Rainwater Harvesting and Groundwater Recharge: Design Optimisation for Semi-Urban Regions

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ABSTRACT

The article, namely "Rainwater Harvesting and Groundwater Recharge: Design Optimisation for Semi-Urban Regions," has effectively explored the fact of how the processes of rainwater harvesting or RWH and groundwater recharge can be improved. The focus is especially put on the semi-urban areas where there are significant limitations despite opportunities. The study has also reviewed design features, as well as technologies and challenges with the help of implementing a secondary qualitative data analysis process. The study concludes by clearly highlighting the need for smart systems as well as strong policies and local involvement. These specific insights may significantly support better planning and sustainability of water in growing semi-urban communities.

Keywords: Rainwater Harvesting, Groundwater Recharge, Semi-Urban, Water Sustainability, Urban Planning, Sustainable Infrastructure, Community Participation

1. INTRODUCTION

1.1 Overview

The concept of Rainwater harvesting or RWH refers to the process of collecting as well as storing rainwater for later use (Eludoyin et al. 2021). On the other hand, the term groundwater recharge refers to the very method of enhancing the natural flow of water into underground reservoirs (Noori et al. 2023). It has been found in research that regions that are semi-urban often face limitations regarding access to central water systems. This is the place where several sustainable practices like rainwater harvesting help in the matter of fulfilling the local needs of water needs. RWH is especially found during dry seasons like Summer. According to the report of 2023, there are over 50% of the global population faces significant water shortages in specific seasons (Kuzma et al. 2023).

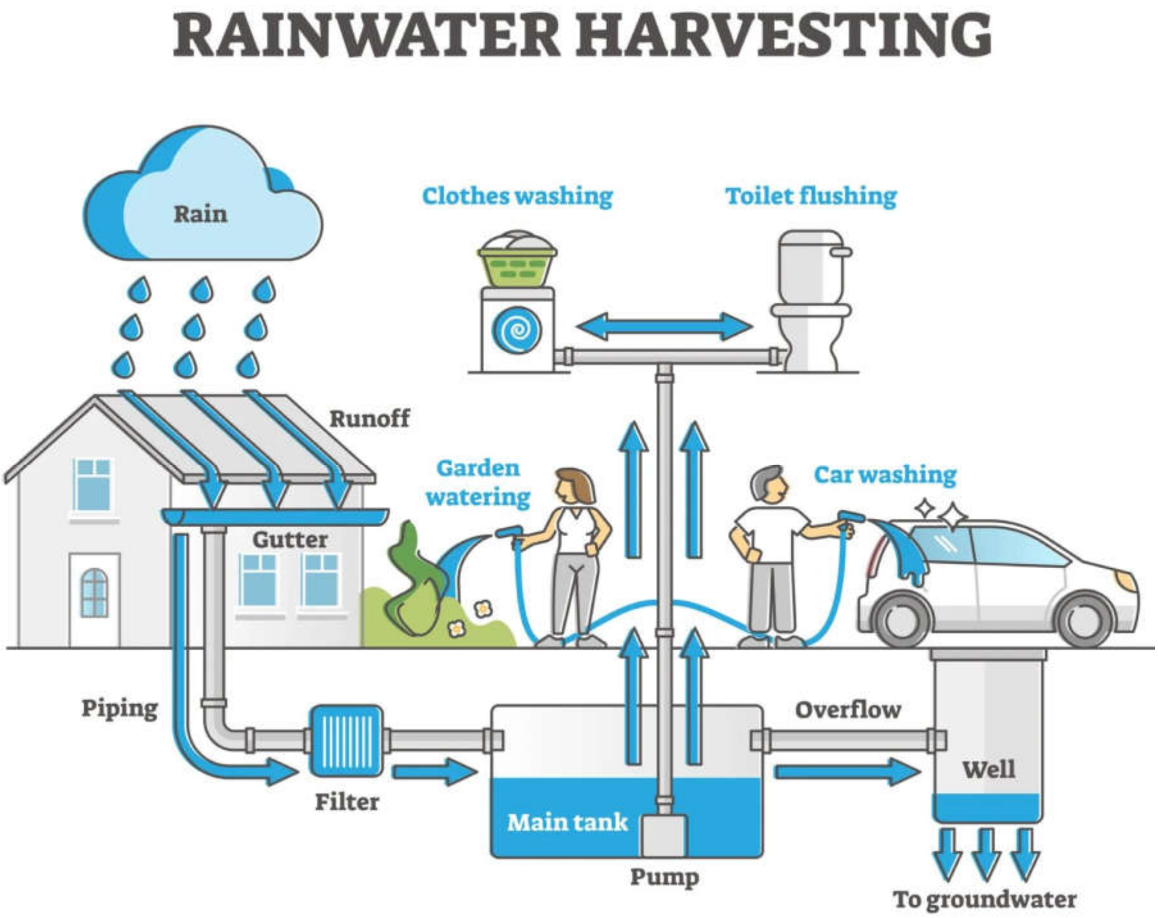

Figure 1: Rainwater Harvesting

(Source: Mishra 2024)

1.2 Problem Statement and Scope of the Study

Several issues, like the rapid growth of urban areas as well as the poor condition of infrastructure, and unplanned settlements significantly contribute to worsening the scarcity of water. On the other hand, various studies have found that the level of groundwater is dropping very fast in many semi-urban areas (Tyagi and Sarma 2021). These specific limitations are actually happening because of the over-extraction of water as well as very limited recharge. This is why the actual purpose of the article is to efficiently explore the improvements of design in rainwater harvesting systems. This specific approach will help in supporting effective groundwater recharge in semi-urban zones.

1.3 Aim of the Study

The major aim of this study is to assess the usefulness of rainwater harvesting systems and how they can be better designed and implemented for the purpose of enhancing groundwater recharge, particularly in semi-urban areas that are experiencing the issue of extreme water scarcity.

1.4 Objectives of the Study

- To identify the most suitable rainwater harvesting methods for semi-urban regions
- To examine design improvements that support efficient groundwater recharge
- To explore the role of technology in improving RWH systems
- To analyse policy and community-level factors that affect RWH implementation
- To recommend sustainable and cost-effective RWH solutions for water-scarce areas

1.5 Research Questions

- What are the best rainwater harvesting methods that can be most suitable for use in semi-urban areas?
- How can the designs be optimised to have a better groundwater recharge?

2. LITERATURE REVIEW

2.1 Insights from Existing Studies

The approach of rainwater harvesting has managed to gain attention throughout the globe. The rapid expansion of RWH is especially driven by the growing scarcity of water. According to the study conducted by ZMR (2025), the global market of RWH has reached $18.75 billion in the year of 2023. It is also expected to grow to 34.47 billion by the year 2032. Biswas et al. (2022) have mentioned in their study that above-ground tanks are found to be commonly used due to their lower cost. On the other hand, underground systems are becoming popular because of their ability to offer better water quality and appearance.

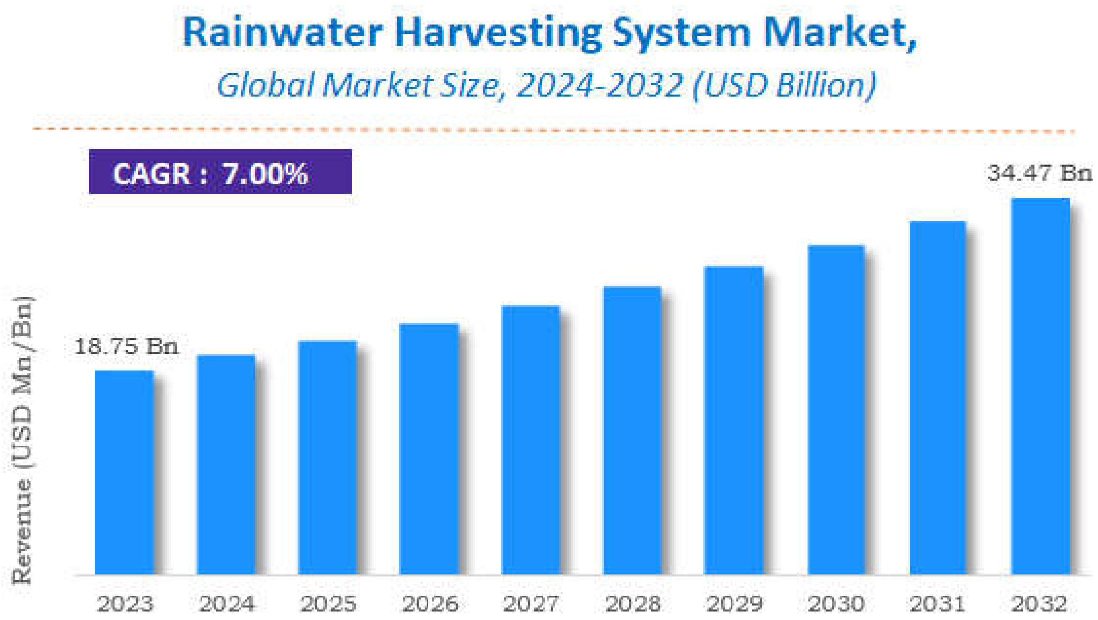

Figure 2: Rainwater Harvesting System Market

(Source: ZMR 2025)

As per the findings of Martos Rosillo et al. (2022), there are several groundwater recharge methods like Managed Aquifer Recharge or MAR and Nature-based Solutions or Nb that are being widely adopted in the modern environment of RWH. On the other hand, Kebede et al. (2024) have mentioned that MAR techniques like infiltration ponds and recharge wells have also offered up to nine times higher recharge rates than traditional systems.

The fact is also true that some of the existing studies have pointed out some critical gaps in the design as well as storage sizing and monitoring of groundwater recharge (Meles et al. 2024). Several other limitations, like higher costs and risks of contamination, are also there that contribute to the limitations of rainwater harvesting. As per the findings of IMARC (2025), the CHHATA project in India, particularly in Odisha, has seen rapid RWH growth. Some other studies have also highlighted the role of policy gaps in Kenya in limiting the progress of RWH (Singh et al. 2024). According to IMARC (2025), RWH also helps the urban communities in Brazil during times of drought. This is why the opinion of the experts is to implement various supportive policies as well as strong involvement of communities to gain long-term success.

Region	Initiative	Impact
India	Odisha’s CHHATA project (2022): 29,500 private and 1,925 govt. buildings equipped	Rapid RWH adoption; 8.8% compound annual growth rate (CAGR)
Africa	Kenya: Policy gaps hinder widespread RWH, but local projects boost resilience	RWH is key for rural water security
Latin America	Brazil: 59% of regions affected by droughts (2023–24); RWH adopted in urban peripheries	Decentralised RWH is used to improve access to water

Table 1: Regional Examples of Rainwater Harvesting Initiatives and Their Impact

Globally, rainwater harvesting is applied in a broad spectrum as the most decentralised and adaptive strategy to cope with the issue of water scarcity. The rapid employment of rainwater harvesting is seen in semi-urban and urban locations. Implementation and success rates of RWH systems across various geographic and socio-political dynamics have already been explored in many studies. A report by Arora (2022), has mentioned that in India, the Odisha government has introduced an exclusive rainwater harvesting scheme that is renowned as ‘Community Harnessing and Harvesting Rainwater Artificially from Terrace to Aquifer' or CHHATA. The major purpose of Odisha behind this scheme is to make rainwater conservation better and improve water quality across urban local bodies and water-scarce blocks.

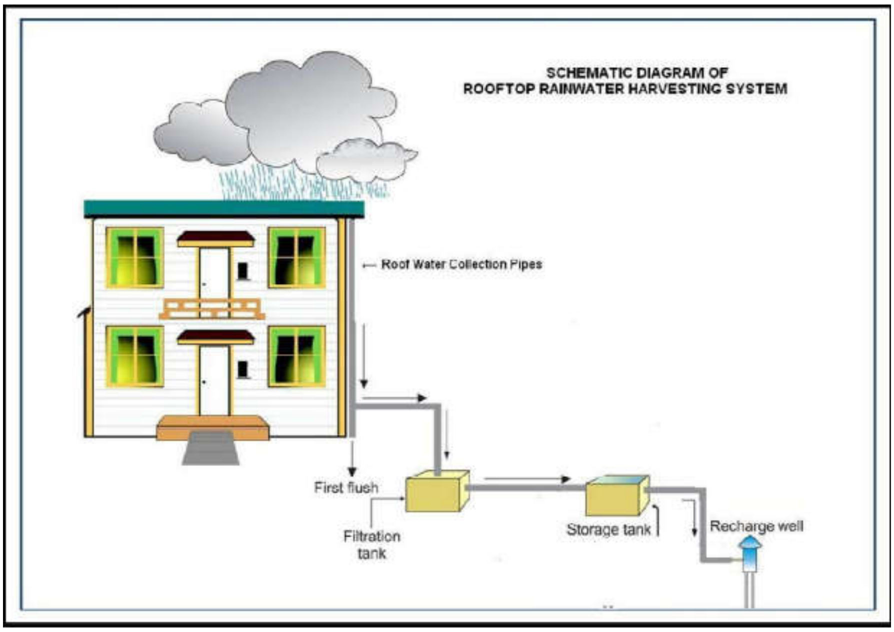

Figure 3: Structure of CHHATA Project

(Source: echhata 2025)

On the opposite side, the approach of Kenya has been more centred on the grassroots. Though policy gaps are present at the national level, local NGOs and community-driven models support the overall adoption of RWH in water-scarce rural and peri-urban regions. It is true that in Kenya, RWH is a major way for rural water security, but the absence of a unified national water harvesting policy hinders its large-scale impact. In this context, the role of smaller community efforts, such as school-based cisterns and NGO-supported tank systems, played a significant role in ensuring measurable success in improving water access and resilience during dry seasons.

Brazil is recognised as one of the northeastern drought-prone areas. Here, Government-led programs like the Boardwalk Cisterns Program supported thousands of farmers by distributing cisterns (Silva et al. 2021). As per the author Silva and her peers (2021), apart from improving water access, the Boardwalk Cisterns initiative also supports food security and crop yield improvements. In RWH, Brazil's approach is slightly different from Kenya's, because this country has utilised more centralised systems, though it relied heavily on public funding and rural stakeholder partnerships. It represents the need for both state facilitation and grassroots execution.

Policy support still works as a determinant of the success or failure of RWH initiatives. As reported by the World Resources Institute, approximately 50% of the world's population, which is around 4 billion, live under highly water-stressed conditions for at least one month of the year. Living in such a level of water stress makes people’s lives, jobs, food and energy security more vulnerable. In the whole world, water is mandatory in various significant fields like growing crops and raising livestock, producing electricity as well as maintaining human health, fostering equitable societies and meeting the world’s climate goals.

When the subject comes to the Indian context, each state follows their own policy frameworks in RWH. In Tamil Nadu, rooftop RWH systems became mandatory in buildings in urban areas as early as 2003 (Vasudevan and Natarajan 2021). Within a decade, the aggressive enforcement model of Tamil Nadu can play a noble role in increasing groundwater levels. On the other hand, Odisha’s CHHATA project steps forward with a more incentive-based model that offers subsidies and technical support in the overall implementation of RWH structures. Besides the broad success of RWH systems in India, there are still some Indian states that are currently not proficient in follow-up audits, which is why abandoned or poor maintenance is seen in RWH systems. In the same context, the obstacles faced by Kenya are entirely different. After being vulnerable to frequent droughts, it is very unfortunate that in Kenya, there is no nationwide RWH mandate. In order to fight against droughts, some divisions have set up their own local rules as well as collaborated with NGOs to set up rainwater harvesting systems. The study by Singh et al. (2024) has found that flexible governance makes each region able to try solutions that fit their local needs, which is more effective compared to the use of a uniform national policy everywhere. On the other hand, the federal government of Brazil emphasise rural areas via grant-supported cistern programs. Although the initial results of such initiatives were promising, but currently a gap is currently noticed in funding. In turn, it affects the long-term sustainability of cistern programs, which means that, though these programs temporarily increase water availability, policy discontinuities hinder the long-term impact of RWH systems in some regions.

Some studies have also mentioned that apart from human efforts and government policies, some emerging technologies are now also helping to improve rainwater harvesting (RWH) in many locations that are fighting the issue of extreme water scarcity. IoT sensors, GIS mapping, and AI are some excellent innovations of technology that are now rapidly applied in order to improve the overall design and management of RWH systems.

Technology	**Function**	**Current Usage**
Smart Sensors	Monitor water levels, detect contamination, and ensure timely maintenance	Rare in semi-urban and low-income areas
GIS Mapping	Helps in locating suitable areas for rainwater harvesting	Limited use in resource-poor regions
AI Tools	Optimizes design and management of RWH systems	Still in early stages of implementation

Table 2: Emerging Technologies in Rainwater Harvesting and Their Application

Apart from adopting technology, there are many countries that implement new ideas where local people take care of RWH systems. Countries like Kenya and India engage school students and community groups in the management of water systems. By involving local people, it will be possible to achieve long-term success in water management for any region.

2.2 Theoretical Framework

The study has effectively followed the principles of "Sustainable Urban Water Management" and "Nature-Based Solutions" (NbS) (Cui et al. 2021). These two specific frameworks are commonly known for supporting eco-friendly water systems using natural processes like soil and vegetation. These are actually supported to efficiently collect as well as store and filter rainwater for a better supply of water simultaneously maintaining the protection of the environment in semi-urban areas. Sustainable Urban Water Management, or SUWM, take the side of integrating rainwater harvesting with urban planning and infrastructure development (Selerio et al. 2021). It mainly aims to reduce water stress, manage stormwater, as well as bring improvement in the overall water reuse practices. The principles of SUWM promote the use of green infrastructure, including green roofs, permeable pavements, and bio-retention areas. It is for supporting the natural water cycle. On the other hand, Nature-Based Solutions or NbS theory emphasises restoring and mimicking natural ecosystems in order to enhance water recharge as well as quality (Sowińska-Świerkosz and García

2022). These methods support environmental protection, while apart from this, they also take sides in improving resilience to climate change and urban flooding. The combination of these approaches can build more reliable, cost-effective, and sustainable water systems in semi-urban areas that benefit both people and nature.

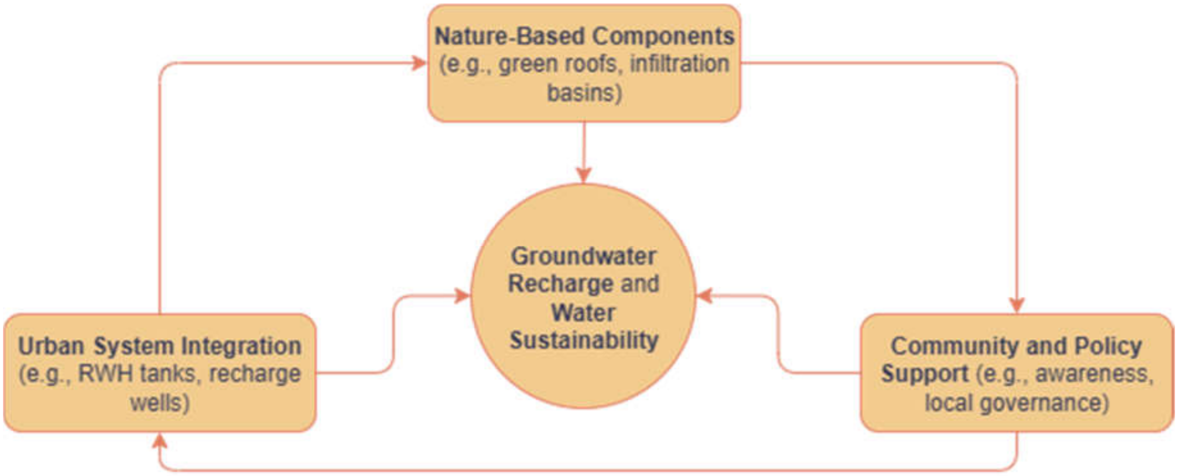

Figure 4: Integrated Framework for Sustainable Rainwater Harvesting (Source: Self-Developed)

3. Methodology

3.1 Research Approach

The study is designed with the help of data collected from secondary sources (Taherdoost 2021). A qualitative approach has also been used to define and analyse the collected data. This means that the study has explored several new ideas and findings from materials that already exist rather than depending on the process of collecting new data. The inclusion of a qualitative data synthesis technique in the study has provided the opportunity for the researchers to offer a deeper understanding of different experiences as well as systems across semi-urban regions. The specific approach also reduces the need to do any kind of fieldwork. In this way, the secondary qualitative approach of collecting and analysing data helps in strengthening the connection between global trends and local practices. Such a method not only saves time but also resources.

Thus, the approach of secondary qualitative research becomes more practical for early-stage research. With the utilisation of a secondary qualitative approach, it has been possible to review different case studies, government reports, and academic articles in studies whcih are very important steps in finding patterns and common issues in the research area. Through progress with a second qualitative research method, the study can establish a strong base of knowledge, which sets the stage for future research or helps local authorities to make better strategies in coping with water scarcity issues through RWH.

3.2 Sources of Data Collection

The key secondary sources that have been used throughout the journey of the study to collect data include peer-reviewed journal articles as well as various government policy reports, NGO case studies, and documents from authorised international organisations (Taherdoost 2021). These specific sources are found to be useful for offering rich insights into areas like rainwater harvesting and the practices of groundwater recharge. Besides peer-reviewed journal articles as well as various government policy reports, NGO case studies, and documents from authorised international organisations, in this study, environmental agencies, global water forums, and academic conference proceedings were also considered for data collection, as these are best for obtaining broader perspectives. The use of such sources determines that the study was supported by reliable evidence. Apart from these scopes, they have also aided in the identification of common practices, regional challenges, as well as opportunities for improvement across various semi-urban contexts.

3.3 Data Analysis Technique

A simple method of content analysis was used in the study to efficiently identify the unique patterns of data across the literature (Narin 2021). Some of the areas of exploration included design challenges as well as policy roles and sustainability. As the stidy progressed with a content analysis method, first of all, the data is categorised on the basis of relevant research questions. Thus, it is easy to draw meaningful conclusions as well as explore trends over different sources. Besides these, a content analysis research way also facilitates the identification of gaps in current practices and helps to propose practical suggestions for improving rainwater harvesting and groundwater recharge systems.

3.4 Limitations

The study has faced some significant limitations. The main limits that came to notice comprise the lack of site-specific data and general findings that may not be properly applicable for including everywhere. On the other hand, it is also considered that the availability and quality of existing literature may also vary regarding the specific differences in regions. As well as the study's sole dependency on secondary data poses a very significant concern in the subject of capturing real-time insights and current community feedback. Such inefficiency further probably compromises the accuracy of local-level recommendations.

4. Findings and Analysis

4.1 Common Design Components

The typical rainwater harvesting or RWH systems include parts like a catchment area (like rooftops), gutters and downpipes to guide the flow of water, as well as first flush diverters to remove any early sign of contaminants, and filtration units for making the water cleaner (Ghosh 2022). The tanks for storing water in RWH systems are sized as per the rate of local rainfall and the average use of water (Shadeed and Alawna 2021). This specific difference in size also remains the same whether the tank is above or below ground. The overflow systems contribute to managing the excess water and preventing its misuse. On the other hand, pumps are actually used for the pressure in setups underground.

In the overall rainwater harvesting process, besides these parts, there is also a need for proper sealing and protection of storage tanks, which helps in avoiding mosquito breeding and algae growth. As seen in the current dynamics, some modern systems have started the use of UV treatment units or automatic level indicators. It facilitates better monitoring of water levels. On the other hand, for holding the efficiency of the system in the long run, good quality piping, anti-leak joints, and regular maintenance schedules are mandatory. On the use of locally available materials, it is also possible to cut down on extra expenses. It also makes the systems more adaptable, not only in rural areas but also in semi-urban settings.

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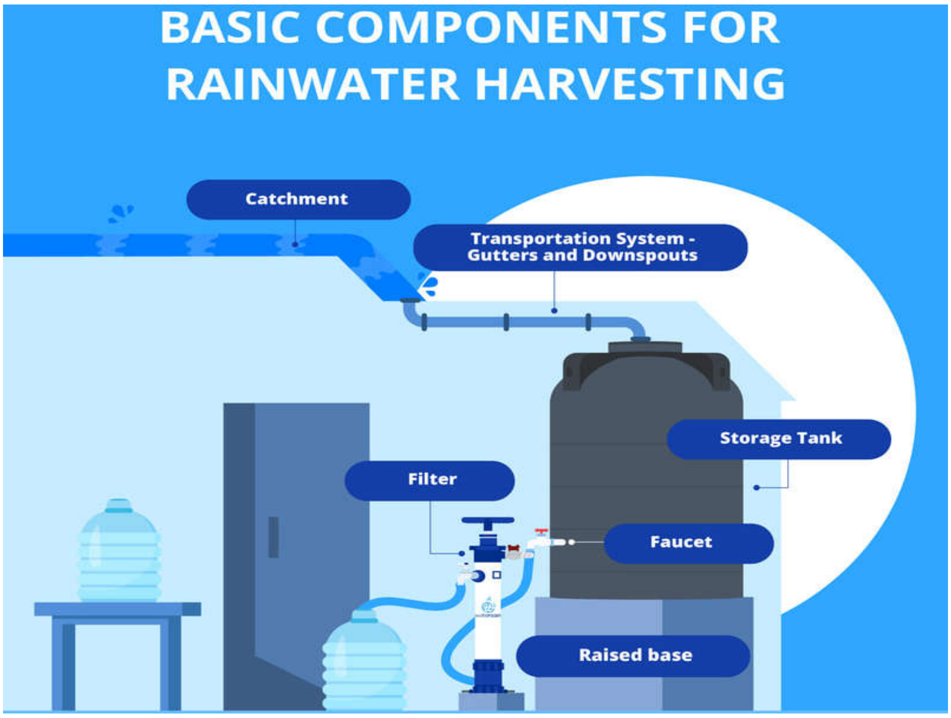

Figure 5: Basic Components for Rainwater Harvesting

(Source: Wateroam 2024)

4.2 Success Stories & Best Practices

The effective implementation of RWH techniques in Chennai has led to the reduction of runoff up to 95% (Puri and Shah 2024). On the other hand, Bengaluru has also been found to have an increase in the rapid adoption of rainwater harvesting due to the public campaigns. Singapore was found to be adopting the technique of rooftop RWH with reservoirs (Sendanayke 2016). It is actually considered as a crucial part of the national water supply strategy of Singapore. Some studies have also found that community-led RWH projects in Kenya have reduced the time spent collecting water (Tsoca 2024). The implementation of cisterns in the RHW system in Brazil was found to increase crop yields and enhance the security of food (Silva et al. 2021). These specific stories of success across the globe clearly highlight the importance as well as the value of involving the community, proper maintenance, as well as support of policy for successful RWH implementation.

On the other hand, based on a 2020 groundwater resource assessment, the CHHATA initiative introduced by the state of Odisha steps forward with the aim of constructing rainwater harvesting structures on the rooftops of nearly 29,500 private buildings and 1,925 government buildings as well as extending their areas by including 52 water-stressed blocks and 27 ULBs. The project has a very sharp aim, which is to harvest approximately 373.52 crore litres of water in the implementation period from 2022–23 to 2026–27. The project will be executed with the use of the existing manpower of the Department of Water Resources, or DoWR, with a total outlay of ₹270 crore. The average cost of each rooftop harvesting structure on government buildings is projected at ₹4.32 lakh. While in rural areas, the expenditure is estimated at around ₹3.06 lakh per building.

4.3 Challenges in Semi-Urban Areas

The space for implementing rainwater harvesting is sometimes found to be very limited in semi-urban areas. This specific limitation is significant for RWH. It contributes to making it hard to install large size of tanks. On the other hand, issues like a lack of awareness and poor upkeep also cause frequent failure of systems. It is found to cost around ₹15,000 to ₹30,000 for the overall setup and ₹500 to ₹2,000 for the yearly maintenance (Oriplast 2023). This higher level of cost also discourages the wide adoption of RWH in semi-urban areas. Contamination is a risk if systems are not well designed.

Challenge	Impact
Limited Space	Difficult to install large tanks due to small building or plot sizes.
Lack of Awareness	Many people are not informed about the benefits and proper use of RWH systems.
Poor Maintenance	Systems often fail due to neglect or lack of regular upkeep.

High Setup Costs	Installation costs range from ₹15,000 to ₹30,000 (Oriplast, 2023).
Maintenance Costs	Yearly maintenance costs range from ₹500 to ₹2,000.
Risk of Contamination	Poorly designed systems may lead to water pollution.

Table 3: Challenges in Implementing Rainwater Harvesting in Semi-Urban Areas

4.4 Technologies Improving Efficiency

Several types of technologies are already available in the market that increase the efficiency of rainwater harvesting and groundwater recharge processes. Some of these specific technologies include percolation pits as well as geo-synthetic filters and nature-based designs (Antigha et al. 2023). On the other hand, tools like IoT sensors, GIS mapping, and several other AI tools nowadays also support the perception of smarter planning, and monitoring, as well as better water use in the process of rainwater harvesting and groundwater recharge.

In addition to this, currently, the development of mobile-based applications allows homeowners and technicians to monitor their RWH systems in real time. Apart from these, the rise of automated valves and smart controllers also plays a major role in the management of the water flow more precisely, also reducing overflow and wastage (Naveenkumar et al. 2024). There are some places, the use of solar-powered pumps has started for move harvested rainwater to storage tanks or for irrigation purposes. In the context of rainwater harvesting systems, the use of emerging technologies opens up a lot of scope, starting from improving water efficiency to reducing manual labour. As they proved enough innovative and budget-friendly options in improving rainwater harvesting systems, they can be more widely adopted in semi-urban and rural areas. Therefore, the use of technology is now making RWH systems more accessible as well as sustainable in the long term.

5. Discussion

The overall analysis of data in the study has found out the fact that the traditional RWH systems, including open tanks and simple pits are easy to build. But they are also found to lack in the aspects of proper filtration and the design of storage. On the other hand, the modern systems of rainwater harvesting work with smart sensors, geo-synthetic filters, and different types of mapping tools. This is why the modern tools of RWH are able to offer better performance and enhanced quality of water.

The fact is also true that the modern RWH systems face some critical barriers. There are many such semi-urban areas that face low public awareness, limited budget as well as weaker enforcement of policies. On the other hand, proper maintenance and the cost needed for this are also considered significant concerns. Despite these specific limitations, there are also some strong opportunities ahead. This is because it is expected that the inclusion of approaches like green infrastructure, public-private partnerships, and better urban-rural collaboration will significantly expand the RWH systems. RWH may ease the pressure on public water supplies if planned well.

6. Recommendations

One of the important recommendations for future RWH systems is that the systems in the semi-urban areas should be compact as well as cost-effective and easy to maintain. On the other hand, the designs of the RWH system must need to include a proper process of filtration and safe systems of managing overflow. It is also crucial for the local governments to offer subsidies, training, as well as strict building rules at the policy level. On the other hand, the effective engagement of communities is key. This is why the approaches of awareness drives as well as school workshops, and involving residents in maintenance may significantly contribute to building trust and ensure success for the long term.

7. Conclusion

The overall journey of the study clearly demonstrates the fact that smart and well-designed rainwater harvesting systems may significantly improve the security of water even in semi-urban areas. The study has also highlighted the value of technology as well as local policies and community support within the overall process of rainwater harvesting and groundwater recharge. The study also opens the door for future research through real-life trials and community-led design with the help of adding to the knowledge of practical solutions. Smart RWH systems help in securing water security as well as support sustainable communities. This is why the study may be helpful in testing long-term impact and adaptability.

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