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A SYSTEMATIC LITERATURE REVIEW ON THE EFFECTIVENESS OF GROUNDWATER REGULATION POLICIES IN AGRICULTURAL REGIONS

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ABSTRACT
Groundwater is essential for global water security, agricultural production, and rural livelihoods. However, excessive groundwater abstraction has resulted in declining water tables, aquifer depletion, reduced groundwater availability, land subsidence, deterioration of water quality, and degradation of groundwater-dependent ecosystems. This paper offers a systematic review of groundwater management policies in agricultural zones using bibliometric analysis and qualitative policy evaluation. Using a PRISMA-based method, fifty-three scholarly papers on the topic, published from 2021 to 2025, were selected from seven thousand six hundred ninety-two references. With the help of bibliometric software like RStudio and VOSviewer, trends in academic research, evolution in themes, keyword clustering, and co-citation network were analysed. As per the study, there was a trend in shifting groundwater management from a resources-driven approach to a governance-driven one focused on sustainability. Some of the key issues identified in the paper include over-abstraction, poor irrigation practices, deteriorating water quality, weak law enforcement, and uncertainties arising from climate change. Research has established that legislation-based actions have a higher success rate than voluntary and technological efforts. The effectiveness of a policy is largely dependent on the strength of its legal framework, monitoring mechanisms, institutional coordination, stakeholder involvement, and consistency with agricultural and energy policies, while failures in policy implementation have been attributed to a lack of strong enforcement mechanisms, poor governance, conflicting subsidies, and political challenges. Some areas where further research could be focused include the behaviour of farmers, climate adaptation in evaluating the performance of policies, integration of groundwater policies with agricultural and energy policies, and impact assessment on small-scale farmers.

KEYWORDS: Groundwater, groundwater recharge, laws and legislation, policy implementation, regulatory framework, sustainability.

INTRODUCTION

Groundwater accounts for about 99% of the world's available freshwater, and supports the livelihoods of more than two billion people, providing about 50% of the world's drinking water, 33% of industrial water, and 40% of irrigation water (Siebert *et al.,* 2010; UN Water, 2018). Linkages to over 53 Sustainable Development Goals (SDGs) targets (El-Agha *et al.,* 2024) make it central to food security, sanitation and poverty alleviation. Despite this, decades of policy-driven agricultural expansion and technological advancements have resulted in intensive groundwater extraction worldwide, leading to groundwater depletion in many aquifer systems. Recent studies indicate that groundwater withdrawals continue to exceed natural recharge rates in several regions across the globe, posing significant challenges to sustainable water management (de Graaf *et al.,* 2019). Furthermore, global water and food demand are projected to increase substantially by 2050 due to population growth, urbanisation, and changing consumption patterns, thereby intensifying pressure on groundwater resources (FAO, 2023; UN-Water, 2024).

Groundwater governance has been studied from various disciplinary perspectives to date. Agricultural water tables are found to be falling (Shah, 2008; Grafton *et al.,* 2018). Moreover, water supplies are depleted, and water quality is compromised in agricultural landscapes (Shah, 2008; Grafton *et al.,* 2018); and the relative effectiveness of water rights regimes and community-based governance is assessed (Jedd *et al.,* 2025; Müller & Boutié, 2022). Economists have evaluated pricing mechanisms and energy subsidies that hinder conservation efforts at the basin level (Mukherji, 2022; Lin *et al.,* 2022), and recent studies have documented the impact of climate variability on the effectiveness of a static water allocation system (Wu *et al.,* 2025; Shiferaw *et al.,* 2024). Notwithstanding this body of knowledge, these views are still disjointed and uncoordinated. There has been no previous systematic review that has incorporated the ecological, institutional, economic, behavioural, and equity aspects to comprehensively examine what is needed for the success or failure of groundwater regulation in agricultural areas, nor a systematic mapping of the bibliometric architecture of this field.

The design and outcome of regulatory responses to groundwater stress have also been quite diverse. Governance innovations like California's Sustainable Groundwater Management Act, managed aquifer recharge schemes in the United States and China, water pricing reforms in China, and agri-environmental schemes in Europe are examples of important innovations (Tzemi *et al.,* 2022; Bartel *et al.,* 2025; Wu *et al.,* 2025). Some depletion trend stabilisers and many irrigation-efficiency policies have created paradoxical rebound effects and agricultural expansion that have led to greater extraction of water (Sharma *et al.*, 2023; Mangal *et al.,* 2025). Lack of enforcement and policy incoherence, as seen in Yemen, Morocco, Jordan, India and China, and governance fragmentation all pose risks to regulatory effectiveness (Al-Falahi & Zhu, 2025; Gupta & Rowan, 2025). Importantly, poorly designed regulations have an adverse impact on smallholder and marginal farmers, which has raised critical equity concerns (Razzaq *et al.,* 2022; Williams *et al.,* 2024).

India faces these global challenges with a high degree of severity as it represents about 28% of global groundwater extraction (FAO, 2024). While groundwater provides the base supplies for most irrigated agriculture in India, rural livelihoods, and drinking water, the country is subjected to severe pressures due to falling groundwater levels, increasing demand for groundwater for irrigation, and changing monsoon patterns (World Bank, 2020). The federal architecture, the Central Groundwater Board, the Central Groundwater Authority and a fragmented set of state laws have historically made the governance of groundwater in India "anarchic": with little regulation of groundwater extraction. Persistent problems such as weak institutional capacity, inadequate inter-departmental coordination, and the continued use of command-and-control systems limit the effectiveness of the regulator (Shah, 2008). India is a critical case study and microcosm of global governance problems (Cullet, 2009).

In this context, this review provides the first integrated and multidisciplinary assessment of the effectiveness of groundwater regulation in agriculture, through systematic policy analysis and a bibliometric mapping of the field's intellectual structure. Specifically, it (i) characterizes dominant research themes and trends using keyword co-occurrence network analysis; (ii) maps influential researchers and scholarly communities by author co-citation analysis; (iii) analyzes the conditions under which regulatory instruments are successful or unsuccessful, both ecologically and in terms of other aspects of groundwater management including institutional, economic, behavioural and equity dimensions; and (iv) identifies persistent governance gaps and develops context-specific policy recommendations for effective, adaptive and socially equitable groundwater management. This review does not just examine the issue from a single-discipline perspective; it is an actionable synthesis for all those researching, practising, and designing policies to address one of the most pressing 21st-century resource governance challenges.

MATERIALS AND METHODS

Through a systematic review and bibliometric analysis of the existing literature, this study assesses the effectiveness of groundwater regulation practices in agricultural regions. The literature was taken from Scopus, as explained in the limitations of the study, which was selected as the primary database for this study due to its comprehensive multidisciplinary coverage, broad indexing of peer-reviewed journals in environmental science, hydrology, agricultural policy, and governance, and its widespread use in bibliometric studies (Moed, 2005). Scopus also provides robust export capabilities compatible with bibliometric analysis tools such as RStudio and VOSviewer, making it particularly suitable for the analytical approach adopted in this study. All literature retrieved was analysed using bibliometric methodologies to present how much research exists on these topics, where it has occurred, which articles have been most heavily cited and through which countries these studies have collaborated with other countries. Analytical software tools such as RStudio and VOSviewer were utilised to analyse data and visualise the growth of water governance-related research and global cooperation in groundwater governance. Moreover, a systematic literature review was carried out following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for methodological transparency and rigour. A full list of the search terms and combinations used to locate publications is included in Table 1. Table 2 shows the inclusion and exclusion criteria used for screening the data to narrow down the sample. The studies included were peer-reviewed articles that centered on the issues of groundwater regulation, agricultural context and the effectiveness of groundwater policy. In contrast, those with little direct connection to these issues were excluded. All qualifying publications were identified by applying the finalised search strategy referenced in Table 1. The four criteria for the methodological evaluation of each of the studies included were: (i) clarity of the research objectives, (ii) appropriateness of the study design and analytical methods, (iii) relevance to the groundwater policy for agriculture, and (iv) empirical support for the study conclusions. All criteria were given a score of 1 for meet and 0 for not, so that the maximum possible quality mark would be 4. Studies that achieved a score of 3 or greater on the four-part study design scale were judged to be methodologically sound and were used in the final synthesis. Two reviewers (the first author and the research supervisor) assessed the title and abstract, full text and quality appraisal independently. Disagreements between any parties during screening or quality assessment were discussed until a consensus was reached. The total number of records retrieved from the finalised search strategy is summarised in Table 1. The predefined search strategy returned 11,261 records in Scopus. In the pre-screening, 10,907 records were excluded according to the established inclusion and exclusion criteria, such as filters like year, subject area, document type, language keywords, and source type. Applying these criteria, 354 records were left for further evaluation. The full texts of these articles were then reviewed for eligibility, and 172 studies were rejected because the title and abstract or the keywords were irrelevant, there was insufficient policy and/or empirical evidence, or these papers did not directly relate to the objectives of the review. The remaining 60 studies fulfilled all the inclusion criteria and were included in the systematic review and bibliometric analysis and are presented in the PRISMA flow chart. (Fig.1). The systematic review and bibliometric analysis were conducted using RStudio and VOSviewer.

Table .1. Search for combinations of keywords and number of records returned from the database.

Database	Search Terms	Number of Articles
Scopus	("groundwater" OR "ground water" OR aquifer*) AND (policy OR regulation* OR governance OR "groundwater management" OR "water law" OR "aquifer governance" OR "managed aquifer recharge" OR recharge OR compliance OR enforcement) AND (agriculture* OR irrigation OR farming)	11261

Table 2. The Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Time Span	2021- 2025	Before 2021
Document Type	Article	Conference paper, Book chapter, Review, Editorial
Language	English	Non-English
Source Type	Journal	Trade journal
Publication Stage	Final	Press
Keywords	Groundwater, Water management, Sustainability, Laws and legislation, Groundwater recharge, Regulatory framework, Policy implementation, Policy approach	All other keywords

Over the past decade or so, policies for managing irrigation water have become a topic of growing research interest in the field of agriculture. This review includes studies published from 2021 to 2025 to capture the latest insights and trends in the field of groundwater governance. This book offers a modern view of the development, adoption and success of groundwater regulation policies in agricultural systems. For this literature review, only research articles in English were chosen, all of which contained a complete research article, since they contained accurate and documented data. Articles other than research articles, for example, conference papers, book chapters, reviews, and editorials, were not included, as they were not considered to be original research and may have repeated information. Studies directly related to groundwater regulation in agriculture were found using the keywords “groundwater,” “water management,” “sustainability,” “laws,” “regulatory frameworks”, and “policy implementation.” Articles were included that were relevant to either regulating groundwater or agricultural water management, irrespective of whether they were open access or not. Full-text articles of all the selected studies were retrieved from the institutional repository or open access sources.

SCREENING

Table 3. Screening criteria used for the selection of studies in the systematic review

Stage	Screening Criteria	Description
Screening	Title and Abstract	Articles containing the predefined keywords in the title and abstract were included in the study.
Screening	Full Text	Relevant papers discussing the predefined keywords in the full text were included in the study.

The screening criteria used for the selection of studies in the systematic review are presented in Table 3. During the initial screening stage, the titles and abstracts of all downloaded review articles were carefully examined. Studies were included if the predefined keywords appeared in the title and/or abstract and were relevant to the scope of the review. In the subsequent stage, the full texts of the shortlisted articles were thoroughly reviewed. Only those papers that explicitly discussed the predefined keywords and were directly relevant to the study objectives were finally included. Figure 1 illustrates the process of study identification, screening, exclusion, and final inclusion adopted for the systematic review following the PRISMA framework.

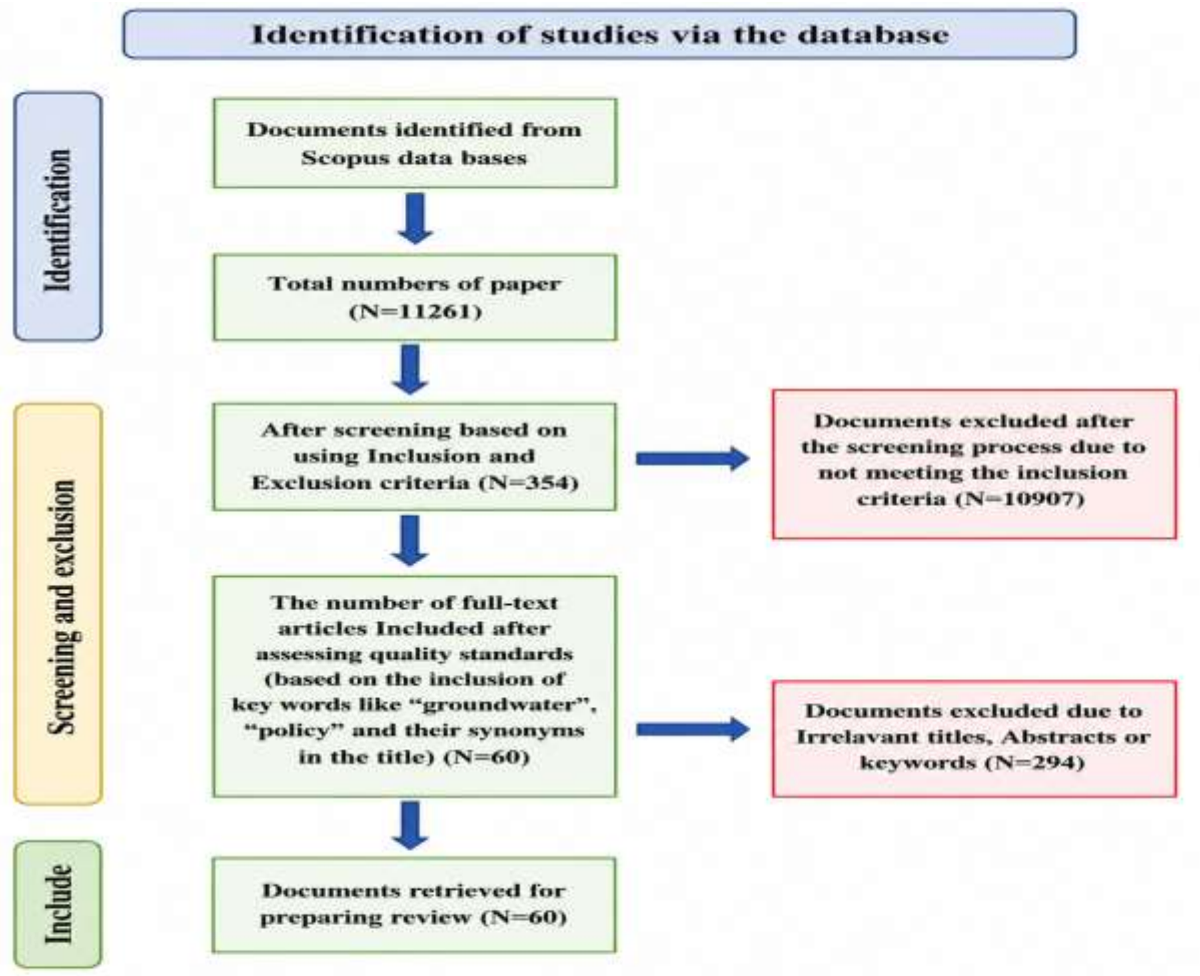

Figure 1. The PRISMA flow chart was followed in the study for selecting documents

RESULTS

Thematic map

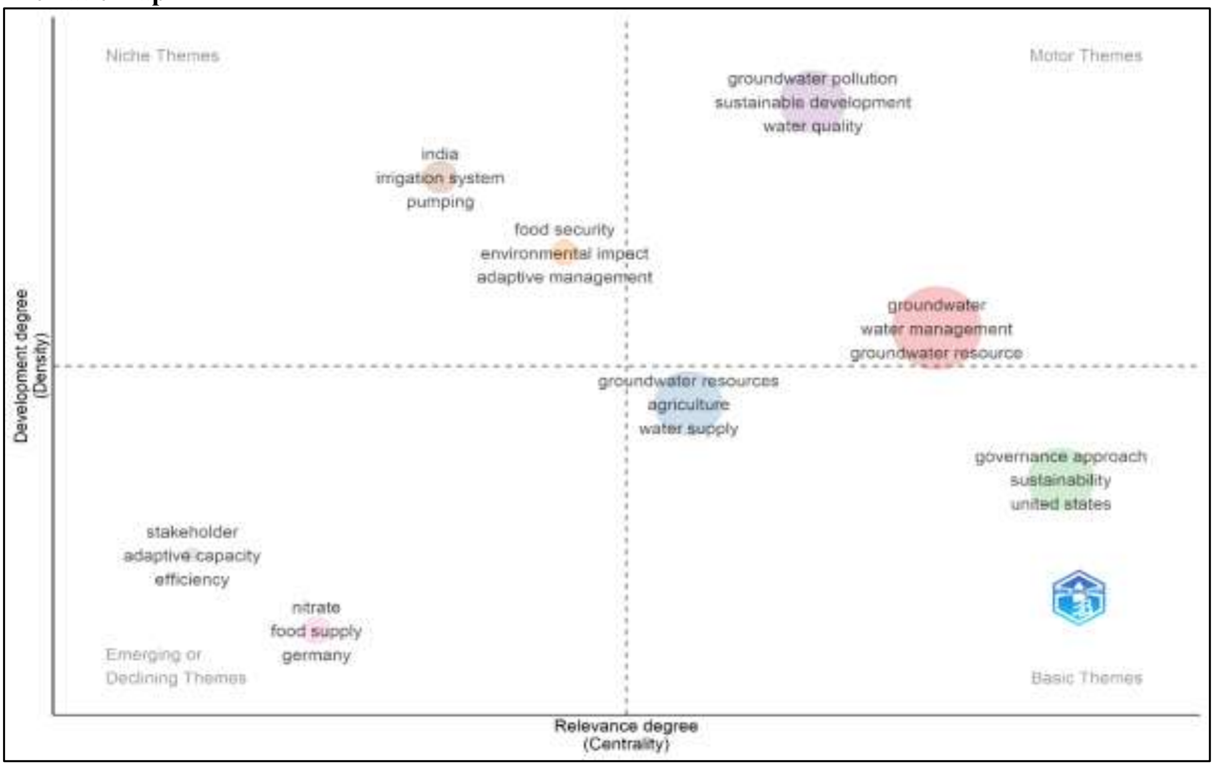

Figure 2. Thematic map of research on the effectiveness of groundwater regulation policies in agricultural regions.

The thematic map of the effectiveness of groundwater regulation in farm areas (Figure 2) showed the relationships between the main themes of the research based on centrality and density. The centrality of research themes in a two-dimensional graph with centrality (x axis) and density (y axis) was shown in the thematic map. Centrality was defined as the extent of association of a research theme with other research themes that are relevant to the theme, and a high centrality score would mean that a research theme was central to a research area. The density was used to describe the degree of development of research themes; themes that were conceptually developed were those that contained closely related keywords. These two dimensions created four different quadrants of research themes: motor, basic, niche and developing/declining. The map showed an evolving but - for now - uneven research environment. Themes related to the behaviour of the motor were located in the upper-right quadrant, signifying conceptually stable and well-connected themes related to groundwater governance research. The basic themes were located in the lower right quadrant, less internally developed, and highly central representing foundational concepts used in most studies but less analytical. The niche themes were presented in the upper left quadrant which refers to specialised but loosely connected research areas. Themes that emerged were grouped in the bottom left quadrant. There was a great variation in node size, suggesting that a few strong concepts garnered the bulk of the research and others were relatively underdeveloped, and a handful of policy-relevant themes were present.

Keyword co-occurrence network

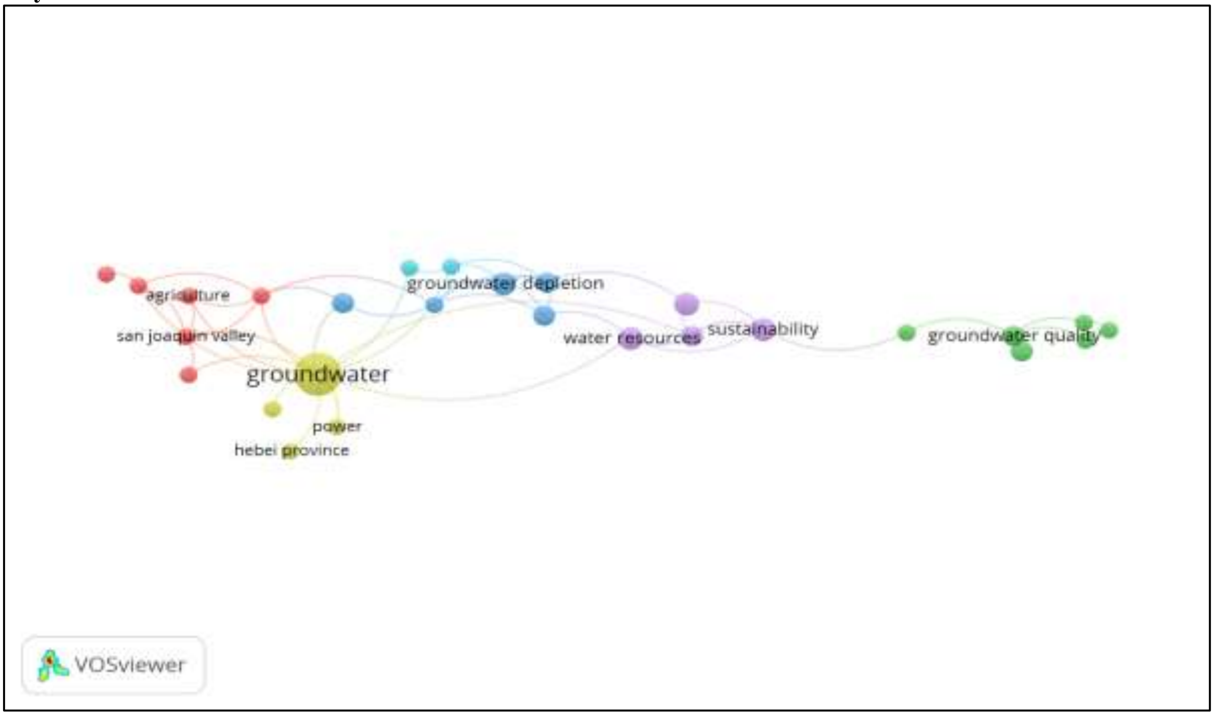

Figure 3. Keyword co-occurrence network illustrating major topics and trends in groundwater regulation and agriculture

The relationship among 53 articles on groundwater was represented by the co-occurrence network of VOSviewer, which was divided into five different colour-coded groups or categories. The keyword co-occurrence network is shown in Figure 3, which identified the main research themes, interrelated topics, and emerging trends in groundwater regulation and agriculture. According to this network, the size of each node indicated how frequently a keyword appeared in the articles, whereas the thickness of the line between connected nodes indicated the strength of co-occurrence between two keywords (i.e., the degree of association). Groundwater" co-occurred with all keywords in the five clusters and was the largest and most central node (located near the midpoint of the entire co-occurrence network). agriculture, groundwater depletion, integrated water supply management, policies and sustainability, quality and safety of groundwater, and contextual themes—were provided below.

Author co-citation network

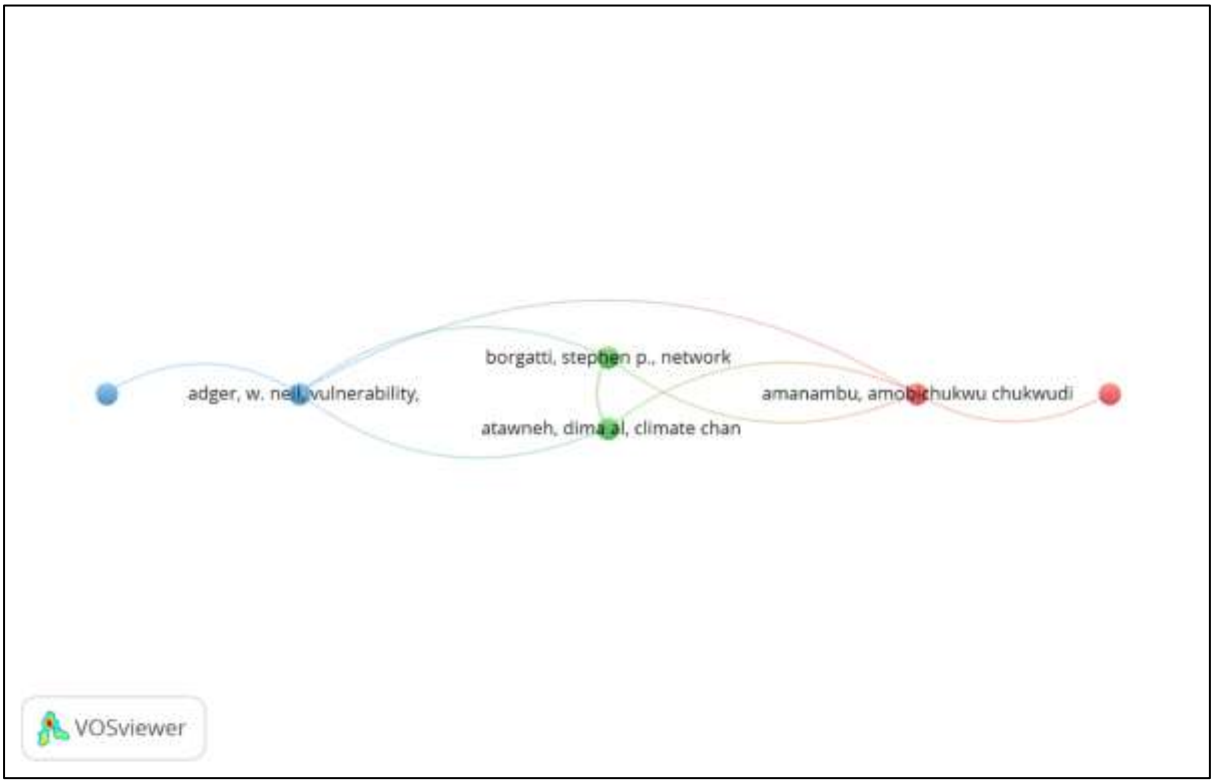

Figure 4. The author's co-citation network identifies influential researchers and major research groups in this field.

Figure 4 presents the author co-citation network, identifying the most influential researchers, collaborative linkages, and major research clusters that contributed to the field of groundwater regulation and agricultural water management. The co-citation network identified four prominent author nodes. W. Neil Adger occupied the most central position and exhibited the strongest co-citation links across the network. Stephen P. Borgatti formed a closely connected secondary node. Dima Al Atawneh bridged the theoretical and applied clusters. Amobichukwu Chukwudi Amanambu formed a distinct applied-research cluster on the periphery of the network, with weaker connections to the central nodes**.**

RESEARCH GAP

Table 4. Research Gap Analysis

No.	Research gap	Description of the gap	Evidence from existing studies
1	Limited linkage between groundwater regulation and long-term agricultural outcomes	Most studies assess short- to medium-term reductions in groundwater extraction, but rarely evaluate whether groundwater recovery can be sustained without compromising long-term agricultural productivity, farmer livelihoods, and food security.	Groundwater recovery observed under SGMA in California and legislative controls in Spain, but long-term agricultural impacts remain unexamined (Rodríguez-Jiménez *et al*., 2025; Bartel *et al*., 2025). Modelling studies say of food security trade-offs, but regulation is not matched with a farming policy (Perez *et al*., 2024).
2	Insufficient integration of groundwater regulation with agricultural and energy policies	Groundwater policies are often implemented in isolation and undermined by energy subsidies, crop procurement policies, and incentives for water-intensive crops, reducing regulatory effectiveness.	Proof from India and China says energy subsidies and crop regulation weaken underwater laws (Mukherji, 2022; Gupta & Rowan, 2025; Liu *et al*., 2025). Few numerical evaluations of integrated Water–Energy–Food policy frameworks exist.
3	Weak understanding of farmer behavior and social acceptance	Technically sound regulations frequently face resistance, low compliance, or behavioral adaptation by farmers, yet socio-institutional and behavioral responses are insufficiently analyzed.	Compliance challenges under SGMA and low enforcement in Morocco and Yemen shows more behavioral gaps (Bartel *et al*., 2025; Muller & Boutie, 2022; El Idrissi *et al*., 2025; Al-Falahi & Zhu, 2025). Less quantitative comparison of participatory versus command-and-control approaches.

4	Limited evaluation under climate change conditions	Most groundwater regulations are evaluated under static climatic assumptions, with limited analysis of performance under climate variability, aridification, and increasing drought frequency.	Adaptive regulation performs somewhat better in China, and climate-linked governance reforms have drawn attention in India, yet dynamic climate-sensitive evaluations remain scarce (Wu *et al*., 2025; Shiferaw *et al*., 2024).
5	Gaps in monitoring, enforcement, and data infrastructure assessment	Even though monitoring and enforcement capacity is critical for policy success, some studies compare the cost-effectiveness, scalability, and equity implications of digital versus conventional monitoring approaches	Digital monitoring improves regulatory output, but inadequate and fragmented data systems exist in many regions (Zhu *et al*., 2023; Catarino *et al*., 2025; Williams *et al*., 2024; Foster & Chilton, 2021).
6	Limited comparative analysis across governance models and scales	Research rarely conducts systematic cross-model comparisons of centralised, economic, voluntary, and polycentric governance approaches under different agricultural and institutional contexts.	Voluntary measures without enforceable limits don't work, while decentralised governance leads to more legitimacy but can decrease enforcement (van den Brink *et al*., 2021; Muller & Boutie, 2022). Absence of meta-analyses comparing governance scales.
7	Underexplored equity and distributional impacts	Most studies prioritise hydrological outcomes and neglect how groundwater regulation affects different farmer groups, particularly smallholders and rural communities.	There is some evidence from Arizona and California that small farmers are disproportionately harmed by weak regulation, but equity outcomes have received little attention (Williams *et al*., 2024; Bartel *et al*., 2025).

Table 4 represents the research gaps that give emphasis about the gaps that are not explored in the existing literature. This table shows the identified research gaps that were obtained after a comprehensive study of the literature retrieved from downloaded review articles and empirical studies related to groundwater regulation in agricultural land. This involved an analysis of these studies, identifying gaps, overlaps and any significant gaps in the existing research on critical policy and sustainability issues. Many research efforts have examined ground water regulation policies, but most are focused on short-term or medium-term policy effects, such as the decrease in groundwater extraction. But there is little evidence whether these regulations can be used to support long-term groundwater recovery without harming farm productivity and the livelihoods and food security of farmers. Furthermore, groundwater policies are often studied in isolation, neglecting the interplay with other policies, such as agricultural, energy and food policies, which have a significant impact on the success of a groundwater policy. There is also great disparity in terms of farmer behaviour and social acceptability of groundwater regulation. Even if policies are technically strong, they can face adaptation responses and poor compliance from farmers or resistance to the policy. Despite this, there is a lack of comparative study of the behavioural, institutional, and participatory approaches, so it is difficult to assess which is most successful in different settings. Furthermore, most policy assessments are based on the assumption of climate stability and have not taken into account climate change, the increasing frequency of droughts or long-term aridification. The review also highlights the lack of evaluation of monitoring, enforcement and data infrastructure. While these are all essential for good groundwater governance, there is a lack of studies which measure the cost-effectiveness, scalability, and equity of digital monitoring systems versus traditional ones. Likewise, a lack of systematic comparison across the different models of governance, such as centralised, decentralised, voluntary, economic and polycentric, complicates the identification of context-specific best-practices. Finally, the equity and distributional effects of groundwater control have been under-researched. Most studies are geared towards the hydrological results, and to a lesser extent, to the impact of regulation on smallholders and vulnerable rural communities. In general, this research gap analysis uncovers a number of key areas for further research. These gaps will be of great value for future research and could help develop more integrated, climate resilient, equitable and socially acceptable groundwater governance frameworks in agricultural areas.

DISCUSSION

Thematic Map

The groundwater governance map shows that there are well-developed and developing research fields in agricultural areas. Groundwater management, water quality, and sustainable development are found in the motor-theme quadrant, indicating that these topics are well developed and are well linked with the extended research field. This trend is in response to the rising concerns over depletion of groundwater, worsening groundwater quality and decreasing water security in agriculture (Dalin *et al.,* 2019; De Graaf *et al.,* 2019). Groundwater resources, water management, governance approaches and water sustainability are dominant in the basic-theme quadrant. These themes are fundamental to the literature and their relatively low density would indicate that they remain very general research carving or conceptual frameworks, rather than areas of very specialised research. This is echoed by previous groundwater governance research, which has found that sustainability and resource management are recurring themes when evaluating groundwater policies and regulatory frameworks (Grafton *et al*., 2018). Themes that are more specific to niche areas, such as irrigation systems and regional studies, seem to be fairly well developed and not as well connected to the broader groundwater governance literature. The pattern indicates that while there have been significant advances in the local solutions to groundwater issues, few results are transferable between regions. Concentrating on the need for more comparative analysis and cross-regional learning, previous studies also emphasized the need for more groundwater governance research of this nature (Tzemi *et al*., 2022; Jedd *et al*., 2025). The themes of adaptive governance, stakeholder involvement, and adaptive capacity are found in the lower-left, suggesting they are becoming more important but are not well developed. Increasing impacts of climate variability and groundwater scarcity have sparked the attention of researchers on the importance of adaptive and participatory governance approaches to sustainable groundwater management (Shiferaw *et al*., 2024; Wu *et al*., 2025). The location of these areas in the thematic map indicates that these regions are expected to develop more in-depth research in the future.

Keyword Co-occurrence Network

The keyword co-occurrence network reveals the multi-disciplinary nature of groundwater regulation research, with high level of connection between groundwater resources, agriculture, water management, sustainability and governance. The keyword 'groundwater' appears prominently in the central role, and is found in many of the connections to 'agriculture-related terms', which suggests that the use of agricultural water continues to be a significant focus of groundwater governance research. This result aligns with previous research that has shown irrigated agriculture to be the main groundwater extraction and depletion activity globally (Grafton *et al*., 2018). There is a growing focus on governance-based approaches to groundwater conservation, as indicated by the close coupling of the groundwater management, sustainability and policy-related keywords. Recent studies have also shown how important institutional coordination and sustainable resource management are to address groundwater stress, as well as the importance of regulatory frameworks (Mukherji, 2022; Muller & Boutie, 2022). The network also identifies links to other sustainability issues related to water use, which aligns with the perception that groundwater management is now being discussed in the context of integrated resource management. This is consistent with research that argues for using a Water–Energy–Food (WEF) nexus approach to enhance coherence of policy, and efficiency of water use (Lin *et al*., 2022; Gupta & Rowan, 2025). Groundwater-related keywords (groundwater quality and groundwater pollution) are less prominently linked to governance and policy themes. This implies that, while there is increasing evidence of the effects of agriculture on groundwater contamination, it is a lesser concern for water quality problems than other components of groundwater management. Previous research also has identified these same gaps, and has suggested that groundwater quality needs to be better reflected in regulatory and management frameworks (Foster & Chilton, 2021; Williams *et al*., 2024). The keyword network illustrates a research area that is increasingly interested in the governance aspects of dealing with groundwater sustainability, but at the same time should be more interested in groundwater quality, adaptation to climate change and integration of policies across multiple sectors.

The author's co-citation network and relevance to groundwater policy

The author's co-citation network offers some clues to the intellectual roots of groundwater governance research. The visibility of authors like W. Neil Adger, Stephen P. Borgatti, Dima Al Atawneh, and Amobichukwu Chukwudi Amanambu also shows that ground water policy research is shaped by a variety of disciplinary approaches, such as environmental governance, social resilience, network analysis, and climate adaptation. Given the centrality of these authors, it seems that groundwater governance is no longer only a water issue, but also a socio-ecological challenge. These findings are in line with recent research (Mukherji, 2022; Muller & Boutie, 2022; Jedd *et al*., 2025) that has made the point that institutional capacity, stakeholder involvement, adaptive governance and social resilience are important in addressing the problem of groundwater depletion and sustainability. The co-citation network also underscores the increasing overlap of climate adaptation research and policy and governance research in the groundwater policy literature. Interdisciplinary approaches that align hydrological considerations with governance, social and institutional aspects are also noted in previous studies as necessary for effective groundwater management (Shiferaw *et al*., 2024; Wu *et al*., 2025). The co-citation network shows that the field of groundwater governance research is becoming more interdisciplinary, as governance of groundwater in agricultural areas is complex, involving environmental, socioeconomic, and institutional aspects.

Effectiveness and Ineffectiveness of Groundwater Policy and Its Factors

A major challenge is to assess how effective is the Groundwater policy and what are the factors contributing to their effectiveness.

This review shows that legally binding groundwater regulations are more likely to be effective at reducing groundwater depletion in agricultural areas than voluntary and/or technology-based approaches. Since then, various regulatory measures, including abstraction licensing, well registration, pumping quotas, and basin-level groundwater management frameworks, have shown positive results in regulating groundwater extraction and ensuring resource sustainability (Rodríguez-Jiménez *et al*., 2025; Zhang *et al*., 2022; Lu *et al*., 2025). The results here confirm earlier work highlighting that the legal mandate, enforceable regulations, and institutional accountability are among the key elements needed to make sure water users adhere to groundwater governance (Mechlem,2016). By contrast, interventions towards voluntary conservation, or efficiency, have proven to be ineffective without a formal system of extraction controls. While these actions can lead to water saving at the farm level, they do not necessarily result in a reduction in overall groundwater abstraction, as water saving may be matched by increased water use intensity or water use expansion (Mangal & Govind, 2025; van den Brink *et al*., 2021). This discovery implies that technological and voluntary measures are most successful if they are part of a wider regulatory setting that sets clear limits to groundwater extraction.

Establish and maintain clarity and enforceability of legal processes.

Common across the studies that have been reviewed is the importance of strong legal rights and effective groundwater extraction restrictions for groundwater regulation to be effective. In some agricultural areas, legal instruments such as abstraction limits, licensing systems and statutory groundwater management frameworks have been linked to the decrease in groundwater abstraction and the improvement in groundwater sustainability (Rodríguez-Jiménez *et al*., 2025; Zhang *et al*., 2022). The results are in line with the literature underlining the importance of institutional capacity to ensure implementation of the policy, as well as the design of the policy itself (Pahl-Wostl, 2009; OECD, 2015; Villholth et al., 2018).On the other hand, a lack of enforcement, illegal groundwater use, and low institutional capacity are shown to significantly diminish the effectiveness of the policy in the literature. The experience in Yemen, India, and Jordan has shown that regulatory efforts can be ineffective if there are poor compliance monitoring and enforcement (Oberhauser *et al*., 2023; Sharma *et al*., 2023; Al-Falahi & Zhu, 2025). This implies that the legal measures are not enough, and it is also important to have effective institutional mechanisms to help enforce the legal measures.

Industry standards of monitoring, metering & data systems are required.

The results of this review demonstrate that in addition to legal aspects, effective groundwater regulation also relies on appropriate monitoring, metering, and data management systems. Groundwater abstraction is accurately measured and this is used to help regulatory agencies to determine compliance, implement limits on extraction and inform policy outcomes. Research from various regions suggests that the use of digital monitoring systems, remote sensing and groundwater information systems can help to improve the effectiveness of groundwater regulation, creating more transparency and accountability in groundwater management (Zhu *et al*., 2023; Catarino *et al.*, 2025). On the other hand, lack of monitoring infrastructure and less good groundwater data may jeopardize regulatory action, even if formal policies are in place. Several agricultural areas indicate that the lack of good abstraction records, well inventories, and enforcement contributes to the ongoing groundwater over-exploitation (Zarepour Moshizi *et al*., 2023; El Idrissi *et al*., 2025). These results are corroborated by previous studies that highlight the importance of monitoring and data systems as a key part of good groundwater governance, enabling evidence-based decision-making and regulatory enforcement (Foster & Chilton, 2021; Williams *et al*., 2024).

Incorporating Managed Aquifer Recharge (MAR) into regulation

The review shows that when pursued in conjunction with sound groundwater regulation, Managed Aquifer Recharge (MAR) can make a significant contribution to groundwater sustainability. Agricultural areas have shown the best success with recharge interventions where extraction controls are also in place, along with monitoring and institutional oversight, to ensure that potential recharge benefits are not undermined by increased groundwater extraction (Quandt *et al*., 2025; Zhang *et al*., 2022). It is consistent with previous studies that have shown that recharge alone is not enough to attain long-term groundwater recovery when groundwater abstraction is not curtailed (Doll et al., 2014). A similar study conducted in the North China Plain indicates that groundwater recovery is more likely with groundwater management measures such as water-transfer and recharge measures in place (Wu *et al*., 2025). The results indicated that MAR should be considered as a complement to the regulatory measures, which means that recharge strategies should be included in the general framework of groundwater management.

Coordinated policies in the energy and agriculture sectors

This review identifies some key points that the effectiveness of groundwater regulation is closely linked to the coherence with agricultural and energy policies. When other policies, such as irrigation expansion programmes, energy subsidies, and promotion of water-consuming crops, promote groundwater extraction, they can undermine groundwater conservation (Gupta & Rowan, 2025; Mangal & Govind, 2025). In this context, the results indicate that the regulation of groundwater resources alone is not a sustainable approach in the absence of a comprehensive policy for water and agricultural production.

On the other hand, groundwater management policy measures such as water pricing reforms, groundwater taxation, and metering systems have shown a negative impact on groundwater use, but they can also lead to improvements in water-use efficiency (Lu *et al*., 2025). The results highlight the need for integrated Water-Energy–Food (WEF) approaches, where policy coordination among the sectors is encouraged to ensure sustainable groundwater use and the mitigation of conflicting incentives for groundwater use (Lin *et al*., 2022; Gupta & Rowan, 2025).

The effective coordination of institutions and the involvement of actors.

This review shows that, apart from regulation, good governance of groundwater is also linked to good institutional coordination and stakeholder involvement. Participatory governance frameworks have the potential to enhance policy legitimacy, transparency, and adherence by boosting the involvement of stakeholders in decision-making processes (Sarami-Foroushani *et al*., 2023; Jedd *et al*., 2024). The results align with previous research which highlight that inclusive governance can improve the effectiveness and social acceptability of groundwater management policies (Villholth *et al.,* 2018). The review, however, argues that stakeholder involvement is not enough to guarantee a good governance of groundwater. Institutions that coordinate participatory mechanisms, governance structures that clarify decision-making processes, and enforcement capacity are more conducive to achieving effective outcomes. Several regions support the finding that fragmented governance systems could reduce the effectiveness of groundwater governance, while basin-level governance systems could promote more sustainable groundwater management (Bellwood-Howard *et al*., 2022). Thus, a mix of participation, institutional coordination, and effective regulatory oversight are needed to achieve successful groundwater governance.

INEFFECTIVENESS OF GROUNDWATER REGULATION POLICY AND ITS FACTORS

In agricultural areas, groundwater policies often fall short when they are based on voluntary involvement, technology-driven solutions, or decentralized authority. Over continents, policy failures are invariably linked to the lack of legally binding limits on extraction, enforcement problems, sectoral incentives, institutional capacity and political economy problems.

Lack of abstraction: limits

A lack of enforceable groundwater abstraction limits is identified as a key reason for the failure of groundwater policy in areas of agriculture. While water-saving technologies and water use efficiency can increase water productivity, there is evidence that this is not enough to alleviate groundwater depletion without restricting groundwater extraction (Mangal & Govind, 2025; Liu *et al*., 2025). However, the improvements made in water-use efficiency have been undone by a combination of irrigation intensification, expansion of agricultural land usage, and continued groundwater extraction in some instances, leading to limited improvements in groundwater sustainability (Li *et al*., 2022; Sharma *et al*., 2023). This is in line with past research, which highlights the need to manage total abstraction of groundwater as opposed to only efficiency-based interventions (Grafton *et al*., 2018). The implementation of groundwater governance, therefore, demands strict limits on water extraction, as well as technology and management tools to ensure that improved efficiency reduces groundwater usage.

No compulsory participation, and poor compliance systems

The review shows that groundwater management programs that rely on voluntary action and incentives may not be effective in stopping groundwater depletion unless they are accompanied by effective regulatory measures. Voluntary programmes can contribute to awareness-raising, involvement of stakeholders as well as local conservation achievements, but often have limited effectiveness in reducing groundwater abstraction as participation is low, compliance with measures is selective, and monitoring of the programmes is weak (van den Brink *et a*l., 2021; Tzemi & Mennig, 2022).Additionally, there is evidence from other regions that voluntary measures have proven to be inadequate for managing the use of groundwater at scales larger than micro (Bellwood-Howard *et al*., 2022; El Idrissi *et al*., 2025). The results align with the general groundwater governance literature that has argued that voluntary approaches work best in combination with a regulatory framework, monitoring systems, and enforcement mechanisms to ensure compliance among water users (Mukherji, 2022; Müller & Boutié, 2022).

Competition from agricultural and energy subsidies

One of the main drivers of the failure to regulate is cited as policy incoherence between groundwater regulation, agricultural development and energy policies. However, groundwater conservation efforts can be hampered by the incentives for extractions, such as agricultural subsidies and irrigation expansion programmes, or energy incentives, which can offset the goals of groundwater regulation (Silva-Novoa Sánchez *et al*., 2022; Gupta & Rowan, 2025). Groundwater policies may exist, but with limited impact on groundwater sustainability due to the effects of groundwater. The results of this study corroborate previous findings where regulatory measures are found to be most effective when they are in line with the general agricultural and energy policies (Mangal & Govind, 2025; Liu *et al*., 2025). Groundwater depletion is likely to continue irrespective of regulations, as policy incentives for groundwater intensive agriculture are still in effect. Thus, more coordination between the water, farm and energy players is needed to reduce conflicting incentives and promote long-term conservation goals in order to achieve sustainable groundwater management.

Inability to coordinate and manage institutions effectively

Institutional fragmentation and governance capacity gaps are highlighted as significant challenges for effective groundwater regulation in the review. Groundwater policies are not always well coordinated among agencies, institutional responsibilities are not clearly defined, technical capacity is limited, and enforcement mechanisms are weak, which can hinder policy implementation, even when it has been formally established (Al-Falahi & Zhu, 2025). The flaws in governance are reducing the ability of institutions to track groundwater use, enforce groundwater regulations, and effectively address groundwater depletion. The results are in line with earlier research which highlights the need for good institutional coherence and governance capacity in implementing sustainable groundwater management (Mukherji, 2022; Müller & Boutié, 2022). However, evidence from multiple regions indicates that the effectiveness of policies is often hindered by weak policy implementation mechanisms and institutions due to poor coordination or insufficient scale or resources, and that coordinated, well-resourced institutions are better able to support policy implementation, compliance and enforcement, and long-term groundwater sustainability (Oberhauser *et al*., 2022; Zarepour Moshizi *et al*., 2023). Hence there is need to further build institutional capacity and enhance intergovernmental coordination, both vertical and horizontal, for effective groundwater regulation.

Political economy constraints

The review found that political economy issues are one of the major challenges to the effective regulation of groundwater in agricultural areas. Competing economic, social and political interests may affect the implementation of groundwater policies, thus restricting the enforcement or adoption of stringent groundwater control measures (Mukherji, 2022; Bartel *et al*., 2025). Agricultural productivity, farmer livelihoods, and stakeholder opposition often lead to resistance to regulation to limit groundwater extraction. This is in line with earlier research that shows that political and institutional factors commonly undermine groundwater governance effectiveness, even in areas of high groundwater depletion (Muller & Boutie, 2022; Aghazadeh *et al*., 2024). These consequences can lead to delays, weakening, or limited enforcement of groundwater policies, that diminishes their ability to promote long term sustainability. Thus, tackling political economy constraints still has to be a key focus of strengthening the implementation and effectiveness of groundwater regulation in agricultural systems.

Limitations of the Study

1. Access Limitation

We recognise that the use of one database is a limitation of access in the present study. A literature search was performed by running a search in the Scopus database accessed through the authors institutional subscription.We recognise that important studies on the subject included in other databases might not have been included in the Scopus coverage, which includes peer-reviewed publications across a wide range of multidisciplinary disciplines. In response to this concern, an Access Limitation statement has been included in the Limitations of the Study area. We have also recognised that further systematic reviews that add further databases could yield a more extensive evidence base.

2. Methodological Limitation

We recognise that the timeframe of this study (2021 to 2025) is a methodological constraint of the present work. This was done specifically to reflect the latest findings, new regulations and approaches relating to groundwater regulation in agricultural settings. A Methodological Limitation statement was included under the Limitations of the Study section, to clarify this methodological choice. We also recognise that future reviews on a wider time span of publications can offer a more in-depth analysis of the evolution and durability of groundwater governance.

CONCLUSION AND RECOMMENDATION

To investigate groundwater regulation policies in agricultural areas, 53 papers were selected from peer-reviewed journals between 2021 and 2025 and analysed in this systematic review. The results highlighted the growing emphasis in groundwater governance research on the concepts of sustainability, policy implementation, and integrated water management approaches. The bibliometric analysis showed that the topics in groundwater management, in sustainability and in governance were the predominant themes in the research, whereas topics like climate adaptation, equity issues and farmer behavioural responses were comparatively under-researched. The review illustrated that groundwater regulation was best conducted if it was accompanied by strong legal confidence, enforceable limits on extraction, strong monitoring systems, institutional coordination and a degree of stakeholder involvement. Generally, groundwater depletion and long-term sustainability of groundwater resources was better achieved when policies were integrated with regulatory measures, monitoring and data-driven decision making. Groundwater regulations, however, were frequently found to be ineffective where they relied on voluntary measures, were not supported by enforcement mechanisms, were given to fragmented governance or were incompatible with agricultural and energy policies which promoted over-extraction of groundwater. The results of this study suggest that groundwater governance should focus on legally binding rules, better monitoring and enforcement, better coordination among institutions, and involvement of stakeholders. Additionally, groundwater policies need to be aligned with other agricultural and energy policies, and should be implemented coherently and sustainably. The review has identified a number of important areas for future research including: (i) the long-term impact of groundwater regulation on the productivity of farming; (ii) incorporating the effects of climate change into groundwater governance; (iii) the impact of farmer behaviour on policy compliance; and (iv) the equity implications of groundwater regulation for smallholder and vulnerable farming communities. Filling these research gaps will help create more sustainable, adaptable and socially inclusive groundwater governance frameworks.

Authors' Contributions

DM carried out the survey, analysed the data, and formulated the manuscript. MR assisted in data collection and analysis as part of the research study. JA contributed by developing ideas and reviewing the manuscript. PM helped in summarising and revising the manuscript. MV contributed to summarising, and JP provided additional support and contributions to the research study.

Compliance with Ethical Standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

Ethical issues: None.

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