modest. This slow growth in the early years can be attributed to the limited technological development and the lower urgency of climate-related challenges during the 2000s. However, in recent years, the advancement of precision agriculture technologies and the growing impact of climate change have contributed to greater research attention and adoption (see Zhang et al., 2022; Gebbers & Adamchuk, 2010).

Below figure indicate the total citation per year of time span 2000-2025.

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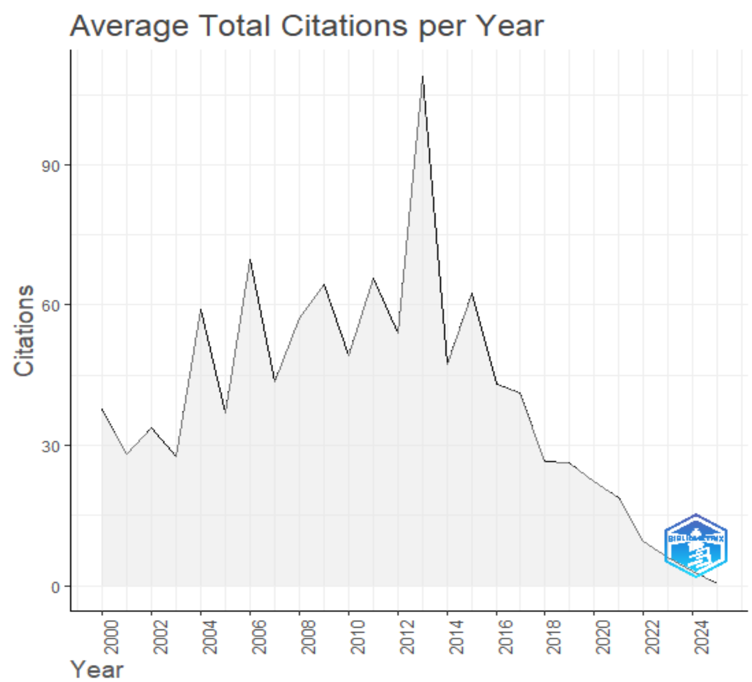
Fig. 2: Average Total Citations per Year



Sources: Self Constructed and Compiled

As illustrated in **Figure,** the trend in average total citations per year shows considerable variation over time. Citations were moderate in the early 2000s, fluctuating between 30 and 60. A sharp increase occurred around 2013, peaking at over 90 citations, indicating a period of heightened academic impact and attention to Precision Agriculture research. However, after 2015, a steady decline is evident, with citation averages gradually falling to below 20 by 2023–2024. This pattern suggests that while earlier studies in the field continue to hold significant influence, more recent publications are still in the process of accumulating citations.

5.3 Leading Countries by Citation in Mountain Precision Agriculture Research

The table below presents the countries that have received the highest total citations for research on mountain precision agriculture over the past 25 years.

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Table 2: Most Cited Countries

Country	Total Citations	Average Article Citations
ETHIOPIA	2521	38.20
USA	1345	31.28
BELGIUM	1081	41.58
CHINA	1065	16.38
NETHERLANDS	1053	36.31
GERMANY	789	52.60
AUSTRALIA	647	28.13
KENYA	616	34.22
ITALY	573	35.81
CANADA	234	29.25
JAPAN	225	13.24
UGANDA	210	35.00
SWITZERLAND	182	36.40
LAOS	180	180.00
UNITED KINGDOM	180	15.00
INDIA	174	19.33
SPAIN	174	24.86
SWEDEN	140	35.00
DENMARK	138	46.00
CHILE	120	30.00

Sources: Self-Constructed and compiled

The citation analysis shows Ethiopia as the most influential country with 2,521 citations, followed by the USA, Belgium, China, and the Netherlands, reflecting strong contributions from both developed and developing nations. Germany, Australia, Kenya, and Italy also play significant roles, while countries such as Canada, Japan, Uganda, and others contribute important regional perspectives. Overall, the results highlight Ethiopia's dominance alongside a diverse global engagement in advancing research on precision agriculture and mountain farming systems.

A temporal comparison reveals a sharp rise in citations between 2013 and 2015. This period corresponds with important technological advancements, such as wider access to UAV technologies, rapid improvements in satellite-based remote sensing, and the proliferation of open-source GIS platforms. These innovations evidently stimulated scholarly interest and facilitated more terrain-specific research across diverse landscapes.

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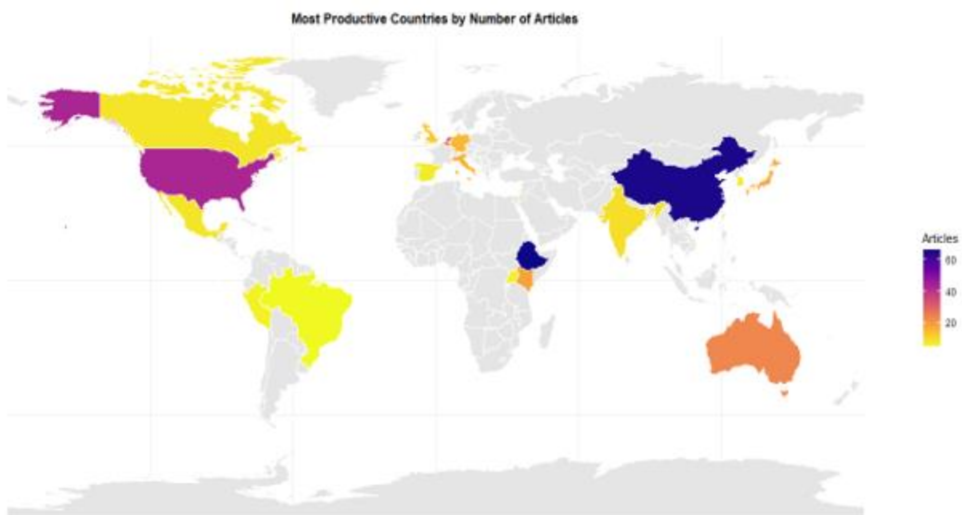
5.4 Most Contributing Countries

The map below illustrates the top 20 countries contributing to research on mountain precision agriculture. Countries shaded in **dark blue** represent those with the highest number of publications, followed by **purple** and **orange,** while **yellow** indicates countries with comparatively fewer publications.

Fig. 3: Top 20 Most Contributing Countries



**Blue–country with Higher Publication, *Yellow- Country with lower Publication

Sources: Self Constructed and Compiled

The map clearly shows that research on mountain precision agriculture is unevenly distributed across the world. A few countries, such as **China** and **Ethiopia**, stand out with the highest number of publications, shown in dark blue. These countries have made significant progress in studying and applying precision agriculture technologies to mountainous and hilly regions. The **United States**, shown in purple, also contributes strongly, reflecting its active role in advancing and collaborating on precision agriculture research globally. **Australia**, shaded in orange, shows moderate research activity, indicating growing interest in adapting precision farming to different landscapes.

Countries like **India, Kenya, Spain, and Japan,** shown in yellow, are emerging contributors, with a smaller but increasing number of publications. Their growing participation suggests a rising awareness of the importance of using modern technologies to address agricultural challenges in mountain areas.

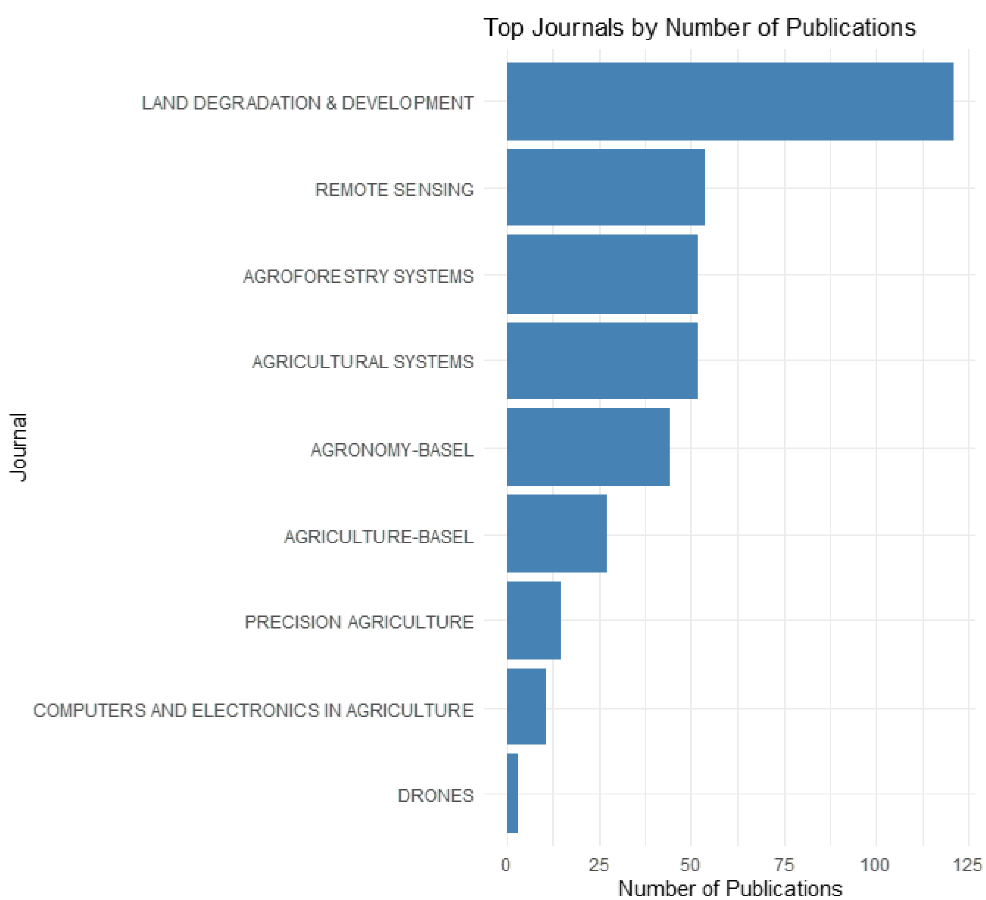
Overall, the figure highlights a clear imbalance in global research efforts, where most publications come from a few key countries. This suggests that more international cooperation and knowledge sharing are needed especially involving developing and mountain-based nations to strengthen research and practical applications of precision agriculture in these regions.

6. UNVEILING KEY CONTRIBUTORS: INFLUENTIAL JOURNALS, AUTHORS, AND SEMINAL WORKS

6.1 Core Journals

The bar diagram below illustrates the core journal contributors in the field of precision agriculture**,** highlighting the journals that have published the highest number of research articles in this domain.

Fig. 4: Top Journals by Publication



Sources: Self Constructed and Compiled

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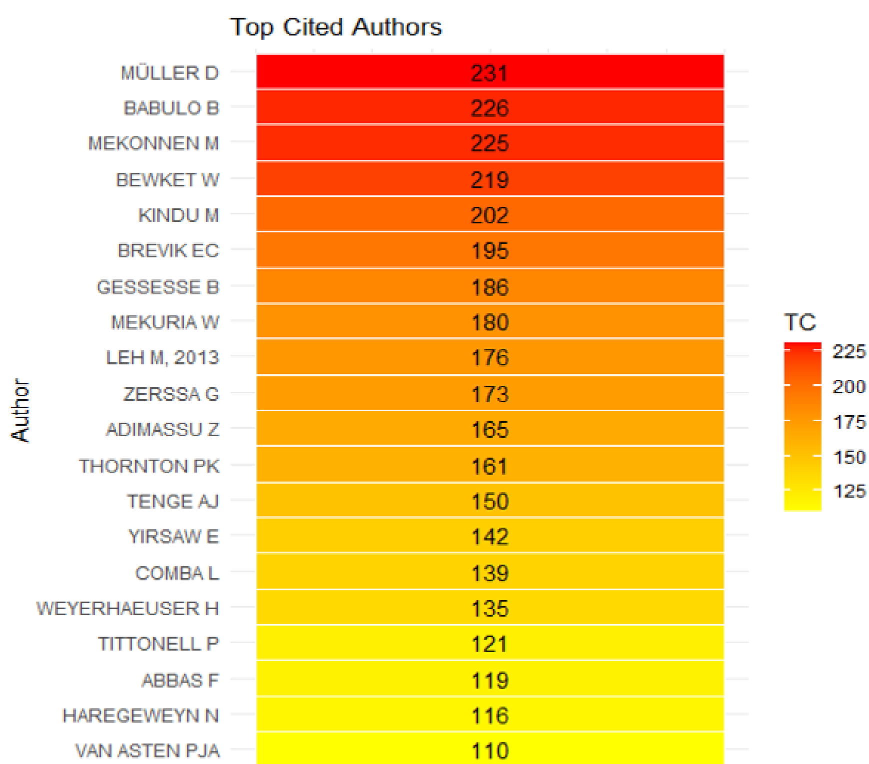
The bibliometric analysis reveals that research on *precision agriculture in mountain regions* is concentrated within a core set of journals. Among these, **Land Degradation and Development** emerge as the leading outlet, publishing the highest number of articles on the subject. It is followed by **Remote sensing**, Agroforestry, and Agriculture System, which also contribute significantly to the field. Together, these journals form the **core knowledge base,** providing consistent platforms for the dissemination of research findings.

Beyond the top tier, publications are scattered across a wider range of journals, each contributing only a small number of articles. This pattern aligns with **Bradford's Law of Scattering**, which states that a small number of journals typically account for the bulk of scholarly output, while the majority of journals publish relatively fewer papers.

The dominance of a few journals underscores their **influence and visibility** in shaping discourse and advancing research in agricultural production and precision agriculture. For future researchers, publishing in these leading journals enhances both the **impact and reach** of their work.

6.2. Influential Authors

Figure 5: Top Cited authors



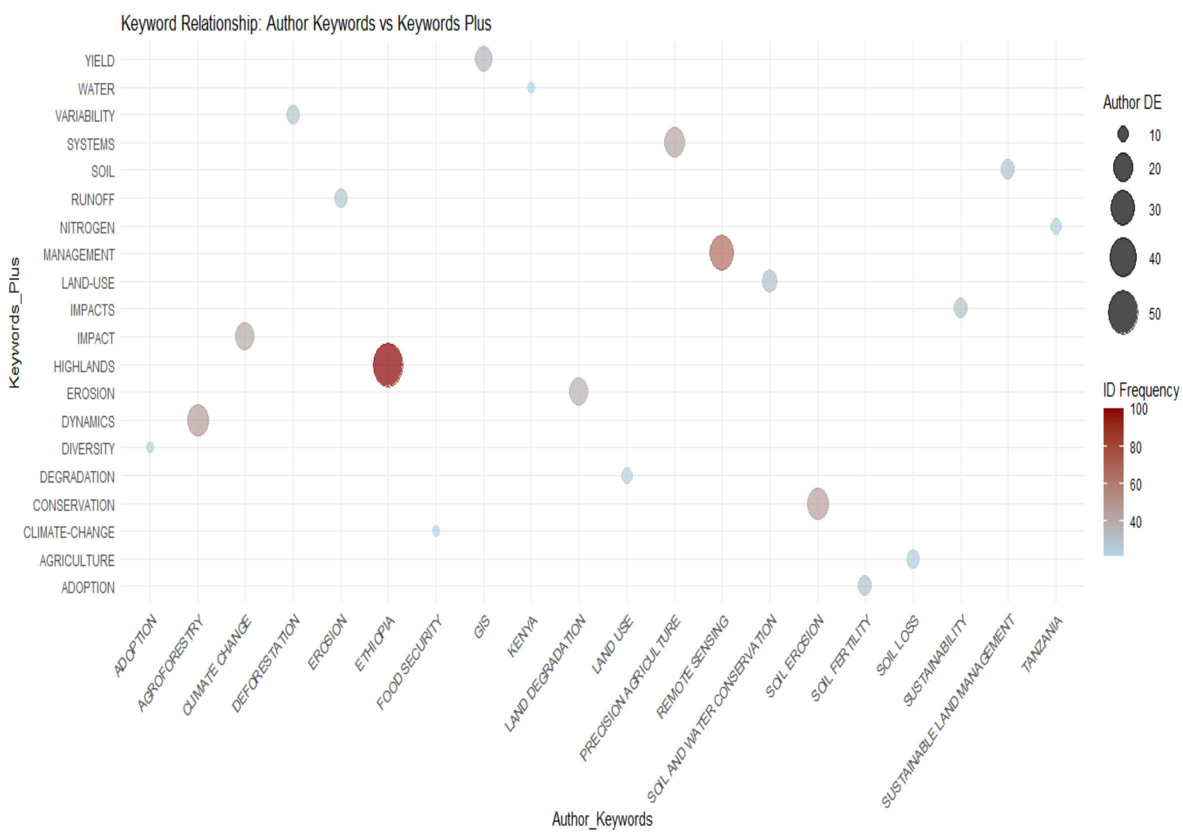
Sources: Self-constructed and Compiled

Figure 5, presents the top-cited authors in the field, with Müller D (231 citations), Babulo B (226 citations), and Mekonnen M (225 citations) leading the list. Other highly cited contributors include Bewket W (219 citations) and Kindu M (202 citations), reflecting their strong influence on agricultural and mountain research. The overall pattern shows that a few key authors dominate citations, while a wider group continues to provide significant supporting contributions, indicating both concentration and diversity in the knowledge base.

7. MAPPING RESEARCH THEMES AND IDENTIFYING KNOWLEDGE GAPS FOR FUTURE DIRECTIONS

7.1. Thematic Clusters

Figure 6: Keyword Co-occurrence Network of Author Keywords and Keywords-Plus in Mountain Agriculture Research



Sources: Self-Constructed and Compiled

In the Figure 5, The keyword co-occurrence analysis reveals three dominant clusters shaping mountain PA research. **Environmental conservation** focuses on soil erosion, land degradation, and climate change, reflecting the ecological fragility of mountain farming systems. **Technology**

integration centers on GIS, UAVs, remote sensing, and digital tools, highlighting the growing role of innovations that adapt precision methods to steep and fragmented terrains. **Socio-economic adoption** includes themes such as food security, sustainability, and farmer adoption, emphasizing the need to understand how smallholders engage with PA technologies.

Together, these clusters show that research on mountain PA is multidimensional balancing environmental concerns, technological advances, and socio-economic realities but adoption and policy-oriented studies remain less developed.

A comparison of technology types further highlights the differing research priorities across regions. While flatland precision agriculture tends to emphasize mechanized systems and variable-rate technologies, mountainous regions rely more heavily on UAV-based monitoring, digital soil mapping, and terrain-adjusted decision-support tools. These distinctions underscore the need for regionally adapted technological pathways.

Overall, the stronger narrative linking between figures and interpretation enriches the discussion and improves clarity.

8. DISCUSSION

Mountain agriculture plays a vital role in sustaining rural livelihoods in countries like Nepal, Bhutan, and other high-altitude regions, but it faces unique challenges. Steep slopes, fragmented landholdings, fragile soils, and variable microclimates make conventional farming difficult, often resulting in lower productivity and greater vulnerability to climate change (Sharma et al., 2022). Precision Agriculture (PA), which uses GPS, remote sensing, UAVs, and data-driven decision-support tools, offers a promising solution to optimize resource use, improve yields, and protect fragile ecosystems (Gebbers & Adamchuk, 2010). Yet, despite its potential, PA in mountainous regions remains far less explored than in flatland, large-scale farms.

Research on this topic was limited in the early 2000s but steadily increased, peaking in 2021. Ethiopia and China emerge as leading contributors, reflecting both developing and developed nations' focus on mountain agriculture challenges. Countries such as Nepal, India, and Bhutan are gradually gaining attention, highlighting the need for locally adapted studies that address smallholder constraints and steep terrain conditions.

Keyword and thematic analysis reveals three main research directions. First, **environmental conservation**, which emphasizes soil erosion control, land degradation, and climate resilience in fragile mountain ecosystems. Second, **technological integration**, focusing on GIS, UAVs, remote sensing, and terrain-adjusted algorithms that allow precise crop and soil management even on steep slopes (Matese et al., 2015; Comba et al., 2020). Third, **socio-economic adoption**, which considers smallholder engagement, sustainability, and food security—but this remains an underexplored

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area, especially in Nepal and similar regions. Core journals such as *Land Degradation & Development* and *Remote Sensing* dominate the field, and influential authors like Müller D, Babulo B, and Mekonnen M have shaped its development.

Despite technological advances, critical gaps remain. Few studies assess the economic feasibility of PA for smallholders, and policy frameworks tailored to mountain contexts are lacking. In Nepal, where most land is mountainous, successful adoption will require terrain-sensitive, cost-effective, and farmer-centered approaches. UAV-based monitoring, GIS-guided interventions, and remote sensing for slope management hold promise, but scaling up these solutions depends on institutional support, training, and local innovation.

In summary, PA offers significant potential to transform mountain agriculture in Nepal and other hilly regions. While research is growing, it remains fragmented and concentrated in a few countries. Future efforts should focus on smallholder adoption, economic feasibility, and policy support to ensure that precision technologies contribute meaningfully to sustainable, resilient mountain farming systems.

9. CONCLUSION

This study provides the first comprehensive bibliometric assessment of precision agriculture research in mountain and hilly regions using Web of Science data from 2000–2025, over 42,000 initial records, 2,111 studies were shortlisted for relevance, and 490 publications were finally reviewed in depth. The results confirm that while PA is widely applied in flatland farming systems, its integration into mountain contexts such as the Himalayas, Andes, and Alpine zones remains fragmented and underrepresented. Mountain agriculture continues to face unique barriers, including steep slopes, heterogeneous microclimates, small landholdings, and fragile ecosystems (Sharma et al., 2022).

A limited set of journals and authors dominate this emerging field, with Ethiopia and China standing out as leading contributors. The thematic analysis shows three major clusters environmental conservation, technological integration, and socio-economic adoption. However, adoption studies, cost–benefit analyses, and mountain-specific policy frameworks remain underexplored (Tsyplenkov et al., 2020).

The study concludes that while technologies such as UAVs, GIS, and remote sensing hold significant potential for addressing terrain-related constraints, their long-term impact depends on greater emphasis on localized, terrain-sensitive, and farmer-centered approaches. Future research should prioritize economic feasibility studies, scalable innovations for smallholders, and supportive institutional frameworks to enable sustainable mountain farming and resilient rural economies.

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10. LIMITATIONS

This study is subject to several limitations inherent to bibliometric research. First, reliance on the Web of Science database introduces potential bias, as certain journals—particularly those from developing or non-English-speaking regions—may be underrepresented. Second, limiting the dataset to English-language publications may exclude valuable regional insights and indigenous knowledge. Third, citation-based metrics tend to favor older publications, meaning recent advances may appear less influential due to citation lag. Finally, while keyword co-occurrence methods improve specificity, they may inadvertently exclude relevant studies where terminology is inconsistent or evolving.

11. FUTURE RESEARCH DIRECTIONS

Future research should prioritize more actionable and region-specific frameworks for scaling precision agriculture in hilly and mountainous regions. This includes developing low-cost, slope-adaptive technologies suitable for smallholder farmers; strengthening digital literacy and extension services; and establishing cooperative-based mechanisms for shared access to UAVs, sensors, and decision-support tools. Moreover, longitudinal field trials in diverse mountain environments would provide deeper insights into the agronomic, economic, and environmental impacts of precision agriculture. Integrating regional datasets especially from South Asia, Africa, and Latin America would also help address geographic imbalances and support cross-regional learning.

12. EXPANDED POLICY, COST-BENEFIT, AND SOCIO-ECONOMIC BARRIERS DISCUSSION

Policy support remains essential for accelerating precision agriculture adoption in mountain regions. Governments and development agencies can play a key role by offering targeted subsidies, improving rural connectivity, and integrating mountain-specific digital agriculture strategies into national agricultural policies. Cost–benefit analyses tailored to small and fragmented mountain farms are also needed, as economic feasibility remains a major constraint for smallholders. Socio-economic barriers including low digital literacy, limited access to capital, inadequate extension services, and cultural preferences for traditional practices continue to hinder adoption. Addressing these challenges requires coordinated efforts across policy, research institutions, and local communities.

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