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Fuzzy Cognitive Mapping in Natural Resource Management: A Global Bibliometric Analysis with India-Specific Insights (1995–2025)

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HIGHLIGHTS

- The field has grown from a niche method into a globally distributed research domain with an 11.75% annual growth rate and thematic focus has shifted from technical modelling toward participatory and climate applications.
- The method's strength lies in encoding expert knowledge without requiring quantitative precision.
- India's 23-document corpus, though small, matches the global citation average (23.7 vs. 22.74 citations per document).

ARTICLE INFO

Keywords: Natural resource management, Participatory modelling, Fuzzy cognitive mapping, Bibliometric analysis, Keyword co-occurrence network, Thematic analysis, Decision support systems.

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ABSTRACT

Natural Resource Management (NRM) is a complex, multi-dimensional domain in which effective impact assessment demands tools capable of handling subjectivity, uncertainty and stakeholder diversity. Fuzzy Cognitive Mapping (FCM) has emerged as such a tool, enabling the integration of qualitative knowledge and stakeholder perspectives into structured causal models. This study presents a bibliometric analysis of Scopus-indexed documents applying FCM in NRM contexts from 1995 to 2025, examining global trends in publication output, leading countries, institutions, journals, and authors. Bibliometric and network visualisation analyses were performed using Biblioshiny (bibliometrix R package) and VOSviewer. Qualitative thematic analysis of India-specific documents was conducted to complement the quantitative findings. The field has grown at an annual rate of 11.75%, with the United States and Greece leading global output. India, though modest in publication volume, shows a dynamic trajectory, with studies spanning precision agriculture, climate change adaptation, conservation conflicts, and disaster resilience. Collectively, the findings highlight FCM's expanding role in applied, participatory, and sustainability-oriented NRM projects.

INTRODUCTION

The phrase "Natural Resource Management" (NRM) gained currency in the United States in the early 1960s, used interchangeably with "environmental management" and "resource management" (Miller et al., 2019). Against a backdrop of climate change, biodiversity loss, and mounting sustainability pressures, NRM research has gained growing attention (Nichols et al., 2011). Effective NRM practices can mitigate climate vulnerability, reduce disaster risk, and support biodiversity conservation (Abramovitz et al., 2001), and NRM is widely recognized as foundational to achieving the United Nations Sustainable Development Goals (Bansal et al., 2022).

However, impacts of NRM are notoriously difficult to assess. The biophysical effects of interventions are hard to quantify due to the intricate interplay of ecological, socio-economic, and

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institutional factors (Rahman, 2026). Impacts are frequently indirect and manifest over extended timescales, complicating attribution and measurement (Falk et al., 2021). Traditional impact assessment methods (Gupta et al., 2020; Gupta et al., 2021; Jha et al., 2025; Krishna et al., 2025) often fall short in capturing the subjective, qualitative, and interdependent characteristics of socio-ecological systems (Obiedat & Samarasinghe, 2022). This makes comprehensive impact assessment a continuing methodological challenge in NRM scholarship (Jain et al., 2025).

Fuzzy Cognitive Mapping (FCM) has emerged as a promising response to this challenge. FCM provides a structured yet flexible framework for incorporating diverse forms of knowledge and stakeholder perspectives into models of system dynamics (Gray et al., 2015; MacMillan et al., 2024). It captures causal relationships between system variables, assigns positive or negative weights to conceptual linkages, and supports "what-if" scenario analyses that can inform adaptive management and planning (Özesmi & Özesmi, 2004). Its capacity to encode expert knowledge without requiring full quantitative precision makes FCM particularly valuable in data-scarce, knowledge-rich contexts.

Despite decades of growing application, no comprehensive bibliometric analysis has examined the structure and global evolution of this literature, nor has its development in India been systematically assessed. India warrants dedicated attention for several reasons. It combines exceptional agrarian complexity, over 140 million farm holdings, the majority smallholder, with acute exposure to climate variability, water stress, and biodiversity pressures. This makes it a high-stakes test case for participatory, knowledge-based NRM tools. Yet India's FCM research has developed with limited visibility in the global conversation, and no study has mapped its trajectory, thematic contours, or connection to international networks. This gap limits evidence-based guidance for researchers and policymakers seeking to apply FCM in Indian NRM contexts. The present study addresses that gap by analysing Scopus-indexed FCM-in-NRM documents from 1995 to 2025, and supplements the bibliometric findings with qualitative thematic analysis of India-specific research.

METHODOLOGY

This study employs bibliometric analysis to examine the structure and development of FCM-related NRM literature (Anuranj & Vishnu, 2026; Donthu et al., 2021). The search was performed using a set of keywords related to fuzzy cognitive mapping (FCM) in natural resource management (NRM). Keywords included 'Fuzzy Cognitive Map', 'Agriculture', 'Livestock', 'Fish', 'Natural Resource', 'Soil', 'Water', 'Watershed', 'Technology Transfer', 'Transfer of Technology', 'Impact Assessment', 'Project Evaluation', 'Impact Pathway'.

The following query was applied to Scopus with time restriction (1995-2025):

(TITLE-ABS-KEY ("fuzzy cognitive mapping" OR "fuzzy cognitive maps") AND TITLE-ABS-KEY ("agriculture" OR "livestock" OR "fish" OR "natural resource" OR "soil" OR "water" OR "watershed" OR "technology transfer" OR "transfer of technology") OR TITLE-ABS-KEY ("impact assessment" OR "project evaluation" OR "impact pathway")

Scopus was selected as the primary database given its standing as a curated, high-quality bibliometric source with broad coverage of peer-reviewed literature across disciplines (Baas et al., 2020). The query uses Boolean AND to require both an FCM term and an NRM-domain term, while OR groups synonyms within each category; impact-related terms are added via a separate OR clause to capture evaluation-focused studies. Inclusion criteria restricted results to peer-reviewed research articles, reviews, and conference papers published in English between 1995 and 2025. Non-English documents, editorials, book chapters, and errata were excluded. Search results were downloaded in .bib and .csv formats. After removing duplicate records and screening for relevance. The final dataset comprised 305 scholarly publications. Bibliometric and visualization analyses were performed using Biblioshiny, the web-based interface of the bibliometrix R package (Aria & Cuccurullo, 2017) and VOSviewer (version 1.6.19) software (Centre for Science and Technology Studies, Leiden University, Leiden, The Netherlands). Qualitative thematic analysis of India-specific abstracts was conducted to identify patterns of FCM application (Krithika et al., 2023).

RESULTS

Descriptive overview and publication trends

Between 1995 and 2025, 305 documents on FCM in NRM appeared across 211 sources at an annual growth rate of 11.75%. The average document age of 7.61 years reflects a young but steadily maturing field, and an average of 22.74 citations per document signals strong academic impact. Collaboration was extensive, with the average paper involved more than four authors, with 39.02% of documents featuring international co-authorship. Journal articles (76%) and conference papers (15%) dominate document types.

For India, 23 documents spanning 22 sources were identified, covering 2015–2025, with an annual growth rate of 5.24%, covering 2015–2025, with an annual growth rate of 5.24% which is lower than the global 11.75%, reflecting India's later entry into the field (first publication in 2015 versus 1995 globally). Indian papers averaged 23.7 citations, closely approximating the global figure, and featured comparable levels of collaborative authorship

Table 1. Descriptive bibliometric overview of FCM-in-NRM literature: global (1995–2025) and India (2015–2025)

Metric	Global (1995–2025)	India (2015–2025)
Sources (journals, books, etc.)	211	22
Documents	305	23
Annual growth rate (%)	11.75	5.24
Document average age (years)	7.61	6.13
Average citations per document	22.74	23.7
References	2526	204
Authors' Keywords (DE)	977	92
Authors	1,030	73
Co-authors per document	4.36	4
International co-authorship (%)	39.02	34.78
Articles/Reviews/Conference papers	244/2/48	20/1/—

(approximately 4 per paper) and international co-authorship (34.78%). The descriptive overview is summarised in Table 1.

Bibliometric analysis tracked the evolution and dynamics of research themes over time. Globally, FCM-based NRM research started with technical foundations like fuzzy sets, knowledge representation, and basic decision-support tools, roughly between 2004 and 2012. By the mid-2010s, attention moved toward complex systems modelling, participatory planning, and decision support. From 2020 onward, the field concentrated on environmental protection, ecosystem services, food security, and conservation, with climate change, land use dynamics, and sustainable resource systems becoming recurring concerns (Figure 1). In India, FCM studies began with a technical emphasis between 2016 and 2018. By 2021, research had expanded toward stakeholder engagement and local contexts. Subsequently, studies turned toward human-dimensions questions like perceptions, decision pathways, and impact assessment, reflecting a broader shift toward applied, people-centred NRM inquiry (elaborated later in Table 2).

Mapping the global research landscape: countries, institutions, and journals

The United States leads global output with 146 publications (Figure 2), a dominance consistent with its large-scale federal funding ecosystem for environmental and agricultural research. Greece ranks second, its disproportionately high output driven by concentrated research groups in computational intelligence and FCM methodology. China, United Kingdom, Canada, Australia, India, Netherlands, Spain, and Turkey complete the top ten, suggesting that FCM-NRM research has diffused well beyond its Euro-American origins.

Wageningen University and Research (Netherlands) lead institutional output with 20 publications, followed by Universidad Politécnica de Madrid (Spain, 17), Michigan State University (USA) and the University of Thessaly (Greece), each contributing 14 publications. Institutions from Italy, Australia, and India also feature prominently. In India, Sri Sivasubramaniya Nadar (SSN) College of Engineering leads with 6 FCM-related publications in NRM domains, followed by the Institute of Rural Management Anand (IRMA). That a single engineering college dominates India's output points to a narrow institutional base, whereas global production is distributed across agricultural, environmental, and engineering departments (Figures 3a, 3b). (Figures 3a, 3b).

Citation count is a widely used indicator of a source's relevance and impact within a research field (Bornmann & Daniel, 2008; Barman et al., 2026). The *Journal of Environmental Management* leads with 10 publications, followed by *Ecology and Society* (8) and *Sustainability (Switzerland)* (7). In India, 22 sources reflect interdisciplinary breadth. Chemosphere leads with 2 articles; *Agricultural Systems, Climatic Change*, and *Global Environmental Change* each feature one publication, spanning agriculture, ecology, engineering and applied mathematics (Figures 4a, 4b).

Intellectual foundations: influential authors and cited works

Author publication count is a standard bibliometric measure of scholarly productivity in each domain (Donthu et al., 2021). Globally, E.I. Papageorgiou leads with 16 articles, followed by S.A. Gray (13) and R. Giordano (10). Several other authors like Kok K, Kokkinos K, Anokhina MY, Arvanitis KG, Groot JCJ, Kyriakarakos G, and Papadakis G had contributed 5 to 6 documents, indicating a moderately concentrated but growing author base. The presence of multiple Greek-affiliated researchers among the top contributors aligned with Greece's strong standing in global FCM-NRM output. In India, H. Chudasama, E.I. Papageorgiou, P.K. Singh, and L.S. Subramanian each contributed 3 publications which is a modest count compared with the global leaders, but notable given India's shorter publication window (2015–2025 versus 1995–2025). Arthi K, Goswami R, Mainuddin M, Malarkodi KP, Poomagal S, and Ray K had contributed two articles, indicating that Indian FCM-NRM research, while growing, remained distributed across a relatively small and emerging author community (Figures 5a, 5b).

Citation frequency is a standard indicator of a document's influence within a given field (Garfield, 1955, 1972). Globally,

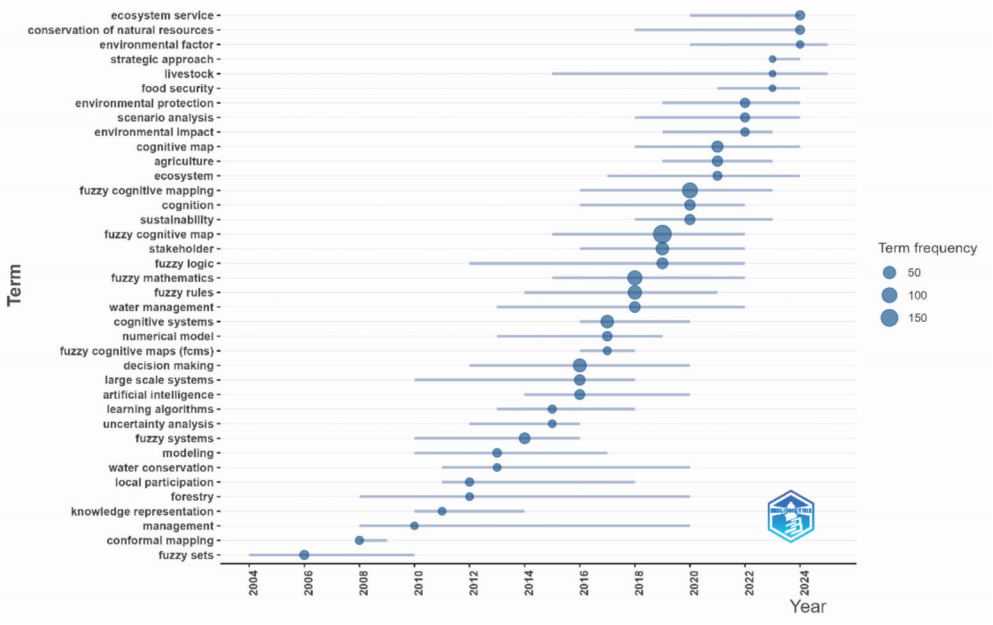

Figure 1. Temporal evolution of trending research topics in FCM-NRM literature, 1995–2025. Emerging topics appear in the upper right quadrant of the figure, and the size of the circles represents their term frequency.

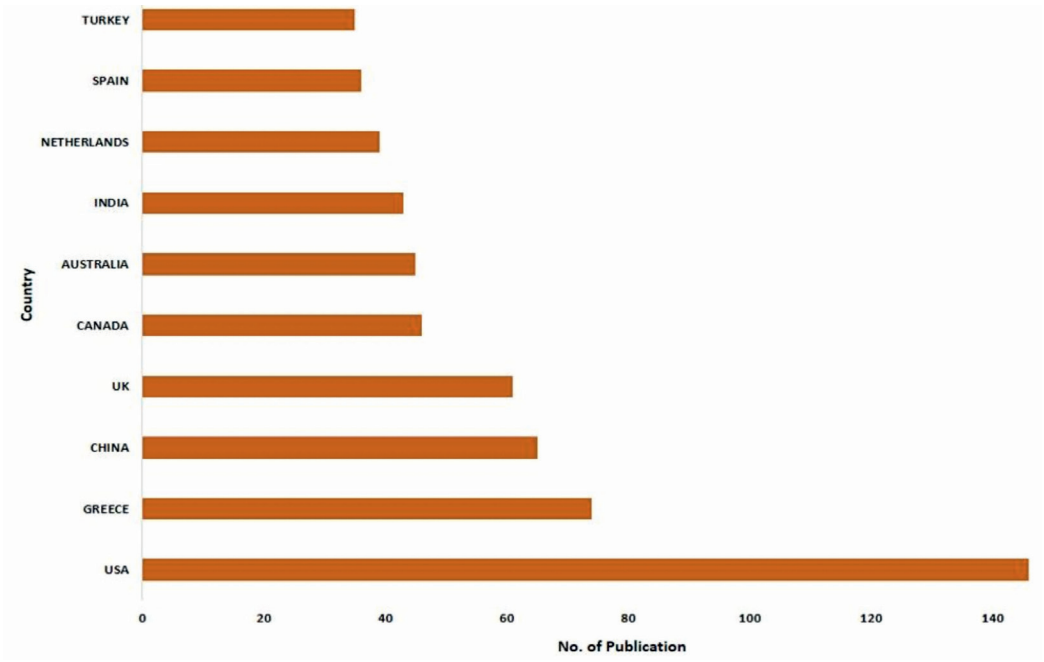

Figure 2. Top ten countries by scientific production in FCM-NRM research, 1995–2025

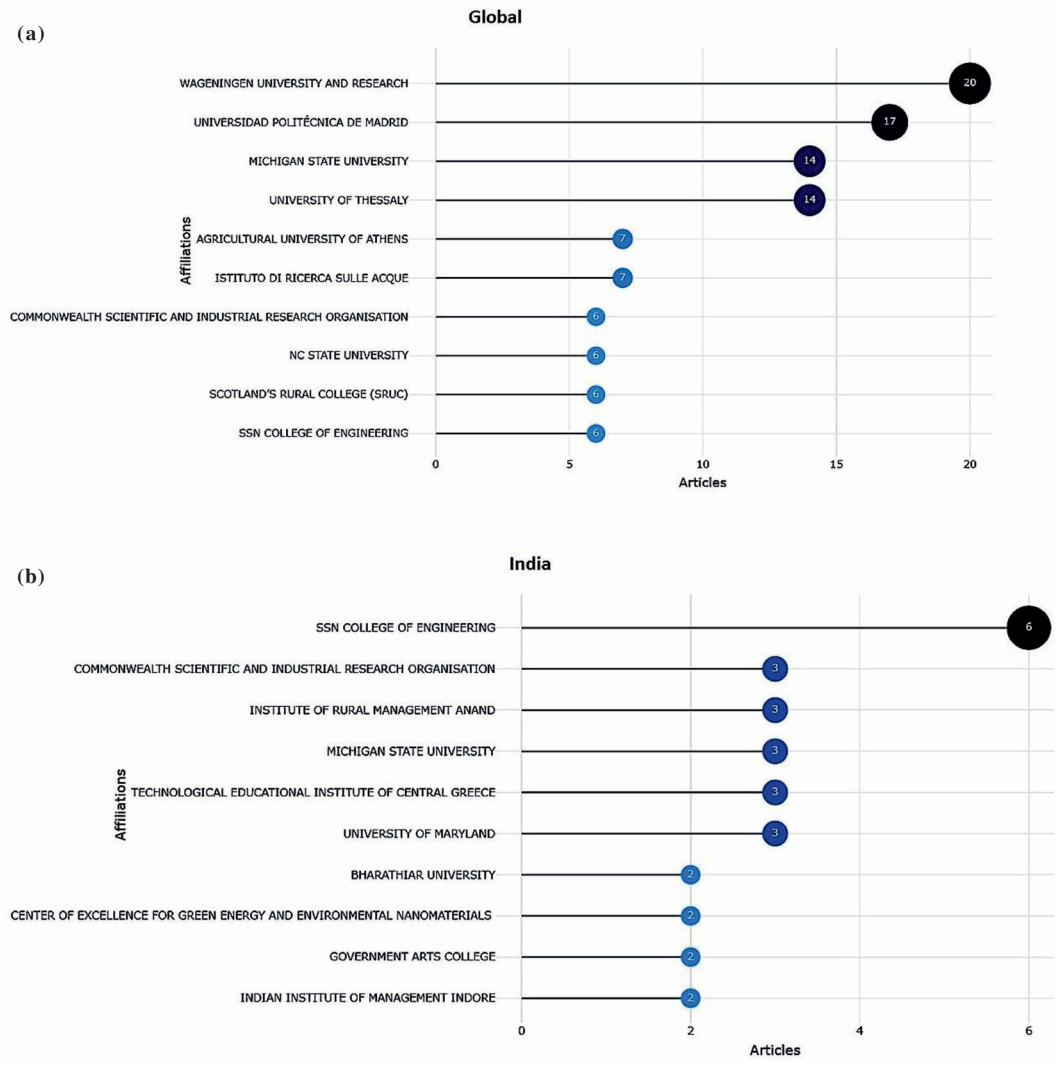

Figure 3. Top ten most productive institutions: (a) global and (b) India

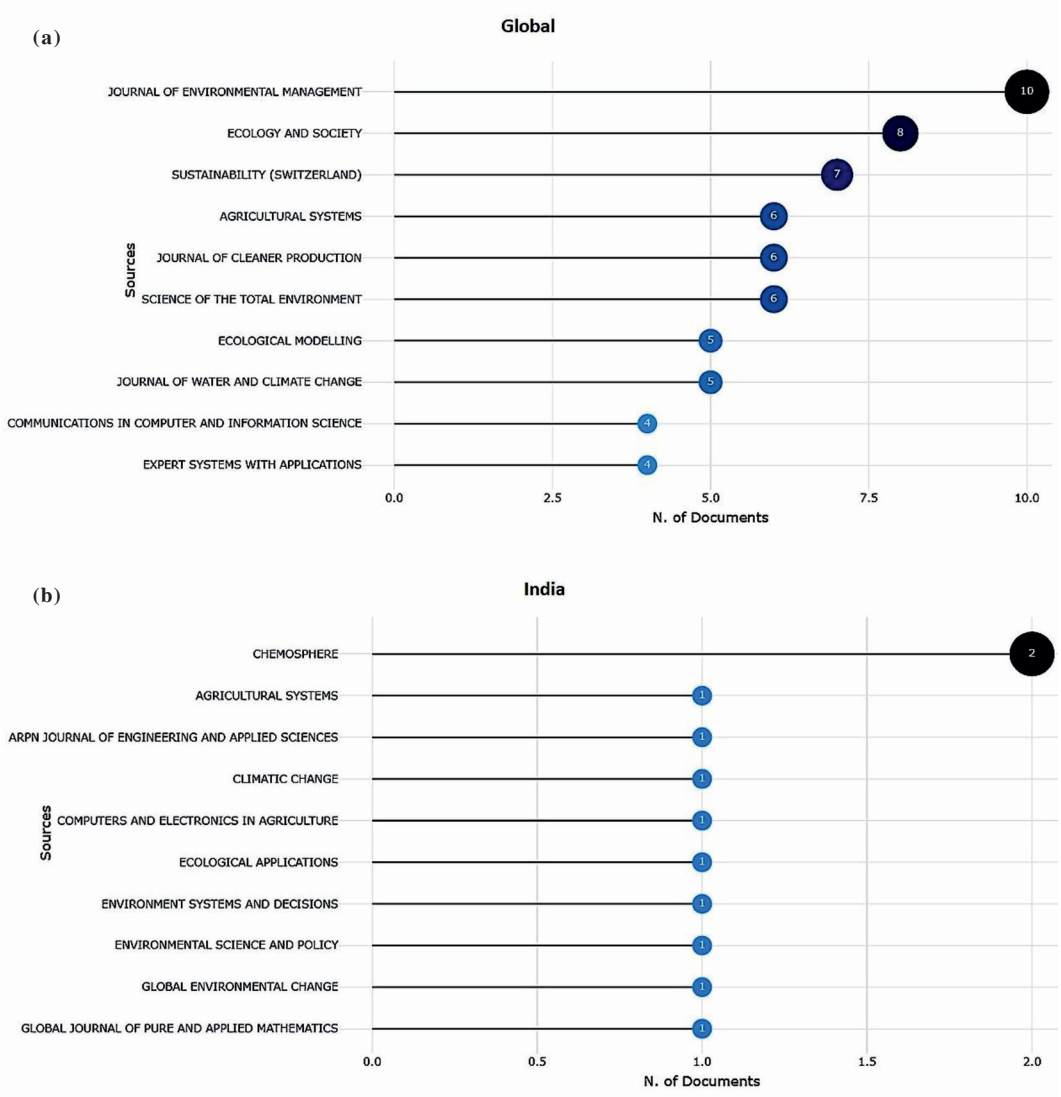

Figure 4. Top ten publishing sources by document count: (a) global and (b) India

Karavas (2015, *Energy Conversion and Management*) ranked first with 272 citations. Gray S.A. (2015, *Ecology and Society*) came second with 245, and Özesmi and Özesmi (2003, *Environmental Management*) third with 188 citations, suggesting longer term impacts and staying power of early participatory FCM work in environmental research (Figure 6).

In India, Singh (2021, *Journal of Cleaner Production*) drew the most citations at 109, followed by Gray (2018, *Ecological Applications*) at 101 (Figure 6). Goswami (2021, *Agricultural Systems*) ranked third with 66 citations marking a strong return for a study published just four years prior. The work examined FCM applications in Indian agricultural systems, and its citation record suggested that integrating stakeholder knowledge into farm-level NRM decisions struck a chord with researchers working on similar problems across South Asia.

Keyword analysis and conceptual structure: global and Indian perspectives

Indian keywords broadly mirrored global patterns but diverged in emphasis: human-centric terms such as "stakeholders" and "human" featured more prominently than in the global set, whereas the global corpus leaned more heavily on technical terms like "fuzzy rules" and "knowledge representation." This divergence likely reflects India's stronger orientation toward participatory field applications rather than algorithmic development. Terms such as "artificial intelligence" and "cognitive systems" also appeared in the Indian literature, indicating that researchers had begun connecting FCM with newer computational frameworks in applied NRM contexts (Figures 7a, 7b).

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The global Keyword Co-occurrence Network is larger and more complex (Figure 8a, 8b). Two dominant nodes, fuzzy cognitive mapping and fuzzy cognitive maps, form the network's core. The red-orange cluster (2018–2020) includes participatory modelling, mental models, social-ecological systems, and natural resource management, showing recent emphasis on participatory and ecological applications. Older keywords (blue-purple, 2010–2012) include decision making and fuzzy sets, reflecting early

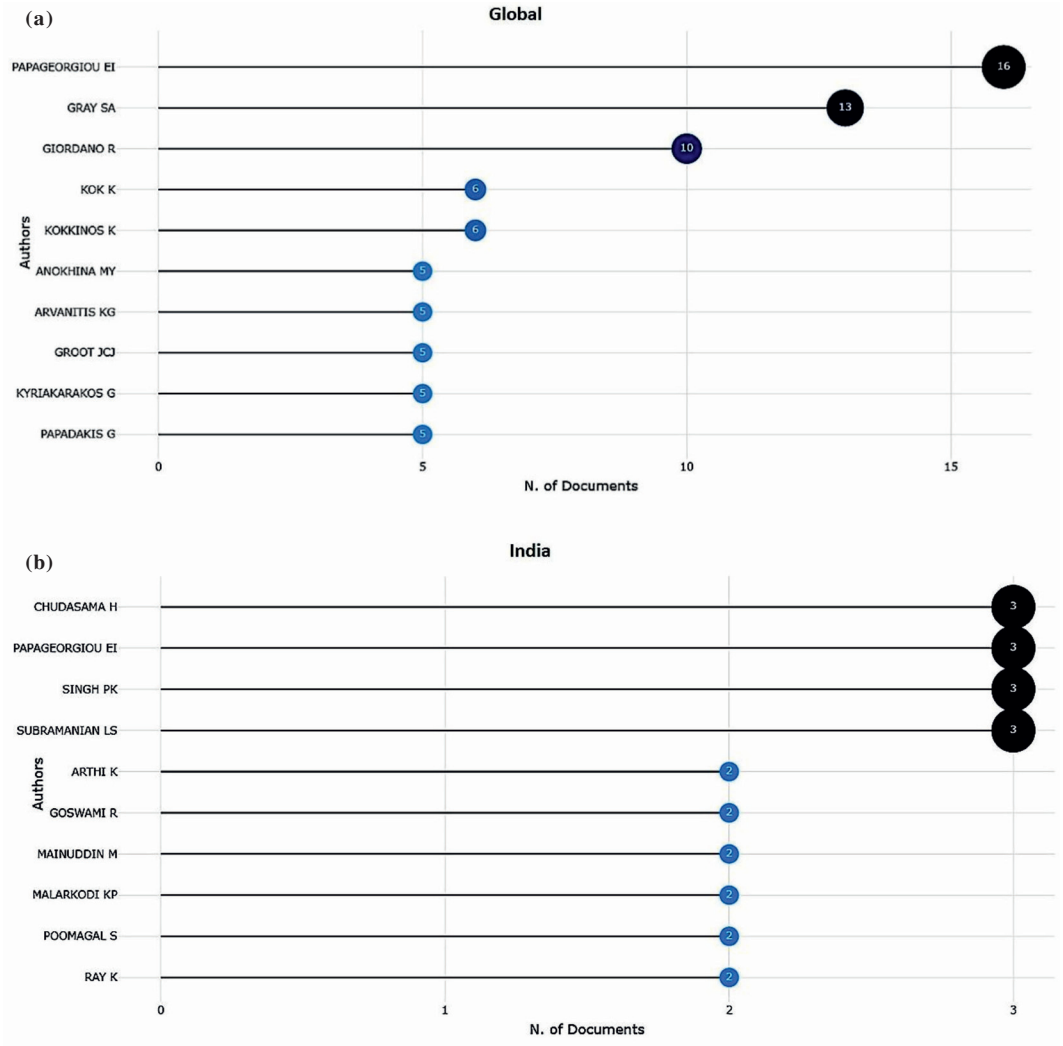

Figure 5. Most productive authors by publication count: (a) global and (b) India

methodological foundations. Stakeholders, sustainability, and agriculture serve as connecting themes across time periods. By contrast, the Indian co-occurrence network is smaller and more tightly focused. The red-orange cluster (2021–2022) centres on fuzzy cognitive maps, sustainability, stakeholders, water management, and environmental protection, reflecting India's recent policy-oriented turn. The blue-purple cluster (2018–2019) groups agriculture, fuzzy systems, fuzzy rules, and cognitive systems, representing the earlier technical phase. Fuzzy mathematics bridges both clusters, suggesting that quantitative formalisation remains a common methodological thread as the field shifts from algorithm-centric to application-centric research.

Thematic analysis of Indian studies

To complement the bibliometric findings, qualitative analysis of abstracts from India-based FCM studies directly addressing agriculture, NRM, and rural development yielded five thematic clusters (Table 2).

Human–environment conflict and ecological risk

Banerjee et al. (2025) applied FCM to model human–elephant conflict in a forested region, translating expert and community mental models into structured risk simulations. Alam et al. (2025) used FCM to examine the social-ecological risks of deep-sea mining. Both studies employed scenario comparison to reveal non-linear system dynamics that conventional linear assessments cannot capture, and recommended preventive and restorative management strategies over reactive responses.

Climate change adaptation and disaster resilience

Singh and Chudasama (2017) assessed community preparedness to cyclones in coastal Odisha; Singh and Chudasama (2020) examined climate adaptation pathways across arid and semi-arid Indian regions, while Panja et al. (2026) traced resilient pathways for climate-resilience agriculture in the coastal zones. Goswami et al. (2021) integrated FCM with qualitative research to explore resilience strategies for smallholder systems disrupted by COVID-19. Goswami et al. (2024) also examined resource recycling and land management for scaling zero-tillage potato cultivation in the coastal Sundarbans. Collectively, these studies demonstrated that climate adaptation was inherently multi-systemic; institutional factors like credit access, extension services, local governance were consistently identified as critical mediators between environmental shocks and household resilience.

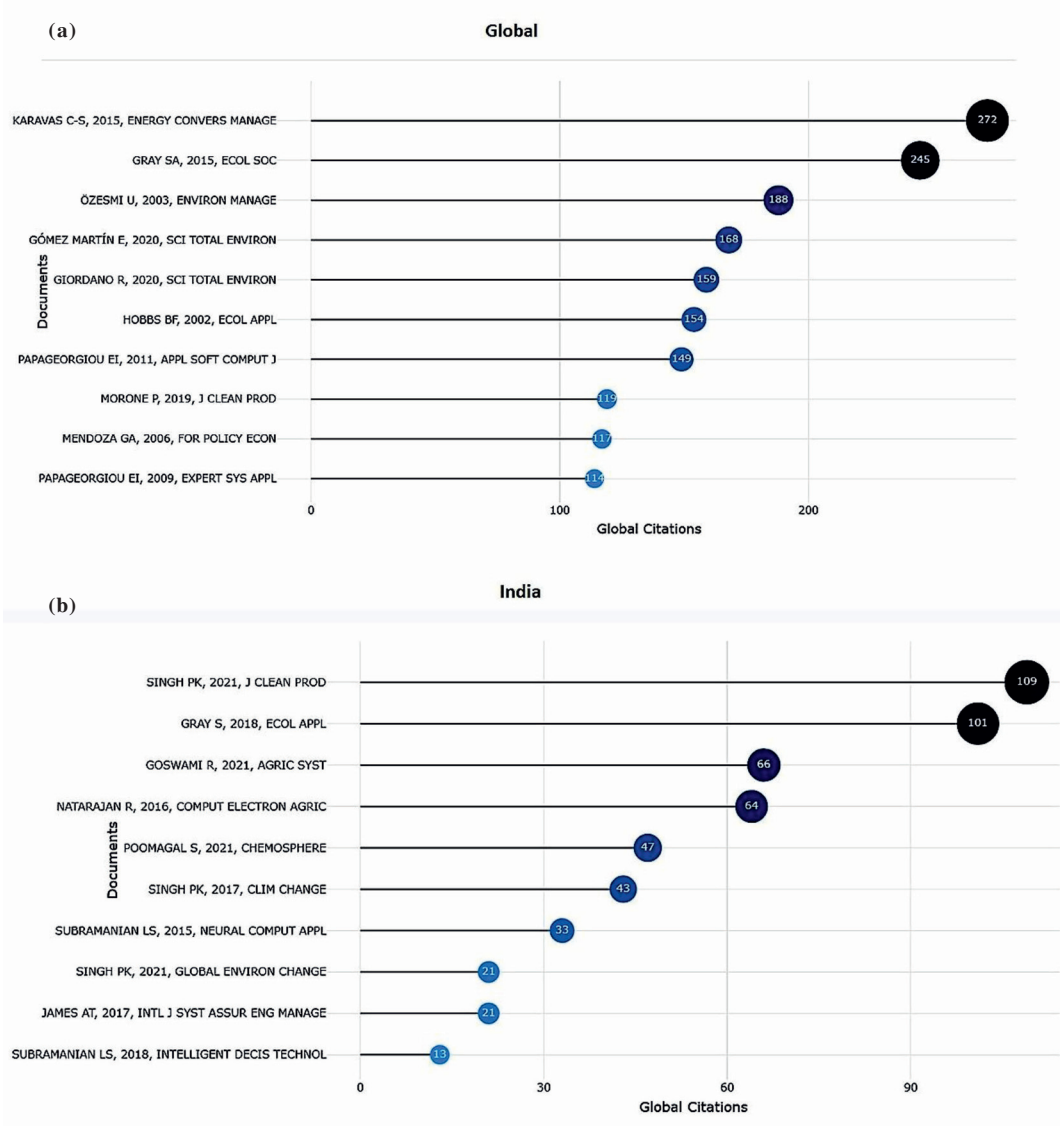

Figure 6. Most cited documents by total citation count: (a) global and (b) India

Table 2. Thematic summary of India-based FCM studies in NRM

Theme	Key studies	FCM application
Human–Environment Conflict & Conservation	Alam et al. (2025); Banerjee et al. (2025)	Stakeholder mental models; risk scenario simulation
Climate Change Adaptation & Disaster Resilience	Goswami et al. (2021, 2024); Singh & Chudasama (2017, 2020); Panja et al. (2026)	Pathway evaluation and resilient pathway identification; multi-stakeholder scenario planning
Sustainable Agriculture & Resource Management	Goswami et al. (2021, 2024); Haldar et al. (2026)	Resource recycling; land management; livelihood diversification and improvement
Precision Agriculture & Crop Yield Prediction	Anantharaj & Thangavelu (2015); Jayashree et al. (2015); Malarkodi & Arthi (2018); Natarajan et al. (2016)	Hybrid learning (FCM + ML); classification and yield prediction
Methodological Development	Jenitha (2017); Gray et al. (2017)	Participatory FCM frameworks; hybrid water demand prediction

Sustainable agriculture and resource management

Goswami et al. (2021, 2024) and Haldar et al. (2026) addressed resource recycling, land management and livelihood improvement as interdependent variables, with FCM providing the relational structure to model co-dependencies. Differentiated. These studies underscored that effective interventions must be differentiated by farm type, with particular attention to constraints specific to smallholders.

Precision agriculture and crop yield prediction

Jayashree et al. (2015), Anantharaj and Thangavelu (2015), Natarajan et al. (2016) and Malarkodi and Arthi (2018) applied

Figure 7. Most frequent author keywords in titles and abstracts: (a) global and (b) India

FCM, frequently hybridized with machine learning algorithms, to yield prediction for commercially significant Indian crops (coconut, sugarcane, groundnut, red chilli). These studies demonstrated that integrating expert domain knowledge with data-driven learning outperforms purely data-driven approaches in low-data, knowledge-rich agricultural settings. The focus on these crops reflects their strategic importance to India's agricultural policy.

Methodological development

Gray et al. (2017) advance the "Four Ps" framework i.e. Purpose, Processes, Partnerships, Products to address recurrent shortcomings in participatory FCM research, including issues of replicability, process transparency, and stakeholder engagement quality. Jenitha (2017) integrates FCM within a hybrid computational architecture for water demand prediction, demonstrating FCM's modularity within larger algorithmic systems.

Cross-cutting observations

Across all themes, Mental Modeler (https://www.mentalmodeler.com/) was frequently cited as the primary web platform for participatory FCM construction, while Python and MATLAB support data-driven implementations. Empirical studies span geographically diverse contexts like the Sundarbans delta, arid Rajasthan, the Malabar Coast, semi-urban Chennai, and cyclone-affected coastal Odisha, demonstrating FCM's applicability across varied socio-ecological settings. Scenario analysis, methodological triangulation (combining FCM with interview analysis, focus group discussions, and machine learning), and explicit policy orientation were hallmarks of the Indian FCM literature.

Taken together, Indian FCM research reveals a field that is small in volume but methodologically diverse and thematically aligned with pressing national priorities–climate adaptation, food security, and stakeholder-driven resource governance–positioning FCM as a versatile tool for evidence-based NRM decision-making in the Indian context.

DISCUSSION

This bibliometric analysis confirms that NRM-related research is a growing, globally distributed field with consistent citation impact and steady thematic evolution spanning three decades (1995 to 2025). The trajectory from technical modelling toward participatory planning, ecosystem services, and climate-oriented sustainability applications is consistent with broader shifts observed across environmental and sustainability science (Ellili, 2024). By utilizing a Scopus-based bibliographic dataset, this study conducts an inclusive and structured analysis of the field, with the overarching aim of advancing scholarly knowledge and providing evidence-based insights into current research trends and emerging future directions.

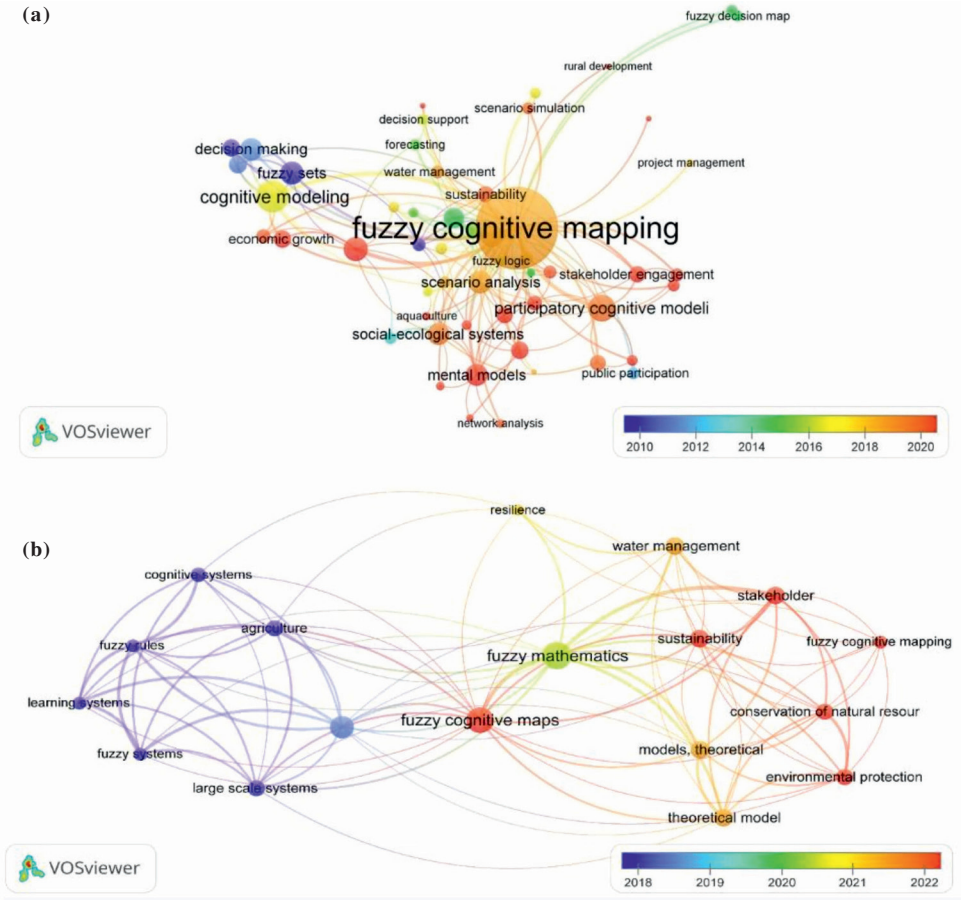

Figure 8. Keyword co-occurrence network and thematic temporal evolution in FCM-NRM literature: (a) global network and (b) India network

The United States leads in overall research output, reflecting sustained federal and institutional investment in environmental and agricultural research through agencies such as USDA and NSF. Greece's disproportionately high output can be attributed to concentrated research groups in computational intelligence, particularly around scholars like E.I. Papageorgiou, who have advanced FCM methodology and its environmental applications. Wageningen University and Research (Netherlands), with its longstanding strengths in agro-ecological and natural resource systems, leads institutional output globally. The *Journal of Environmental Management* and *Ecology and Society* serve as primary publishing venues within the field, signalling meaningful integration across both applied management communities and ecological theory scholarship. At the author level, Karavas et al. commands the leading position in the global citation landscape with 272 citations, reflecting significant scholarly influence in shaping the field's intellectual direction. The field further demonstrates strong collaborative dynamics, with cross-institutional and cross-national partnerships increasingly characterizing its output over the observed timespan.

India's NRM literature exhibits comparable citation impact and a distinctive thematic profile. The prominence of SSN College of Engineering (Tamil Nadu) as the leading institutional contributor reflects growing and concentrated domestic investment in NRM-related research. At the author level, P.K. Singh leads the Indian citation landscape with 109 citations, underscoring meaningful scholarly influence within the national context. Journals such as Chemosphere, Agricultural Systems, and Climatic Change serve as primary publishing outlets for India-based research, indicating interdisciplinary engagement across environmental, agricultural, and climate domains. Indian studies increasingly emphasize stakeholder engagement, human perceptions, agriculture and decision-support systems, where thematic priorities align closely with global research trajectories while simultaneously addressing India's heterogeneous agro-ecological contexts and community-specific NRM challenges. From a policy standpoint, these findings suggest that FCM can serve as a practical tool for participatory policy design, enabling policymakers to incorporate diverse stakeholder mental models into scenario planning for climate adaptation, resource allocation, and disaster preparedness.

Several limitations warrant acknowledgement and require consideration when interpreting the findings of this study. First, the exclusive reliance on Scopus as the sole bibliographic database restricts the comprehensiveness of the analysis, potentially excluding relevant literature indexed elsewhere. Future studies incorporating Web of Science, Google Scholar, or other complementary databases would substantially broaden coverage and enhance the representativeness of findings. Second, the India-specific thematic analysis is conducted manually using MS Word, without the assistance of dedicated qualitative research software. Software-assisted analytical approaches such as NVivo, ATLAS.ti, or comparable platforms have the potential to considerably improve both the methodological rigour and the reproducibility of thematic outcomes in future investigations. Third, network-based analytical methods

including co-authorship analysis, co-citation analysis, bibliographic coupling, and related structural approaches remain beyond the scope of the present study owing to time constraints. Future research incorporating these methods would provide a richer and more architecturally nuanced understanding of the field's intellectual structure and collaborative networks. Finally, existing studies tend to concentrate on a single domain of natural resources, with limited cross-domain integration within any unified research framework. Future investigations that deliberately incorporate multiple domains spanning agriculture and allied sectors, forestry, water resources, and beyond have the potential to offer a substantially more holistic understanding of the broader NRM landscape.

CONCLUSION

FCM-based research in NRM demonstrates robust global growth, high citation impact, and expanding international collaboration, led by the United States and Greece with the field maturing from technical modelling foundations toward applied, participatory, and sustainability-oriented inquiry India's FCM literature, though smaller in volume, is dynamic and growing. Institutions including IIT Delhi, IRMA, and RKMVERI contributing to a distinctive research agenda spanning precision agriculture, climate adaptation, conservation conflict and disaster resilience. Indian FCM research serves three interrelated functions,– capturing stakeholder mental models, analysing system complexity and supporting scenario-based policy decisions. As artificial intelligence and digital platforms become more deeply integrated with FCM methodologies, the field is well-positioned to contribute to global sustainability, equity, and resilience agendas, particularly in the data-scarce, knowledge-rich settings that define much of rural India. Future research should explore the integration of artificial intelligence techniques, such as deep learning for automated weight calibration and large language models for participatory elicitation, with FCM methodologies to enhance scalability and predictive accuracy.

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Conflict of interest: The authors declare no conflict of interest associated with the research.

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