

Development of Sustainable and Cost-Effective Framework for Rain Water Treatment

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Abstract:

Rainwater harvesting is a critical approach to addressing water scarcity. However, untreated rainwater collected from ground pits often contains impurities that limit its usability. This research develops a sustainable and cost-effective framework for treating rainwater collected in ground pits. The study focuses on designing a low-cost treatment system that incorporates natural filtration materials, minimal energy resources, and minimal maintenance requirements.

Two different locations were selected to collect rainwater. Ground of Punjab Agricultural University, Ludhiana (Punjab) is selected as first location as an urban area. Second location is selected at Sidhwan Bet, Ludhiana (Punjab) as rural area. When rainfall occurs, the water will be collected from the pit dug on the open grounds of above said two locations. Quality of water collected from these two locations were compared and Cost-Effective framework for the treatment of rain water was prepared. The study revealed that reverse osmosis and activated carbon filtration achieved superior water quality at higher cost. The reduction in TDS of water was noted in Reverse osmosis method of water treatment. The pH value of water obtained from reverse osmosis method was also very low. Filter method proved effective for rainwater treatment as rainwater has very low TDS during collection of water. Increase in value of TDS was noted for the rainwater collected from ground pit with time when left undisturbed for month. Cotton rope method was proven more effective than jute rope method as quality of water can be improved with increase in density of used cotton.

Keywords: harvesting, maintenance, addressing.

1. Introduction

Water scarcity is a growing concern globally, affecting both developed and developing regions. Rainwater harvesting has emerged as a sustainable solution, offering significant potential to supplement water resources. Despite its benefits, untreated rainwater often contains impurities such as turbidity, high levels of dissolved solids, and microorganisms. Access to clean and potable water remains a critical challenge in many parts of the world, driven by population growth, urbanization, and the increasing impacts of climate change. As global water demand continues to rise, traditional water sources are under mounting pressure, leading to widespread water scarcity in urban and rural settings. Rainwater harvesting (RWH) has emerged as a viable and sustainable solution to alleviate this issue by capturing, storing, and utilizing rainwater. However, the untreated rainwater collected often

contains contaminants that make it unsuitable for various uses without adequate treatment. This research aims to develop a sustainable and cost-effective framework for rainwater treatment, focusing on the unique challenges associated with water collected from ground pits.

The potential of rainwater harvesting lies not only in its ability to supplement water supply but also in its role as a decentralized and environmentally friendly resource management strategy. Previous studies have explored various aspects of RWH, including its application in urban and rural settings, system design, and economic feasibility (Abdullah et al., 2024; Ali et al., 2024). However, the quality of harvested rainwater often varies significantly depending on the collection method, location, and environmental conditions. Rainwater collected from open ground pits is particularly susceptible to contamination from soil, debris, microbial pathogens, and dissolved organic and inorganic matter. This necessitates the development of treatment systems tailored to the unique characteristics of ground pit rainwater.

The growing interest in rainwater treatment is accompanied by advancements in filtration technologies, water quality monitoring, and resource-efficient designs. Traditional methods, such as reverse osmosis and activated carbon filtration, are effective in removing impurities but are often associated with high costs, energy consumption, and maintenance requirements (Bagheri & Davani, 2024; Böpple et al., 2024). These challenges limit their applicability, particularly in resource-constrained settings. To address these limitations, researchers have explored alternative approaches, such as natural filtration materials, low-cost adsorption systems, and biofilm-based treatments (Kim & Han, 2015; Shaheed et al., 2017). This study builds on these innovations by proposing a framework that prioritizes sustainability, cost-effectiveness, and ease of implementation.

The research presented here is unique in its focus on comparing rainwater quality collected from two distinct locations in Punjab, India: the urban environment of Punjab Agricultural University in Ludhiana and the rural setting of Sidhwan Bet. These locations were selected to provide insights into the varying characteristics of rainwater in different contexts, influenced by factors such as land use, population density, and pollution levels. By analyzing the water quality from these sites, the study identifies key parameters that influence the effectiveness of different treatment methods. Additionally, it evaluates the performance of innovative techniques, such as cotton rope filtration, which has shown promise as a low-cost and efficient alternative to conventional methods.

The study's findings contribute to the growing body of knowledge on rainwater harvesting and treatment, offering practical solutions for enhancing water quality in urban and rural settings. By integrating principles of sustainability and affordability, the proposed framework addresses critical gaps in current practices. It aligns with global efforts to promote water security, reduce dependence on centralized water supply systems, and mitigate the environmental impacts of overextraction from natural water sources.

Water scarcity is a pressing issue in Punjab, a state that has historically relied on extensive groundwater extraction to meet its agricultural and domestic water needs. Overextraction has led to significant declines in groundwater levels, exacerbating the need for alternative water sources. Rainwater harvesting has gained attention as a potential solution to this crisis, offering a decentralized approach to water management that complements existing infrastructure. However, the practical challenges of

implementing RWH systems, particularly in rural areas, underscore the need for cost-effective and low-maintenance treatment solutions.

Urban areas in Punjab face additional challenges related to water quality, including pollution from industrial activities, vehicular emissions, and urban runoff. These contaminants can significantly degrade the quality of rainwater collected from ground pits, necessitating treatment systems capable of addressing a wide range of impurities. Conversely, rural areas often encounter challenges related to accessibility, affordability, and technical expertise, which limit the adoption of advanced treatment technologies. This study's dual focus on urban and rural contexts provides a comprehensive understanding of the diverse challenges and opportunities associated with rainwater treatment in Punjab. To address these challenges, this research investigates low-cost rainwater treatment systems leveraging natural and energy-efficient materials to ensure safe and sustainable water quality. This study focuses on rainwater collected from two locations in Ludhiana, Punjab—a densely populated urban area and a rural region. The comparison of water quality from these areas provides insights into regional differences in rainwater characteristics. Furthermore, the cost-effectiveness of various treatment methods is evaluated to identify an optimal solution that balances efficiency, sustainability, and affordability.

The primary objectives of this research are:

1. To evaluate the quality of rainwater collected from ground pits in two distinct locations: an urban area (Punjab Agricultural University, Ludhiana) and a rural area (Sidhwan Bet, Ludhiana).
2. To compare the effectiveness of various rainwater treatment methods, including reverse osmosis, activated carbon filtration, and natural filtration techniques, with a focus on cost, sustainability, and water quality improvement.
3. To develop a cost-effective and sustainable framework for rainwater treatment that incorporates locally available materials, minimal energy inputs, and low maintenance requirements.
4. To provide actionable recommendations for policymakers, practitioners, and communities to enhance the adoption of rainwater treatment systems in resource-constrained settings.

2. Materials and Methods

2.1 Study Areas

The study analyzed rainwater collected from two locations in Ludhiana, Punjab:

- **Urban Site:** Punjab Agricultural University, Ludhiana.
- **Rural Site:** Sidhwan Bet, Ludhiana.

At each site, rainwater was collected in ground pits during rainfall events. Water samples were collected after 6 hours and 6 months of stagnation and tested for various physicochemical properties.

2.2 Parameters Tested

Key water quality parameters were tested, including:

- **Odor**

- **Color**
- **Electrical Conductivity (EC)**
- **Total Dissolved Solids (TDS)**
- **Turbidity**
- **pH**
- **Biochemical Oxygen Demand (BOD)**
- **Chemical Oxygen Demand (COD)**

2.3 Treatment Methods

Several rainwater treatment methods were tested, including:

1. **Coagulation:** Addition of coagulants to reduce turbidity and color.
2. **Mechanical Filtration:** Using sand and gravel filters.
3. **Activated Carbon Filtration:** Granular and powdered activated carbon were used to remove organic impurities and improve color.
4. **Reverse Osmosis (RO):** Advanced filtration to remove TDS and microorganisms.
5. **Natural Filtration (Jute and Cotton Ropes):** Utilizing natural fibers for low-cost filtration.

2.4 Cost Analysis

The cost of each treatment method was evaluated based on materials, energy consumption, and maintenance requirements. The cost-effectiveness was calculated as the ratio of water quality improvement to the cost incurred.

3. Results and Discussion

3.1 Initial Water Quality Assessment

The initial water quality assessment revealed significant differences between urban and rural samples, as shown in Table 1. Key observations include:

- TDS levels increased drastically after 6 months of stagnation, particularly in rural samples.
- Turbidity decreased significantly over time, likely due to sedimentation.
- The pH of water increased marginally after 6 months.
- Testing results for collected rainwater samples are summarized in Table 1 below:

Table 1. Initial Rainwater Testing Results

Parameter	Tested for Ludhiana after 6 hours undisturbed	Tested for Ludhiana after 6	Percentage Change (in %)	Tested for Sidhwa bet after 6 hours undisturbed	Tested for Sidhwa bet after 6	Percentage Change (in %)

		months undisturbed			months undisturbed	
Odor	NIL	NIL	-	NIL	NIL	-
True Color (HU)	3.122	14.831	375.05	3.79	15.211	301.34
Electrical Conductivity (µs/cm)	33	101	206.06	29	106	265.52
TDS (ppm)	4	49	1125	3	61	1933.33
Turbidity (NTU)	58	5	-91.38	65	4	-93.85
Hardness (ppm)	0	0	0	0	0	0
pH (ppm)	5.5	6.5	18.18	6.0	6.5	8.33
BOD (mg/L)	0.6	1.0	66.67	0.0	0.0	0
COD (mg/L)	3.0	4.0	33.33	0.0	0.0	0

3.2 Treatment Efficiency

3.2.1 Ludhiana Samples (6 hours) The results of various treatment methods applied to Ludhiana samples collected after 6 hours are presented in Table 2. Reverse osmosis and powdered activated carbon yielded the best results in reducing TDS and improving color and pH. However, natural filtration using jute and cotton ropes showed potential for cost-effective treatment. Rainwater collected from Ludhiana (6 hours) was tested after different treatments. The results shown in Table 2.

Table 2: Testing Results of Ludhiana Rainwater (6 hours) After Treatment

Treatment Method	Turbidity (NTU)	TDS (ppm)	Color (HU)	BOD (mg/L)	COD (mg/L)	Electric Conductivity (µs/cm)	pH
Coagulation	23.2	3	1.56	0	2.4	14.7	5.15
Mechanical Filtration	29	4	2.18	0.5	2.7	32.3	5.5
Granular Activated Carbon	17.4	34	0.93	0	1.5	23.1	5.85

Powdered Activated Carbon	11.6	39	0.62	0	1.2	19.8	5.90
Reverse Osmosis	2.9	4	0.15	0	0	0.60	4.90
Jute Rope Technique	34.8	32	2.49	0.5	2.85	32.3	6.00

Rainwater collected from Ludhiana (6 months) was tested after different treatments. The results shown in Table 3.

Table 3: Testing results of Rainwater collected from Ludhiana (6 months) after treatment

Treatment Method	Turbidity (NTU)	TDS (ppm)	Color (HU)	BOD (mg/L)	COD (mg/L)	Electric Conductivity (µs/cm)	pH
Coagulation	2	44	7.41	0	2.8	30.9	6.4
Mechanical Filtration	2.5	48	10.38	0.6	3.6	95.9	6.5
Granular Activated Carbon	1.5	60	4.44	0	2	70.7	6.8
Powdered Activated Carbon	1	68	2.96	0	1.4	68.6	6.82
Reverse Osmosis	0.25	15	0.24	0	0	2.02	4.95
Jute Rope Technique	3	62	11.86	0.9	3.8	105.5	6.75

Rainwater collected from Sidhwa bet (6 hours) was tested after different treatments. The results shown in Table 4.

Table 4: Testing results of Rainwater collected from Sidhwa bet (6 hours) after treatment

Treatment Method	Turbidity (NTU)	TDS (ppm)	Color (HU)	BOD (mg/L)	COD (mg/L)	Electric Conductivity (µs/cm)	pH
Coagulation	26	3	1.895	0	0	26.1	5.70

Mechanical Filtration	32.5	3	2.653	0	0	27.5	6.0
Granular Activated Carbon	19.5	34	0.97	0	0	20.3	6.35
Powdered Activated Carbon	13	40	0.75	0	0	17.4	6.40
Reverse Osmosis	3.25	3	0.18	0	0	0.5	4.90
Jute Rope Technique	39	27	3.032	0	0	28.4	6.3

Water collected from Sidhwa bet (6 months) was tested after different treatments. The results shown in Table 5.

Table 5: Testing results of Rainwater collected from Sidhwa bet (6 months) after treatment

Treatment Method	Turbidity (NTU)	TDS (ppm)	Color (HU)	BOD (mg/L)	COD (mg/L)	Electric Conductivity (µs/cm)	pH
Coagulation	1.6	54	7.60	0	0	95.4	6.4
Mechanical Filtration	2	58	10.64	0	0	100.7	6.5
Granular Activated Carbon	1.2	80	4.56	0	0	84.2	6.88
Powdered Activated Carbon	0.8	92	3.04	0	0	93.6	6.9
Reverse Osmosis	0.2	20	0.36	0	0	2.1	4.95
Jute Rope Technique	2.4	75	12.16	0	0	109.8	6.75

Flocculation Process can be used to increase the pH of rainwater after above mentioned treatment as pH of rainwater is lesser even after treatments. Lime is easily available and cost-effective material which can be used as alkaline additives to increase pH of water.

3.3 Cost Analysis

A cost analysis of the treatment methods is summarized in Table 6. Reverse osmosis emerged as the most expensive option due to energy requirements, while natural filtration methods were highly affordable but less effective.

Table 6: Cost Analysis of Treatment Methods

S. No.	Treatment Method	Cost for 1000 Liters (INR)	Effectiveness (%)
0	Coagulation	200	60
1	Mechanical Filtration	400	70
2	Granular Activated Carbon	800	80
3	Powdered Activated Carbon	1000	90
4	Reverse Osmosis	4000	95
5	Jute Rope Technique	50	50

The cost analysis for treating 1000 liters of rainwater using various methods highlights significant differences in cost and effectiveness across the six treatment methods evaluated. The bar chart of cost analysis conducted per 1000 ltr. of rainwater is shown in figure 1.

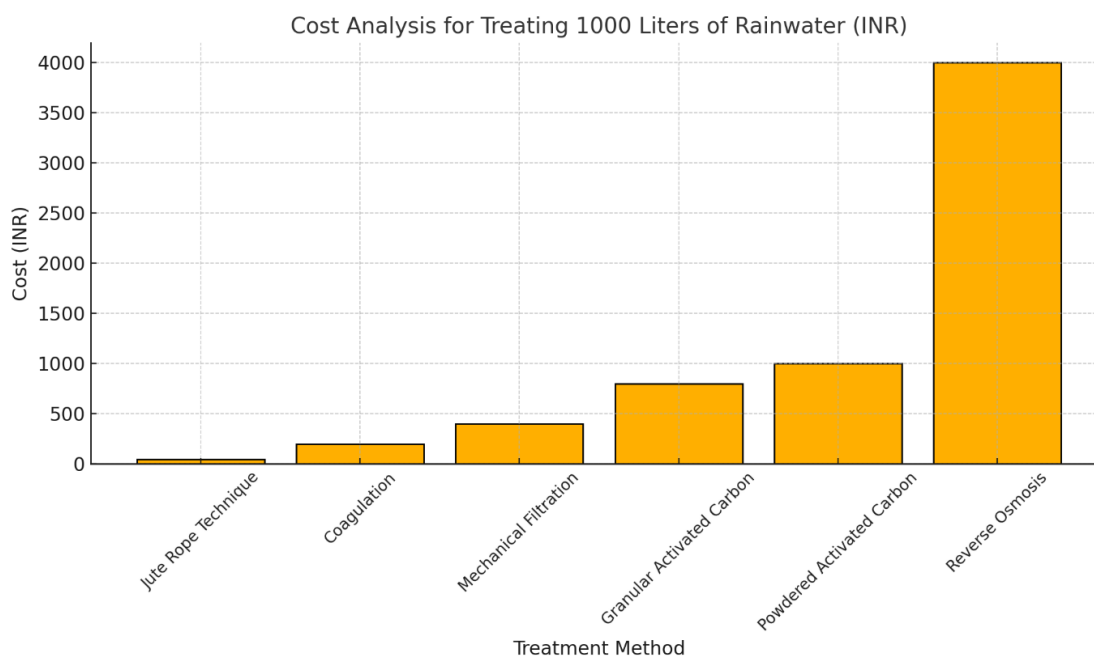


Figure 1: Cost analysis for treating 1000 ltr. of rainwater

Below are the key observations and explanations:

3.3.1 Jute Rope Technique

- **Cost:** ₹50 per 1000 liters (lowest among all methods).
- **Effectiveness:** 50%.
- **Explanation:** This method relies on the natural filtration capacity of jute ropes, making it a highly economical option. However, the lower effectiveness indicates that it is suitable for regions where basic filtration is acceptable but may not meet stringent water quality standards.

3.3.2 Coagulation

- **Cost:** ₹200 per 1000 liters.
- **Effectiveness:** 60%.
- **Explanation:** Coagulation involves adding coagulants to precipitate impurities. It is a low-cost treatment method suitable for reducing turbidity and improving color. However, it does not significantly impact other parameters like TDS or COD, which limits its overall effectiveness.

3.3.3 Mechanical Filtration

- **Cost:** ₹400 per 1000 liters.
- **Effectiveness:** 70%.
- **Explanation:** This method uses sand and gravel filters to remove suspended particles. It is slightly more effective than coagulation and provides improved filtration at a modest increase in cost. It is ideal for areas with access to basic mechanical filtration setups.

3.3.4 Granular Activated Carbon (GAC)

- **Cost:** ₹800 per 1000 liters.
- **Effectiveness:** 80%.
- **Explanation:** Granular activated carbon is effective in removing organic impurities, odor, and improving water color. The cost is relatively higher due to the material used but remains a sustainable option for achieving higher water quality.

3.3.5 Powdered Activated Carbon (PAC)

- **Cost:** ₹1000 per 1000 liters.
- **Effectiveness:** 90%.
- **Explanation:** PAC offers better performance than GAC by removing finer impurities and reducing chemical oxygen demand (COD). However, its higher cost reflects the finer granularity and higher efficiency of the material used.

3.3.6 Reverse Osmosis (RO)

- **Cost:** ₹4000 per 1000 liters (highest among all methods).

- **Effectiveness:** 95%.
- **Explanation:** RO is the most effective method, capable of removing TDS, microorganisms, and almost all impurities. However, it is also the most expensive, requiring significant energy and maintenance. It is suitable for areas where high-quality water is essential and cost is less of a concern.

The cost effectiveness of method used is shown in figure 2.

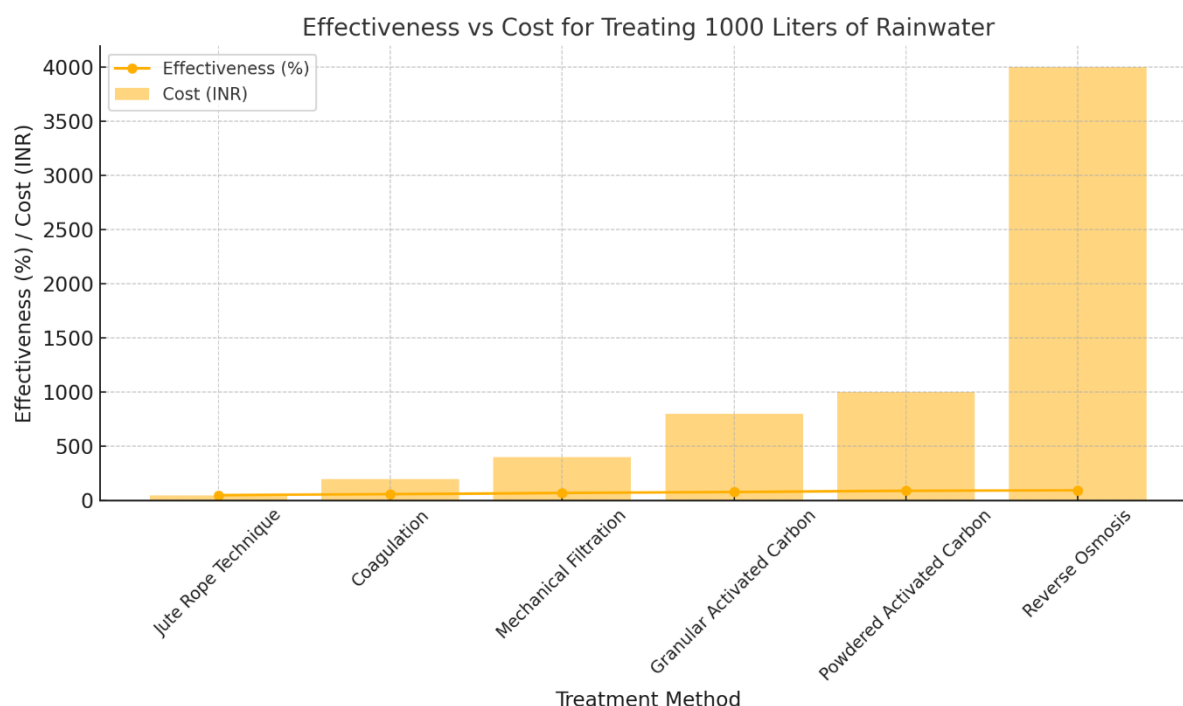


Figure 2: Cost effectiveness of method used to purify 100 ltr. of rainwater

4. Conclusion and Recommendations

The study demonstrates the feasibility of treating rainwater using various methods to achieve desired water quality. Reverse osmosis and activated carbon filtration proved most effective but incur higher costs. Natural filtration using cotton ropes offers a cost-effective alternative for regions with limited resources. Future research should focus on optimizing natural filtration systems and integrating renewable energy for sustainable rainwater treatment.

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