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Ashay Devidas Shende and Sandeep Prabhudas Tembhurkar

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Review Paper

Rainwater Harvesting as a Sustainable Approach to Agricultural Water Management: A Review and Analysis

Ashay Devidas Shende [1†] and Sandeep Prabhudas Tembhurkar [2]

[1]Civil Engineering, K.D.K. College of Engineering, Nagpur, Maharashtra, India ashayshende220@gmail.com
[2]Civil Engineering, SSVPS's Bapusaheb Shivajirao Deore College of Engineering Dhule, India stembhurkar@gmail.com

† Corresponding author: Ashay Devidas Shende; ashayshende220@gmail.com
ORCID IDs of Authors
Ashay Devidas Shende- 0000-0002-2082-1311
Sandeep Prabhudas Tembhurkar- 0000-0003-2937-1019

Abstract

Water harvesting is now considered one of the effective ways of resolving scarcity of water for agricultural usage, limited availability of groundwater resources and the variability of water availability arising from climate change. The objective of this review is to critically discuss the role of RWH in sustainable agricultural water management, and to explore its hydrological, agronomic, environmental and socio-economic benefits. Subsequently, on application of PRISMA criteria, articles suited to the systematic review were identified; those comprised peer-reviewed articles, conference papers, technical reports and policy documents from 2000 to 2026. The literature was examined to evaluate the dynamics of rainfall–runoff, soil moisture conservation, groundwater recharge, crop production, climate change resilience, technological innovations, and governance issues of RWH systems. The results depict that farm ponds, check dams, percolation tanks, recharge pits and rooftop harvesting systems have a positive impact on groundwater availability, recharge, soil water conservation and agricultural production, especially in rainfed and semi-arid regions. In general, adoption of rainwater harvesting techniques is a practical and comprehensive method for enhancing water security and fostering greater adaption and resilience for a more sustainable agriculture.

Keywords: Groundwater Recharge; Climate Resilience; Rainwater Harvesting; Sustainable Agriculture; Watershed Management; Hydrological Buffering.

1. INTRODUCTION

Water scarcity has emerged as one of the most critical global challenges affecting environmental sustainability, agricultural productivity, and socio-economic development in the twenty-first century. Rapid population growth, urban expansion, industrialization, and climate change have intensified pressure on already limited freshwater resources. Agriculture remains the largest consumer of freshwater globally, accounting for nearly 70% of total water withdrawals, primarily to meet the continuously increasing food demand of a growing population (Allen and Ingram, 2002; Kaur, 2022) However, many regions, particularly arid and semi-arid zones, are already experiencing severe water stress due to declining groundwater reserves, erratic rainfall patterns, and rising climatic variability (Garrote, 2017). This imbalance between agricultural water demand and available freshwater resources has created an urgent need for sustainable and resilient water management strategies.

Conventional irrigation systems, including canal-based irrigation and groundwater extraction, have historically supported agricultural intensification and food security. Nevertheless, these systems are increasingly associated with significant environmental, technical, and economic limitations. Excessive groundwater abstraction has resulted in alarming depletion rates in several agricultural regions, especially in India, where groundwater contributes substantially to irrigated farming (Jain et al., 2021),(Dangar, Asoka and Mishra, 2021). Similarly, traditional flood irrigation methods often exhibit poor water-use efficiency because of high conveyance and application losses. Infrastructure deterioration, unequal water distribution, high energy requirements for pumping, and inadequate maintenance further reduce the operational efficiency of conventional irrigation systems (Abdullaev et al., 2009). Moreover, climate-induced fluctuations in rainfall and river discharge have made surface irrigation systems increasingly unreliable. Subsequently, the implementation of decentralized rainwater harvesting initiatives has occured as a vital climate-smart strategy to alleviate these vulnerabilities by optimizing the use of locally available freshwater (Arvind, 2025; Singh, 2026). By capturing and storing ephemeral surface runoff, these systems mitigate the impact of unpredictable precipitation while simultaneously enhancing soil moisture levels and facilitating artificial groundwater recharge (Biswas et al., 2025; Vorotyntseva et al., 2025). These decentralized infrastructures function as essential buffers against hydrological stress, potentially reducing the reliance on over-extracted aquifers and mitigating the frequency of drought-induced crop failures (Aggarwal, 2025; Alao et al., 2025). Furthermore, the integration of these systems is particularly critical in arid and semi-arid environments where heightened evaporation rates and shifting precipitation regimes threaten the stability of food production (Hafeez et al., 2025; Khairy et al., 2025).

In response to these challenges, sustainable agricultural water management approaches have gained considerable attention. Among these, rainwater harvesting (RWH) has re-emerged as a viable and environmentally sustainable alternative for improving agricultural water security. RWH involves the collection, storage, and productive utilization of rainwater runoff from rooftops, land surfaces, or catchment areas (Campisano et al., 2017). Traditional systems such as farm ponds, tanks, check dams, contour bunds, and percolation pits are now being integrated with modern hydrological modeling and storage optimization techniques to enhance efficiency and adaptability (Basinger, Montalto and Lall, 2010; Hashim et al., 2013) Previous studies have demonstrated that RWH can significantly improve supplemental irrigation, groundwater recharge, soil conservation, and crop productivity while enhancing resilience against climatic uncertainties (Mahato, Mishra and Debnath, 2020; Behera et al., 2023) Historical evidence underscores that such decentralized methodologies, once integral to indigenous resource management, are essential for restoring community resilience in the face of contemporary environmental shifts (Singh, 2025). By capturing and storing precipitation that would otherwise be lost to runoff or evaporation, these systems effectively bridge moisture deficits during critical crop growth stages, thereby stabilizing yields in regions plagued by erratic inter-seasonal rainfall (Abdeen, 2025). Moreover, the implementation of these practices facilitates a decentralized approach that alleviates pressure on centralized water distribution networks, which are often inadequate in rural and semi-arid contexts (Om et al., 2025; Reddy, 2025).

This review critically evaluates the role of rainwater harvesting in sustainable agricultural water management by examining its technical, hydrological, environmental, and socio-economic dimensions. The study further analyzes the effectiveness of various RWH systems, identifies implementation challenges and policy gaps, and highlights their contribution toward climate-resilient agriculture and long-term water security.

2. MATERIALS AND METHODS

This review employed a systematic and evidence-based literature synthesis approach to critically evaluate the role of rainwater harvesting (RWH) in agricultural water management. Relevant scientific literature was collected from major academic databases, including Scopus, Web of Science, and Google Scholar, to ensure broad disciplinary coverage and inclusion of both foundational and recent scientific advancements. Peer-reviewed journal articles, technical reports, conference papers, and policy documents published between 2000 and 2025 were considered for analysis. The selected time frame enabled the integration of historical developments with emerging innovations associated with climate-resilient agricultural water management. The selection process was guided by a four-step methodology to categorize contemporary harvesting and artificial recharge techniques, ensuring a comprehensive assessment of their biophysical, economic, and social outcomes (Kanase and Takalkar, 2025). This methodology facilitates a cross-disciplinary synthesis of evidence across diverse agro-climatic zones, addressing the critical institutional and socio-economic constraints that often impede project longevity (TIMIȘ et al., 2025; Singh et al., 2026).

The literature selection process was guided by predefined inclusion and exclusion criteria to maintain methodological rigor and scientific reliability. Studies were included when they explicitly addressed agricultural applications of rainwater harvesting, including hydrological performance, soil moisture conservation, groundwater recharge, irrigation efficiency, crop productivity, socio-economic impacts, or climate adaptation functions (Rai et al., 2025). Both, quantitative and qualitative investigations were considered to capture diverse methodological perspectives and regional experiences. Particular emphasis was placed on studies conducted under varying agro-climatic and socio-environmental conditions to improve the representativeness and comparative value of the review. Publications lacking methodological clarity, empirical relevance, or direct linkage to agricultural water management were excluded from the synthesis.

The selected literature was systematically categorized into thematic domains, including hydrological processes, agronomic impacts, technological and engineering aspects, groundwater recharge mechanisms, socio-economic implications, and policy or institutional dimensions. A qualitative interpretative synthesis method was adopted to identify recurring patterns, research trends, technological advancements, and existing knowledge gaps across the reviewed studies. Comparative regional analysis was further conducted using case studies from South Asia, Sub-Saharan Africa, the Middle East, and developed regions to evaluate the performance and adaptability of RWH systems under contrasting environmental and institutional settings.

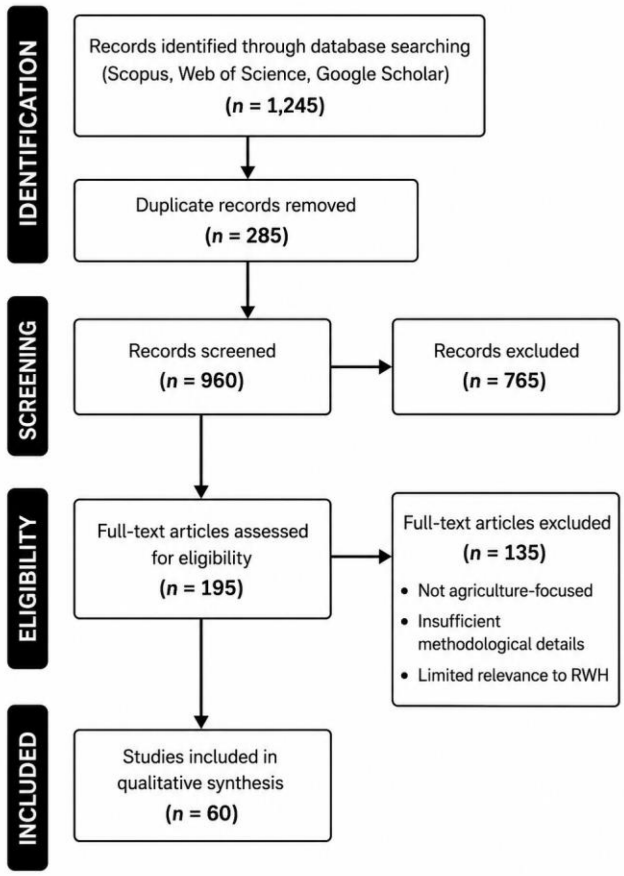

Fig. 2.1. PRISMA flow diagram of literature selection and screening process.

The literature selection process was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency and reproducibility in the identification, screening, eligibility assessment, and inclusion of studies. Combinations of keywords were searched in the Scopus, Web of Science, and Google Scholar databases to gather information. Studies were screened after duplicate removal using the titles, abstracts, and full-text evaluation based on pre-established inclusion and exclusion criteria. Thematic synthesis and critical analysis of the last set of eligible studies (Fig. 2.1) were performed. This review relied exclusively on previously published secondary literature and publicly accessible data sources; therefore, no human participants, animal experimentation, or intervention-based field studies were involved. Consequently, formal ethical approval was not required for the present study.

3. RESULTS

The present review demonstrates that rainwater harvesting (RWH) plays a critical role in strengthening agricultural water security, improving hydrological sustainability, and enhancing climate resilience under conditions of increasing rainfall variability and groundwater depletion. The reviewed studies collectively indicate that RWH functions not only as a water conservation strategy but also as an integrated resource management approach capable of supporting sustainable agricultural intensification. The effectiveness of RWH systems, however, is strongly influenced by climatic conditions, watershed characteristics, technological design, institutional support, and farmer participation.

3.1 Hydrological and Agronomic Implications

3.1.1 Rainfall–Runoff Dynamics

The hydrological efficiency of rainwater harvesting is primarily determined by the interaction between rainfall intensity, infiltration capacity, evapotranspiration, and runoff generation. In many agricultural landscapes, a substantial proportion of rainfall is lost through surface runoff before it can contribute to crop growth or groundwater recharge. The reviewed literature indicates that structures such as contour bunds, farm ponds, recharge pits, and check dams effectively intercept runoff and convert it into productive water storage. These interventions reduce soil erosion, moderate peak runoff, and improve watershed hydrological balance. In addition, watershed-scale RWH systems contribute to sediment retention and improved downstream water regulation, thereby enhancing long-term environmental sustainability.

3.1.2 Soil Moisture Conservation and Groundwater Recharge

One of the most significant agronomic benefits of RWH is the improvement of soil moisture availability. In-situ conservation measures, including mulching, tied ridges, conservation tillage, and contour farming, enhance infiltration and reduce evaporative losses, thereby maintaining favorable root-zone moisture conditions during dry periods. Improved soil moisture not only stabilizes crop growth but also enhances nutrient availability and microbial activity within the soil system.

The review further highlights the importance of RWH in groundwater recharge. Percolation tanks, recharge shafts, and check dams facilitate aquifer replenishment by increasing infiltration through permeable soil layers. Several studies reported measurable increases in groundwater levels and improved well recovery rates in regions where decentralized recharge structures were implemented. Such findings are particularly important in groundwater-stressed agricultural areas where excessive abstraction threatens irrigation sustainability.

3.2 Contribution to Climate Resilience and Sustainable Development

Rainwater harvesting has emerged as an important climate adaptation strategy in drought-prone and semi-arid agricultural regions. By storing excess rainfall during wet periods and providing supplemental irrigation during moisture stress, RWH improves drought resilience and reduces the vulnerability of farming systems to rainfall uncertainty. The reviewed evidence suggests that harvested rainwater can substantially improve crop productivity, cropping intensity, and farm income when strategically applied during critical crop growth stages.

Beyond agricultural productivity, RWH contributes directly to several United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action). Its role in groundwater conservation, runoff regulation, and ecosystem restoration also supports SDG 15 (Life on Land). Furthermore, decentralized and community-managed RWH systems promote participatory governance and equitable water distribution, strengthening institutional sustainability in rural landscapes.

3.3 Emerging Innovations and Future Research Needs

Recent advances in digital technologies have opened new opportunities for improving the efficiency and scalability of rainwater harvesting systems. IoT-based sensors, remote sensing platforms, artificial intelligence, and GIS-supported hydrological modeling are increasingly being explored for real-time monitoring, predictive runoff analysis, and watershed prioritization. These technologies can improve storage management, irrigation scheduling, and decision-making under variable climatic conditions.

Fig 3.1 Interactive sunburst visualization of future perspectives and policy recommendations for rainwater harvesting (rwh)

Despite these advancements, important research gaps remain. Long-term empirical studies evaluating structural durability, sedimentation dynamics, maintenance requirements, and lifecycle performance of RWH systems are still limited. Similarly, governance-related issues such as institutional coordination, policy effectiveness, financing mechanisms, and social equity require greater scientific attention. Future research should therefore adopt interdisciplinary approaches integrating hydrology, climate science, agricultural engineering, socio-economics, and policy analysis to develop resilient and context-specific RWH frameworks.

3.4 Statistical Synthesis of the Reviewed Literature

A descriptive statistical synthesis was conducted to provide a comprehensive overview of the studies included in this systematic review and to identify emerging research patterns in rainwater harvesting for sustainable agricultural water management. The study selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, ensuring a transparent and reproducible approach to literature identification, screening, eligibility assessment, and final inclusion of relevant studies (A). The annual publication trend (B) demonstrates a marked increase in research output during the last decade, particularly after 2020, reflecting the growing global emphasis on climate change adaptation, water scarcity mitigation, and sustainable agricultural practices. Geographical analysis (C) indicates that the majority of studies were conducted in Asia, especially India, followed by Africa and Europe, highlighting the concentration of research efforts in regions facing significant water-related challenges. Furthermore, thematic classification (D) reveals that groundwater recharge, soil moisture conservation, crop productivity, climate resilience, watershed management, and geospatial technologies constitute the principal areas of investigation. Policy and governance aspects have also gained increasing attention in recent years, indicating a broader shift towards integrated water resource management. Overall, the statistical synthesis illustrates the rapid evolution of rainwater harvesting research and establishes a strong foundation for the detailed thematic discussion presented in the subsequent sections.

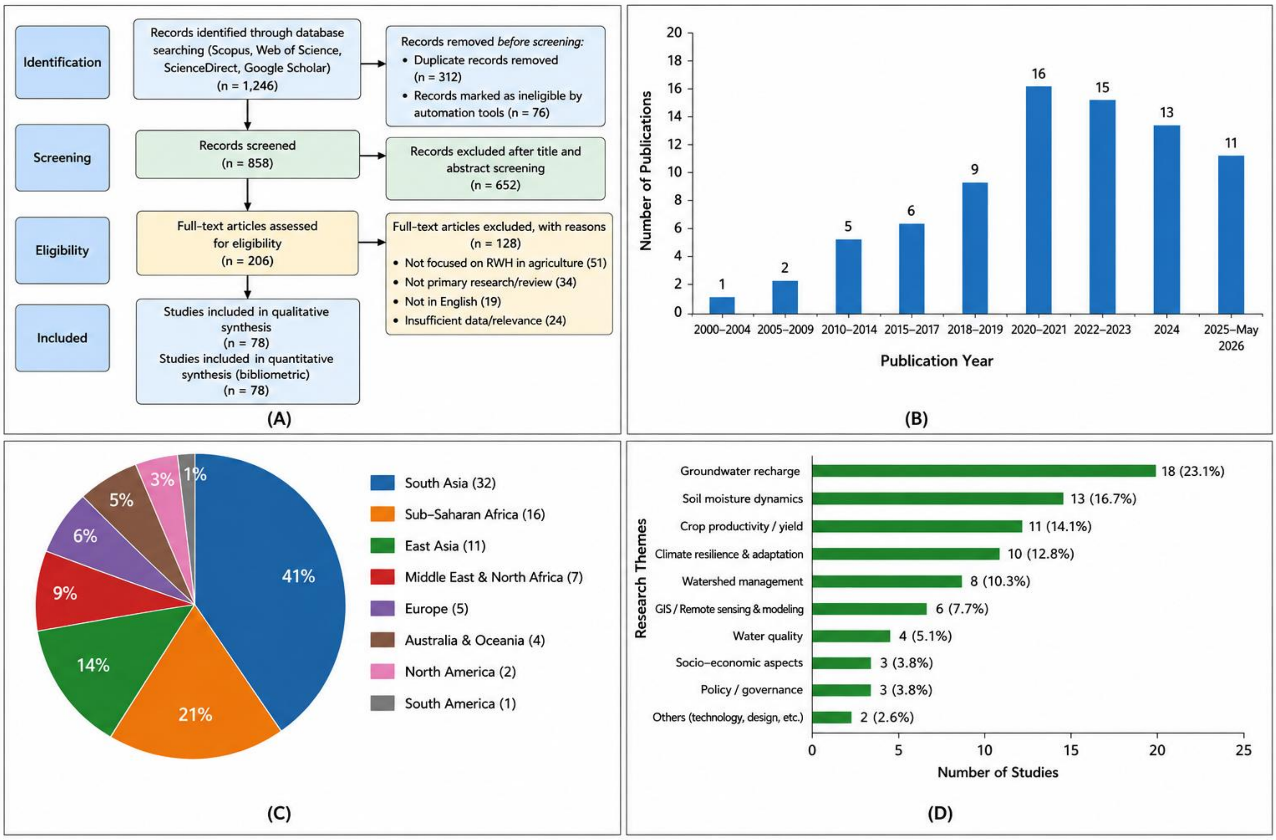

Fig. 3.2 Statistical synthesis of the literature included in the systematic review: (A) PRISMA flow diagram showing the study selection process; (B) annual publication trend of the included studies; (C) geographical distribution of the reviewed studies; and (D) thematic distribution of research areas related to rainwater harvesting.

4. DISCUSSION

The findings of the present study highlight the growing significance of rainwater harvesting (RWH) and integrated watershed management as effective strategies for addressing water scarcity, groundwater depletion, and climate-related hydrological uncertainties. The observed improvements in water availability, groundwater recharge, and agricultural sustainability are consistent with earlier studies conducted across semi-arid and water-stressed regions. Similar conclusions were reported by Hydrology researchers such as (Rai et al., 2025) and (Biazin et al., 2011), who emphasized that rainwater harvesting enhances climate resilience by improving water storage capacity and reducing dependence on unreliable rainfall patterns. Likewise, (Abdulla and AL-SHAREEF, 2009) demonstrated that rooftop rainwater harvesting systems can substantially supplement domestic water supplies in arid environments, supporting the broader applicability of decentralized water conservation approaches.

TABLE 4.1 CRITICAL EVALUATION OF RAINWATER HARVESTING CASE STUDIES IN AGRICULTURAL WATER MANAGEMENT

Region / Case Study	Rainwater Harvesting Approach	Key Outcomes	Critical Evaluation	Citations
India (Semi-arid regions)	Small dams and community water harvesting structures	Improved irrigation access, poverty reduction, reduced social conflicts	Effective for rural livelihoods, but long-term sustainability depends on maintenance, governance, and equitable water distribution	(Agoramoorthy, Chaudhary and Hsu, 2009)
Jordan	Rooftop rainwater harvesting	Increased household water	Technically feasible and cost-effective, though	(Abdulla and AL-SHAREEF, 2009)

	systems	availability in water-scarce areas	storage limitations and water quality concerns remain significant	
Sub-Saharan Africa	Rainwater harvesting in rainfed agriculture	Enhanced soil moisture and crop productivity	Adoption constrained by financial barriers, climate variability, and weak institutional support	(Biazin et al., 2011; Umukiza et al., 2023)
Karnataka, India	Integrated farming with water harvesting structures	Increased groundwater recharge, productivity, and farm income	Positive economic impacts observed, but scalability depends on regional hydrology and farmer participation	Nagaraj et al. (2008)
West Bengal, India	Traditional tank irrigation systems	Stabilized groundwater levels and irrigation supply	Decline of traditional systems linked with groundwater depletion, highlighting policy neglect and poor maintenance	(Chowdhury and Behera, 2018)
Semi-arid India	Watershed-based rainwater harvesting	Improved water availability and agricultural resilience	Downstream impacts and unequal water access require integrated watershed governance	(Bouma, Biggs and Bouwer, 2011)
Malaysia	Large-scale optimized rainwater harvesting systems	Improved storage efficiency and system reliability	Advanced simulation models improved efficiency, but implementation costs may limit rural adoption	(Hashim et al., 2013)
Australia (Melbourne)	Stormwater harvesting for park irrigation	Reduced dependence on potable water	Urban systems show high reuse potential, though infrastructure investment and maintenance are challenging	Day and Sharma (2020)
China (Semiarid region)	Ridge–furrow rainwater harvesting with supplementary irrigation	Increased water-use efficiency and stable crop yields	Long-term field evidence supports effectiveness, but supplementary irrigation remains necessary during drought years	(Day and Sharma, 2020)
Iraq	Rainwater harvesting for drinking and agricultural use	Improved water accessibility and quality monitoring	Water quality management remains a critical challenge for safe long-term utilization	(Zhang et al., 2021)
Europe	Modern rainwater harvesting systems	Enhanced urban and agricultural water sustainability	Strong policy integration and technological advancement support adoption, but economic feasibility varies regionally	(Al-Fahal et al., 2024)
India (National perspective)	Artificial recharge and groundwater-focused RWH systems	Improved groundwater recharge potential	Effectiveness highly dependent on-site selection, hydrogeology, and recharge structure design	(Wartalska et al., 2024)
Global urban systems	Urban rainwater harvesting integration	Reduced runoff and supplemental irrigation supply	Urban adoption is increasing, but system reliability depends on rainfall variability and storage optimization	(Mahato, Mishra and Debnath, 2020; Mishra et al., 2022)

Climate-resilient agriculture (Global)	Climate-adaptive rainwater harvesting systems	Enhanced resilience to drought and rainfall variability	Climate change increases uncertainty, requiring integrated modelling and adaptive management strategies	(Campisano et al., 2017; Xu et al., 2023)
India (Traditional systems)	Indigenous water harvesting structures	Sustainable local water conservation and cultural acceptance	Traditional systems are environmentally sustainable but increasingly threatened by modernization and policy neglect	(Garrote, 2017; Rai et al., 2025)
Global reviews	Agricultural rainwater harvesting systems	Improved irrigation efficiency and water conservation	Broader adoption hindered by economic, technical, and institutional constraints despite strong environmental benefits	(Bhattacharya, 2015; Rekha, 2021)

The results also indicate that rainwater harvesting contributes significantly to groundwater recharge and watershed sustainability. This observation aligns with the findings of (Nagaraj, Chandrakanth and Prathima, 2008; Mahato, Mishra and Debnath, 2020; Mishra et al., 2022)charge structures such as percolation tanks, check dams, and farm ponds improve groundwater storage and increase agricultural productivity. In the Indian context, these outcomes are particularly relevant because excessive groundwater extraction has become a critical concern in many agricultural regions. Studies by (Dangar, Asoka and Mishra, 2021; Jain et al., 2021; Devineni, Perveen and Lall, 2022)similarly warned that declining groundwater levels threaten future cropping intensity and food security. Therefore, the present findings reinforce the argument that RWH systems can play a major role in mitigating groundwater stress while supporting sustainable agricultural development.

The study further highlights the importance of hydrological modelling and geospatial tools in evaluating watershed behaviour and identifying suitable intervention sites (Government of Odisha, 2017). Earlier, investigations using the SWAT model by (Agrawal, Verma and Tripathi, 2009; Aalami, Abbasi and Niksokhan, 2018; Wu et al., 2023)demonstrated that integrated modelling approaches are highly effective for simulating runoff, sediment transport, and watershed prioritization. Similarly, (Bailey et al., 2025) emphasized the improved capability of coupled SWAT+MODFLOW frameworks in representing surface–subsurface water interactions. The current findings support these studies by showing that modelling-based assessments can provide scientifically reliable information for planning efficient rainwater harvesting systems and sustainable watershed interventions. Nevertheless, uncertainties concomitant with calibration, climate projections, and land use dynamics remain important restrictions, as also emphasised by (Aghsaei et al., 2020; Aamery, Fox and Mahoney, 2021)aspect emerging from the analysis is the influence of land use and climate variability on hydrological responses. Previous studies by (Xia, Qiu and Li, 2012; Chang-chu, 2014; Geris et al., 2022)demonstrated that changes in land cover and increasing climatic extremes significantly alter runoff generation, groundwater recharge, and sediment yield. The present study similarly indicates that rainfall variability and watershed degradation can reduce the efficiency of traditional water conservation systems if not properly managed. (Allen and Ingram, 2002) also emphasized that climate change is likely to intensify hydrological uncertainty globally, thereby increasing the need for adaptive water management strategies. Consequently, integrating climate-resilient infrastructure with watershed restoration measures becomes essential for long-term water sustainability.

TABLE 4.2 SOCIOECONOMIC AND ENVIRONMENTAL INSIGHTS FROM RAINWATER HARVESTING CASE STUDIES

Region/Country	Case Study Focus	Socioeconomic Insights	Environmental Insights	Key Outcomes	Citations
India (Semi-arid regions)	Small dams and community rainwater harvesting	Reduced rural poverty, improved livelihoods, minimized social conflicts over water	Enhanced local water storage and drought resilience	Strengthened community-based water management	(Jan, Chen and Lo, 2006; Agora Moorthy, Chaudhary and Hsu, 2009) I
Jordan	Rooftop rainwater harvesting for domestic and agricultural use	Reduced dependence on costly external water supply	Improved water conservation in arid environments	Increased household water security	Abdulla and Al-Shareef (2009); Jatiya and Hosokawa (2004)
Central Asia	Collective irrigation water management	Strengthened farmer participation and institutional cooperation	Improved irrigation efficiency and reduced water losses	Better governance of shared water resources	Abdullaev et al. (2009); Kumar (2024)
West Bengal, India	Traditional tank irrigation systems	Decline of traditional systems affected rural agricultural sustainability	Falling groundwater levels due to reduced recharge	Highlighted need for restoration of traditional systems	Chowdhury and Behera (2018);López-Lambraño and López-Ramos (2019)
Karnataka, India	Integrated farming with water harvesting	Increased crop productivity and farm income	Enhanced groundwater recharge potential	Improved net economic returns for farmers	(Nagaraj, Chandrakanth and Prathima, 2008; Mukherji, 2020)
Sub-Saharan Africa	Rainwater harvesting in rainfed agriculture	Improved food security and farmer resilience	Reduced soil erosion and runoff losses	Increased agricultural sustainability under climate stress	Temesgen et al. (2012);Pari et al. (2021)
India	Traditional water harvesting structures	Strengthened local water governance and cultural sustainability	Improved groundwater recharge and water conservation	Promoted sustainable water-use practices	Bhattacharya (2015); Salem et al. (2015)
Iran (Anzali Wetland)	Land-use change and watershed management	Agricultural pressure altered water-use dynamics	Increased sediment yield and degradation risks	Demonstrated importance of integrated watershed planning	Aghsaei et al. (2020)
Malaysia	Optimization of large-scale rainwater harvesting	Reduced operational water costs	Improved efficiency of water resource utilization	Enhanced sustainability of urban–agricultural	Hashim et al. (2013); Srushtitha et al. (2024)

	systems			systems	
India	Community rainwater harvesting structures	Improved equity and farm-level benefits among rural households	Strengthened sustainability of local water systems	Positive social acceptance and resilience outcomes	Alam et al. (2022a); Foster et al. (1993)
Africa (Arid and Semi-arid lands)	Rainwater harvesting under water scarcity	Increased livelihood adaptation opportunities	Enhanced drought mitigation and ecosystem resilience	Addressed water insecurity challenges	(García-Ávila et al., 2023; Umukiza et al., 2023)
China (Semiarid region)	Ridge–furrow rainwater harvesting for wheat production	Stabilized farmer yields and economic returns	Improved water-use efficiency and reduced irrigation demand	Water-saving agriculture-maintained crop productivity	(Cheema, Immerzeel and Bastiaanssen, 2013; Zhang et al., 2021)
Europe	Modern rainwater harvesting systems	Promoted sustainable urban and agricultural water use	Reduced pressure on freshwater resources	Increased climate adaptation capacity	Wartalska et al. (2024); Ali (2017)
Australia	Stormwater harvesting for irrigation	Reduced dependence on potable water for parks and agriculture	Improved urban water recycling	Supported sustainable urban irrigation management	Day and Sharma (2020); Bandi and Patil (2022)
Global	Environmental assessment of rainwater harvesting systems	Economic feasibility varies with scale and technology	Reduced runoff, flooding, and freshwater extraction	Long-term sustainability depends on local adaptation	Teston et al. (2022); Velasco-Muñoz et al. (2019)

The socio-economic implications of rainwater harvesting are equally significant. Studies by (Agoramoorthy, Chaudhary and Hsu, 2009; Bhattacharya, 2015; Alam et al., 2022)sed water harvesting structures not only improve water security but also reduce poverty, strengthen local livelihoods, and minimize social conflicts related to water access. Similar trends were evident in the present study, where improved water availability contributed to enhanced agricultural stability and resource accessibility. Nevertheless, some researchers have cautioned that poorly planned rainwater harvesting interventions may generate downstream externalities or inequitable water distribution. For example, (Bouma, Biggs and Bouwer, 2011) observed that excessive upstream water harvesting in semi-arid watersheds may reduce downstream flows and negatively affect other users. Therefore, the success of RWH initiatives depends on balanced watershed-scale planning, stakeholder participation, and equitable governance frameworks.

The discussion also highlights the increasing role of technological innovation in improving rainwater harvesting efficiency. Recent studies have explored the integration of digital technologies, simulation models, and intelligent monitoring systems for optimizing water storage and distribution. (Hashim et al., 2013; Maqsoom et al., 2021; Mohammed and Mohammed-Ali, 2025)vanced simulation and modelling approaches can significantly improve the design and operational efficiency of large-scale RWH systems. Similarly, (Campisano et al., 2017; Xu et al., 2023; Wartalska et al., 2024)importance of urban rainwater utilization and smart water management systems under conditions of rapid urbanization and climate stress. The present findings support these perspectives and suggest that integrating digital tools, remote sensing, GIS, and predictive hydrological models could substantially improve future watershed management practices.

Despite the positive outcomes, several challenges remain. In many developing regions, insufficient technical expertise, financial constraints, lack of maintenance, and weak institutional coordination continue to limit the long-term effectiveness of RWH systems. Similar concerns were raised by (Kotchoni et al., 2018; Rekha, 2021; Hangshing, Vijayan and Sivasuriyan, 2023; Umukiza et al., 2023)articularly in relation to rural and semi-arid regions. In addition, water quality issues associated with harvested rainwater require careful attention, as highlighted by (Al-Fahal et al., 2024). Therefore, future research should focus not only on hydrological performance but also on water quality assessment, socio-economic feasibility, and policy integration.

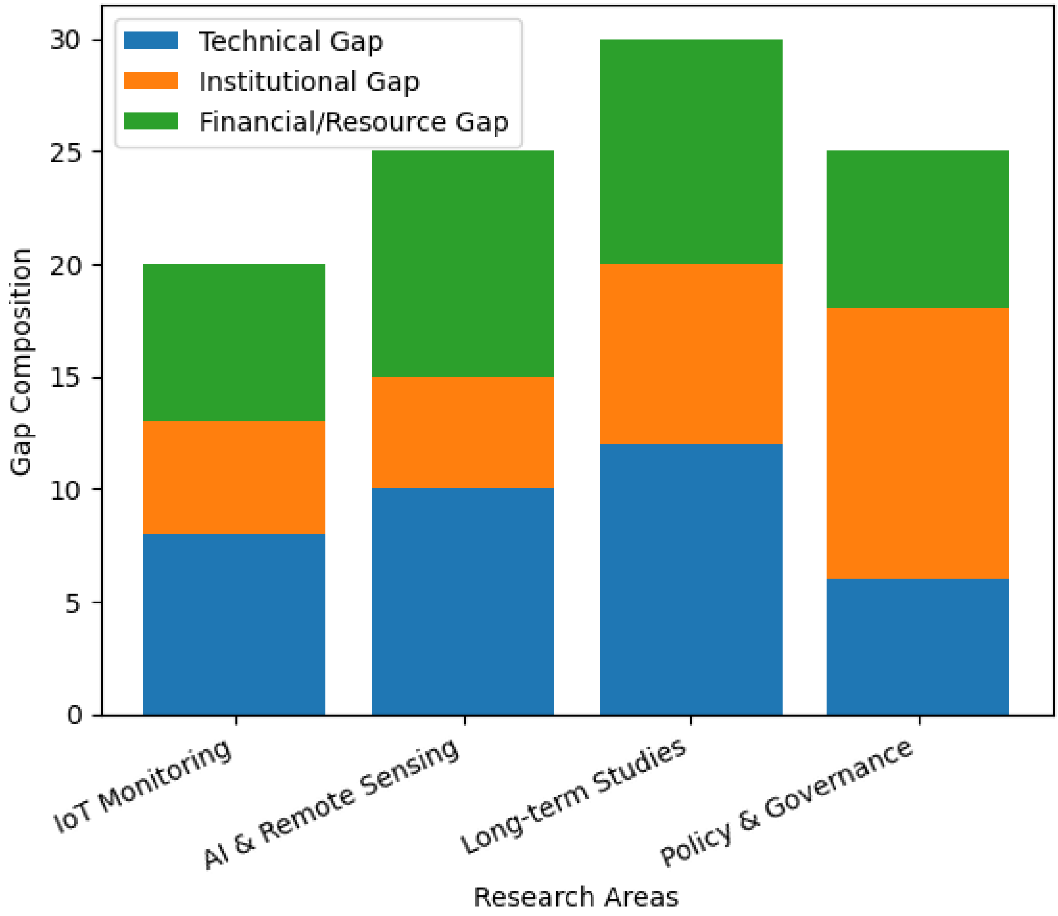

Fig 4.1 Research gaps and emerging innovation in rainwater harvesting key research areas.

Overall, the present study confirms that rainwater harvesting and integrated watershed management represent sustainable and climate-resilient solutions for improving water security and agricultural productivity. However, effective implementation requires multidisciplinary approaches that combine hydrological modelling, community participation, technological innovation, and adaptive policy support. Future studies should further investigate the long-term impacts of climate change, land use transformation, groundwater–surface water interactions, and smart water management technologies to strengthen the sustainability and scalability of rainwater harvesting systems in diverse environmental settings.

Future Research Directions

Future research should move beyond descriptive assessments of rainwater harvesting (RWH) and focus on hypothesis-driven investigations that generate robust scientific evidence under diverse agro-climatic conditions. Long-term field experiments are needed to quantify the effects of RWH on groundwater recharge, soil moisture dynamics, crop productivity, and farm resilience under changing climate scenarios. Future studies should also evaluate the effectiveness of integrating RWH with precision irrigation, Internet of Things (IoT)-based monitoring, remote sensing, and artificial intelligence for optimizing water-use efficiency. In addition, socioeconomic and policy-oriented research is required to understand the factors influencing adoption, maintenance, and scalability of community-based RWH systems.

The following testable research questions deserve particular attention: **(i)** Does integrating RWH with smart irrigation significantly improve water-use efficiency and crop yield compared with conventional irrigation? **(ii)** How does long-term adoption of RWH influence groundwater recharge and watershed sustainability across different agroecological regions? **(iii)** Which socioeconomic, institutional, and policy factors most strongly determine farmer adoption and sustained use of RWH technologies? **(iv)** Can AI- and GIS-based decision-support systems improve the planning, design, and performance of decentralized rainwater harvesting interventions under future climate variability?

5. CONCLUSIONS

The review confirms that rainwater harvesting represents a scientifically sound and environmentally sustainable approach for addressing agricultural water scarcity under changing climatic conditions. Properly designed RWH systems improve water availability, groundwater recharge, soil moisture conservation, and crop productivity while simultaneously reducing runoff losses and land degradation. The integration of modern technologies, supportive policies, and participatory governance frameworks can further enhance the effectiveness and scalability of RWH interventions. However, long-term sustainability depends on appropriate site selection, technical maintenance, institutional coordination, and equitable access to resources. Consequently, rainwater harvesting should be recognized as a central component of climate-resilient and sustainable agricultural water management strategies worldwide.

Author Contributions: Conceptualization, ADS and SPT; methodology, ADS and SPT; software, ADS; validation, ADS and SPT; formal analysis, ADS; investigation, ADS and SPT; resources, SPT; data curation, ADS; writing—original draft preparation, ADS; writing—review and editing, ADS and SPT; visualization, ADS; supervision, SPT; project administration, SPT. All authors have read and agreed to the published version of the manuscript.

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REFERENCES

1. Aalam, M.T., Abbasi, H. and Niksokhan, M.H., 2018. Comparison of two calibration-uncertainty methods for Soil and Water Assessment Tool in stream flow and total suspended solids modelling. *Journal of Water and Soil Science*, 28(3), pp.53–64. https://water-soil.tabrizu.ac.ir/article_8123.html?lang=en
2. Aamery, N.A., Fox, J.F. and Mahoney, T., 2021. Variance decomposition of forecasted sediment transport in a lowland watershed using global climate model ensembles. *Journal of Hydrology*, 602, 126760. https://doi.org/10.1016/j.jhydrol.2021.126760
3. Abdeen, S., 2025. Sustaining Productivity of Egyptian Water Resources Under Climate Changes – A Review. *Current Applied Science and Technology*. https://doi.org/10.55003/cast.2025.258101
4. Abdulla, F. and Al-Shareef, A., 2009. Roof rainwater harvesting systems for household water supply in Jordan. *Desalination*, 243(1–3), pp.195–207. https://doi.org/10.1016/j.desal.2008.05.013
5. Abdullaev, I., Kazbekov, J., Manthritilake, H. and Jumaboev, K., 2009. Water user groups in Central Asia: Emerging form of collective action in irrigation water management. *Water Resources Management*, 24(5), pp.1029–1043. https://doi.org/10.1007/s11269-009-9484-4
6. Aggarwal, R.K., 2025. India’s Escalating Water Crisis and the Expanding Role of Rainwater Harvesting in Sustainable Resource Management. *International Journal of Science and Research*, pp.984–994. https://doi.org/10.21275/SR251208221535
7. Aghsaei, H., Dinan, N.M., Moridi, A., Asadolahi, Z., Delavar, M., Fohrer, N. and Wagner, P.D., 2020. Effects of dynamic land use/land cover change on water resources and sediment yield in the Anzali wetland catchment, Gilan, Iran. *Science of the Total Environment*, 712, 136449. https://doi.org/10.1016/j.scitotenv.2019.136449
8. Agoramoorthy, G., Chaudhary, S. and Hsu, M.J., 2009. Sustainable development using small dams: An approach to avert social conflict and relieve poverty in India's semi-arid regions. *Asia Pacific Journal of Social Work and Development*, 19(2), pp.52–69. https://doi.org/10.1080/21650993.2009.9756063

9. Agrawal, N., Verma, M.K. and Tripathi, M.P., 2009. Effective management of critical sub-watersheds using SWAT model, remote sensing and GIS. *Agricultural Engineering Today*, 33(4), pp.15–20.
10. Alam, M.F., McClain, M.E., Sikka, A., Daniel, D. and Pande, S., 2022a. Benefits, equity, and sustainability of community rainwater harvesting structures: An assessment based on farm scale social survey. *Frontiers in Environmental Science*, 10, 1043896. https://doi.org/10.3389/fenvs.2022.1043896
11. Alam, M.F., McClain, M., Sikka, A. and Pande, S., 2022b. Understanding human–water feedbacks of interventions in agricultural systems with agent based models: A review. *Environmental Research Letters*, 17, 103003. https://doi.org/10.1088/1748-9326/ac91e1
12. Alao, J.O., Eze, S.U., Onyenweife, G.I., Ibe, A.A., Otorkpa, O.J., Ayejoto, D.A., Abubakar, F., Abdulsalami, M. and Abdulmalik, D.O., 2025. Enhancing water security through integrated storage mechanisms and rainwater harvesting for sustainable development. *Discover Sustainability*, 6(1). https://doi.org/10.1007/s43621-025-01914-2
13. Al-Fahal, A., Ahmed, A., Mohammed, A.K. and Mohammed-Ali, W., 2024. Evaluation of rainwater harvesting systems for drinking water quality in Iraq. *International Journal of Design & Nature and Ecodynamics*, 19(1), pp.111–117. https://doi.org/10.18280/IJDNE.190113
14. Allen, M.R. and Ingram, W.J., 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature*, 419(6903), pp.224–232. https://doi.org/10.1038/nature01092
15. Ali, A., 2017. Evaluating rainwater harvesting systems in arid and semi-arid regions.
16. Arvind, A., 2025. Role of Irrigation and Water Management in Sustainable Agriculture. *Phyton*, 65. https://doi.org/10.64526/phyton-annales.v65is1.76
17. Bailey, R.T., Abbas, S., Arnold, J.G. and White, M.J., 2025. SWAT+MODFLOW: A new hydrologic model for simulating surface-subsurface flow in managed watersheds. *Geoscientific Model Development*, 18(17), pp.5681–5697. https://doi.org/10.5194/gmd-18-5681-2025
18. Bandi, A.H. and Patil, N.S., 2022. Estimation of water balance components for the watershed of Ghataprabha Subbasin. *Nature Environment and Pollution Technology*, 21(3), pp.1395–1400. https://doi.org/10.46488/NEPT.2022.v21i03.048
19. Basinger, M., Montalto, F. and Lall, U., 2010. A rainwater harvesting system reliability model based on nonparametric stochastic rainfall generator. *Journal of Hydrology*, 392, pp.105–118. https://doi.org/10.1016/j.jhydrol.2010.07.039
20. Behera, B., Chowdhury, K., Mishra, T. and Rahut, D.B., 2024. Climate variability and rainwater harvesting structures. *International Journal of Water Resources Development*, 40(3), pp.487–505. https://doi.org/10.1080/07900627.2023.2279962
21 Bhattacharya, S., 2015. Traditional water harvesting structures and sustainable water management in India: A socio-hydrological review. *International Letters of Natural Sciences*, 37, pp.30–38.
22 Biazin, B., Temesgen, M., Sterk, G., Abdulkedir, A. and Stroosnijder, L., 2011. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – A review. *Physics and Chemistry of the Earth*, 47–48, pp.139–151.
23 Biswas, A., Sarkar, S., Das, S., Dutta, S., Roy Choudhury, M., Giri, A., Bera, B., Bag, K., Mukherjee, B., Banerjee, K., Gupta, D. and Paul, D.,2025. Water scarcity: A global hindrance to sustainable development and agricultural production – A critical review of the impacts and adaptation strategies. *Cambridge Prisms: Water*, 3. doi:10.1017/wat.2024.16
24 Bouma, J.A., Biggs, T.W. and Bouwer, L.M., 2011. The downstream externalities of harvesting rainwater in semi-arid watersheds: An Indian case study. *Agricultural Water Management*, 98, pp.1162–1170.
25 Campisano, A., Butler, D., Ward, S., Burns, M.J., Friedler, E., DeBusk, K., Fisher-Jeffes, L.N., Ghisi, E., Rahman, A., Furumai, H. and Han, M., 2017. Urban rainwater harvesting systems: Research, implementation and future perspectives. *Water Research*, 115, pp.195–209. DOI:10.1016/j.watres.2017.02.056
26 Central Ground Water Board (CGWB), 2022. *Ground Water Year Book 2021–2022: South Eastern Region*. New Delhi: Ministry of Jal Shakti, Government of India.
27 Dangar, S., Asoka, A. and Mishra, V., 2021. Causes and implications of groundwater depletion in India: A review. *Journal of Hydrology*, 596, 126103. https://doi.org/10.1016/j.jhydrol.2021.126103
28 Day, J. and Sharma, A., 2020. Stormwater harvesting infrastructure systems design for urban park irrigation: Brimbank Park, Melbourne case study. *AQUA – Water Infrastructure, Ecosystems and Society*, 69, pp.844–857. https://doi.org/10.2166/aqua.2020.047
29 Devineni, N., Perveen, S. and Lall, U., 2022. Solving groundwater depletion in India while achieving food security. *Nature Communications*, 13(1), 3374. https://doi.org/10.1038/s41467-022-31122-9
30 Fernando García-Ávila, Guanoquiza-Suárez, M., Guzmán-Galarza, J., Cabello-Torres, R. and Valdiviezo-Gonzales, L., 2023. Rainwater harvesting and storage systems for domestic supply: An overview of research for water scarcity management in rural areas. *Results in Engineering*, 18, 101153. https://doi.org/10.1016/j.rineng.2023.101153
31 Foster, S.S.D., Morris, B.L. and Lawrence, A.R., 1993. Effects of urbanization on groundwater recharge. In: Wilkinson, W.B. (Ed.), *Groundwater Problems in Urban Areas*. Thomas Telford Ltd., London, pp.43–63.

32 Garrote, L., 2017. Managing water resources to adapt to climate change: Facing uncertainty and scarcity in a changing context. *Water Resources Management*, 31(10), pp.2951–2963. https://doi.org/10.1007/s11269-017-1714-6
33 Geris, J., Comte, J.-C., Franchi, F., Petros, A.K., Tirivarombo, S., Selepeng, A.T. and Villholth, K.G., 2022. Surface water-groundwater interactions and local land use control water quality impacts of extreme rainfall and flooding in a vulnerable semi-arid region of Sub-Saharan Africa. *Journal of Hydrology*, 609, 127834. https://doi.org/10.1016/j.jhydrol.2022.127834
34 Government of Odisha, 2017. *An Overview of Irrigation Scenario*. Department of Water Resources, Government of Odisha, Bhubaneswar.
35 Hafeez, M.M., Cheema, M.J.M., Liaqat, U.W., Amin, M. and Usman, M., 2025. Mapping of potential storages and rainwater harvesting sites in arid region of Indus basin using analytical hierarchy technique. *Scientific Reports*, 15, 36947. https://doi.org/10.1038/s41598-025-20915-9
36 Hangshing, L., Vijayan, D. and Sivasuriyan, A., 2023. A study of rainwater harvesting for sustainable water resource management in Nagaland, Northeast India: A review. *Acta Scientiarum Polonorum Architectura*, 21(4). https://doi.org/10.22630/ASPA.2022.21.4.30
37 Hashim, H., Hudzori, A., Yusop, Z. and Ho, W.S., 2013. Simulation based programming for optimization of large-scale rainwater harvesting system: Malaysia case study. *Resources, Conservation and Recycling*, 80, pp.1–9. https://doi.org/10.1016/j.resconrec.2013.05.001
38 Jain, M., Fishman, R., Mondal, P., Galford, G.L., Bhattarai, N., Naeem, S., Lall, U. and DeFries, R.S., 2021. Groundwater depletion will reduce cropping intensity in India. *Science Advances*, 7(9), eabd2849. https://doi.org/10.1126/sciadv.abd2849
39 Jan, C.D., Chen, T.H. and Lo, W.C., 2007. Effect of rainfall intensity and distribution on groundwater level fluctuations. *Journal of Hydrology*, 332(3–4), pp.348–360. https://doi.org/10.1016/j.jhydrol.2006.07.010
40 Jatiya, V.K. and Hosokawa, T., 2004. Significance of rainwater harvesting in mega-diversity water resource country: India. *Journal of Rainwater Catchment Systems*, 10(1), pp.21–28. https://doi.org/10.7132/JRCSA.KJ00003257926
41 Kanase, J.N. and Takalkar, S.D., 2025. Sustainable agriculture and water management. *Zenodo*. https://doi.org/10.5281/zenodo.18016545
42 Kaur, A., 2022. *Ground Water Year Book of Haryana State (2021–2022).* https://doi.org/10.13140/RG.2.2.32249.89441
43 Khairy, W., Abd-Elhamid, H., Zelenakova, M. and Mahmoud, A.A., 2025. Developing an efficient, low-cost and nature-based technology of wastewater treatment for climate resilience in isolated rural areas. *Journal of Water and Climate Change*. https://doi.org/10.2166/wcc.2025.761
44 Kotchoni, D., Vouillamoz, J.-M., Lawson, F.M., Adjomayi, P., Boukari, M. and Taylor, R., 2018. Relationships between rainfall and groundwater recharge in seasonally humid Benin. *Hydrogeology Journal*, 27(2), pp.447–457. https://doi.org/10.1007/s10040-018-1806-2
45 Kumar, S., 2024. Design of rain water harvesting system for efficient water scarcity and flood management in India. *International Journal of Environment and Climate Change*, 14(6), pp.295–303. https://doi.org/10.9734/IJECC/2024/v14i64229
46 López-Lambraño, A.A. and López-Ramos, A., 2019. Design criteria for planning agricultural rainwater harvesting systems: A review. *Applied Sciences*, 9(24), 5298. https://doi.org/10.3390/app9245298
47 Mahato, S., Mishra, A. and Debnath, S., 2020. Impact of rainwater harvesting structures on groundwater recharge potential in India. *International Journal of Current Microbiology and Applied Sciences*, 9(6), pp.66–74. https://doi.org/10.20546/ijcmas.2020.906.008
48 Maqsoom, A., Aslam, B., Ismail, S., Thaheem, M.J., Ullah, F., Zahoor, H., Musarat, M.A. and Vatin, N.I., 2021. Assessing rainwater harvesting potential in urban areas: A building information modelling (BIM) approach. *Sustainability*, 13(22), 12583. https://doi.org/10.3390/su132212583
49 Mishra, U., Mohapatra, A.K., Mandal, A. and Singh, A., 2023. Identification of potential artificial groundwater recharge sites in an alluvial setting. *Groundwater for Sustainable Development*, 20, 100875. https://doi.org/10.1016/j.gsd.2022.100875
50 Mohammed, A.J. and Mohammed-Ali, W.S., 2025. The sustainable relevance of modeling in water distribution system. *Innovative Infrastructure Solutions*, 10, 367. https://doi.org/10.1007/s41062-025-02168-7
51 Mukherji, A., 2022. Sustainable groundwater management in India needs a water-energy-food nexus approach. *Applied Economic Perspectives and Policy*, 44(1), pp.394–410. https://doi.org/10.1002/aepp.13123
52 Nagaraj, N., Chandrakanth, M.G. and Prathima, R., 2008. Impact of water harvesting on groundwater recharge, productivity and net returns with integrated farming systems approach in eastern dry zone of Karnataka. Conference Paper. Colombo, Sri Lanka: International Water Management Institute.
53 Hari Om, Pal, K., Singh, T., Panchal, D., Sharma, S., Dhauni, L.S. and Kumar, S., 2025. Optimizing rainwater harvesting systems: Techniques and trends. *International Journal of Research in Civil Engineering and Technology*, 6(1), pp.9–12. https://doi.org/10.22271/27078264.2025.v6.i1a.75
54 Pari, L., Suardi, A., Stefanoni, W., Latterini, F. and Palmieri, N., 2021. Economic and environmental assessment of two different rainwater harvesting systems for agriculture. *Sustainability*, 13(7), 3871. https://doi.org/10.3390/su13073871

55 Rai, G. and Upadhyay, S., 2025. Climate resilient strategies for sustainable water resource management in agriculture: A review. *Plant Archives*, 25(1), pp.861–868. https://doi.org/10.151470/PLANTARCHIVES.2025.v25.no.1.130
56 Reddy, K.C., 2025. Rainwater harvesting systems in urban and rural India: Performance and policy review. *International Journal for Research in Applied Science and Engineering Technology*, 13(7), pp.1158–1164. https://doi.org/10.22214/ijraset.2025.73101
57 Rekha, J., 2021. Rainwater harvesting in India. *Artha Journal of Social Sciences*, 1, pp.49–56. https://doi.org/10.12724/ajss.1.4
58 Salem, H.M., Valero, C., Muñoz, M.Á. and Gil-Rodríguez, M., 2015. Effect of integrated reservoir tillage for in-situ rainwater harvesting and other tillage practices on soil physical properties. *Soil and Tillage Research*, 151, pp.50–60. https://doi.org/10.1016/j.still.2015.02.009
59 Singh, A., 2026. Climate-smart water harvesting approaches for sustainable horticulture in arid regions. *Journal of Environmental Biology*, 47(2). https://doi.org/10.22438/jeb/47/2/editorial
60 Singh, K.K., Kleinhans, M., Markham, K., Mensah, F., BenYishay, A. and Adewopo, J., 2026. Investment trends and evaluation gaps in rainwater harvesting in Sub-Saharan African drylands. *Agricultural Water Management*, 327, 110265. https://doi.org/10.1016/j.agwat.2026.110265
61 Singh, S.K., 2025. Rainwater harvesting systems in urban and rural India: Performance and policy review. *International Journal for Research in Applied Science and Engineering Technology*, 13(7), pp.1165–1171. https://doi.org/10.22214/ijraset.2025.73128
62 Srushtitha, S., Ranjitha, S., Siri Gowri, Chandana, V., Bhuvan Adithya and Roopa K. Murthy, 2024. Design and implementation of rainwater harvesting systems. *International Advanced Research Journal in Science, Engineering and Technology*, 11(2). https://doi.org/10.17148/IARJSET.2024.11217
63 Temesgen, M., Biazin, B., Sterk, G., Abdulkedir, A. and Stroosnijder, L., 2012. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa: A review. *Physics and Chemistry of the Earth*, 47–48, pp.139–151. https://doi.org/10.1016/j.pce.2011.08.015
64 Teston, A., Scolaro, T.P., Maykot, J.K. and Ghisi, E., 2022. Comprehensive environmental assessment of rainwater harvesting systems: A literature review. *Water*, 14(17), 2716. https://doi.org/10.3390/w14172716
65 Timiș, C.M., Vornicu, L., Pașcalău, R. and Șmuleac, L.F., 2025. Integrated water resource management for climate-resilient agriculture. *Research Journal of Agricultural Science*, 57(4), pp.365–371. https://doi.org/10.59463/rjas.2025.4.44
66 Umukiza, E., Ntole, R., Chikavumbwa, S.R., Bwambale, E., Sibale, D., Jeremiah, Z., Apollonio, C. and Petroselli, A., 2023. Rainwater harvesting in arid and semi-arid lands of Africa: Challenges and opportunities. *Acta Scientiarum Polonorum Formatio Circumiectus*, 22(2), pp.41–52. https://doi.org/10.15576/ASP.FC/2023.22.2.03
67 Velasco-Muñoz, J.F., Aznar-Sánchez, J.A., Batlles-de la Fuente, A. and Fidelibus, M.D., 2019. Rainwater harvesting for agricultural irrigation: An analysis of global research. *Water*, 11(7), 1320. https://doi.org/10.3390/w11071320
68 Vorotyntseva, L., Panarin, R., Kucher, A., Tsybulska, J., Krupin, V., Zawalińska, K., Skorokhod, I. and Broyaka, A.., 2025. Sustainable management of agricultural soil and water resources: Current trends and challenges from global and Ukrainian perspectives. *Environmental Sciences Europe*, 37(1). https://doi.org/10.1186/s12302-025-01220-8
69 Wartalska, K., Grzegorzek, M., Bełcik, M., Wdowikowski, M., Kolanek, A., Niemierka, E., Jadwiszczak, P. and Kaźmierczak, B., 2024. The potential of rainwater harvesting systems in Europe: Current state of the art and future perspectives. *Water Resources Management*, 38(12), pp.4657–4683. https://doi.org/10.1007/s11269-024-03882-0
70 Wu, T., Zhu, L.-J., Shen, S., Zhu, A.-X., Shi, M. and Qin, C.-Z., 2023. Identification of watershed priority management areas based on landscape positions: An implementation using SWAT+. *Journal of Hydrology*, 619, 129281. https://doi.org/10.1016/j.jhydrol.2023.129281
71 Xia, J., Qiu, B. and Li, Y., 2012. Water resources vulnerability and adaptive management in the Huang, Huai and Hai river basins of China. *Water International*, 37(5), pp.523–536. https://doi.org/10.1080/02508060.2012.724649
72 Xu, J., Dai, J., Wu, X., Wu, S., Zhang, Y., Wang, F., Gao, A. and Tan, Y., 2023. Urban rainwater utilization: A review of management modes and harvesting systems. *Frontiers in Environmental Science*, 11, 1025665. https://doi.org/10.3389/fenvs.2023.1025665
73 Zhang, C., Dong, Z., Guo, Q., Hu, Z., Li, J., Wei, T., Ding, R., Cai, T., Ren, X., Han, Q., Zhang, P. and Jia, Z., 2022. Ridge-furrow rainwater harvesting combined with supplementary irrigation: Water-saving and yield-maintaining mode for winter wheat in a semiarid region based on an 8-year in-situ experiment. *Agricultural Water Management*, 259, 107239. https://doi.org/10.1016/j.agwat.2021.107239