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MORALITY BEFORE KNOWLEDGE

Condition drivers and challenges for implementing rainwater harvesting: Insights from Bangladesh, Ethiopia, and Indonesia

Herbert Adi Lumbanbatu[1,*]
[1] *Department of Environmental Science, Graduate School of Sustainable Development, Universitas Indonesia, Jakarta, DKI Jakarta 10430, Indonesia.*
*Correspondence: herbertadiputra@gmail.com

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ABSTRACT

Background: The limited availability of water complicates the realization of the universal right to clean and safe drinking water. Rain Water Harvesting (RWH) is a time-tested sustainable rainwater management practice that provides numerous benefits. This research aims to address the practical knowledge gap and establish a comparative framework for analyzing the conditions, drivers, and critical challenges of RWH implementation in Bangladesh, Ethiopia, and Indonesia, with the objectives of improving water supply and reducing groundwater extraction in the residential sector. **Methods:** A systematic literature review was conducted, focusing on journal articles, conference papers, and reviews indexed in Scopus. **Findings:** The drivers affecting RWH implementation at the research sites such as water source scarcity, seawater intrusion in coastal areas, excessive groundwater extraction, contamination from arsenic and iodine, and droughts exacerbated by climate change. Innovations such as automated first-flush RWH technology, GAMA-Rainfilter, modular RWH systems, and roadwater harvesting have been developed to enhance water supply and mitigate groundwater extraction. Critical challenges in RWH implementation include unpredictable rainy days, assurance of rainwater quality, limited technology to enhance health standards for rainwater, difficulties in scaling up and installing systems for uneducated and poor people, affordability issues, lack of incentives, insufficient institutional and governance support, low acceptance levels, and inadequate regulation and enforcement. **Conclusion:** A comparative analysis of Bangladesh, Ethiopia, and Indonesia indicates that the success of RWH implementation depends not only on rainfall availability but also on intricate interactions among technical, economic, social, and institutional factors. **Novelty/Originality of this article:** This research provides a comprehensive approach to analyzing the drivers and challenges of RWH implementation in countries with diverse geographical and socioeconomic contexts, incorporating five dimensions to enhance understanding of the factors influencing the success of RWH initiatives.

KEYWORDS: excessive groundwater; limited piping water; RWH; SDG 6; water scarcity.

1. Introduction

Access to clean and safe drinking water is an inherent right for all individuals (United Nations, 2010). Although 75% of the Earth's surface is covered by water, just 3% of water bodies are appropriate for drinking and meet the needs of industry and agriculture; 29.9% is groundwater, and 1.2% is surface water such as rivers and lakes (Jamal et al., 2023). The global water crisis is a complex challenge that involves various aspects such as quantity, quality, and access to water resources (UN-Water, 2013). Only 45% of countries are adequately progressing toward achieving SDG 6: Clean water and sanitation (UN-Water,

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2021). Water supply management is crucial for mitigating risks associated with hunger, epidemic diseases, inequality both within and across nations, political instability, and natural disasters (UN-Water, 2021).

Water is an urgent concern on both local and worldwide magnitudes, encompassing two opposing points, solutions and problems, consequently mandating an integrated approach (Dewi et al., 2023). The 2023 WHO report shows that (a) more than 2 billion people lived in areas with water shortages due to climate change and growing populations; (b) 1.7 billion people drank water that was contaminated with feces; (c) 505,000 people died each year from diarrhea and unsafe drinking water; and (d) only 73% of the world's population had access to safe and clean drinking water. Low- and middle-income countries, especially in the regions of Sub-Saharan Africa and South Asia, experience significant disparities in access to clean water, presenting the greatest obstacle to achieving universal access to this vital resource (FAO & UN Water, 2021). The quantity and quality of water, together with the threat of climate change, present a significant barrier for nations in arid and semi-arid regions to attain food security (Gebru et al., 2021). Accelerated urbanization, climate change, demographic transformations, population expansion, alterations in land use and cover, socioeconomic developments, and institutional capacities augment the strain on water supply and quality (Gule et al., 2024). Climate change has heightened the frequency of drought events, rendering it a global concern (Salman & Khalek, 2025). One major global challenge affecting the availability of clean water is the overconsumption of groundwater (Hasan et al., 2025).

The extensive extraction of groundwater has caused land subsidence, seawater intrusion in coastal areas, increased depths of groundwater wells, and higher costs for groundwater extraction pumps in many regions (Konikow & Bredehoeft, 2020; International Groundwater Resources Assessment Centre, 2018). Excessive groundwater depletion affects large regions of the Middle East, South Asia, and Central Asia, as well as various local areas around the world. In many developing countries, particularly in sub-Saharan Africa (e.g., Ethiopia, Kenya), groundwater serves as a primary source of drinking water for urban dwellers, with an estimated 30% relying on it (Gebreslassie et al., 2025). Coastal regions frequently experience restricted access to freshwater sources and depend significantly on groundwater; yet, over-extraction results in seawater intrusion (Mukarram et al., 2023). Groundwater has emerged as a convenient source for human use; nevertheless, excessive extraction in major urban areas has caused the depletion of aquifer strata, leading to geological and environmental disruptions (Jamal et al., 2023). Excessive groundwater extraction necessitates stringent regulations to ensure sustainable water utilization and future water availability and to avert land subsidence (Jakariya et al., 2024; Taftazani et al., 2022).

Research by Hasan et al. (2025) stated, rainwater harvesting (RWH) has become a prevalent technique, recognized as one of the most cost-effective and environmentally beneficial water conservation methods, providing numerous important advantages for both humankind and the natural ecosystem. RWH restores the natural hydrological cycle, recharges groundwater, and mitigates alterations in water flow patterns caused by urban development (de Sá Silva et al., 2022; Shamsuddin et al., 2025). RWH in developed countries emerges as a novel approach to establish and sustain long-term water supply systems, serving as a valuable resource during arid periods, fulfilling the water requirements for humans, livestock, and irrigation (Roba et al., 2022). Based on Gebreslassie et al. (2025) and Munna et al. (2020), RWH can help alleviate this excessive groundwater extraction and provide a viable option for drinking water supply, which currently relies on traditional systems and centralized distribution (Wahyuningsih et al., 2020). RWH is a feasible alternative method for the collection and storage of rainfall from edifices, catchment zones, terrestrial surfaces, or thoroughfares. The water collected by the RWH system serves as an alternative source for household needs, sanitation, or irrigation (Vidal et al., 2024). RWH constitutes a nature-based solution that includes all acts dependent on ecosystems and their services to address many societal challenges (Caparrós-Martínez et al., 2020). RWH contributes to green infrastructure for urban flood resilience (Khodadad et al., 2023), sustainable urban development (de Sá Silva et al., 2022), supplying sustainable freshwater to areas suffering surface water scarcity or with no surface water at all (Setianingsih & Setiacahyandari, 2025), and zero carbon emissions throughout the collecting and storage of rainwater harvests (Lestari et al., 2025).

This study employs rainwater management theories as a sustainable strategy for water conservation, benefiting humankind and the environment. Rainwater constitutes a significant source of freshwater, applicable for diverse activities such as domestic consumption, irrigation, cattle husbandry, and groundwater replenishment (Mukarram et al., 2023). Rainwater management involves more than just urban drainage engineering, which has a technological focus. It also acts as a comprehensive framework that plays a significant role in creating healthy, livable, and sustainable urban environments (Grigg, 2024). Effective rainwater management can mitigate the danger of water shortages and improve global food security (Duguna & Januszkiewicz, 2020). During the rainy season, 40% of rainfall is transformed into surface runoff, whereas the use of RWH alleviates water scarcity and mitigates flood stagnation (Debebe et al., 2023a). RWH is a time-tested sustainable rainwater management practice that provides numerous benefits for enhancing water resilience (Muhammad et al., 2025).

Prior scholars who have successfully conducted a bibliometric analysis of RWH on a global scale, such as Ali et al. (2025), Bañas et al. (2023), Campisano et al. (2017), Geraldes et al. (2024), Morote et al. (2020), Nandi & Gonela (2022), Shemer et al. (2023), Velasco-Muñoz et al. (2019), and Yildirim et al. (2022). A practical knowledge gap exists when comparing country classifications based on income levels. This research aims to conduct a comparative analysis of the conditions, drivers, and challenges that influence the implementation of RWH in Bangladesh, Ethiopia, and Indonesia. The focus is on how RWH can enhance water supply and decrease groundwater extraction in the residential sector. The research offers insightful information about the importance of managing rainwater resources and comprehending RWH systems. It emphasizes the necessity for resilient and sustainable RWH infrastructures to ensure the availability, quality, and continuity of harvested rainwater. Such goals can be achieved through a thorough understanding of these systems, requiring engagement from government agencies, NGOs, and the private sector.

2. Methods

2.1 Profile of the research location

The research area consists of Ethiopia in Africa, Bangladesh in South Asia, and Indonesia in Southeast Asia. Table 1 provides a comparative description of water resource conditions in these countries, including population size, income classification, climate risk, and access to safely managed drinking water and sanitation. In addition, Figure 1 presents the projected water stress levels for Ethiopia, Bangladesh, and Indonesia by 2040, based on data from the World Resources Institute, which underscores the rationale for selecting these countries as the primary focus of this study.

Table 1. Description of the research area

No	Information	Bangladesh	Ethiopia	Indonesia	Source
1	Total population (million) – 2023	171.47	128.69	281.19	United Nations (n.d.)
2	World Bank country classifications by income	lower-middle income	low-income	upper-middle income	World Bank (n.d)
3	Climate risk rank	46	12	93	Germanwatch (n.d.)
4	Level of freshwater stress (%) – 2021	5.7	32.3	29.7	Ritchie & Roser (2015)

5	Share using safely managed drinking water (%) - 2022	59.1	13.2	30.3	Ritchie et al. (2019a)
6	Deaths by unsave water source – 2021	23,017	28,203	33,703	Ritchie et al. (2019a)
7	Using safely managed drinking water services (%) – 2022	59.1	13.2	30.3	Ritchie et al. (2019a)
8	People not using safely managed drinking water services (million) - 2022	69.9	107.05	192.12	Ritchie et al. (2019a)
9	GDP per capita for improving drinking water source – 2022	USD 7,888	USD 2,656	USD 13,334	Ritchie et al., 2019a
10	Deaths by unsafe sanitation – 2021	1,435	893	8,987	Ritchie et al. (2019a)
11	People not using safely managed sanitation (million) – 2022	118.16	114.47	n/a	Ritchie et al. (2019b)

The research area consists of Ethiopia in Africa, Bangladesh in South Asia, and Indonesia in Southeast Asia. Based on Figure 1, the World Resources Institute's forecasts for 2040 show that Ethiopia will experience medium to high water stress, Bangladesh will face very high stress, and Indonesia will encounter high stress. These projections highlight the urgency of water resource challenges in the selected countries and serve as a strong rationale for choosing them as the primary focus of this research.

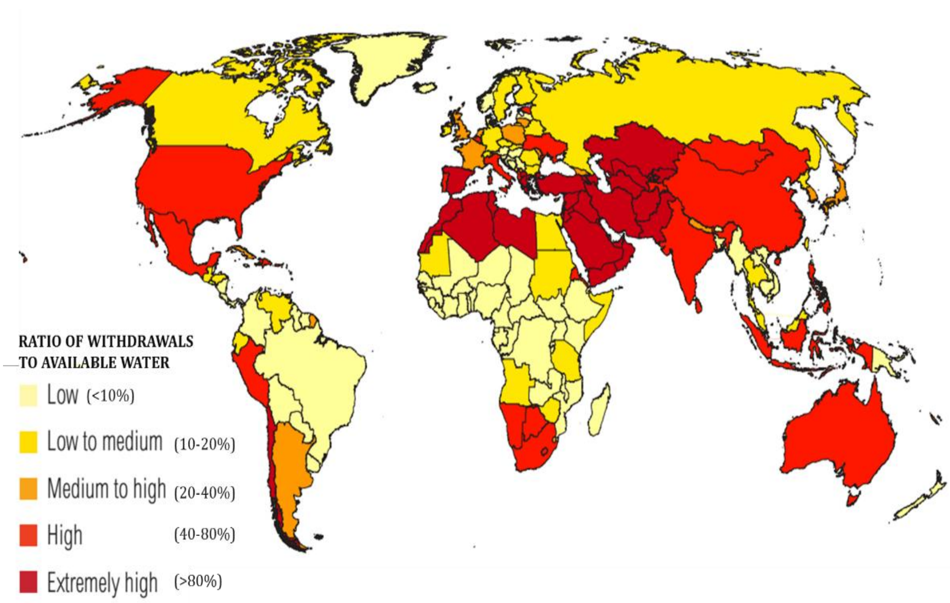

Fig. 1 Country-level water stress in 2040
(Luo et al., 2015)

2.2 Data article collection

Data acquisition included compilation of journal articles, conference proceedings, and reviews. The search period was from 2020 to 2025, the language was limited to English, the document type was restricted to "Article," "Conference Paper," and "Review," the publication stage was limited to "Final," the source type was limited to "Journal" and "Conference Proceeding," and the country was limited to "Bangladesh," "Ethiopia," and

“Indonesia.” A total of 196 articles were initially retrieved from the Scopus database using the keywords "water" OR "freshwater" OR "groundwater" and "rainwater AND harvesting." Articles were then manually assessed for relevance by reviewing titles, abstracts, research objectives, and research focus. The inclusion criteria for selecting articles are (a) the application of RWH to address water scarcity and decrease excessive groundwater extraction and (b) the use of RWH in the residential sector. The filtering process resulted in identifying 81 articles as appropriate and 115 as inappropriate. The analysis excludes articles related to harvested rainwater, which is used in various buildings like commercial establishments, schools, airports, and universities, and those focused on water resource management, groundwater, or climate change impacts, as they are not relevant to the research objectives and outcomes.

Table 2. Number and distribution of articles by country and year

Year	Appropriate articles			Inappropriate articles
	Bangladesh	Ethiopia	Indonesia	
2020	3	5	3	16
2021	3	2	9	22
2022	8	4	3	19
2023	5	3	2	29
2024	7	3	7	21
2025	4	3	7	8

3. Results and Discussion

3.1. Condition drivers of rainwater harvesting implementation in Bangladesh

3.1.1 The dual challenges, drinking water access and excessive groundwater

Bangladesh is a tropical monsoon nation marked by warm, humid summers, relatively cool, arid winters, and substantial monsoonal precipitation. The primary water issues in Bangladesh pertain to excessive flooding during the monsoon season and an extended dry period (Rahman et al., 2022). The coastal region of Bangladesh is confronted with the threat of tidal surges, resulting in incessant sedimentation and erosion, flooding spreading 150 km from the shoreline, contaminated freshwater sources (Khan & Paul, 2025), critical freshwater scarcity, seawater intrusion, and contamination issues (Abdullah et al., 2024; Afsari et al., 2022; Ashrafuzzaman et al., 2023; Mukarram et al., 2023; Rana & Moniruzzaman, 2023; Saha et al., 2024). As an example, Sandwip, Kutubdia, and Hatiya in the Bay of Bengal frequently face issues such as coastal erosion and tropical cyclones (Alam & Mallick, 2022). Salinity has increased by 45% over the past fifty years in all six coastal districts, presenting various health risks for over 20 million people. The salinity crisis is most acute in the Bagerhat and Satkhira districts and coastal villages of Chittagong district (Jabed et al., 2020; Samaddar et al., 2022). The southwestern coastal regions of Bangladesh, including Shyamnagar Upazila, encounter elevated tides that lead to the salinization and degradation of primary drinking water sources (Afsari et al., 2022). Scheelbeek et al. (2017) demonstrate that the drinking water utilized by coastal populations in Bangladesh, sourced from ponds and wells, possesses elevated sodium levels that are above the daily consumption threshold, which is associated with heightened blood pressure, increased risk of hypertension, cardiovascular complications, and mortality.

Bangladesh is currently facing significant contamination from arsenic poisoning in its groundwater and soil. Boreholes have gained popularity in Bangladesh owing to their user-friendliness; excessive groundwater extraction has led to arsenic contamination, with millions of individuals consuming water containing arsenic levels surpassing 10 μg/l (Jakariya et al., 2024; Habib et al., 2024). Presently, around 80% of the irrigation water supply during the dry season is sourced from groundwater, which is essential for fulfilling the increasing demand for food production, while roughly 98% of potable water is obtained from groundwater (Alam & Mallick, 2022). Bangladesh experienced a rise in the number of tube wells, increasing from 93,000 in 1982–1983 to nearly 800,000 by 1999–2000 (Jakariya et al., 2024). Assessments have been conducted in 59 out of 64 districts, revealing arsenic levels that exceed the WHO's safe limit of 10 μg/L. It is estimated that more than 80 million people in Bangladesh are at risk of health issues due to the consumption of arsenic-contaminated drinking water (Habib et al., 2024). Jakariya et al. (2024) discovered that in 11 regions of Sonargaon Upazila, households were excavating wells to depths exceeding 183-213 m to access potable water. The widespread presence of arsenic in drinking water has led to numerous health issues, including skin lesions, cancer, and other serious conditions (Alam & Mallick, 2022).

Dhaka, the capital city of Bangladesh, is grappling with issues related to both urban flooding and droughts (Rahman et al., 2022). Dhaka is facing rapid depletion of its groundwater resources, with levels dropping over 60 meters in the last half-century and exceeding 3 meters per year in the city center. If this trend continues and insufficient recharge persists, the average static water level in the city could decline by 161 meters by 2050 (Moshfika et al., 2022). Dhaka has yet to implement integrated urban water management, which encompasses RWH and the reuse of wastewater (Huq et al., 2024). The surface water surrounding Dhaka is significantly polluted and unsuitable for treatment as drinking water (Karim et al., 2015). Bangladesh's annual rainfall of 2,400 mm makes RWH suitable for urban, peri-urban, and rural areas, particularly in coastal regions, because of the challenges in accessing clean water caused by salinity, limited surface water sources, and climate change (Hasan & Irfanullah, 2022). Since 1984, RWH has been providing access to alternative water sources in the coastal regions of Bangladesh but is limited in Dhaka City (Huq et al., 2024).

3.1.2 Climate change

Flooding is the most common and devasting natural disaster in Bangladesh (Alam & Mallick, 2022). Bangladesh has encountered over 20 drought occurrences, with 47% of its regions classified as high-risk for drought and 33% of the population residing in drought-prone areas (Mou et al., 2023). Bangladesh exhibits considerable susceptibility to climate change, especially in the northwestern region, where severe drought is prevalent, posing a substantial threat to the agricultural sector in the coming decades (Salman & Khalek, 2025). Climate change negatively impacts Bangladesh by increasing the frequency and severity of floods, worsening drainage congestion, raising sea levels and salinity, and causing more sedimentation in floodplains. It also intensifies pressure on freshwater resources, leads to harsher drought conditions, accelerates river erosion, and results in more intense and frequent cyclones and storms (Alam & Mallick, 2022). Climate change may diminish Bangladesh's food production by 33% and jeopardize the national economy (Anik et al., 2021).

The southwestern coast of Bangladesh increased groundwater salinity due to ongoing tidal variations and coastal flooding. Drinking water contaminated with salt can lead to skin conditions, hair loss, digestive issues, and high blood pressure (Alam & Mallick, 2022). Research by Ashrafuzzaman et al. (2023) found that climate changes impact sea level, therefore increasing salinity and health problems. Over 70% of respondent across 12 unions in Shyamnagar Upazila, located in the southwestern coastal region of Bangladesh, suffer from adverse health effects due to lack of safe drinking water, including dysentery, diarrhea, urinary tract infections, gastrointestinal malnutrition, hypertension, dermatological conditions, and reproductive health issues in women.

3.1.3 Economic

The implementation of RWH in cities across Bangladesh offers significant economic benefits. In Dhaka City, for example, utilizing a catchment area of 140 m^2 and a storage tank of 40 m^3 leads to estimated monetary savings of approximately 2,000 BDT (Karim et al., 2015). Across six major cities in Bangladesh, the implementation of RWH with a roof area of 200 m^2 can yield around 500–800 m^3 of harvested rainwater annually, with an investment payback period between 2 and 6 years. The economic savings for each city are as follows; Dhaka 4,430 BDT, Chittagong 5,805 BDT, Rajshahi 2,954 BDT, Khulna 3,856 BDT, Sylhet 8,239 BDT, and Barishal 4,237 BDT (Bashar et al., 2018).

3.1.4 Social

Water has become an essential resource for life, serving as a means of pollution removal and transporting soil nutrients. It also holds significant importance in the beliefs and religious practices of various communities in Bangladesh. High salinity levels are forcing coastal communities to migrate to urban areas, leading to increased density in the slum regions of Bangladeshi cities (Rahman et al., 2022). The public awareness in Dhaka City for the implementation of RWH is between 30-62% (Huq et al., 2024).

3.1.5 Technology innovation

Tests assessing the physicochemical, microbiological, and heavy metal of RWH systems in Dhaka City show that it is entirely safe for all uses. Therefore, it may serve as a smart and cost-effective solution to mitigate the depletion of surface and groundwater resources (Rahman et al., 2022; Tarek et al., 2022). Jamal et al. (2023) developed a low-cost fabricated sensor-driven RWH technique called automated first-flush rainwater for use in Dhaka City. Chemical, physical, and microbial contamination factors were assessed for this RWH. The results indicate that this approach can produce potable water and is suitable for nearly all applications. The collected rainwater is subjected to a three-stage purification process, which includes ultraviolet light exposure, sedimentation, and activated carbon filtration. The average annual cost for home water supply is 15.18 taka, equivalent to 0.18 dollars per 1,000 liters. If the RWH technique is implemented in all residential buildings in Dhaka city, it could lead to annual savings of at least 22.76 million dollars.

Nipun et al. (2024) conducted a trial of rooftop RWH in Rajshahi City, Bangladesh. The results indicated that (a) a maximum of 110.75 m^3 of rainwater was collected annually from a 100 m^2 rooftop area, (b) there was a 75.85% reduction in dependency on conventional water supply systems, (c) the harvested rainwater results complied with WHO standards for physical and chemical parameters, and (d) the removal of pathogenic microorganisms is necessary for meeting potable and culinary water requirements. For a 100 m^2 rooftop area, it can be useful to reduce water costs compared to conventional methods, amounting to USD 90.15 per year.

An integrated RWH and MAR model that conducted in drought-prone Barind Tract can be used simultaneously for RWH and aquifer recharge (Hossain et al., 2024). Islam et al. (2021) conducted a design for a community RWH system in Paikgacha that shows the following benefits: (a) 90% reliability for 100 L per day household demand; (b) a payback period of 8 years; and (c) a positive net present value (NPV) within 25 years. Haque et al. (2021) developed an Internet of Things (IoT)-based RWH system that allows users to monitor the system at all times. This IoT-based system is equipped with various sensors, including a rain sensor, pH sensor, total dissolved solids (TDS) sensor, waterproof temperature sensor, water level sensor, turbidity sensor, and a TTGO T-Call ESP32 SIM800L module. The system operates effectively both when electricity is available and during power outages, utilizing an uninterruptible power supply.

3.2 Condition drivers of rainwater harvesting implementation in Ethiopia

3.2.1 The dual challenges, drinking water access and excessive groundwater

Sixty-seven percent of Ethiopia's territory is categorized as dry or semi-arid, encompassing over 90 districts and more than 2 million households, which are susceptible to drought and face significant water scarcity (Roba et al., 2022). Ninety percent of the food supply for the Ethiopian population is sourced from smallholder farmers who depend on rainfall (Mengistu, 2021). Ethiopia has endured significant droughts resulting in food scarcity and famine during the 1980s, substantial floods from 1988 to 2006, and a population that is politically, socially, and economically fragile (Marie et al., 2020). RWH has been in practice since 560 BC, with historical evidence observable in locations such as the Palace of Queen Sheba, the Palace of Axum, the Mahbre Selassie Monastery in Gondar, and the Debrekerbie Monastery in Shoa for agricultural, religious, and raw water supply reasons (Roba et al., 2022). Ethiopia has no capability to efficiently harness surface water resources, thus relying predominantly on rainfall sources (Duguna & Januszkiewicz, 2020). In urban regions and industrial zones of Ethiopia, groundwater depletion in Addis Ababa and the Hawassa industrial sector occurs at a rate of 1-3 meters year (Kebede et al., 2023).

Addis Ababa, capital city of Ethiopia, is facing a water crisis attributed to (a) inadequate access and distribution of water resources, (b) insufficient planning and management of water resources, (c) degradation of natural resources resulting in diminished water quality, (d) only 55% of the population having access to water supply, but only 50% receiving continuous water service for more than 12 hours per day (Gule et al., 2024). Drought-prone eastern Somalia and the Borena zone have been severely affected by droughts since 2020, leading to livestock fatalities and crop losses (Bojer et al., 2024). Communities in the Dawe River basin are experiencing a severe shortage of water, forcing water harvesting a fundamental part of life (Harka et al., 2020).

3.2.2 Climate change

Ethiopia has diverse topography, characterized by variable climates, temperatures, and rainfall across its areas. The southern and southwestern regions experience elevated rainfall and humidity, whilst the northeastern, eastern, and southern areas are distinguished by arid and semi-arid climates with minimal rainfall (Bojer et al., 2024). People living in arid and semi-arid regions face unpredictable droughts, resulting in poor hydrological and climatic balance (Bereded et al., 2025; Chimdessa et al., 2023). Variability and climate change have emerged as critical concerns, with droughts and floods occurring every 3-5 years in Eastern Ethiopia, pressing pressure on small-scale farmers (Tolossa et al., 2020). In-situ and ex-situ rainwater gathering methods significantly improve soil moisture, reduce runoff, and encourage groundwater recharge. This increase in agricultural yield subsequently diminishes hazards and has a positive effect on other ecosystems (Tolossa et al., 2020). Climate change causes irregular rainfall patterns in Ethiopia, leaving a significant portion of the population without sustainable access to sufficient water to meet their needs (Gebremedhn et al., 2023).

3.2.3 Economic and social

Ethiopia's agriculture, a significant contributor to the country's GDP and export value, faces challenges such as crop failures, livestock mortality, and economic shocks due to prolonged dry seasons, droughts, and floods (Debebe et al., 2023a; Debebe et al., 2023b; Roba et al., 2022; Tolossa et al., 2020). Roba et al. (2022) demonstrated several advantageous outcomes of RWH implementation in Ethiopia, specifically, (a) enhancing crop yields by as much as 56%; (b) augmenting groundwater levels in the root zone by up to 30%; (c) reducing losses during extended dry periods; (d) boosting sorghum yields by 41%, and by 180% when paired with fertilizer; and (e) the execution of 732,336 programs, benefiting 3.7 million individuals. Mekuria et al. (2020) surveyed 196 farming households in the Kutaber District, South Wollo Zone, Amhara regional state, concluded that the implementation of RWH led to a 35.13% increase in farmers' income and satisfied 15.56% of their daily caloric requirements.

Mengistu (2021) conducted a study involving 270 small-scale farmers in the Raya-Alamata District of Northern Ethiopia. The findings indicate that rainwater harvesting

(RWH) is effectively utilized by these farmers as a strategy to mitigate water scarcity. The harvested rainwater is applied for multiple purposes, including cattle hydration, forest restoration, and fulfilling daily potable water needs.

3.2.4 Technology innovation

RWH techniques in Ethiopia include constructing ponds, micro-dams, embankments, and terraces. These common methods of rainwater collection encompass runoff irrigation, flood irrigation, in-situ water harvesting, and rooftop water harvesting (Duguna & Januszkiewicz, 2020). RWH is integrated into rural development projects (IRDP) by building ponds, micro-dams, and rooftop catchments to meet water needs for both domestic and irrigation purposes (Duguna & Januszkiewicz, 2020). Demessie & Woldeyohannes (2024) suggest using sand dams to collect rainwater, helping to refill groundwater in farming areas along the Mai Gobo River in the Hawzen district of Tigray, Northern Ethiopia, which often faces drought and lower crop yields. Sand dams effectively mitigate the risk of pollution, minimize water loss due to evaporation in the dry season, and biomass production rose by 2.4 kg for each cubic meter of water utilized.

Roadwater harvesting is being implemented along a 64 km stretch of road in the Saesie Tsaeda Emba District, Hawzien District, and Klite Awlaelo District of Northern Ethiopia. This initiative diverts water runoff from the road into ditches, roadside drains, or road embankments. As a result, it assists farmers in coping with drought periods, enhances soil moisture, reduces the risk of flooding, and replenishes ponds, shallow wells, and small dams for livestock and crop production (Gebru et al., 2020).

3.3 Condition drivers of rainwater harvesting implementation in Indonesia

3.3.1 The dual challenges, drinking water access and excessive groundwater

Indonesia is a tropical country with high rainfall so that the use of rainwater as an alternative water source has great potential to be implemented in Indonesia (Sabrina & Juliana, 2025). The Indonesia Central Statistics Agency disclosed that access to drinking water sources among Indonesian families comprises 8.92% piped water, 32.33% groundwater, and 40.64% bottled water, with the remaining sourced from springs, surface water, and rain. Access to piped drinking water is below 10% in 17 other provinces. In Jakarta, the metropolitan heart of Indonesia, piped water sources service merely 7.64% of the population. Mostly Indonesian metropolitan city are constructed on impermeable surfaces and possess inadequate drainage capacities for rainwater runoff, and the soil's incapacity to absorb rainwater exacerbates the prevalence of puddles and flooding in these regions (Suprapti et al., 2024). Numerous cities, such as Kupang, have frequent droughts, causing crises such as agricultural failures, food insecurity, and public health issues (Syarifuddin et al., 2024). Limited access to clean water occurred particularly in Indonesia's outermost, remote, or isolated islands, such as Sepatin Village in Kutai Kertanegara (Diansyukma, 2021).

Groundwater extraction is frequently employed by the Indonesian populace, particularly in North Jakarta (Hasibuan et al., 2025), Bandar Lampung City (Purwadi et al., 2023), small islands such as Seribu Island (Setianingsih & Setiacahyandari, 2025) and Nusa Penida Island (Setiawan & Nandini, 2022), urban peripheries, and rural areas such as Teluk Awur village (Setiadi et al., 2024) that do not have piped drinking water services. Groundwater levels in North Jakarta have declined due to excessive extraction, decreasing at a rate of 8 cm per year from 1982 to 1991, escalating to 26 cm per year from 1991 to 1997, and further increasing to 31.9 cm per year from 1997 to 2005 (Taftazani et al., 2022). Purwadi et al. (2023) conducted a modelling analysis of the decline in groundwater levels in the northern part of Bandar Lampung City (Rajabasa, Labuhanratu, and Tanjungsenang sub-districts) and found that the current well depth will increase from 10–40 meters to 8 meters.

3.3.2 Climate change

The village of Tanah Merah, located in Indragiri Hilir Regency, is a coastal region facing challenges related to freshwater availability, seawater intrusion, and numerous environmental issues. RWH exhibits a reliability rate of merely 78% in the dry season; nevertheless, its efficacy diminishes significantly during extended periods of drought (Suprayogi et al., 2024). The potential of RWH is implemented in Seraya Village, Karangasem Regency, as a strategy to mitigate drought conditions in the dry season. The findings indicate that (a) rainwater harvesting generates a surplus of approximately 12% above total water requirements, (b) 77% of the RWH potential is realized during the rainy season, while 23% is accessible in the dry season, and (c) the recommended tank design possesses a capacity of 35.56 m^3 with optimal dimensions of 6m × 3.95m × 1.5m (Ardana et al., 2025).

3.3.3 Social

The Climate Village Program/*Program Kampung Iklim* (Proklim) in Pendowoharjo Village, Sleman Regency, has demonstrated that 25 residents are utilizing harvested rainwater (Sumbodo et al., 2021). The community's acceptance of RWH exhibits diverse outcomes in the urban agglomeration of Yogyakarta. The survey conducted by Triyono et al. (2021) yielded the following findings; (a) 90% of respondents exhibit hesitance towards utilizing rainwater for consumption, (b) 87% perceive the quality of rainwater as insufficient, (c) 13% express apprehensions regarding the irregular availability of rainwater, and (d) 83% are uninformed about rainwater harvesting technology.

3.3.4 Technology innovation

Muktiningsih & Putri (2021) investigated the application of basic filtration technology utilizing media including sand, gravel, activated carbon, cotton, sponge, and zeolite with a thickness of 105 cm and a filtration duration of 10–15 minutes. The finding concluded that the filtered rainwater complies with health quality standards, serving as a viable alternative water source and effectively mitigating drought during the dry season. Kurniawan et al. (2022) suggested a modular RWH system that can hold 32 liters to help urban residents accept it better, as traditional cylindrical systems are often too big and there isn't enough land. The components of modular RWH system are (a) modul tank capacity 32 liters, (b) filter modul, (c) closer and joint, (d) distributing modul.

Suprapti et al. (2025) developed a community-based domestic rainwater harvesting system (CDRWH) model as an innovative approach to enhance system effectiveness and capture rainwater runoff in the Jagakarsa region of South Jakarta. This area faces several challenges; (a) a lack of potable water and a high risk of flooding, (b) 75% of the region has poor natural rainwater absorption capacity, (c) the existing drainage system is insufficient to manage flood runoff, and (d) land subsidence occurs at a rate of approximately 2 cm per year, as observed during the 2009-2010 period. The findings from Suprapti et al. (2025) indicate the following, (a) for a roof area of $70m^2$, the CDRWH system improves water supply by 56-73% in dry years, 54-72% in normal years, and 40-59% in wet years, while also reducing flooding by 27-44% in dry years, 28-46% in normal years, and 41-60% in wet years; (b) For a roof area of $100m^2$, the CDRWH system boosts water supply by 41-58% in dry years, 39-59% in normal years, and 28-46% in wet years, with flood reduction of 42-59% in dry years, 41-61% in normal years, and 54-71% in wet years.

Maryono et al. (2022) advocate for the GAMA-Rainfilter as an RWH technology implemented with 59 household participants in Yogyakarta Province. The main components of GAMA-Rainfilter are filtering, storage, and distribution for utilization and releasing excess rainwater. The findings concluded that (a) the water is physically odorless, tasteless, and colorless, with a neutral pH ranging from 6.4 to 7.2, conforming to quality standards; (b) the apparatus effectively filters leaves, coarse sediment, and fine sediment from the roof; and (c) 75% of the community responded positively, as evidenced by their understanding of the device's functionality and their use of harvested rainwater for daily needs. However, the GAMA-Rainfilter requires regular monthly maintenance, and when used for drinking water, it must still undergo chlorination or boiling due to the incomplete elimination of E. coli.

Lestari et al. (2025) propose a hybrid infrastructure design to mitigate flooding and water scarcity in the Sunter River, particularly in the Kelapa Gading Barat sub-district of North Jakarta. The hybrid infrastructure design comprises rainwater harvesting systems, rooftop gardens for rainfall collection and absorption, water tank reservoir modules, and infiltration trenches. The hybrid infrastructure design offers advantages including (a) the harvesting of 2,107m^3 of rainwater per day, (b) the management of rainfall runoff at a rate of 143,259m^3 per second, and (c) ideal storage capacity for rainwater over an average of 15 wet days annually.

Muhammad et al. (2025) developed a DWQS RWH, which comprises (a) essential filtration elements including a primary screen, first flush diverter, sediment filter, activated carbon filter, and reverse osmosis membrane; and (b) supplementary filtration components such as a post-carbon filter, UV sterilizer, storage tank, monitoring system, and booster pump. The DWQS RWH effectively preserves the quality of harvested rainwater by adhering to drinking water quality standards, as evidenced by laboratory test results for turbidity, BOD, and pH parameters. This system ensures the provision of safe drinking water in regions with scarce water resources, minimizes the energy needed for water treatment and distribution, and inhibits the proliferation of mosquito larvae in the stored water. Taufikurahman et al. (2024) carried out RWH by integrating greywater processing, aquaculture ponds, and constructed wetlands. The constructed wetland pond serves to purify greywater from bathrooms and manage precipitation runoff during peak periods. The fish pond features a water circulation system and filter designed for aquaponics, utilizing water sourced from the greywater filtration of the constructed wetlands.

3.4 Critical challenges the implementation of rainwater harvesting

3.4.1 The frequency and intensity of unpredictable rainy days

Global climate change has resulted in increasingly irregular precipitation patterns in numerous regions. Rainfall data for southeast Ethiopia show an overall decline from 1980 to the present. This decrease has led to intense and frequent droughts (Bojer et al., 2024). The implementation of RWH must adapt to the abundance or availability of rainfall at the local level or site location to achieve optimal efficiency and value. The variability in the timing, volume, and duration of precipitation obstructs the efficient execution of RWH implementation. The variability of annual rainfall has introduced uncertainty in planning the capacity of RWH systems. The uneven distribution of rainfalltypically occurring over a span of 3 to 4 monthsposes challenges in designing an RWH system capable of meeting water needs during the prolonged dry season, as well as determining the RWH's storage capacity. Table 3 describes challenges and solutions related to the frequency and intensity of rainy days.

Designing an RWH storage capacity that can handle excess rainfall during the rainy season presents a dilemma in effectively addressing drought conditions during the extended dry season. The issue of rainfall is not only the average total yearly precipitation but also the intricacies of its distribution, intensity, and duration, all of which are increasingly affected by global climate change. Extreme rainfall, characterized by high intensity over a short period, leads to significant runoff and diminishes the effectiveness of RWH. The design of suitable RWH capacity involves integrating climate and weather change analysis to ensure long-term stability in water storage. The dimensions of the RWH tank must align with the household population to guarantee enough water supply year-round. The efficacy of RWH design is also dependent upon the building's roof area (Setianingsih & Setiacahyandari, 2025).

Table 3. Challenges and solutions related to the frequency and intensity of rainy days

No	Authors	Challenges	Solutions
1	Ghosh & Ahmed (2022)	34.7% can make use of rainwater throughout the year, both during rainy season and dry season.	Alternative water sources such as pond sand filters, ponds, tube wells.
2	Setiadi et al. (2024)	RWH capacity fulfills only 45-60% of the village's water requirements due to a 10-20% reduction in rainfall volume.	Utilizing extensive roof areas on public buildings and increasing the capacities of rainwater storage tanks.
3	Mbarep et al. (2022)	Sikka District's rainwater harvesting is only enough for 19.52% of the population.	Utilizing additional sources of clean water that can be used during the dry season.
4	Bojer et al. (2024)	13% of the area was classified as an excellent and suitable zone for RWH in the Somali and Borena Zones of the Oromia Regional State in Ethiopia.	Site visits, ground validation, and complete socio-economic data are needed to execute the RWH system.
5	Naus et al. (2020)	37% of the inhabitants utilize RWH due to its convenience, affordability, and a satisfactory water supply available during the rainy season.	Financial aid, land allocation, water treatment equipment, and large storage of harvested rainwater.

3.4.2 Quality assurance of rainwater harvesting

Water safety plans for RWH systems are needed to mitigate the risk of microbial and chemical contamination that affects water quality (Ghosh & Ahmed, 2023). The process of capturing, storing, and utilizing rainwater can lead to contamination if there is no treatment system in place to maintain long-term water quality. Rainwater from roofs may contain various pollutants, including human, animal, and bird excrement; dust; urban pollution particles; pesticides; inorganic ions; and dissolved compounds (Haque et al., 2021). Atmospheric and rooftop pollutants must be diminished or eradicated during the deployment of RWH to avert contamination of the collected rainwater (Shamsud din et al., 2025). Incorporating water treatment technology to comply with health quality criteria may be essential for its usage as drinking water (Maryono et al., 2022; Muktiningsih & Putri, 2021). Table 4 describes challenges and solutions related to the quality assurance of RWH.

Table 4. Challenges and solutions related to the quality assurance of rainwater harvesting

No	Authors	Decription problems	Solutions
1	Khan & Paul (2025)	89.94% of households use rainwater for daily needs and drinking, with only 23-25% using conventional filter treatment and potassium alum.	Strengthening the economy, enhancing financial support, and providing social safety net programmes
2	Sabrina & Juliana (2025)	pH from harvested rainwater is acidic.	Disinfection and filtration are needed before storage in the ground tank and roof tank and distribution to each house.
3	Azmanajaya et al. (2024)	9.1% cleaned water tanks twice a year, 46.8% never cleaned their gutter, 79.9% did not clean roofs, and 61% did not have a water treatment system.	Extensive of social institutions for provide water treatment methods at home, collaboration, and strengthening adherence to the water quality regulations.
4	Dewi et al. (2023)	The society believes that rainwater contains harmful materials for humans and other organisms, contaminated by atmospheric pollution, and no success stories of RWH practices exist.	Prioritizing water supply from PAMSIMAS and deep wells.
5	Ghosh & Ahmed (2022)	97% of the users did not test harvested rainwater and 72% drank rainwater without any treatment.	Used home filtration, adding chemicals (alum, disinfectant),

			boiling, or other processed to minimize the health risk.
6	Faza & Suwartha (2021)	The quality of rainwater is affected by unclean gutters, atmospheric pollutants, and low-quality roof surfaces. The parameters of pH, color, TDS, and E. coli fail to comply with clean water standards.	A foundational rainwater quality treatment facility is provided.
7	Marcos et al. (2021a)	prospective adoption of RWH as a substitute to raw water sources varies from 2.27% to 12.73% due to Bekasi City is extensive industrial and transportation movement.	Carry out the initial discharge and some filtering.
8	Diansyukma (2021)	TDS, pH, and turbidity meeting quality standards. Coliform levels exceed acceptable limits due to deteriorating roof quality and lack of basic treatment.	Support from all stakeholders is needed to provide basic water treatment.
9	Rahman et al. (2021)	Harvested rainwater quality differs during the rainy and post-rainy seasons. During the rainy season, turbidity, zinc, and pH meet Bangladesh and WHO drinking water quality standards. However, after the rainy season, faecal coliform, total coliform, and Pb do not meet these standards.	• Harvested rainwater should be treated effectively to reduce the toxicity and danger for drinking purposes. • Monitor and undertake disinfection. • Regular clean-up of the catchment area to remove dust and debris. • Periodical cleaning of the reservoir tank. • Proper hygenic practices and maintenance of harvested rainwater. • Continuous training by the local government to ensure safe.
10	Wahyuningsih et al. (2020)	Harvested rainwater quality is significantly influenced by roofing materials like asbestos, clay tiles, zinc, and galvanized iron. Turbidity, pH, sulfate, Fe, and Zn values meet health quality standards, while nitrite and coliform concentrations don't. Clay tile roofs have the best quality for harvesting rainwater. Harvested rainwater is only for sanitation purposes.	Water treatment unit is needed to meet the health quality standards for drinking.

A lack of public awareness, limited availability of nearby laboratories, and insufficient access to reliable testing instruments constitute major obstacles for users aiming to assess the quality of RWH outcomes (Ghosh & Ahmed, 2022). The community's lack of organized educational programs on water quality management and limited access to disinfection and filtration methods worsens RWH quality, leading to reduced motivation. Successful adoption of RWH requires community-based adaptive strategies involving active participation at all stages in technology selection, construction, and monitoring of collected rainwater quality.

3.4.3 Limited technology to improve the health standard of rainwater for consumption

Rainwater in urban environments is typically polluted due to airborne dust; the presence of debris can promote the proliferation of microbiological species in the water. The design of catchment areas must preserve the quality of captured rainwater; therefore, RWH should be conducted scientifically rather than conventionally (Jamal et al., 2023). An affordable and user-friendly system for monitoring water quality presents a significant information gap for users of RWH systems. This gap arises from the absence of an effective and rapid method to determine whether the harvested and stored rainwater is safe for consumption in accordance with health standards or if it requires additional treatment.

Innovative advancements in the production of cost-effective RWH treatment components and real-time water quality monitoring technologies, using basic sensors in conjunction with mobile devices, will bolster customer confidence in the RWH system. A collaborative strategy involving research institutions, businesses, banking, government, and the community is essential for developing effective technological solutions for water treatment and quality monitoring. Additionally, investment or green financing support is vital for promoting research and development of ready-to-use and durable RWH technologies, which will facilitate the broader adoption of RWH as a safe and sustainable source of drinking water in the future.

3.4.4 Limited scalling up and ease of installation for uneducated and poor people

The implementation of RWH often follows a top-down approach, wherein the community is considered the concern, and RWH systems are directly installed in the houses of the residents (Dewi et al., 2023). RWH, supported by government aid programs, NGOs, or specific institutions, often uses a "learning by doing" approach or direct demonstrations, which may lack significant information transfer. This method frequently leads to people involved acquiring practical experience without a comprehensive grasp of the fundamental ideas or optimal practices. Consequently, their long-term efficacy and sustainability may be harmed.

Protocols for design and installation, regular inspections, and maintenance of rainwater collection systems must be instituted. The obstacles to installing RWH become apparent in low-income and low-educated areas that find it challenging to comprehend intricate technical instructions and necessitate professional installation assistance. Consequently, RWH advantages are sometimes confined to pilot project implementations or are applicable solely to specific socio-economic groups that are more financially and educationally equipped. An example of RWH implementation in Lay Gayint District is that the literacy rate of 48.15% raises concerns regarding the adoption and effective utilization of RWH (Demeke et al., 2021). The success of RWH is still measured by comparing the number of structures built to the value of sustainable water supply for life and long-term welfare, as originally mandated by RWH.

RWH systems built in Eastern Ethiopia have many problems, such as poor site choice, rushed construction without proper planning, leaks, work done by untrained workers, lack of coordination during the process, and a mismatch between the amount of water collected and the size of land owned because the design and execution were not aligned (Tolossa et al., 2020). Roba et al. (2022) revealed that farmers in Ethiopia are hesitant to use RWH due to the uncertainty of rainfall, making the benefits of RWH not worth the construction costs incurred. Around 24% of RWH systems in southern Bangladesh are non-functional due to inadequate maintenance and lack of user awareness and management, posing a long-term challenge (Ghosh & Ahmed, 2023).

Gebru et al. (2021) identified the obstacles to implementing RWH in rural Ethiopian communities, specifically, (a) the biophysical compatibility of RWH systems with topography, soil, hydrology, geology, and environmental, social, and cultural factors; (b) the equitable distribution of water resources between upstream and downstream communities; (c) the prohibitive costs of RWH for impoverished rural populations; (d) the insufficient support from financial institutions for credit facilities or subsidies for installation expenses; and (e) the lack of monitoring and evaluation regarding the functionality and long-term advantages of the established RWH systems. The obstacles to RWH implementation in six principal coastal regions of BangladeshKhulna, Barisal, Feni, Noakhali, Bagerhat, and Patuakhaliidentified by Mukarram et al., (2023) include (a) 68.6% lack of knowledge and information, (b) 89.3% inadequate comprehension of water conservation and its economic significance, (c) 90% absence of management and ineffective governance, and (d) 58% financial limitations. Mukheibir dan Ahmed (2023) highlighted the challenges faced in expanding RWH implementation in developing countries after the piloting phase: technical complexities that are not aligned with the local human resource capacity, reliance on external experts, and a lack of consideration for the socio-economic capabilities of the users.

The limitations of scale and the ease of installing RWH emphasize the necessity for a more comprehensive community-based strategy. Non-literate visual and experiential learning methodologies, such as videos, might be beneficial. Enhancing institutional and regional frameworks at the local level, coupled with the establishment of appropriate supporting ecosystems, serves as a solution for delivering inclusive and sustainable water supply to the most marginalized communities.

3.4.5 Affordability to access rainwater tanks for rural and marginalized people

An effective site for surface RWH was determined by taking into account both biophysical and socioeconomic factors (Bereded et al., 2025). Bangladesh has adopted RWH for multiple uses (Rahman et al., 2022), yet, the implementation of RWH for the urban poorest and people living in slums to enhance access to water, sanitation, and hygiene (WASH) remains limited (Afsari et al., 2022). RWH, a long-standing Ethiopian program, is not easily accessible to rural communities and relies heavily on the support of funders, advocates, and government agencies (Roba et al., 2022).

The financial affordability of accessing and installing rainwater collecting tank systems is a significant obstacle for rural, coastal, and other vulnerable groups, particularly in low- and middle-income countries. For marginalized and vulnerable societies, household income priorities are centered on fulfilling fundamental necessities such as food, healthcare, and education. The high initial capital expenditures required for acquiring essential infrastructure, including storage tanks, distribution systems, filters, and other important components, frequently exceed the financial capacity of the most vulnerable, informal income, and daily wage laborers. Vulnerable or marginalized people are facing clear land ownership access for the RWH site location (Demeke et al., 2021). This contradicts the reality that this vulnerable demographic resides in regions significantly susceptible to the adverse impacts of excessive rainfall, flooding, runoff, and limited access to potable water.

3.4.6 Lack of incentives

Afsari et al. (2022) identified the deficiencies and obstacles associated with implementing RWH in Shyamnagar Upazila, Satkhira District, southwestern Bangladesh. Weaknesses include insufficient legislation, high initial costs, significant dependence on the duration and intensity of rainfall, and variability in the quantity and quality of harvested water based on catchment size and material. The benefit-cost ratios suggest that the RWH project in Dhaka City is economically advantageous in wet and average years; however, in the worst-case scenarios, such as dry years, the project is deemed non-beneficial (Karim et al., 2015).

High-quality RWH components will become very expensive in remote areas, coastal regions, and small islands. The island's geographical conditions, along with difficult transportation access, increase the costs of transporting materials, contribute to a shortage of skilled labor, and prolong the time required to reach the site for RWH installation. The absence of microcredit schemes, subsidies, or credit assistance for the implementation of RWH in remote areas, coastal regions, and small islands with limited surface water sources becomes an obstacle to its implementation. Direct incentives for the adoption of rainwater collection at the household or neighborhood level are currently absent. The absence of support may hinder the implementation of sustainable water management ways, essential for mitigating water scarcity. In the absence of financial incentives or subsidies, numerous households or communities may hesitate to engage in RWH systems, irrespective of their long-term advantages. Fiscal incentives or subsidies can encourage the community to embrace and expand RWH (Dewi et al., 2023).

The cohesive strategy in incentive programs is needed in the disjunction among sectorssuch as water, buildings, and the environment. The effective implementation of RWH in low- and middle-income countries such as (1) subsidy interventions, incentives, and micro-financing programs; (2) mandatory adoption of RWH for all new building construction projects; (3) support for transportation and material costs to reduce expenses; (4) a cooperative approach to the establishment of communal or neighborhood scale RWH systems to ease the financial burden; and (5) providing subsidies for maintaining or handling of RWH for poor and marginalized people in rural, coastal, and other vulnerable populations. The policy for implementing RWH to improve water management is not solely an individual obligation; it is a vital component of the national water resilience strategy, which balances long-term needs with the immediate economic challenges faced by marginalized communities.

3.4.7 Lack of institution and governance supports

A perception survey of RWH systems in the Khulna and Satkhira Districts of southwestern coastal Bangladesh revealed that respondents lacked operation and maintenance training, did not receive monitoring assistance or usage instructions, utilized rainwater without treatment, and never assessed the quality of the collected rainwater (Ghosh & Ahmed, 2022). The Ethiopian government promotes RWH with geomembranes, but the technology is less effective due to user negligence and the implementing organizations' lack of skills and knowledge (Gebremedhn et al., 2023). A lack of staff and qualified professionals supporting maintenance has contributed to serious damage to the RWH ponds constructed in Sekota and Lasta Kebeles, Ethiopia (Wale et al., 2022). The primary obstacle to effectively implementing and maintaining RWH systems after construction is the insufficient follow-up and support from organizations and government entities that provide assistance for RWH during the maintenance phase (Roba et al., 2022). The RWH pond constructed by the Agriculture and Rural Development Office (ARDO) in Lay Gayint District since 2013 has exhibited imperfections in quality, production, and sustainability (Demeke et al., 2021).

Support and technical capacity enhancement after the installation of RWH systems are critically important. Such assistance includes providing operation and maintenance guidelines, establishing protocols for mitigating and managing microbiological and chemical contamination, and implementing consistent and rigorous monitoring and evaluation measures to ensure the sustainability of the RWH implementation program. Urban development authorities must integrate, inform, and enforce the implementation of RWH, comply with regulations, and provide various conveniences to achieve scalability benefits for city residents (Huq et al., 2024).

3.4.8 Lack of community or neighborhood acceptance and support

RWH as a rainwater management approach is executed at the local level, specifically on a household scale; therefore, it significantly depends on the community's involvement and capability for effective implementation (Dewi et al., 2023). The individual RWH model is easier to maintain due to ownership, while the communal model faces challenges in promoting responsibility and commitment distribution among community members (Mukaromah, 2020).

Initiatives that involve significant community engagement, inquisitiveness through regular inquiry, receptiveness to new knowledge, passion, inventiveness, proactivity, and independence are crucial for addressing the lack of clean water and ensuring the future sustainability of RWH (Karmilah & Madrah, 2024). The aspects of willingness, ability, and community approval are essential for determining the success of RWH in providing daily water needs (Dewi et al., 2023). The attitude of individuals toward RWH greatly affects its adoption in residential areas. Intervention through education, socialization, training, and empowerment could boost the community's understanding and attitudes (Marcos et al., 2021a). Communities require an adaptation process to alter their perceptions and transition from their current water supply sources. This change should involve knowledge transfer and learning from experiences (Mukaromah, 2020). Swarnokar et al. (2025) showed that training and knowledge exchange are highly beneficial in addressing adaptation and mitigating the impacts of cyclones that jeopardize water resource availability. Community-based initiatives and capacity-building programs must be implemented to strengthen local solutions for coping and promote RWH to access drinking water (Ashrafuzzaman et al., 2023). Table 5 describes challenges and solutions related to community or neighborhood support.

Table 5. Challenges and solutions related to community or neighborhood support

No	Authors	Decription problems	Solutions
1	Salman & Khalek (2025)	3% of farmers employ RWH as a strategy to adjust to drought-prone conditions.	• Community capacity for maintaining RWH systems • Provide periodic maintenance funds.
2	Dewi et al. (2023)	The economic and financial value of RWH is minimal because it fails to address water needs adequately during the dry season. RWH is not considered a primary necessity. Additionally, RWH can be challenging to implement due to a lack of understanding of its functionality.	• Improving community understanding and participation. • Enhancing knowledge through mentorship and education. • The development of leadership and networks is crucial. • Respect and understand the local community's values. • Community leaders are actively involved in correcting misconceptions about rwh. • The community engages in regular discussions and communication about rwh practices.
3	Samaddar et al. (2022)	The media offers no support and RWH pioneer adopters not actively promoting the benefits within or outside their community	• Spreading awareness knowledge about RWH • Incentives to motivate or to disseminate the information of RWH.
4	Marcos et al. (2021b)	The residents of Bekasi utilize 49% of harvested rainwater only for gardening and sanitation purposes.	• Socialization and discussion to carry out RWH. • Involving the community and non-government organizations in environmentally friendly activities.
5	Demeke et al. (2021)	72.2 % of the households have not participated in the site selection, design, construction, and maintenance of the RWH pond which might reduce the sustainability ponds	• Onsite training about the operation and maintenance. • Active involvement and awareness creation. • Community participation enhances skill development and a sense of ownership.

3.4.9 Lack of regulation and enforcement support

Afsari et al. (2022) identified the deficiencies and obstacles associated with implementing RWH in Shyamnagar Upazila, Satkhira District, southwestern Bangladesh. Weaknesses include insufficient legislation, high initial costs, significant dependence on the duration and intensity of rainfall. Coherent and coordinated actions and policies from many important authorities are essential to sustain the city's future water supply and resources (Moshfika et al., 2022). Huq et al. (2024) emphasize the need for strict compliance with RWH installations to align with building regulations and facilitate the permitting process for RWH integration in the provision of clean water.

4. Conclusions

The sustainability of water supply can be enhanced through various raw water sources, such as surface water, groundwater, and rainwater, along with comprehensive policies, inter-institutional collaboration, and consistent practices. However, low-middle-income, low-income, and upper-middle-income countries face significant challenges from issues such as scarcity, pollution, population growth, expanding economies, land use changes, urbanization, and climate change. Historically, initiatives such as RWH have faced multidimensional resistance. Rainwater offers numerous advantages in Ethiopia and Bangladesh, but Indonesia still relies on groundwater. Despite these challenges, the use of RWH could significantly improve water supply sustainability, such as in towns and villages in Ethiopia and the coastal regions of Bangladesh.

Shifting the mindset and perception that water scarcity does not exist is crucial in this study area to encourage transformative actions for RWH implementation. This, in turn, promotes sustainability, enhances well-being, fosters a healthy environment, and advances the achievement of SDG 6. Scalability in RWH implementation can be achieved through public awareness campaigns, educational initiatives, financial incentives, community engagement, incorporation of RWH into building codes for new residential construction and urban development, financial incentives, and the integration of local knowledge to promote long-term resilience in RWH systems. Additionally, utilizing communal or neighborhood-based RWH systems, particularly in drought conditions, may reduce both up-front and maintenance costs compared to individual systems.

Based on the research findings, the proposed agenda for future research includes several key initiatives; (a) conducting multicriteria analyses using GIS applications to identify potential RWH site locations at regional, district, or local scales. This initiative should be pursued in Indonesia, as previously demonstrated in Ethiopia by or in Bangladesh (b) economic drivers analysis from an Indonesian perspective; (c) developing innovative monitoring devices, sensors, or technologies to ensure the quality and continuity of potable RWH; (d) improving the energy efficiency of groundwater pumping systems; (e) implementing handling and training programs to enhance community knowledge; and (f) analyzing the economic and financial feasibility of community- or neighborhood-based RWH systems. Social engineering is critical to developing a comprehensive societal understanding of RWH implementation by disseminating information, generating interest, persuading and mentoring users, and utilizing local change agents. The provision of RWH systems with water treatment technology should be considered mandatory basic infrastructure, rather than an alternative in water scarcity areas. Including RWH as a new indicator in SDG 6 could enhance its scalability and ensure a sustainable raw water source in areas with limited access to safe drinking water, sanitation, and hygiene.

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Author Contribution

The author, H.A.L, independently carried out all aspects of this research, including conceptualization, methodology, validation, and data curation. He was fully responsible for drafting the manuscript, conducting the review and editing process, and preparing the visualization of the results. H.A.L, has read and approved the final version of the manuscript, and takes full responsibility for its content

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Biography of Author

Herbert Adiputra Lumbanbatu, Obtained a bachelor's degree in regional and urban planning at the Bandung Institute of Technology. Since 2024, I have been fulfilling a master's degree in Environmental Science at the Universitas Indonesia.

- Email: herbertadiputra@gmail.com
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A