



Role of Rainwater Harvesting in Enhancing Agricultural Sustainability in Bihar

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ABSTRACT

Agricultural sustainability in Bihar is strongly constrained by erratic monsoon rainfall, seasonal water scarcity, declining groundwater levels in localized pockets, and increasing production risks under smallholder-dominated farming systems. Rainwater harvesting (RWH) has been promoted as a decentralized, low-cost strategy to enhance water availability and improve resilience, yet empirical evidence from the region remains limited. This study evaluates the role of rainwater harvesting in strengthening agricultural sustainability across contrasting agro-hydrological settings in Bihar. A mixed-methods cross-sectional approach was adopted, combining household surveys ($n = 120$), on-farm hydrological measurements, crop performance monitoring, and key informant interviews. Comparative analysis between farms with and without rainwater harvesting structures assessed impacts on irrigation frequency, groundwater response, crop yields, economic returns, and farmer perceptions. Results indicate that adoption of rainwater harvesting reduced seasonal irrigation dependence, supported localized groundwater recharge, and significantly enhanced yields in rice–vegetable systems through timely supplemental irrigation. Economic assessment revealed favorable benefit–cost relationships, particularly where harvested rainfall enabled diversification into high-value horticultural crops. Farmer perceptions emphasized improved water security and reduced crop failure risk as major advantages, while high initial investment, land constraints, and limited technical support emerged as key barriers to wider adoption. Overall, the findings demonstrate that rainwater harvesting contributes to agricultural sustainability in Bihar through improved water security, livelihood stability, and resilience to intra-seasonal dry spells. However, scaling up requires integrated policy support, capacity building, and community-oriented approaches to ensure equitable and long-term benefits.

Keywords: rainwater harvesting; agricultural sustainability; groundwater recharge; smallholder farming; Bihar

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1. INTRODUCTION

Bihar is predominantly an agrarian state in eastern India, where more than two-thirds of the population depends directly or indirectly on agriculture for livelihood and food security (Government of India, 2022). Agricultural production in the region is strongly influenced by monsoon rainfall, which exhibits high inter-annual and intra-seasonal variability, leading to frequent drought-like conditions during critical crop growth stages despite an overall moderate annual rainfall (Kumar, Singh, & Sharma, 2018). Seasonal water scarcity, declining groundwater levels in selected agro-ecological zones, increasing pressure on surface water resources, and progressive soil degradation collectively threaten long-term agricultural sustainability in the state (Pandey, Mishra, & Tripathi, 2019). These challenges are further exacerbated by climate change-induced shifts in rainfall intensity and distribution, which increase runoff losses while reducing effective soil moisture availability for crops (IPCC, 2021).

Rainwater harvesting (RWH), defined as the systematic collection, storage, and utilization of precipitation at household, farm, and watershed scales, has emerged as an important adaptive strategy for water-stressed agricultural landscapes (FAO, 2013). The approach emphasizes decentralized water management, allowing rainfall to be conserved close to where it falls, thereby minimizing runoff, soil erosion, and nutrient losses (Agarwal & Narain, 1997). Numerous studies have demonstrated that RWH interventions can enhance soil moisture regimes, improve groundwater recharge, and stabilize crop yields under rainfed and partially irrigated systems (Smith & Jones, 2012; Panwar et al., 2016). In regions dominated by small and marginal farmers, such interventions are particularly relevant due to their relatively low capital requirement and compatibility with traditional farming practices (Reddy & Singh, 2018).

In Bihar, a range of rainwater harvesting techniques are practiced or promoted, including farm ponds, check dams, contour bunding, percolation pits, and rooftop harvesting systems for supplemental irrigation and domestic use (Kumar et al., 2018). Farm ponds serve as on-site reservoirs that store excess monsoon runoff and provide lifesaving irrigation during dry spells, while contour bunds and check dams slow down surface flow and enhance infiltration into the soil profile (Pandey et al., 2019). Rooftop harvesting systems, although smaller in scale, contribute to homestead-level water security and indirectly support agricultural activities such as nursery raising and kitchen gardening (FAO, 2013). Collectively, these practices reduce dependence on erratic canal supplies and energy-intensive groundwater extraction, thereby lowering

production risks and input costs for farmers (Reddy & Singh, 2018).

Although government programs and development agencies have increasingly emphasized rainwater harvesting as a component of sustainable agriculture and climate-resilient farming, empirical evidence documenting its agronomic, economic, and hydrological impacts in Bihar remains fragmented and spatially uneven (Kumar et al., 2018). Many existing assessments are localized, short-term, or focused primarily on infrastructure creation rather than performance outcomes, limiting their usefulness for policy formulation and scaling strategies (Pandey et al., 2019). Moreover, farmer perceptions, institutional constraints, and maintenance challenges are often underreported, despite their critical role in determining long-term adoption and effectiveness (Agarwal & Narain, 1997).

Against this backdrop, the present study seeks to evaluate the role of rainwater harvesting in enhancing agricultural sustainability in Bihar through an integrated approach. By combining farmer surveys, on-farm measurements of water storage and crop response, and stakeholder interviews, the study aims to generate comprehensive evidence on the benefits, limitations, and scalability of RWH interventions. The findings are expected to contribute to a more nuanced understanding of decentralized water management as a pathway toward resilient and sustainable agricultural systems in eastern India.

2. MATERIALS AND METHODS

2.1 Study design and location

The investigation adopted a mixed-methods, cross-sectional research framework in order to capture both quantitative outcomes and qualitative insights related to rainwater harvesting practices. The study was conducted in Bihar, eastern India, a state characterized by pronounced spatial variation in rainfall distribution, topography, and water availability. To reflect this heterogeneity, three districts were purposively selected based on contrasting agro-hydrological conditions. Vaishali district represents low-lying alluvial plains that experience seasonal flooding and generally shallow groundwater tables. Rohtas district typifies relatively elevated terrain with moderate rainfall, where small farm ponds and traditional water conservation structures are already visible in parts of the landscape. The peripheral zones of Patna district were included to represent peri-urban and fringe agricultural areas facing intense pressure on groundwater resources due to rapid urban expansion and competing water demands.

Within each district, two administrative blocks were chosen to ensure spatial spread and variability in farming practices. From each block, twenty farming households were selected, resulting in a total sample size of 120 respondents. The sampling strategy

deliberately included both adopters and non-adopters of rainwater harvesting to enable comparative assessment. Seventy households had implemented at least one rainwater harvesting structure, while fifty farms without such interventions served as controls. Matching was carried out as far as possible on the basis of landholding size, dominant cropping system, and access to conventional irrigation sources to reduce confounding effects.

2.2 Data collection

Multiple data collection techniques were employed to capture biophysical, socioeconomic, and institutional dimensions of rainwater harvesting.

2.3 Household survey:

Primary information was gathered through a structured questionnaire administered via face-to-face interviews. The survey documented household characteristics, farm size, land use pattern, cropping sequence, and sources of irrigation. Detailed information on rainwater harvesting structures—including type (farm pond, rooftop collection unit, percolation pit, contour bund, or check dam), year of construction, installation cost, maintenance requirements, and frequency of use—was recorded. Farmers were also asked to share their perceptions regarding benefits, constraints, and changes in agricultural performance following adoption. Socioeconomic indicators such as input expenditure, labor use, and approximate farm income were included to contextualize agronomic outcomes. Field surveys were conducted between June and September 2025, coinciding with the monsoon and early post-monsoon period, when most rainwater harvesting structures are actively utilized.

2.4 Hydrological measurements:

To assess water storage and recharge potential, a subset of eighteen farms equipped with farm ponds was selected, with equal representation from each district. Pond dimensions were measured using depth–area techniques, allowing estimation of effective storage capacity. In addition, shallow groundwater monitoring wells were installed at six farm clusters, one per cluster, to observe changes in water table depth. Measurements were taken before the onset of the monsoon and repeated after the monsoon season to capture short-term recharge effects associated with rainfall and harvesting interventions.

2.5 Crop growth and yield observations:

Crop performance was monitored on selected plots under rice–wheat and rice–vegetable production systems, which are

common in the study area. Both rainwater harvesting–supported fields and comparable control plots were included. Observations were recorded at multiple crop growth stages, including germination percentage, tiller density in cereal crops, above-ground biomass during the vegetative phase, and final grain or marketable yield at harvest. This approach enabled evaluation of both early growth responses and end-season productivity.

2.6 Key informant interviews:

To complement farm-level data, semi-structured interviews were conducted with key stakeholders. Participants included agricultural extension personnel, representatives of non-governmental organizations involved in water management, and local community leaders. These interactions focused on institutional support mechanisms, awareness and utilization of subsidy schemes, technical guidance availability, and perceived barriers to wider adoption of rainwater harvesting practices.

2.7 Data analysis

Quantitative information obtained from surveys and field measurements was compiled and organized using spreadsheet software. Descriptive statistics were generated to summarize patterns across districts and farming categories. Continuous variables were expressed as means with corresponding standard deviations, whereas categorical data were presented as percentages or frequencies. Comparative analyses between rainwater harvesting adopters and non-adopters were carried out using paired *t*-tests, or suitable non-parametric alternatives when assumptions of normality were not satisfied. Economic evaluation involved simple cost–benefit comparisons that considered construction expenses, maintenance costs, and incremental income derived from yield improvements. Qualitative data from key informant interviews were transcribed and subjected to thematic coding, allowing identification of recurring constraints, enabling factors, and institutional gaps influencing adoption.

2.8 Ethical considerations

Participation in the study was entirely voluntary, and informed consent was obtained from all respondents prior to data collection. Personal identifiers were removed during data processing to ensure confidentiality and anonymity. At the conclusion of fieldwork, participating farmers were provided with a brief, non-technical summary of the study objectives and preliminary observations, along with practical suggestions for improving the efficiency and maintenance of low-cost rainwater harvesting structures.

3. RESULTS

3.1 Adoption pattern and structural diversity of rainwater harvesting

Field observations revealed a substantial level of adoption of rainwater harvesting interventions across the study area. Out of the 120 surveyed farming households, 70 holdings (58%) had established at least one structure aimed at conserving or storing rainfall. Adoption intensity varied across districts, reflecting differences in topography, exposure to water stress, and access to extension support. Farm ponds emerged as the most prevalent intervention, recorded on 40 farms, particularly in Rohtas and the peri-urban zones of Patna, where individual landholdings were relatively larger and excavation was feasible. Contour bunding and reinforced field bunds were observed on 28 farms, mainly in Vaishali, where flood moderation and runoff control were considered equally important as storage. Rooftop collection systems connected to storage tanks were documented in 15 households, primarily supporting nursery raising, livestock, and small-scale irrigation near homesteads. Percolation pits were present on 10 farms, often combined with bunding or ponds, indicating a tendency toward integrated water management rather than reliance on a single structure.

Measurements from a subset of eighteen farm ponds showed marked variability in storage capacity, reflecting differences in design, land availability, and construction investment. Pond volumes ranged from 120 m³ in smallholder-managed units to as high as 580 m³ in farms with mechanized excavation. The mean effective storage capacity was 320 m³, with a standard deviation of 110 m³, indicating considerable heterogeneity even within similar agro-ecological settings. Larger ponds were generally associated with diversified cropping systems that included vegetables or fodder crops alongside cereals.

3.2 Water availability and irrigation behavior

Clear differences were observed in irrigation practices between farms with rainwater harvesting and those dependent solely on conventional sources. Households utilizing harvested rainfall reported fewer irrigation events during the cropping season, particularly during short dry spells following monsoon breaks. On average, farms equipped with rainwater harvesting structures applied irrigation 3.1 times per season, whereas non-adopting farms required approximately 4.9 irrigation events to

sustain comparable crops. The reduction of nearly two irrigations per season was statistically significant ($p < 0.01$) and translated into lower energy use and reduced dependence on erratic canal schedules or diesel-powered pumps.

Groundwater monitoring further supported these observations. Post-monsoon measurements from six monitoring wells indicated a discernible rise in shallow water tables in areas where percolation-oriented structures were clustered. Mean groundwater levels increased by 0.25 m following the monsoon in such locations, with individual wells showing rises between 0.12 and 0.40 m. In contrast, control clusters lacking rainwater harvesting interventions exhibited only marginal changes, with an average increase of 0.05 m and higher variability. These differences suggest that localized recharge effects were enhanced where runoff was deliberately slowed and directed into the subsurface.

3.3 Crop growth response and yield outcomes

Crop performance data demonstrated differentiated responses across production systems (Fig. 1). In rice–vegetable rotations, supplemental irrigation derived from stored rainwater played a decisive role during moisture-stress periods. Vegetable plots receiving one to two additional irrigations from farm ponds showed improved early establishment, higher vegetative biomass, and prolonged fruiting duration. Average marketable yield in these plots reached 6.2 t ha⁻¹, compared to 5.1 t ha⁻¹ in adjacent control fields. The observed 22% increase was statistically significant ($p = 0.03$) and was most pronounced in tomato and okra crops, where moisture sensitivity during flowering and fruit set is high.

Responses in rice–wheat systems were more modest. Wheat yields on farms with access to harvested rainwater averaged 3.0 t ha⁻¹, while fields without such support produced around 2.8 t ha⁻¹. Although this represented a 7% improvement, the difference was not statistically significant ($p = 0.18$). Interviews and field notes indicated that wheat cultivation relied heavily on groundwater and canal irrigation during the rabi season, reducing the relative contribution of monsoon-stored water. Nevertheless, farmers reported qualitative benefits, such as timely pre-sowing irrigation and reduced risk during early growth stages, even where yield gains were limited.

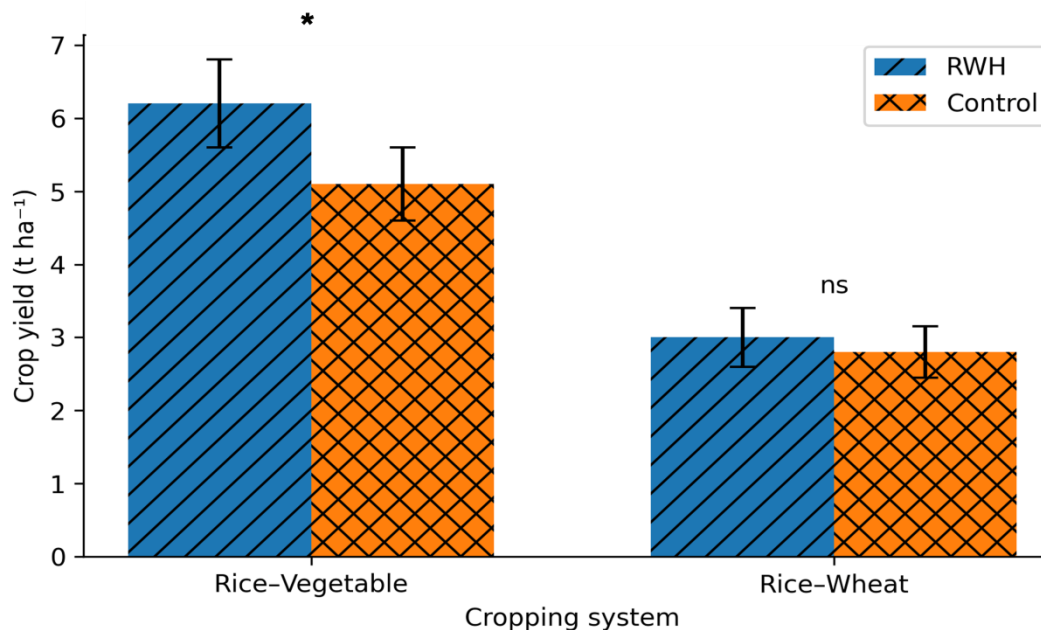


Figure 1. Effect of rainwater harvesting (RWH) on crop yield under rice-vegetable and rice-wheat cropping systems in Bihar. Bars represent mean yield (t ha⁻¹) $\pm$ standard deviation. Yield enhancement under RWH was significant in rice-vegetable systems ($p < 0.05$), while differences in rice-wheat systems were not significant.

3.4 Economic indicators

Economic assessment revealed that investment in rainwater harvesting structures generated favorable returns under most observed farming conditions. Farmers reported that constructing a medium-capacity farm pond of approximately 300 m³ required an average expenditure of INR 48,000, inclusive of earthwork, lining where applicable, and hired labor. Reported costs showed considerable dispersion, ranging from INR 30,000 for smaller, manually excavated ponds to nearly INR 80,000 where machinery and protective linings were used. When the initial expenditure was distributed over an assumed functional lifespan of ten years using a straight-line approach, the annualized cost was estimated at nearly INR 4,800 per farm (Fig. 2).

Income analysis indicated that access to stored rainwater enabled farmers to expand vegetable cultivation during moisture-limited periods, particularly after the monsoon. Average additional net earnings derived from vegetable crops irrigated with pond water were calculated at approximately INR 8,500 per year. In several cases, higher returns were recorded where farmers grew market-oriented crops such as tomato, brinjal, or chilli, benefiting from offseason price premiums. Even in the absence of direct financial assistance, the ratio between incremental income and annualized expenditure remained positive for a majority of adopters, suggesting economic viability under smallholder conditions. Farms

integrating rainwater harvesting with diversified cropping strategies demonstrated faster cost recovery compared to cereal-dominated systems.

3.5 Farmer perceptions and constraints

Perception-based responses highlighted strong appreciation for the stabilizing role of rainwater harvesting in agricultural operations. A large proportion of adopters (82%) identified enhanced water security as the most significant outcome, emphasizing the psychological assurance of having water available during dry spells. Nearly half of the respondents (46%) reported that harvested rainfall allowed cultivation of an additional vegetable crop during dry months, thereby improving household income and dietary diversity. Reduced probability of crop failure was mentioned by 39% of farmers, particularly those cultivating rainfed rice or early-season vegetables. Improved access to drinking water for livestock was also noted by 31% of households, reflecting indirect benefits beyond crop production.

Despite these advantages, several constraints limited wider adoption. High initial investment emerged as the most frequently cited barrier, reported by 72% of non-adopters and marginal farmers. Limited land availability for excavation restricted uptake on smaller holdings, affecting 45% of respondents. A lack of technical guidance regarding site selection, design, and maintenance was mentioned by 40% of

farmers, often leading to underperforming structures. Silt challenges for 29% of adopters, particularly in areas with heavy runoff. Additionally, 25% of respondents indicated inadequate access to information on government support schemes, resulting

accumulation and recurring maintenance requirements posed in missed opportunities for financial assistance and technical training.

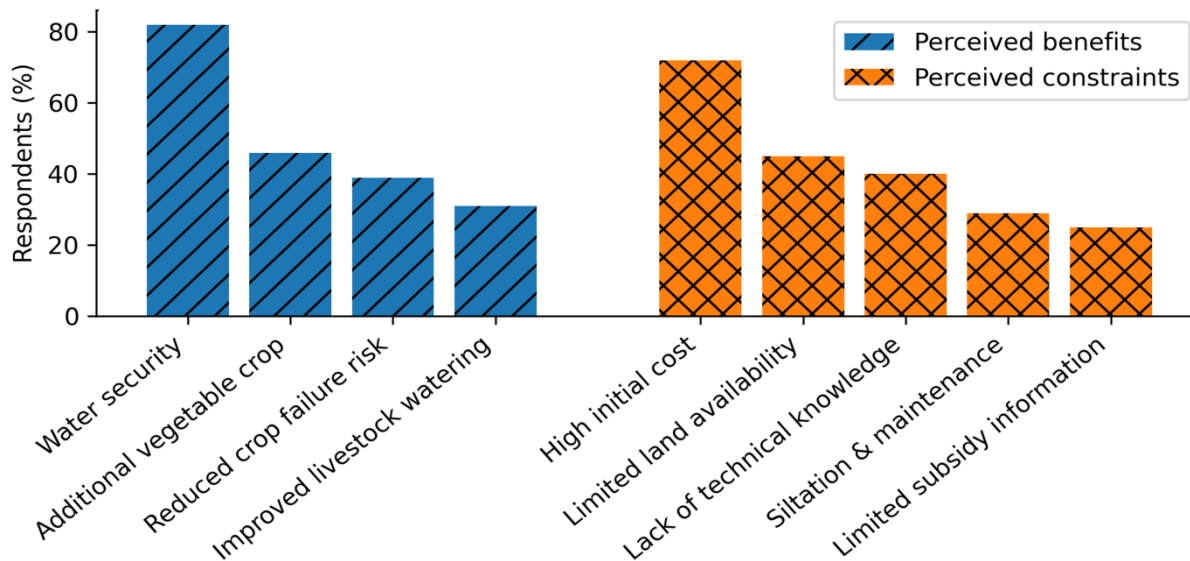


Figure 2. Perceived benefits and constraints associated with rainwater harvesting adoption among farming households in Bihar. Values denote the percentage of respondents reporting each indicator. Enhanced water security and opportunities for additional vegetable cultivation were the most frequently cited advantages, while high initial investment and limited land availability emerged as major barriers to adoption.

4. DISCUSSION

4.1 Evidence of benefits

The present findings reinforce earlier empirical and conceptual studies that identify rainwater harvesting as a critical intervention for enhancing agricultural sustainability in monsoon-dependent regions (FAO, 2013; Panwar et al., 2016; Kumar et al., 2018). Improved on-farm water availability reduced farmers' vulnerability to rainfall variability, a factor repeatedly highlighted as a major constraint in eastern Indian agriculture (Pandey et al., 2019; IPCC, 2021). Access to harvested rainfall enabled timely supplemental irrigation during moisture-sensitive crop stages, particularly flowering and early reproductive phases, which are known to exert disproportionate influence on final yield formation (Reddy & Singh, 2018; Rockström et al., 2010). As a result, households experienced enhanced production stability, a benefit that extends beyond yield metrics to livelihood security and risk management (FAO, 2013).

Observed improvements in shallow groundwater levels further support earlier evidence that decentralized water storage can

strengthen localized recharge processes when implemented across farm clusters rather than in isolation (Agarwal & Narain, 1997; Kumar et al., 2018). Such recharge effects are especially relevant in landscapes where intensive groundwater extraction has lowered water tables during the post-monsoon period (Central Ground Water Board [CGWB], 2021). By moderating seasonal declines in groundwater availability, rainwater harvesting indirectly contributes to long-term irrigation resilience and reduces energy consumption associated with pumping (Reddy & Singh, 2018; Pandey et al., 2019). These multiple pathways illustrate that the benefits of rainwater harvesting are cumulative and system-wide rather than confined to individual plots.

4.2 Heterogeneous impacts across cropping systems

The magnitude and nature of benefits varied substantially among cropping systems, underscoring the context-specific performance of rainwater harvesting interventions (Panwar et al., 2016; Kumar et al., 2018). Vegetable-based systems demonstrated stronger yield and income responses, largely because such crops exhibit high sensitivity to short-term water stress and respond rapidly to supplemental irrigation

(Rockström et al., 2010; FAO, 2013). In contrast, cereal-dominated rotations, particularly rice–wheat systems, showed reliance on canal irrigation and deeper aquifers during the dry season (Pandey et al., 2019; CGWB, 2021).

Nevertheless, limited yield gains should not be interpreted as marginal effectiveness. Even modest improvements contributed to reduced production risk, improved crop establishment, and enhanced farmer confidence, outcomes widely recognized as critical under climate uncertainty (IPCC, 2021; Reddy & Singh, 2018). Similar observations have been reported from other rainfed and semi-irrigated regions, where the stabilizing function of harvested rainfall outweighs absolute yield enhancement in farmer decision-making (Rockström et al., 2010; Panwar et al., 2016). These findings highlight the importance of evaluating rainwater harvesting through a resilience-oriented lens rather than a narrow productivity framework.

Scalability and adoption barriers

Despite clear agronomic and hydrological advantages, scaling rainwater harvesting remains constrained by a combination of economic, spatial, and institutional factors (FAO, 2013; Pandey et al., 2019). High initial investment emerged as a dominant barrier, particularly for marginal farmers with limited access to credit or subsidies, a pattern consistent with national-level assessments of decentralized water interventions (Agarwal & Narain, 1997; Kumar et al., 2018). Land scarcity further restricts adoption in densely populated regions, where fragmented holdings limit the feasibility of individual storage structures (Reddy & Singh, 2018).

Technical limitations related to site selection, design parameters, and maintenance practices were also evident, echoing concerns raised in earlier watershed development evaluations (Panwar et al., 2016; Pandey et al., 2019). Streamlined subsidy mechanisms, simplified administrative procedures, and greater transparency in scheme implementation could substantially lower adoption thresholds (FAO, 2013; Government of India, 2022). Promotion of low-cost alternatives such as rooftop collection systems, percolation pits, and shared community ponds may further enhance inclusivity while improving landscape-scale recharge efficiency (Agarwal & Narain, 1997; Kumar et al., 2018). Strengthening extension services through farmer field schools and demonstration sites remains essential for addressing persistent knowledge gaps and ensuring structural longevity (Reddy & Singh, 2018).

4.3 Environmental and social implications

comparatively smaller yield increments, reflecting greater

From an environmental standpoint, rainwater harvesting reduces surface runoff velocity, limits soil erosion, and minimizes nutrient leaching, processes that collectively support long-term soil fertility and land productivity (FAO, 2013; Rockström et al., 2010). Enhanced infiltration contributes to maintaining subsurface moisture regimes, which play a critical role in sustaining crop growth during intermittent dry periods (Panwar et al., 2016). However, poorly designed or inadequately maintained structures may disrupt natural drainage or create stagnant water bodies, potentially increasing vector-borne disease risks (Pandey et al., 2019; CGWB, 2021). These concerns underline the necessity of technical guidelines, periodic maintenance, and monitoring frameworks.

Equity considerations remain central to sustainable implementation. Land-poor households and tenant farmers often lack the resources or space required for individual infrastructure, leading to uneven benefit distribution (Agarwal & Narain, 1997; Reddy & Singh, 2018). Community-managed storage systems and cooperative water-sharing arrangements offer viable pathways for addressing such disparities while strengthening social cohesion (FAO, 2013). Participatory planning approaches have been shown to improve both adoption rates and long-term functionality, particularly in heterogeneous rural settings (Kumar et al., 2018).

4.4 Limitations and future research needs

The present study is constrained by its limited spatial coverage and relatively short observation period, factors that restrict extrapolation across Bihar's diverse agro-climatic zones (Pandey et al., 2019). Temporal variability in rainfall and groundwater dynamics necessitates longer monitoring horizons to capture cumulative impacts and structural performance over time (CGWB, 2021; IPCC, 2021). Additionally, the absence of detailed hydrological modeling limits precise quantification of recharge contributions and downstream effects.

Future research should prioritize large-scale, multi-year investigations employing randomized or matched-control designs to strengthen causal inference (FAO, 2013; Kumar et al., 2018). Integration of water balance modeling, sedimentation analysis, and socioeconomic assessment would provide a more comprehensive understanding of sustainability outcomes across landscapes (Rockström et al., 2010; Panwar et al., 2016). Such evidence is essential for informing policy frameworks that position rainwater harvesting as a core strategy for climate-resilient agriculture in eastern India.

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