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Development and Evaluation of Rooftop Rainwater Harvesting in Southern Rajasthan: A Comprehensive Review of Filtration Technologies and Water Quality Dynamics

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Abstract

Increasing water scarcity, groundwater depletion, and climate variability have intensified the need for sustainable alternative water resources, particularly in arid and semi-arid regions. Rooftop rainwater harvesting (RRWH) has emerged as an effective decentralized approach for augmenting water availability while reducing dependence on conventional freshwater sources. Despite its considerable potential, the quality of harvested rainwater is often compromised by physicochemical and microbiological contaminants originating from roof catchments, atmospheric deposition, and storage systems. Consequently, efficient and affordable filtration technologies are essential for ensuring the safe domestic utilization of harvested rainwater. This review critically examines the current state of rooftop rainwater harvesting with a particular emphasis on filtration technologies, water quality dynamics, and their applicability in semi-arid regions such as Southern Rajasthan, India. The review synthesizes published literature on the influence of roofing materials, rainfall characteristics, first-flush diversion systems, and low-cost point-of-use filtration technologies including sand, gravel, activated carbon, charcoal, ceramic, and hybrid multi-stage filtration systems. The performance, advantages, and limitations of these technologies are comparatively evaluated with respect to the removal of suspended solids, turbidity, dissolved contaminants, and pathogenic microorganisms. The literature indicates that conventional filtration systems effectively remove coarse particulate matter but exhibit limited efficiency in eliminating dissolved pollutants and microbial contaminants. In contrast, integrated multi-stage filtration systems combining physical filtration, adsorption, and ceramic microfiltration demonstrate superior water treatment performance while remaining economically feasible for decentralized applications. The review further identifies significant research gaps concerning long-term field evaluation of passive gravity-driven filtration systems under localized monsoonal conditions and varying rooftop catchment materials in Southern Rajasthan. The findings provide a scientific basis for developing sustainable, low-cost filtration systems capable of improving harvested rainwater quality and supporting regional water security.

Keywords: Rooftop rainwater harvesting; Rainwater quality; Filtration technologies; First-flush diverter; Water quality; Hybrid filtration; Southern Rajasthan; Water security; Sustainable water management.

1. Introduction

Freshwater scarcity has become one of the most pressing environmental and socio-economic challenges of the twenty-first century. Rapid population growth, urbanization, industrial development, climate change, and unsustainable groundwater abstraction have significantly increased the gap between water demand and available freshwater resources (Khanal, 2020; Lepcha et al., 2024; Singh et al., 2025). The situation is particularly severe in arid and semi-arid regions, where rainfall is highly variable in both space and time and conventional water resources are increasingly unable to meet domestic, agricultural, and industrial demands.

India faces substantial water stress due to declining groundwater reserves and uneven rainfall distribution. Rajasthan, occupying nearly 10% of the country's geographical area while possessing only a small fraction of its freshwater resources, represents one of the most water-deficient states in India. Southern Rajasthan experiences irregular monsoonal rainfall, prolonged dry periods, high evapotranspiration, and increasing groundwater depletion, making sustainable water resource management a regional priority (Biswa, 2018; Gavhane et al., 2023). Traditionally, communities in Rajasthan have relied on indigenous rainwater harvesting structures such as **Taankas, Kundis, Johads, and Baoris**, which have successfully supported domestic water requirements for centuries. However, increasing urbanization, changing land-use patterns, and growing water demand have renewed interest in engineered rooftop rainwater harvesting (RRWH) systems as decentralized and sustainable alternatives for augmenting water supplies (Singh Rathore et al., 2020; Singh & Turkiya, 2017).

Rooftop rainwater harvesting involves collecting precipitation from building rooftops and conveying it through gutters, downpipes, filtration units, and storage tanks for subsequent use. Properly designed RRWH systems can substantially reduce dependence on municipal water supplies, enhance groundwater recharge, mitigate urban flooding, and improve resilience against climate variability (Campisano et al., 2017; Jaradat & Özkök, 2024; Zhang et al., 2012). Previous studies have demonstrated that RRWH systems can satisfy a significant proportion of domestic water demand while simultaneously reducing stormwater runoff and associated environmental impacts (Basinger et al., 2010; Campisano et al., 2017).
Although rainwater is generally considered one of the cleanest natural water sources before atmospheric contact, harvested rooftop runoff often undergoes considerable quality deterioration before storage. Roof surfaces accumulate dust, suspended particles, leaves, organic debris, bird and animal droppings, insects, and atmospheric pollutants during dry periods. These contaminants are washed into storage systems during rainfall events, particularly during the initial runoff or "first flush," resulting in elevated turbidity, total suspended solids (TSS), chemical oxygen demand (COD), dissolved solids, and microbial contamination (Meera & Ahammed, 2006; Abu-Zreig et al., 2019; Bañas et al., 2023). Numerous investigations have reported the presence of indicator microorganisms, including total coliforms, *Escherichia coli*, and enterococci, in untreated harvested rainwater, highlighting the potential health risks associated with direct consumption without appropriate treatment (Morales Rojas et al., 2021; Raimondi et al., 2023).

The quality of harvested rainwater is influenced by multiple factors including roofing material, antecedent dry period, rainfall intensity, atmospheric conditions, surrounding land use, storage design, and maintenance practices (Meera & Ahammed, 2006; Abu-Zreig et al., 2019). Reinforced cement concrete (RCC), clay tiles, galvanized metal sheets, and terracotta-covered roofs each contribute distinct physicochemical characteristics to roof runoff. Consequently, effective treatment systems are essential to ensure harvested rainwater complies with drinking or domestic water quality standards.

Various low-cost point-of-use filtration technologies have been developed to improve harvested rainwater quality. Conventional sand and gravel filters primarily remove suspended solids and reduce turbidity through physical straining. Activated carbon and charcoal filters adsorb dissolved organic compounds, improve taste and odor, and reduce selected chemical contaminants. Ceramic filters provide effective removal of bacteria and protozoa through micro-porous size exclusion, while advanced membrane-based systems achieve superior microbial removal but remain relatively expensive for decentralized rural applications (Shafiquzzaman et al., 2020; Ciawi & Khoiruddin, 2024; Sombei, 2025). Recent studies consistently demonstrate that hybrid multi-stage filtration systems combining first-flush diversion, coarse filtration, adsorption media, and ceramic microfiltration achieve significantly greater treatment efficiency than individual filtration units (Dobrowsky, 2014; Raimondi et al., 2023).

Despite substantial advances in rooftop rainwater harvesting research worldwide, relatively limited information is available regarding the long-term performance of passive, gravity-driven filtration systems under the climatic conditions of Southern Rajasthan. Most published studies have focused either on system design, storage optimization, or laboratory-scale filtration performance, while comprehensive evaluations integrating roof characteristics, water quality dynamics, filtration efficiency, and regional applicability remain scarce. Furthermore, there is limited evidence concerning the suitability of locally available filtration media for decentralized domestic applications under highly seasonal monsoon conditions.

Accordingly, this review aims to synthesize existing knowledge on rooftop rainwater harvesting with particular emphasis on filtration technologies and harvested water quality. The review critically evaluates the mechanisms, performance, advantages, and limitations of commonly employed filtration systems while identifying research gaps relevant to semi-arid environments. The findings are intended to provide a scientific foundation for the development of sustainable, affordable, and efficient rooftop rainwater filtration systems capable of improving domestic water security in Southern Rajasthan and other water-stressed regions.

2. Methodology and Literature Review

2.1 Review Methodology

This study adopts a narrative critical review approach to synthesize existing knowledge on rooftop rainwater harvesting (RRWH), with particular emphasis on harvested water quality and filtration technologies suitable for decentralized domestic applications in semi-arid regions. Unlike experimental investigations, the review integrates findings from published research to identify current developments, compare filtration technologies, evaluate their effectiveness, and determine research gaps relevant to Southern Rajasthan, India.

The literature reviewed comprises peer-reviewed journal articles, review papers, doctoral dissertations, technical reports, and conference publications focusing on rooftop rainwater harvesting, rainwater quality, filtration technologies, storage systems, and water quality assessment. Priority was given to studies published during the last two decades while incorporating several landmark publications that established the scientific basis for rooftop rainwater harvesting and water quality management (Liaw & Tsai, 2004; Meera & Ahammed, 2006; Abbasi & Abbasi, 2011).

The review was organized around four principal research questions:

1. What filtration technologies are currently employed in rooftop rainwater harvesting systems?
2. How do these filtration technologies influence the physicochemical and microbiological quality of harvested rainwater?
3. Which filtration technologies are most appropriate for semi-arid environments such as Southern Rajasthan?
4. What knowledge gaps remain for future research?

To answer these questions, published studies were comparatively analyzed according to the following criteria:

- Climatic and geographical conditions of the study area;
- Characteristics of rooftop catchments;
- Physicochemical and microbiological quality of harvested rainwater;
- Filtration media and treatment mechanisms;
- Removal efficiency for physical, chemical, and biological contaminants;
- Operational requirements, maintenance, and economic feasibility;
- Suitability for decentralized and resource-limited applications.

The collected literature was subsequently classified into five thematic categories:

1. Rooftop rainwater harvesting potential and system design;
2. Rainwater quality and contamination dynamics;
3. Water quality assessment methods;
4. Filtration technologies and treatment performance;
5. Research gaps and future technological developments.

This thematic organization enables systematic comparison among different studies while identifying common findings and unresolved challenges associated with rooftop rainwater harvesting.

2.2 Global Development of Rooftop Rainwater Harvesting Research

Rainwater harvesting has evolved from a traditional water conservation practice into an important component of integrated urban and rural water resource management. Increasing freshwater scarcity, rapid urbanization, and climate variability have accelerated research on rooftop rainwater harvesting worldwide (Khanal, 2020; Campisano et al., 2017; Singh et al., 2025).

Earlier investigations primarily focused on estimating the quantity of harvestable rainwater and determining appropriate storage capacities (Liaw & Tsai, 2004). Subsequent studies expanded their scope to include system reliability, economic feasibility, and optimization of storage tanks under varying climatic conditions (Basinger et al., 2010; Amos et al., 2016; Jaradat & Özkök, 2024). More recent research has increasingly emphasized harvested water quality, public health concerns, and sustainable treatment technologies necessary for potable and non-potable applications (Brião et al., 2024; Raimondi et al., 2023).

Several studies have demonstrated that rooftop rainwater harvesting can substantially reduce dependence on centralized water supplies. For example, Basinger et al. (2010) reported considerable reductions in potable water demand and stormwater runoff through optimized rooftop harvesting systems. Similarly, Campisano et al. (2017) observed that appropriately designed systems could save between 38% and 65% of domestic water used for toilet flushing, while Jaradat and Özkök (2024) estimated that nationwide implementation of rooftop rainwater harvesting could contribute significantly to Jordan's annual water supply.

In addition to water conservation, rooftop rainwater harvesting contributes to groundwater recharge, flood mitigation, climate resilience, and sustainable urban water management (Zhang et al., 2012; Gwenzi & Nyamadzawo, 2014; Singh et al., 2025). Consequently, RRWH has become an important strategy for achieving sustainable development goals related to water security.

2.3 Rooftop Rainwater Harvesting in India and Semi-Arid Regions

In India, rooftop rainwater harvesting has gained increasing importance due to declining groundwater levels, erratic monsoon rainfall, and expanding domestic water demand. Rajasthan, one of India's most water-deficient states, has a long tradition of indigenous rainwater harvesting structures including Taankas, Kundis, Johads, and Baoris, reflecting centuries of adaptation to water scarcity (Singh Rathore et al., 2020).

Modern RRWH systems are increasingly being promoted throughout Rajasthan to supplement domestic water supplies and reduce groundwater exploitation. Studies conducted in Rajasthan have demonstrated considerable potential for rooftop harvesting in both urban and rural settings (Biswa, 2018; Gavhane et al., 2023; Kumar et al., 2024). GIS-based investigations have further identified highly suitable locations for rainwater harvesting structures by integrating rainfall, land use, slope, drainage density, and soil characteristics (Dadhich & Mathur, 2016; Gavhane et al., 2023).

Several investigations have also highlighted the importance of optimizing rooftop area, storage tank capacity, and runoff coefficients to maximize harvesting efficiency (Liaw & Tsai, 2004; Mun & Han, 2012). These studies collectively indicate that well-designed rooftop harvesting systems can significantly improve local water availability while reducing dependence on groundwater resources.

2.4 Water Quality Considerations in Rooftop Rainwater Harvesting

Although rainwater is naturally low in dissolved impurities before atmospheric contact, its quality changes considerably after interacting with rooftop catchments. Numerous studies have shown that harvested rainwater frequently contains elevated concentrations of suspended solids, organic matter, microorganisms, and occasionally dissolved metals depending on roofing materials and surrounding environmental conditions (Meera & Ahammed, 2006; Abu-Zreig et al., 2019; Bañas et al., 2023).

Roof materials influence several physicochemical characteristics of harvested water. Reinforced concrete roofs may increase pH, hardness, and dissolved solids due to cement leaching, whereas metal roofs can contribute trace metals through corrosion. Dust accumulation, leaves, insects, animal droppings, and atmospheric deposition substantially increase turbidity and suspended solids, particularly during the first rainfall following prolonged dry periods (Abu-Zreig et al., 2019).

Microbiological contamination represents the greatest public health concern associated with rooftop rainwater harvesting. Reviews conducted by Meera and Ahammed (2006), Morales Rojas et al. (2021), and Raimondi et al. (2023) consistently reported the presence of total coliforms, *Escherichia coli*, Enterococcus species, and other pathogenic microorganisms in untreated harvested rainwater. These contaminants primarily originate from bird droppings, animal activity, insects, and organic debris accumulated on roof surfaces.

Consequently, harvested rainwater generally requires appropriate treatment before being considered suitable for domestic consumption.

2.5 Development of Low-Cost Filtration Technologies

Ensuring safe utilization of rooftop harvested rainwater depends largely on effective filtration and treatment systems. Considerable research has therefore focused on developing affordable filtration technologies capable of removing physical, chemical, and microbiological contaminants.

Traditional filtration systems composed of graded sand and gravel remain among the most widely adopted due to their simplicity, low cost, and ability to remove suspended solids and turbidity. However, these filters exhibit relatively poor performance in removing dissolved contaminants and pathogenic microorganisms (Shafiquzzaman et al., 2020).

Activated carbon and charcoal have been widely incorporated into filtration systems because of their high adsorption capacity for dissolved organic compounds, taste, odor, and selected chemical pollutants. Multi-layer filters combining sand, charcoal, gravel, and locally available media have demonstrated improved treatment performance compared with conventional single-media filters (Dobrowsky, 2014; Kumar et al., 2024).

Recent advances in ceramic filtration have substantially improved microbial removal efficiency through micro-porous size exclusion mechanisms. Ceramic filters have demonstrated removal efficiencies exceeding 97% for turbidity and suspended solids while effectively reducing bacterial contamination (Ciawi & Khoiruddin, 2024). Nevertheless, their performance decreases for dissolved contaminants, requiring complementary treatment processes.

Advanced membrane technologies and nanomaterial-coated filtration systems have shown excellent removal efficiencies for microorganisms and trace contaminants. However, their relatively high installation and maintenance costs currently limit widespread adoption in low-income and rural communities (Sombei, 2025).

As a result, recent literature increasingly recommends hybrid multi-stage filtration systems that integrate first-flush diversion, coarse filtration, activated carbon adsorption, and ceramic filtration to maximize overall treatment efficiency while maintaining affordability and operational simplicity (Raimondi et al., 2023; Brião et al., 2024).

2.6 Research Trends and Existing Knowledge Gaps

The literature demonstrates a clear transition from quantity-based assessments of rooftop rainwater harvesting toward comprehensive investigations of water quality and decentralized treatment technologies. While considerable progress has been achieved in optimizing storage systems and evaluating filtration media, several important research gaps remain.

First, relatively few studies have evaluated long-term field performance of passive gravity-driven filtration systems under highly seasonal monsoonal climates typical of semi-arid regions. Second, comparative investigations involving different rooftop materials under identical environmental conditions remain limited. Third, there is insufficient information regarding the durability, maintenance requirements, and life-cycle performance of low-cost hybrid filtration systems developed using locally available materials. Furthermore, most published studies evaluate filtration performance under laboratory conditions, whereas long-term field validation under actual household operating conditions is still scarce. Additional research is therefore required to optimize hybrid filtration configurations that simultaneously achieve high removal efficiencies for suspended solids, dissolved contaminants, and pathogenic microorganisms while remaining economically feasible for decentralized domestic water supply systems.

Addressing these knowledge gaps is essential for improving rooftop rainwater harvesting systems in Southern Rajasthan and other semi-arid regions experiencing increasing water scarcity.

3. Rainwater Quality and Catchment Characteristics

The quality of harvested rooftop rainwater is a critical factor determining its suitability for domestic, agricultural, and potable applications. Although rainwater is generally regarded as one of the cleanest natural water sources before reaching the earth's surface, its quality undergoes considerable changes during atmospheric transport, contact with rooftop catchments, and subsequent storage. Numerous studies have demonstrated that harvested rainwater often contains varying concentrations of physical, chemical, and microbiological contaminants, making appropriate treatment essential before human consumption (Meera & Ahammed, 2006; Raimondi et al., 2023; Brião et al., 2024).

The quality of rooftop runoff is influenced by multiple interacting factors, including roofing material, antecedent dry period, rainfall characteristics, atmospheric pollution, surrounding environmental conditions, storage systems, and maintenance practices. Understanding these factors is fundamental for designing efficient filtration systems capable of producing safe and reliable water supplies.

3.1 Factors Influencing Rooftop Rainwater Quality

The composition of harvested rainwater depends on both natural and anthropogenic factors. During dry weather, roof surfaces gradually accumulate atmospheric dust, suspended particles, leaves, pollen, insects, bird droppings, and other organic debris. Industrial emissions, vehicle exhaust, and agricultural activities may further contribute airborne pollutants that settle on rooftop surfaces. These accumulated contaminants are washed into storage systems during subsequent rainfall events, particularly during the initial runoff known as the *first flush* (Abu-Zreig et al., 2019; Bañas et al., 2023).

Rainfall intensity and duration also significantly influence harvested water quality. Initial rainfall events generally exhibit higher concentrations of suspended solids, dissolved substances, and microorganisms because contaminants accumulated during antecedent dry periods are rapidly mobilized. As rainfall continues, contaminant concentrations gradually decline owing to the progressive cleaning of roof surfaces, resulting in improved water quality during later stages of the rainfall event (Abu-Zreig et al., 2019).

Environmental conditions surrounding buildings further affect rainwater quality. Roofs located near industrial areas, busy roads, agricultural fields, or densely vegetated environments are more susceptible to contamination from particulate matter, heavy metals, pesticides, and biological materials. Consequently, harvested rainwater quality may vary considerably even within the same climatic region.

3.2 Influence of Rooftop Catchment Materials

Roof catchment material is one of the most influential factors governing the physicochemical characteristics of harvested rainwater. Different roofing materials contribute varying quantities of dissolved minerals, suspended solids, and trace contaminants while also influencing runoff efficiency and pollutant accumulation.

Common roofing materials used in India include reinforced cement concrete (RCC), clay tiles, galvanized iron sheets, corrugated metal roofs, and terracotta-covered roofs. Studies have shown that reinforced concrete roofs frequently increase the pH, calcium hardness, alkalinity, and total dissolved solids (TDS) of harvested water because of cement leaching during early rainfall events (Bañas et al., 2023). Metal roofs may contribute trace concentrations of iron, zinc, or other metals through gradual corrosion, whereas clay-tiled roofs generally release fewer dissolved constituents but may accumulate greater quantities of dust and organic matter owing to their relatively rough surface characteristics (Meera & Ahammed, 2006). Experimental studies comparing different roofing materials have reported considerable variations in water quality parameters such as electrical conductivity (EC), turbidity, suspended solids, and biochemical oxygen demand (BOD). Erikottil and Sathian (2014) observed that runoff collected from clay-tiled roofs, terracotta-paved RCC roofs, old RCC roofs, and new RCC roofs exhibited similar pH values close to neutrality, whereas turbidity, suspended solids, and EC varied depending on roof type and rainfall events. These findings indicate that roofing material influences water quality primarily through differences in surface roughness, weathering characteristics, and contaminant accumulation rather than through major changes in acidity or alkalinity.

In semi-arid regions such as Southern Rajasthan, prolonged dry seasons allow substantial accumulation of dust and windblown particles on roof surfaces. Consequently, rooftop characteristics become increasingly important in determining the initial pollutant load entering rainwater harvesting systems.

3.3 Physicochemical Characteristics of Harvested Rainwater

The physicochemical quality of rooftop rainwater is commonly evaluated using parameters including pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), hardness, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and selected heavy metals.

Among these parameters, turbidity and suspended solids generally exhibit the greatest variation following rainfall events. Elevated turbidity primarily results from roof dust, soil particles, decaying organic matter, and atmospheric deposition accumulated during dry periods. High turbidity not only reduces the aesthetic quality of harvested water but also interferes with subsequent disinfection processes by shielding microorganisms from treatment.

Several studies have reported that TDS and hardness are generally higher during the first rainfall events of the monsoon season before gradually declining as roofs become naturally cleaned by continued precipitation (Abu-Zreig et al., 2019). Similarly, RCC roofs may initially contribute increased alkalinity and calcium hardness owing to cement dissolution, whereas weathered roofs often release greater concentrations of suspended particles because of surface deterioration.

Organic contamination is commonly assessed using biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Elevated values indicate the presence of decomposing organic matter such as leaves, bird droppings, and other biological debris. Such contamination not only deteriorates water quality but also promotes microbial growth during storage if appropriate treatment is not provided.

Although heavy metals are generally present at low concentrations, localized contamination may occur depending on roofing materials and surrounding environmental conditions. Consequently, regular monitoring of physicochemical parameters remains essential for evaluating the safety of harvested rainwater.

3.4 Microbiological Quality and Public Health Concerns

Microbiological contamination represents the most significant limitation to the direct use of rooftop harvested rainwater for drinking purposes. Unlike physicochemical contaminants, pathogenic microorganisms pose immediate health risks and may cause waterborne diseases if untreated water is consumed.

The principal sources of microbial contamination include bird droppings, animal faeces, insects, decaying vegetation, and airborne microorganisms deposited on rooftop surfaces during dry weather. These contaminants are subsequently transported into storage tanks during rainfall events.

Numerous investigations have consistently reported the presence of total coliforms, *Escherichia coli*, faecal coliforms, Enterococcus species, and other pathogenic microorganisms in untreated rooftop runoff (Meera & Ahammed, 2006; Morales Rojas et al., 2021; Raimondi et al., 2023). The occurrence of these microbial indicators demonstrates that harvested rainwater frequently fails to comply with international drinking water standards without additional treatment.

Microbial contamination tends to be highest during the initial stages of rainfall because the first runoff transports accumulated biological materials from roof surfaces. The associated health risks include gastrointestinal infections, diarrhoeal diseases, and other waterborne illnesses, particularly among children, elderly individuals, and immunocompromised populations.

Consequently, effective filtration combined with appropriate disinfection or microbial removal technologies is indispensable whenever rooftop harvested rainwater is intended for potable use.

3.5 Water Quality Assessment and Monitoring

Assessment of harvested rainwater quality requires systematic monitoring of physical, chemical, and microbiological parameters. Traditional water quality assessment has relied primarily on individual laboratory measurements; however, integrating multiple parameters into Water Quality Indices (WQIs) provides a more comprehensive evaluation of overall water quality.

Abbasi and Abbasi (2011) highlighted that conventional WQIs are largely based on physicochemical parameters and frequently neglect biological indicators despite their direct relevance to public health. The authors advocated incorporating bioassessment-based indicators into water quality evaluation to improve diagnostic capability, particularly for developing countries where microbiological contamination remains a major concern.

Routine monitoring of harvested rainwater should therefore include both physicochemical parameters (such as pH, turbidity, EC, TDS, hardness, BOD, and COD) and microbiological indicators including total coliforms and *Escherichia coli*. Such comprehensive assessment enables effective evaluation of filtration performance and ensures harvested rainwater satisfies intended water quality standards.

3.6 Implications for Filtration System Design

The diverse range of contaminants present in rooftop runoff demonstrates that no single treatment process is capable of providing complete purification. Suspended solids, dissolved organic compounds, nutrients, trace metals, and pathogenic microorganisms require different removal mechanisms, including sedimentation, physical filtration, adsorption, and microbial disinfection.

Consequently, filtration systems intended for rooftop rainwater harvesting should be designed according to the characteristics of local catchment materials, rainfall patterns, and anticipated contaminant loads. In semi-arid regions such as Southern Rajasthan, where extended dry periods lead to substantial pollutant accumulation on rooftops, incorporating an effective first-flush diverter followed by multi-stage filtration becomes particularly important.

The literature consistently indicates that integrated treatment systems combining first-flush diversion, coarse filtration, adsorption media, and fine filtration offer superior protection against both physicochemical and microbiological contamination compared with conventional single-stage filters. Therefore, understanding rainwater quality dynamics forms the scientific basis for selecting appropriate filtration technologies, which are discussed in the following section.

4. Filtration Technologies for Rooftop Rainwater Harvesting

4.1 Introduction

Although rooftop rainwater harvesting (RRWH) provides a sustainable alternative water source, harvested rainwater generally requires treatment before domestic use because runoff acquires various physical, chemical, and microbiological contaminants while flowing across roof surfaces. The composition of these contaminants depends on roof characteristics, atmospheric deposition, surrounding environmental conditions, rainfall intensity, and storage practices. Consequently, filtration represents the most critical component of an RRWH system, directly influencing the quality and safety of stored water.

An effective filtration system should remove suspended solids, organic matter, dissolved contaminants, pathogenic microorganisms, unpleasant taste and odor, while remaining affordable, easy to maintain, and suitable for decentralized applications. Numerous treatment technologies have therefore been developed, ranging from simple gravel filters to advanced membrane-based systems. However, no individual filtration medium is capable of removing every class of contaminant. Recent research increasingly recommends multi-stage treatment systems that integrate different filtration mechanisms to achieve comprehensive water purification (Dobrowsky, 2014; Raimondi et al., 2023; Sombei, 2025).

4.2 First-Flush Diverter

The first-flush diverter is widely recognized as the first and most essential treatment component of rooftop rainwater harvesting systems. Its primary function is not filtration but prevention of contamination by diverting the initial runoff generated during rainfall events.

During prolonged dry periods, rooftops accumulate dust, bird droppings, leaves, insects, atmospheric pollutants, and other contaminants. The initial rainfall mobilizes these deposits, producing runoff with substantially higher turbidity, suspended solids, organic matter, dissolved ions, and microbial contamination than later rainfall. Abu-Zreig et al. (2019) demonstrated that turbidity, hardness, and total dissolved solids were highest during the first storms of the rainy season and gradually decreased after successive rainfall events. Similar observations have been reported by Bañas et al. (2023), who emphasized that the initial runoff contains the highest pollutant concentrations due to accumulated atmospheric deposition.

To minimize this contamination, first-flush diverters automatically bypass the first 1–2 mm of rainfall before allowing cleaner runoff to enter the storage tank. Zabidi et al. (2020) reported that incorporating first-flush devices significantly reduces suspended solids and organic loading entering downstream filtration units while extending filter lifespan by reducing clogging.

Although first-flush systems do not independently produce potable water, they substantially improve the performance of subsequent filtration stages and are therefore considered indispensable in modern rooftop rainwater harvesting systems.

4.3 Screen and Mesh Filters

Screen or mesh filters constitute the primary physical filtration stage immediately downstream of rooftop gutters. These filters remove large suspended materials including leaves, twigs, insects, feathers, and coarse debris before water enters finer filtration media.

Micro-mesh filters generally consist of stainless-steel or polymer screens with small pore openings that physically intercept coarse particles while allowing water to pass through. Their principal advantage lies in their simplicity, low installation cost, minimal hydraulic resistance, and ease of cleaning.

Erikottil and Sathian (2014) evaluated an improved roof water filtration system incorporating a reusable micro-mesh filter followed by secondary filtration units. Their investigation demonstrated that the mesh filter alone removed approximately 81% of suspended particles and turbidity while significantly reducing

biochemical oxygen demand. However, because mesh filters operate exclusively through physical straining, they provide little protection against dissolved contaminants and microorganisms.
Consequently, screen filters are generally regarded as pre-treatment units that protect downstream filtration media rather than complete treatment systems.

4.4 Sand and Gravel Filters

Sand and gravel filtration remains one of the oldest and most widely adopted technologies for decentralized water treatment because of its low construction cost, simple operation, and locally available materials.

The filtration mechanism primarily involves physical straining, sedimentation, interception, and adsorption onto sand particle surfaces. Larger suspended particles become trapped within pore spaces, while finer particles gradually settle within the filter bed as water moves downward through successive gravel and sand layers.

Several investigations have confirmed that conventional sand filters effectively reduce turbidity, suspended solids, and visible particulate matter (Shafiquzzaman et al., 2020). Similarly, Kumar et al. (2024) evaluated different low-cost filter configurations for rooftop rainwater harvesting and reported filtration efficiencies ranging from approximately 83% to 97%, depending on media arrangement.

Despite these advantages, conventional sand filters exhibit several limitations. Their effectiveness decreases considerably for dissolved contaminants such as nitrates, phosphates, dissolved organic compounds, and heavy metals. Furthermore, fine particles progressively clog pore spaces, reducing filtration rates and increasing maintenance requirements. Biofilm accumulation may also occur if cleaning intervals are neglected.

Nevertheless, owing to their affordability and ease of construction, sand and gravel filters remain an important component of rural rainwater harvesting systems, particularly when integrated with complementary treatment technologies.

4.5 Activated Carbon and Charcoal Filters

Activated carbon and charcoal are among the most widely used adsorption media in decentralized water treatment systems. Their extremely high internal surface area enables efficient adsorption of dissolved organic compounds, colour, taste, odour, chlorine residues, pesticides, and selected heavy metals.
Unlike sand filtration, which primarily removes suspended particles, activated carbon functions through adsorption, whereby dissolved molecules attach to the porous carbon surface through physical and chemical interactions.

Dobrowsky (2014) emphasized that activated carbon substantially improves aesthetic water quality by reducing taste, odour, and dissolved organic carbon. Likewise, Kumar et al. (2024) reported improved filtration efficiency after incorporating charcoal into multilayer rooftop rainwater filters.

Experimental investigations conducted by Erikottil and Sathian (2014) further demonstrated that combining charcoal with micro-mesh filtration significantly reduced turbidity, electrical conductivity, biochemical oxygen demand, and microbial contamination compared with mesh filtration alone.

However, adsorption capacity gradually declines as pore spaces become saturated. Consequently, activated carbon requires periodic replacement or regeneration to maintain treatment efficiency. Inadequate maintenance may result in microbial colonization of exhausted carbon beds.

4.6 Ceramic Filtration

Ceramic filtration has emerged as one of the most promising low-cost technologies for decentralized drinking water treatment. Ceramic filters are manufactured from porous clay materials that contain interconnected microscopic pores capable of retaining suspended solids and microorganisms through size exclusion.

Unlike conventional sand filters, ceramic membranes effectively remove bacteria, protozoa, and fine suspended particles while maintaining relatively simple operation under gravity-driven conditions.

Shafiquzzaman et al. (2020) evaluated low-cost ceramic filters under arid environmental conditions and reported turbidity removal efficiencies exceeding 97%, together with substantial reductions in suspended solids and microbial contamination. Similarly, Ciawi and Khoiruddin (2024) reviewed recent advances in antibacterial ceramic filters and concluded that silver-impregnated ceramic media exhibit exceptional bacterial removal through combined physical filtration and antimicrobial activity.

Despite these advantages, ceramic filters possess relatively limited capacity for removing dissolved salts and low-molecular-weight organic compounds. Furthermore, pore blockage progressively reduces filtration rates, necessitating routine cleaning.

Nevertheless, ceramic filtration represents one of the most suitable treatment technologies for rural households because it combines high microbial removal efficiency with low energy requirements and simple operation.

4.7 Advanced Membrane and Nanotechnology-Based Filters

Recent developments in membrane science have produced highly efficient filtration systems capable of removing bacteria, viruses, dissolved organic matter, and trace contaminants simultaneously.

These systems include ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and nanomaterial-coated membranes incorporating antimicrobial nanoparticles such as silver (Ag) and zinc oxide (ZnO).

Brião et al. (2024) reported that combining ultrafiltration with ultraviolet disinfection or chlorination produces harvested rainwater meeting potable water standards. Likewise, Ciawi and Khoiruddin (2024) observed excellent microbial inactivation using antibacterial ceramic membranes coated with silver nanoparticles.

Although these technologies provide outstanding treatment efficiency, several limitations restrict their widespread adoption in rural communities. High installation costs, membrane fouling, pressure requirements, skilled maintenance, and potential nanoparticle release remain important challenges (Sombei, 2025).

Consequently, advanced membrane systems are currently more suitable for institutional or centralized applications than small decentralized household systems.

4.8 Hybrid Multi-Stage Filtration Systems

Current research increasingly concludes that no single filtration medium can effectively remove every category of contaminant present in rooftop runoff. Physical particles, dissolved organic compounds, nutrients, trace metals, bacteria, viruses, and protozoa each require different treatment mechanisms. Hybrid filtration systems therefore combine multiple treatment stages to maximize overall removal efficiency.

A typical hybrid filtration sequence consists of:
Roof Catchment → First Flush Diverter → Mesh Filter → Sand and Gravel Filter → Activated Carbon/Charcoal → Ceramic Filter → Storage Tank

Within this configuration:

- the first flush removes highly contaminated initial runoff;
- mesh filters intercept coarse debris;
- sand and gravel remove suspended solids;
- activated carbon adsorbs dissolved organic compounds and improves taste and odour;
- ceramic filtration removes bacteria and fine suspended particles.

Studies by Dobrowsky (2014), Raimondi et al. (2023), Kumar et al. (2024), and Brião et al. (2024) consistently demonstrate that hybrid systems outperform single-media filters because different treatment mechanisms operate sequentially.

For semi-arid regions such as Southern Rajasthan, hybrid gravity-driven filtration systems offer several advantages:

- high treatment efficiency;
- low energy requirement;
- inexpensive construction materials;
- simple operation;
- reduced maintenance costs;
- suitability for rural households.

These characteristics make hybrid filtration the most promising approach for sustainable decentralized rooftop rainwater harvesting.

4.9 Comparative Assessment of Filtration Technologies

A comparison of the reviewed filtration technologies indicates that each treatment method possesses distinct strengths and limitations (Table X). Conventional sand and gravel filters remain highly effective for turbidity reduction but provide limited microbial removal. Activated carbon substantially improves chemical quality and aesthetic characteristics through adsorption, whereas ceramic filters provide excellent microbial removal but only moderate dissolved contaminant removal.

Advanced membrane systems demonstrate the highest treatment efficiencies but remain economically unsuitable for widespread rural implementation. Conversely, hybrid filtration systems combine complementary treatment mechanisms and therefore achieve the most balanced overall performance.

The literature consistently indicates that future decentralized rainwater harvesting systems should emphasize passive, gravity-driven hybrid filtration configurations incorporating first-flush diversion, coarse filtration, adsorption media, and ceramic filtration. Such systems offer the best compromise between water quality improvement, affordability, operational simplicity, and long-term sustainability under the climatic conditions of Southern Rajasthan.

5. Comparative Analysis and Discussion

5.1 Comparative Performance of Filtration Technologies

The reviewed literature demonstrates that the effectiveness of rooftop rainwater filtration depends not only on the individual filtration medium but also on the nature of contaminants present in harvested runoff. Physical, chemical, and microbiological pollutants exhibit distinct characteristics and therefore require different treatment mechanisms. Consequently, no single filtration technology is capable of providing comprehensive purification of harvested rainwater.

The first-flush diverter consistently emerged as the most effective pre-treatment component across the reviewed studies. Although it does not directly purify water, diverting the initial roof runoff substantially reduces the pollutant load entering subsequent filtration units. Studies by Abu-Zreig et al. (2019) and Bañas et al. (2023) demonstrated that the first rainfall after prolonged dry periods contains the highest concentrations of suspended solids, organic matter, and microbial contaminants. Removing this highly contaminated fraction improves overall treatment efficiency while extending the operational life of downstream filters.

Conventional mesh filters provide an economical and simple method for removing coarse debris such as leaves, insects, feathers, and other visible particulates. Their contribution is primarily limited to protecting downstream filtration units from clogging rather than improving overall water quality. Because they rely solely on mechanical screening, mesh filters have negligible effectiveness in removing dissolved pollutants or pathogenic microorganisms.

Sand and gravel filters remain the most widely adopted filtration technology owing to their low construction cost, simple design, and use of locally available materials. These filters effectively reduce turbidity, suspended solids, and particulate organic matter through sedimentation, interception, and physical straining. However, the literature consistently reports limited removal of dissolved contaminants and only partial reduction of microbial populations. Filter clogging, reduced hydraulic conductivity, and frequent maintenance further limit long-term performance, particularly in regions with high dust accumulation such as Southern Rajasthan.

Activated carbon and charcoal filters significantly improve the chemical and aesthetic quality of harvested rainwater. Their large internal surface area provides efficient adsorption of dissolved organic compounds, taste- and odour-causing substances, and selected trace contaminants. However, adsorption is a finite process, and treatment efficiency gradually decreases as adsorption sites become saturated. Regular replacement or regeneration of activated carbon is therefore essential to maintain filtration performance.
Among low-cost technologies, ceramic filtration exhibited the highest microbial removal efficiency. Ceramic filters effectively remove bacteria, protozoa, and fine suspended particles through micro-porous size exclusion while requiring minimal energy input. Studies reviewed in this paper consistently reported substantial reductions in microbial indicators following ceramic filtration. Nevertheless, ceramic filters have limited capacity for removing dissolved inorganic salts and low-molecular-weight organic compounds, indicating that they are most effective when integrated with adsorption-based treatment processes.

Advanced membrane technologies, including ultrafiltration, nanofiltration, and reverse osmosis, demonstrated superior removal efficiencies for virtually all categories of contaminants. These systems produce water that frequently satisfies international drinking water standards. However, their widespread application in decentralized rooftop rainwater harvesting remains constrained by high installation costs, membrane fouling, energy requirements, and maintenance complexity. Consequently, membrane technologies are currently more appropriate for institutional and centralized treatment facilities than for rural household applications.

Overall, the comparative analysis clearly indicates that filtration technologies should be regarded as complementary rather than competing treatment options. Each technology addresses specific contaminant groups, making integrated treatment systems substantially more effective than individual filtration units.

5.2 Effect of Catchment Characteristics on Filtration Performance

The reviewed studies collectively demonstrate that roof catchment characteristics strongly influence filtration efficiency. Roofing materials determine both the quantity and composition of contaminants entering rainwater harvesting systems. Reinforced cement concrete roofs frequently increase alkalinity, hardness, and dissolved solids due to cement leaching, whereas clay-tiled roofs tend to accumulate larger quantities of dust and organic debris because of their relatively rough surfaces. Metal roofs may contribute trace metals through corrosion, particularly under acidic atmospheric conditions.

Antecedent dry periods also play a significant role in determining filtration requirements. In semi-arid climates, prolonged dry seasons allow substantial accumulation of atmospheric dust, particulate matter, bird droppings, and organic debris on rooftop surfaces. As a result, the pollutant load entering harvesting systems during the first rainfall event is considerably greater than in humid environments. Under such conditions, incorporating first-flush diversion and efficient pre-filtration becomes essential for maintaining overall treatment efficiency and extending filter service life.

Rainfall intensity similarly influences harvested water quality. Low-intensity rainfall generally removes accumulated contaminants gradually, whereas intense rainfall events rapidly mobilize large quantities of roof deposits, producing short-term increases in turbidity and suspended solids. These observations emphasize that filtration systems should be designed according to local climatic conditions rather than adopting a universal configuration.

5.3 Suitability of Filtration Technologies for Decentralized Applications

An important objective of rooftop rainwater harvesting is to provide sustainable and affordable water treatment solutions for decentralized domestic use. Therefore, filtration technologies should be evaluated not only on contaminant removal efficiency but also on cost, operational simplicity, maintenance requirements, availability of construction materials, and long-term sustainability.

Conventional sand, gravel, and charcoal filters continue to offer significant advantages for rural communities because they utilize inexpensive, locally available materials and require minimal technical expertise. However, relying exclusively on these filters may not consistently achieve drinking water standards, particularly with respect to microbial contamination.

Ceramic filtration provides an effective balance between treatment performance and affordability. Gravity-driven ceramic filters require no external energy source and can substantially improve microbiological water quality while maintaining relatively simple operation. These characteristics make ceramic filtration particularly attractive for household-scale applications in developing countries.

Although advanced membrane technologies offer superior purification performance, their high cost and operational complexity limit their practical application in low-resource settings. Consequently, most recent studies recommend hybrid treatment systems that integrate low-cost physical filtration with adsorption and ceramic filtration rather than relying exclusively on sophisticated membrane technologies.

5.4 Advantages of Hybrid Multi-Stage Filtration Systems

One of the most consistent findings emerging from the reviewed literature is the superiority of hybrid multi-stage filtration systems over single-stage treatment units. Since different contaminants require different removal mechanisms, integrating multiple filtration media allows each treatment stage to target a specific group of pollutants.

A typical hybrid system consists of a first-flush diverter followed by mesh filtration, sand and gravel filtration, activated carbon adsorption, ceramic filtration, and finally storage. Within this configuration, coarse particles are removed during the initial stages, dissolved organic compounds are adsorbed by activated carbon, and microorganisms are eliminated through ceramic microfiltration.

Several studies reported that hybrid systems achieve significantly higher reductions in turbidity, suspended solids, biochemical oxygen demand, dissolved organic matter, and microbial contamination than conventional filters operating independently. Furthermore, distributing treatment among multiple stages reduces the loading on individual filtration media, decreases clogging, extends filter lifespan, and reduces maintenance frequency.

For semi-arid regions such as Southern Rajasthan, where rooftop runoff exhibits high seasonal variability and elevated particulate loads during the onset of the monsoon, hybrid filtration provides a practical and sustainable solution capable of producing consistently improved water quality under decentralized operating conditions.

5.5 Implications for Southern Rajasthan

Southern Rajasthan experiences irregular rainfall, prolonged dry periods, increasing groundwater depletion, and growing domestic water demand. These conditions make rooftop rainwater harvesting an important supplementary water resource. However, the climatic characteristics of the region also promote substantial accumulation of dust and atmospheric particulates on rooftop surfaces, resulting in poor water quality during the initial rainfall events.

Based on the reviewed literature, an effective rooftop rainwater harvesting system for Southern Rajasthan should incorporate four essential treatment components: (i) a first-flush diverter to exclude highly contaminated initial runoff, (ii) a mesh filter for removal of coarse debris, (iii) a multilayer sand–gravel–activated carbon filter for reducing suspended solids and dissolved organic contaminants, and (iv) a ceramic filter for microbial removal prior to storage.

Such a gravity-driven multi-stage filtration system combines high treatment efficiency with affordability, simple maintenance, and the use of locally available materials, making it particularly suitable for rural households, educational institutions, and community buildings. Moreover, integrating these treatment stages can substantially improve harvested rainwater quality while reducing dependence on increasingly stressed groundwater resources.

5.6 Overall Discussion

The collective evidence indicates that rooftop rainwater harvesting has evolved from a simple water collection practice into an integrated decentralized water treatment strategy. Recent research has progressively shifted from maximizing harvested water quantity toward ensuring water quality and public health protection. This transition has driven the development of increasingly sophisticated filtration systems capable of addressing the diverse contaminants present in rooftop runoff.

Despite these advances, no universally applicable filtration technology currently exists. The performance of any treatment system depends on local climatic conditions, rooftop materials, pollutant characteristics, maintenance practices, and intended water use. Therefore, filtration technologies should be selected through site-specific evaluation rather than generalized recommendations.

Among the reviewed technologies, hybrid gravity-driven filtration systems provide the most balanced combination of contaminant removal efficiency, affordability, operational simplicity, and sustainability. These systems are particularly well suited to decentralized rooftop rainwater harvesting in semi-arid regions, where maximizing water quality using low-cost, locally available materials remains a primary objective.

6. Research Gaps and Future Scope

6.1 Research Gaps

The literature reviewed demonstrates substantial progress in rooftop rainwater harvesting (RRWH) research over the past two decades. Early investigations primarily focused on estimating the quantity of harvestable rainwater and optimizing storage capacities, whereas more recent studies have increasingly emphasized water quality assessment and the development of efficient filtration technologies. Despite these advances, several important research gaps remain, particularly concerning decentralized applications in semi-arid regions.

6.1.1 Limited Long-Term Field Evaluation

Most published studies have evaluated filtration systems under laboratory or short-term experimental conditions. While these investigations provide valuable information regarding contaminant removal efficiencies, they often fail to represent actual field conditions where rainfall variability, seasonal changes, roof ageing, dust accumulation, and maintenance practices influence system performance. Long-term monitoring studies evaluating filtration efficiency over multiple monsoon seasons are still limited, particularly under the climatic conditions of Southern Rajasthan.

6.1.2 Insufficient Comparative Studies on Roofing Materials

Roof catchment material plays a significant role in determining harvested rainwater quality. Although several studies have investigated individual roof types, comprehensive comparative evaluations involving reinforced cement concrete (RCC), clay tiles, terracotta-paved roofs, galvanized iron sheets, and other locally used roofing materials under identical environmental conditions remain scarce. Such comparisons are essential for understanding the influence of roofing material on contaminant loading and for designing appropriate filtration systems.

6.1.3 Limited Integration of Physicochemical and Microbiological Assessment

Many investigations emphasize either physicochemical parameters (such as pH, turbidity, electrical conductivity, and total dissolved solids) or microbiological indicators (such as total coliforms and *Escherichia coli*), but relatively few studies comprehensively evaluate both groups simultaneously. Since harvested rainwater quality is influenced by multiple contaminant classes, integrated assessment is necessary to accurately determine treatment requirements and ensure compliance with drinking water standards.

6.1.4 Lack of Standardized Evaluation of Low-Cost Filtration Media

Numerous low-cost filtration materials—including sand, gravel, charcoal, activated carbon, ceramic media, and locally available natural adsorbents—have been investigated independently. However, their performance has often been evaluated using different experimental conditions, making direct comparison difficult. Standardized testing protocols are required to compare filtration efficiency, hydraulic performance, maintenance requirements, and service life under similar operating conditions.

6.1.5 Inadequate Research on Hybrid Gravity-Driven Systems

The reviewed literature consistently demonstrates the superior performance of hybrid multi-stage filtration systems. Nevertheless, relatively few investigations have optimized the design configuration, sequencing of filtration media, hydraulic loading rate, and maintenance schedule for passive gravity-driven systems intended for decentralized household applications. Further research is required to determine the most effective filter combinations using locally available materials while minimizing operational costs.

6.1.6 Limited Regional Studies in Semi-Arid India

Most existing studies have been conducted in tropical, humid, or temperate climatic regions. Comprehensive investigations addressing rooftop rainwater quality and filtration under the semi-arid climatic conditions of Southern Rajasthan remain limited. Regional differences in rainfall intensity, antecedent dry periods, atmospheric dust loading, and roofing materials necessitate site-specific evaluations rather than direct adoption of findings from other geographical regions.

6.2 Future Scope

Future research should focus on developing sustainable, affordable, and region-specific rooftop rainwater treatment systems capable of providing safe domestic water supplies under varying climatic conditions.
One important research direction is the long-term field validation of hybrid gravity-driven filtration systems. Continuous monitoring over multiple rainfall seasons would provide valuable information regarding filtration efficiency, clogging behaviour, maintenance frequency, and operational reliability under actual household conditions.

Future investigations should also evaluate locally available filtration materials that can reduce construction costs while maintaining high treatment efficiency. Natural adsorbents, agricultural by-products, modified biochar, and indigenous filtration media may provide economical alternatives to commercially available activated carbon, particularly in rural communities.

Another priority involves integrating advanced analytical techniques with conventional water quality monitoring. Simultaneous assessment of physicochemical parameters, microbial indicators, heavy metals, and emerging contaminants would provide a more comprehensive understanding of harvested rainwater quality and associated public health risks.

The application of computational tools such as Geographic Information Systems (GIS), remote sensing, machine learning, and hydrological modelling offers additional opportunities for optimizing rooftop rainwater harvesting systems. These technologies can assist in identifying suitable harvesting locations, predicting water demand, optimizing storage capacity, and improving filtration system design under future climate scenarios.

Climate change adaptation should also become an important component of future RRWH research. Alterations in rainfall intensity, seasonal distribution, and extreme weather events may significantly influence rooftop runoff quality and system performance. Understanding these impacts will support the development of resilient rainwater harvesting systems capable of maintaining water quality under changing climatic conditions.

Finally, future studies should incorporate economic evaluation, life-cycle assessment, and social acceptance analysis to improve the practical implementation of rooftop rainwater harvesting technologies. Such interdisciplinary research will facilitate wider adoption of decentralized rainwater harvesting systems in water-scarce regions.

7. Conclusions

Rooftop rainwater harvesting has emerged as an effective and sustainable approach for augmenting freshwater availability in regions experiencing increasing water scarcity, groundwater depletion, and climate variability. The reviewed literature demonstrates that RRWH systems can substantially contribute to domestic water supply while reducing dependence on centralized water distribution networks and improving resilience against seasonal water shortages.

However, harvested rainwater quality remains strongly influenced by roof catchment characteristics, atmospheric deposition, antecedent dry periods, rainfall patterns, and storage conditions. Consequently, untreated rooftop runoff frequently contains elevated concentrations of suspended solids, dissolved organic matter, nutrients, and pathogenic microorganisms that may limit its suitability for direct human consumption.

The review further demonstrates that filtration constitutes the most critical component of rooftop rainwater harvesting systems. Individual filtration technologies exhibit distinct treatment capabilities. First-flush diverters effectively reduce initial contaminant loads, mesh filters remove coarse debris, sand and gravel filters provide efficient turbidity reduction, activated carbon improves chemical and aesthetic water quality through adsorption, and ceramic filters offer excellent microbial removal. Advanced membrane technologies achieve the highest purification efficiency but remain economically impractical for many decentralized rural applications due to high installation and maintenance costs.

Among the reviewed treatment approaches, hybrid multi-stage filtration systems consistently provide the most comprehensive and balanced performance. By integrating first-flush diversion, physical filtration, adsorption, and ceramic microfiltration, these systems effectively address the diverse range of contaminants present in rooftop runoff while remaining affordable, energy-efficient, and suitable for decentralized applications. Their ability to combine complementary treatment mechanisms makes them particularly appropriate for household-scale rainwater harvesting systems.

For semi-arid regions such as Southern Rajasthan, the reviewed evidence suggests that gravity-driven hybrid filtration systems constructed using locally available materials represent a practical solution for improving harvested rainwater quality. Such systems can enhance water security while minimizing construction costs, operational complexity, and maintenance requirements.

Nevertheless, significant knowledge gaps remain regarding long-term field performance, optimization of filtration media combinations, region-specific system design, and standardized evaluation methods. Addressing these limitations through multidisciplinary research will improve the reliability and sustainability of rooftop rainwater harvesting systems and support their broader adoption as an integral component of decentralized water resource management.

Overall, this review highlights that effective rooftop rainwater harvesting is not solely dependent on maximizing water collection but also on ensuring consistent water quality through appropriate filtration technologies. The development of low-cost, efficient, and locally adaptable hybrid filtration systems will play a crucial role in achieving sustainable water security in Southern Rajasthan and other water-stressed regions facing increasing pressure on conventional freshwater resources.

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