6TH International Conference and Workshop on Engineering and Technology Research (ICWETR) LAUFET 2025: 144-162

IoT-Enabled Rainwater Harvesting Storage: A Smart Approach to Water Management Sustainability

[1]Olaoye R. A., [2]Akindoyin J. S., [3]Olabanji O. M. and [4]Adeshiyan S. A.

[1,2,3,4]*Department of Civil Engineering, Faculty of Engineering and Technology, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.*

https://www.laujet.com/

Keywords:

Smart rainwater harvesting,
Water quality monitoring,
Real-time sensors,
Turbidity,
pH level,
Sustainability

Corresponding Author:
jonathanakindoyin@gmail.com

ABSTRACT

Rainwater harvesting (RWH) is an effective strategy for mitigating water scarcity, but traditional systems lack real-time monitoring and automation, leading to a deficiency in water quality and quality management. This study developed a smart RWH storage system using a structured approach that integrated system development, real-time monitoring, and water quality assessment. The system incorporated ultrasonic sensors for water level detection, pH sensors for acidity monitoring, and turbidity sensors for water clarity evaluation, all connected to an ATMEGA 328 microcontroller for automated data logging. Installed on a 534 m² catchment area, the system consisted of a 1000ℓ tank for raw rainwater collection and a 500ℓ tank for filtered water storage. Over two months, the system harvested 854,610 litres of rainwater, with 408,050 litres filtered for use. An average daily collection of 306 litres of filtered water met the needs of a 10-person workforce. Water quality analysis showed pH levels between 6.35 and 7.08, within WHO standards (6.5–8.5), but turbidity ranged from 38.71 to 94.93 NTU, exceeding the WHO limit of ≤5 NTU, indicating a need for filtration. Results confirmed that smart RWH systems optimize water collection, enhance monitoring, and improve water savings efficiency by approximately 93.7% over conventional methods. Future improvements, including advanced filtration (UV sterilization) and expanded catchment areas, will enhance system performance.

INTRODUCTION

Water scarcity remains a serious global challenge, affecting millions worldwide and threatening sustainable development. As urbanization and industrialization continue to expand, the demand for freshwater resources has increased dramatically. Traditional water management strategies often struggle to keep up with the growing population and fluctuating climatic conditions. Consequently, alternative water sources, such as rainwater harvesting (RWH), have gained prominence as viable solutions to mitigate water shortages and promote sustainable water use (Raimondi *et al*. 2023; Ross *et al*., 2022; Palla, and Gnecco 2022; Olaoye *et al*., 2013). RWH is an ancient practice that involves collecting and storing rainwater for later use in domestic, agricultural, and industrial applications. While conventional RWH systems have been widely used for decades, they often lack efficiency due to the absence of real-time monitoring and automated management systems (García-Ávila *et al*., 2023).

Despite the benefits of RWH, many traditional systems face critical limitations, including the lack of storage monitoring mechanisms, which often lead to water overflow and waste (Ghodsi *et al*., 2023). Additionally, the inability to track and regulate water consumption for specific uses, such as sanitation and irrigation, reduces the overall efficiency of these systems. Another major concern is water quality, as rainwater collected from rooftops is often contaminated with dust, bird droppings, and other pollutants. Without proper treatment and continuous monitoring, harvested rainwater may not meet health and safety standards, making it unsuitable for drinking and hygiene-related applications (Sazakli *et al*., 2019). Moreover, many conventional RWH systems rely heavily on manual operations, requiring frequent human intervention to monitor storage levels, check for contamination, and control distribution. These limitations reduce the effectiveness of traditional RWH and hinder its adoption, particularly in urban and industrial settings (Okoye *et al*., 2015).

The introduction of smart rainwater harvesting systems has the potential to address these challenges by integrating advanced sensors and automation to enhance efficiency and reliability. Smart RWH systems utilize ultrasonic sensors to monitor water levels, pH sensors to assess acidity, and turbidity sensors to track water clarity, ensuring that stored water meets required quality standards. These systems provide real-time data on water storage and consumption, allowing users to optimize rainwater usage and prevent wastage. Additionally, automated filtration and treatment mechanisms can be integrated to enhance the usability of collected water. The use of smart technology enables remote monitoring, predictive analytics, and automated alerts, reducing the need for manual supervision and increasing the overall efficiency of rainwater harvesting systems (Singh *et al*., 2020).

However, despite the potential advantages of smart RWH systems, their adoption remains relatively low due to several challenges. The high initial cost of implementation poses a barrier, particularly in low-income communities and developing regions. Additionally, technical complexities related to installation, maintenance, and data management may limit accessibility for non-technical users (Bhallamudi *et al*., 2023). Addressing these challenges requires an interdisciplinary approach that combines engineering, environmental science, and information technology to develop cost-effective, scalable, and user-friendly solutions.

This study is aimed at designing and implementing a smart rainwater harvesting storage system that integrates smart sensors for real-time water level and quality monitoring. The system is intended to provide an efficient, automated, and user-friendly solution to enhance the effectiveness of rainwater harvesting for various applications, including domestic, commercial, and laboratory use. The study focused on analyzing the variations in water level, pH, and turbidity over different rainfall intervals and determining how water storage levels influence water quality. By leveraging advanced sensors and data analytics, this research seeks to develop a practical and scalable RWH system that optimizes water conservation, improves water quality, and reduces reliance on conventional water supplies.

Previous Works

Several studies have explored rainwater harvesting systems and their potential to alleviate water scarcity. Ward *et al*. (2010) examined the performance of large-scale RWH systems and found that while they can reduce municipal water demand, their efficiency is often hindered by quality control issues and storage limitations. Campisano and Modica (2012) conducted a study on optimal storage tank sizing for domestic RWH systems, demonstrating that proper tank sizing can minimize water overflow and maximize collection efficiency. However, their research also highlighted the impact of climatic variability and user behaviour on system performance, emphasizing the need for adaptive and automated solutions.

The application of smart water management technologies in RWH has been an area of growing research interest. Monteiro *et al*. (2022) examined how smart rainwater can reduce urban stormwater. Sunkpho and Ootamakorn

(2011) developed a real-time water quality monitoring system using wireless sensor networks, proving that continuous tracking of water parameters can enhance contamination detection and safety. Their findings support the integration of smart devices in water management, though they also noted challenges related to sensor accuracy and maintenance over time. Similarly, K and John (2024) explored the use of IoT in smart irrigation systems, where real-time data on soil moisture and weather conditions was used to optimize water distribution and reduce wastage. The findings revealed that IoT-based automation improves water use efficiency but requires stable internet connectivity and reliable power sources, factors that may also affect the feasibility of smart RWH systems in some regions.

In addition to water management optimization, studies have also investigated the quality of harvested rainwater and factors influencing contamination. Olaoye and Olaniyan (2012) analyzed the impact of different roofing materials on rainwater quality, showing that aluminium roofs yielded the highest water quality, while asbestos and concrete roofs resulted in increased turbidity and chemical contamination. The study presents the importance of proper collection surface selection and regular filtration to ensure safe water storage. Furthermore, Monteiro (2022) reported that smart systems have advantages when used for urban stormwater reduction. Fewkes and Butler (2000) highlighted the advantages of automated RWH systems over conventional systems, demonstrating that sensor-based monitoring reduces inefficiencies and optimizes water usage. The findings supported the integration of IoT in rainwater management, aligning with the goals of this study.

Overall, these previous works provided valuable insights into the challenges and opportunities associated with RWH systems. While research has proven the effectiveness of automated monitoring and smart technologies in water management, gaps remain in cost-effective implementation, long-term sustainability, and user-friendly system design. This study builds upon these existing findings by developing a fully automated, real-time smart RWH system that addresses both water quantity and quality concerns, ensuring efficient, safe, and scalable rainwater harvesting solutions.

MATERIALS AND METHODS

Materials Used

The smart rainwater harvesting system was designed using a combination of plumbing components, electronic sensors, and data-logging devices to ensure automated operation and real-time monitoring. The collection system utilized downspouts, which directed rainwater from the catchment area to two storage tanks. The tanks were connected through a network of pipes, valves, and fittings, allowing for controlled water transfer and filtration. A carbon filter was placed between the two tanks to improve water quality by removing larger particles and impurities before storage in the final tank.

The system's control unit was built around an ATMEGA 328 microcontroller**,** which is presented in Figure 1, which served as the central processor, managing input from the sensors and facilitating real-time data processing. Ultrasonic sensors presented in Figure 2 were installed at the top of both tanks to continuously monitor water levels, ensuring precise measurements of storage capacity and inflow. Additionally, a pH sensor presented in Figure 3 was placed in the first tank to monitor the acidity of the harvested water, providing essential data on potential contamination and suitability for use. A turbidity sensor was included to assess the clarity of the water, detecting variations that might indicate the presence of suspended particles or contaminants.

To ensure data storage and retrieval, an SD card module as displayed in Figure 4 was integrated into the system, enabling continuous logging of sensor readings. A 16x2 LCD depicted in Figure 5 was also included to provide real-time feedback to users regarding water levels, pH, and turbidity, enhancing user interaction with the system. The entire control mechanism was housed in a 6x6-inch adaptable box, protecting the electronic components from environmental exposure. The system was powered by a 12V 5A battery, as displayed in Figure 6 and supported by bulk converters to ensure a stable voltage supply for efficient operation.

The smart rainwater harvesting system was designed using a combination of plumbing components, electronic sensors, and data-logging devices to ensure automated operation and real-time monitoring. The collection system utilized downspouts, which directed rainwater from the catchment area to two storage tanks. The tanks were connected through a network of pipes, valves, and fittings, allowing for controlled water transfer and filtration. A carbon filter was placed between the two tanks to improve water quality by removing larger particles and impurities before storage in the final tank.

The system's control unit was built around an ATMEGA 328 microcontroller**,** which is presented in Figure 1, which served as the central processor, managing input from the sensors and facilitating real-time data processing. Ultrasonic sensors presented in Figure 2 were installed at the top of both tanks to continuously monitor water levels, ensuring precise measurements of storage capacity and inflow. Additionally, a pH sensor presented in Figure 3 was placed in the first tank to monitor the acidity of the harvested water, providing essential data on potential contamination and suitability for use. A turbidity sensor was included to assess the clarity of the water, detecting variations that might indicate the presence of suspended particles or contaminants.

To ensure data storage and retrieval, an SD card module as displayed in Figure 4 was integrated into the system, enabling continuous logging of sensor readings. A 16x2 LCD depicted in Figure 5 was also included to provide real-time feedback to users regarding water levels, pH, and turbidity, enhancing user interaction with the system. The entire control mechanism was housed in a 6x6-inch adaptable box, protecting the electronic components from environmental exposure. The system was powered by a 12V 5A battery, as displayed in Figure 6 and supported by bulk converters to ensure a stable voltage supply for efficient operation.

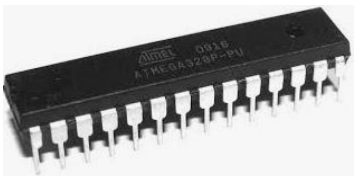

Figure 1: ATMEGA 328 microcontroller

Figure 2: Ultrasonic sensor

Figure 3: pH sensor

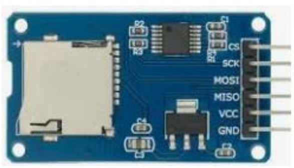

Figure 4: SD card module

Figure 5: 16x2 LCD

Figure 6: 12V 5A battery

System Design and Implementation

The design of the smart rainwater harvesting system incorporated both hardware and software elements to ensure optimal functionality. The circuit was configured to allow seamless integration of sensors with the microcontroller, ensuring accurate data acquisition and storage. The ultrasonic sensors were connected to digital input pins on the microcontroller, while the pH and turbidity sensors were linked to analogue input pins for continuous monitoring. The SD card module was configured to store readings at predefined time intervals, ensuring a comprehensive dataset for later analysis. The LCD was programmed to show real-time sensor readings, allowing for immediate feedback on system performance.

The software for the system was developed using C++ on the Arduino IDE, enabling efficient data handling and decision-making. A flowchart of the C++ developed is shown in Figure 7 he code was structured to include initialization functions, data acquisition routines, and data processing algorithms. A logging function was implemented to write sensor data to the SD card, ensuring reliable long-term storage. The system was designed to trigger alerts when water levels approached critical thresholds, providing an added layer of functionality for improved water management.

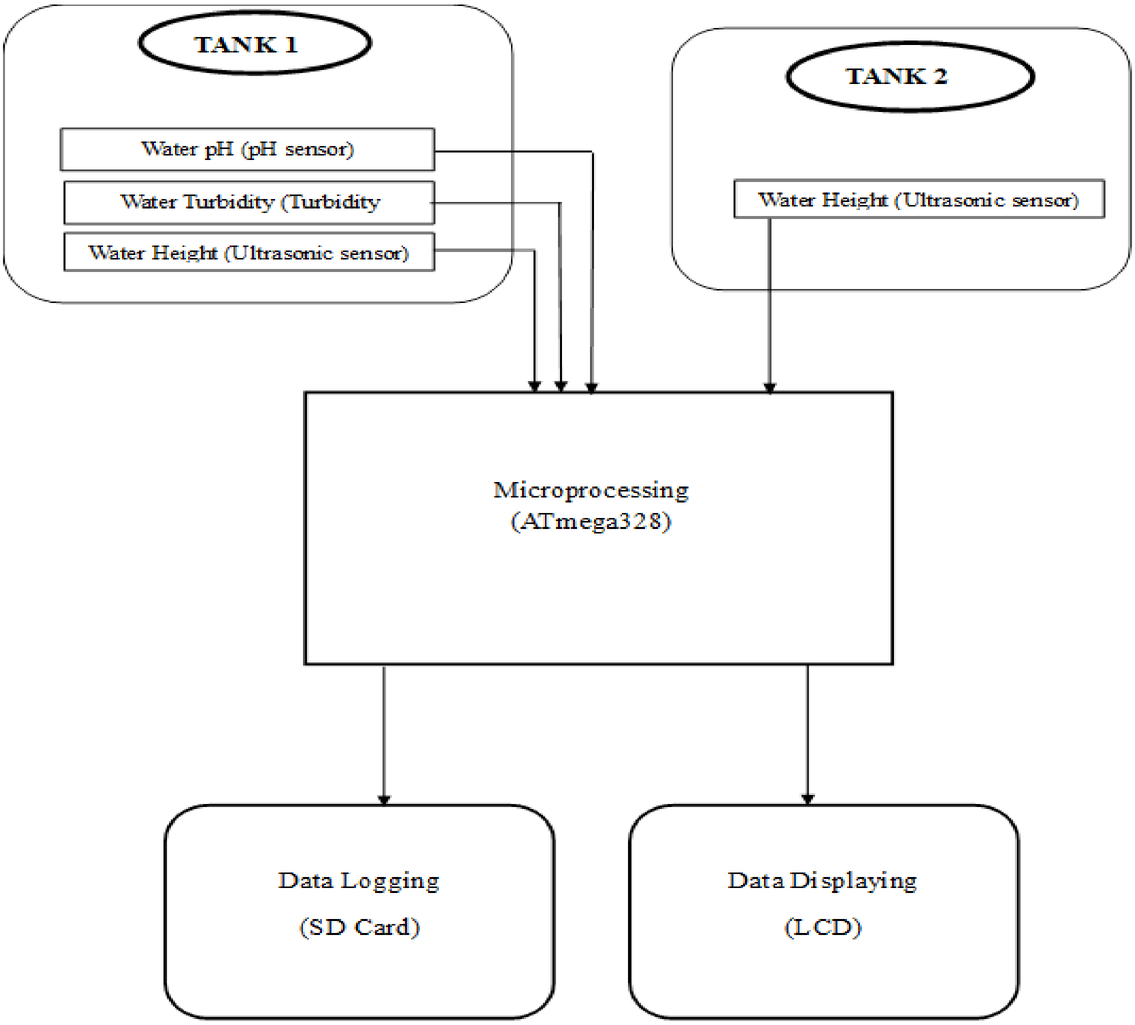

Figure 7: Flowchart of C++ on the Arduino IDE

The complete system was installed at the Department of Civil Engineering, Ladoke Akintola University of Technology, ensuring a controlled environment for performance evaluation. Plate 1 shows the fully assembled device for the smart rainwater harvesting system.

Plate 1: Smart device

Rainwater Catchment and Collection System

The catchment system consisted of a 534 m² roof area, which was selected for its high runoff efficiency and ability to collect substantial volumes of rainwater. Downspouts were installed at key points along the roof's edge to direct rainwater into the storage system. The first storage tank was designed to receive unfiltered rainwater, allowing for sedimentation before water was transferred to the second tank. This configuration minimized the entry of larger debris into the final storage unit, improving overall water quality. Figure 8 presents the block diagram of the collection and storage system, highlighting the flow of water from the roof to the tanks.

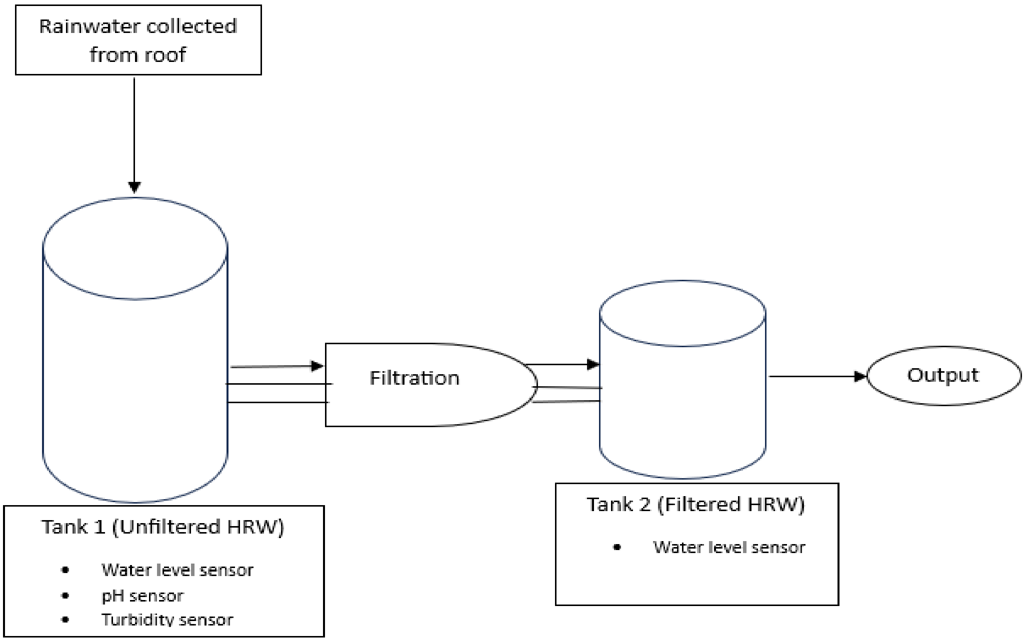

Figure 8: Schematic Design of the Smart RWH Storage System

The two tanks were strategically placed to facilitate gravitational flow, reducing the need for additional pumping mechanisms. The first tank acted as a primary storage unit for raw rainwater, while the second tank stored filtered water for distribution. A carbon filter, as shown in Plate 2, was positioned between the two tanks to remove coarse impurities, enhancing the effectiveness of the storage system. Figure 9 showcases a 3D representation of the constructed smart rainwater harvesting system consisting of two tanks: a 1000ℓ tank for initial collection and a 500ℓ tank for filtered water storage. The 1000ℓ and 500ℓ tanks were used as a pilot study for the storage of the harvested rainwater; bigger sizes of tanks can also be used.

Plate 2: Carbon Filter

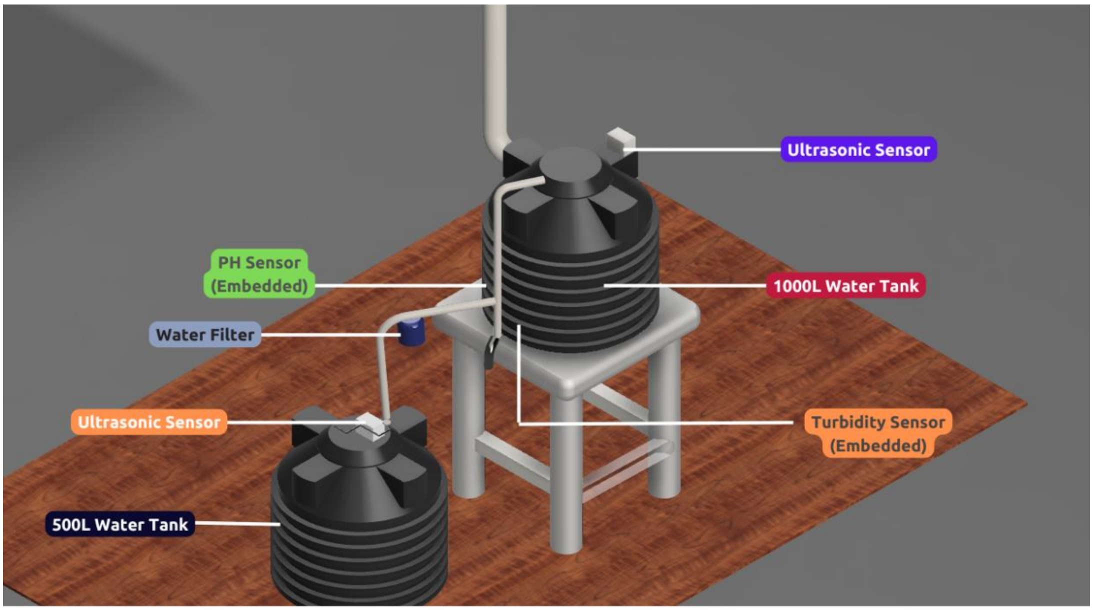

Figure 9: 3D Rendered Design of the Smart Rainwater Harvesting Storage System

(a) Sample Collection

Rainwater samples were collected at regular intervals from the harvesting system. The intervals were every 5 minutes daily and data were collected for 60 days (2 months); these collections helped to capture variations over different periods. This process helped understand how water quality and quantity change over time.

(b) Measurement and Monitoring

Water level, pH and turbidity were measured for each collected sample using ultrasonic sensors, a pH sensor and a turbidity sensor. The ultrasonic sensors, pH sensor and turbidity sensor were calibrated to ensure accurate readings. The measurements were recorded and transmitted to a central data logger for further analysis (SD card). Water level sensors were used to continuously monitor the volume of water collected in the storage tanks. This data helped to understand the efficiency of water collection and storage over time. pH sensors measured the acidity or alkalinity of the collected rainwater. This data was crucial for ensuring the safety and suitability of the water for various applications. Turbidity sensors measured the clarity of the water. High turbidity levels can indicate the presence of suspended particles and contaminants, which can affect water quality.

(c) Data Analysis

The collected data were analyzed to determine the changes in water level, pH, and turbidity over time. Statistical software such as Microsoft Excel was used for the data analysis and determination of the Pearson correlation coefficient.

(d) The Effect of pH and Turbidity on Water Level

After computing and analyzing the data, detailed graphs were plotted to illustrate the relationship between water level and time for each pH and turbidity level. These graphs provided a visual representation of how water levels fluctuated over time under different weather patterns, such as heavy rainfall and storms. Following the graphing process, a thorough comparison of the water level changes associated with each pH and turbidity level was also conducted. This comparative analysis enabled the discernment and quantification of the specific effects that pH and turbidity have on water levels. By examining these relationships, a deeper understanding of the dynamic interactions between these parameters and their impact on the efficiency of the smart rainwater harvesting system was gained.

RESULTS AND DISCUSSION

Design of a Smart Rainwater Harvesting Storage System

The smart rainwater harvesting system was designed and constructed with two storage tanks: a 1000ℓ tank with a height of 1.25m for collecting raw rainwater and a 500ℓ tank with a height of 0.8m for filtered water storage. Each tank was equipped with ultrasonic sensors for water level monitoring, while the pH and turbidity sensors were integrated into the 1000ℓ tank to assess water quality. The system was controlled by an ATMEGA 328 microcontroller, which processed and stored real-time data on an SD card module. The constructed smart rainwater harvesting is presented in Plate 3.

Water Demand and Rainwater Harvesting Capacity

The system was designed to meet WHO's daily water demand, which ranges between 50 and 100 litres per person per day, with toilet flushing consuming 15–30 litres per person per day. The system successfully provided an average of 306 litres of filtered water daily, which was sufficient for a 10-person workforce. The total roof catchment area was measured at 534 m^2, yielding a total raw rainwater collection of 854,610 litres, of which 408,050 litres were filtered and stored in the 500ℓ tank. If the catchment area were expanded to 1,150 m^2, which is the total roof area of the building, the system's harvesting potential would increase significantly by a projected yield of 1,837,875.5 litres of raw rainwater annually.

Plate 3: Smart RWH Storage System

Rainwater collected per square meter;

$$\text{Rainwater per square meter} = \frac{\text{Total Raw Rainwater Collected}}{\text{Catchment Area}}$$

$$= \frac{854{,}610 \text{ litres}}{534 \text{ m}^2}$$

$$= 1{,}597.27 \text{ litres/m}^2$$

If the catchment area is expanded to 1,150 m², the new collection potential would be:

New Collection Potential = Rainwater per square meter× Expanded Catchment Area

= 1,597.27 litres/m^2 × 1,150 m^2

=1,837,875.5 litres

The smart system demonstrated its efficiency in optimizing rainwater usage compared to traditional systems, which often lack automated monitoring and real-time data tracking. Calculations indicated that the system achieved a water savings efficiency of approximately 93.7%, preventing unnecessary water wastage.

Calculation of the Water Savings Percentage

Total Water Demand (TWD) = Water Usage x 365 days

TWD = 300 litres/day x 365

TWD = 109,500 litres/year

Water Savings (WS) = Rainwater Harvested

WS = 408,050 litres

Water Savings Percentage (WS%) = (WS / TWD) x 100

WS% = (408,050 / 109,500) x 100

WS% ≈ 373%

However, since WS% exceeds 100%, it indicates that rainwater harvesting exceeds total water demand and the harvested rainwater can be used for other purposes like cooking and laundry.

Effective Water Savings Percentage (EWS%) = (WS / TWD) x (Storage Tank / WS)

EWS% = (408,050 / 109,500) x (1000 / 408,050)

EWS% ≈ 93.7%

This shows that all harvested rainwater is used and there are no losses due to evaporation, leakage, or overflow.

Variations in Water Level, pH, and Turbidity

(a) Water Level and Volume Trends

The 1000ℓ tank showed a steady increase in water levels after heavy rainfall, with an average daily gain of 500 litres. The 500ℓ tank, which stored filtered water, recorded an average increase of 280 litres per rainfall event. Figures 10 and 11 illustrate the variations in water levels, while Figures 12 and 13 show the cumulative volume of water collected and stored, reflecting a more comprehensive view of the system's storage capacity and efficiency. The volume graphs provide insight into the total amount of water stored after accounting for the storage and filtration processes, whereas the level graphs offer a more immediate visual of how quickly the tanks fill during rainfall events

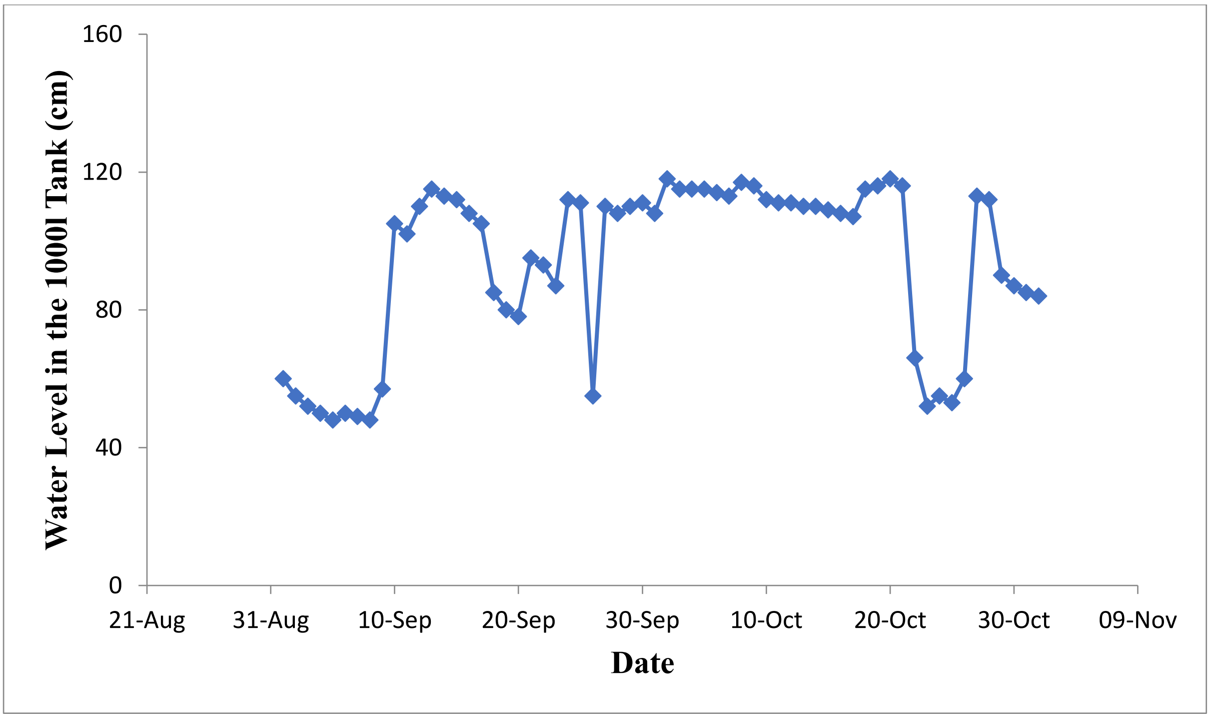

Figure 10: Variation in Water Level for the 1000ℓ Tank Measured from September 1 2024 to November 1 2024

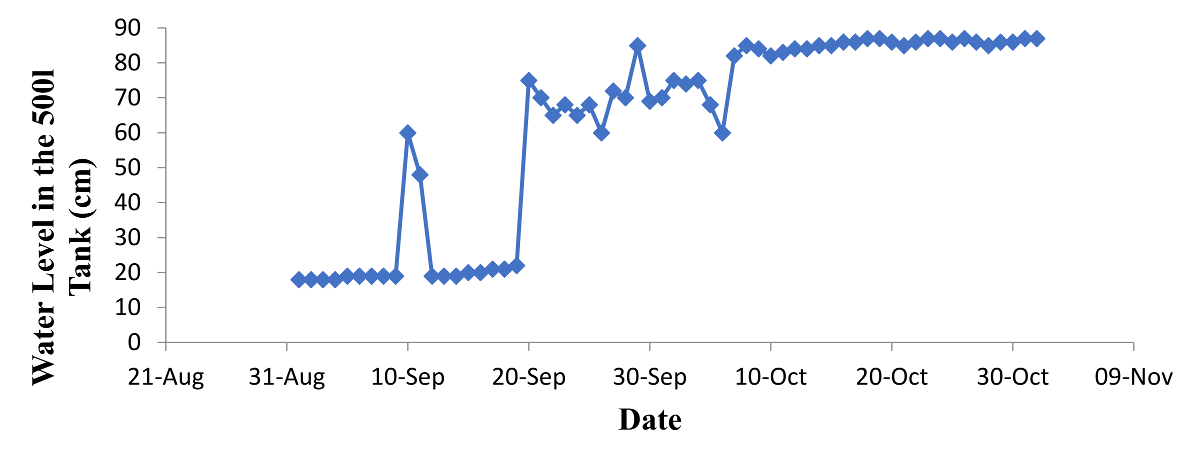

Figure 11: Variation in Water Level for the 500ℓ Water Tank Measured from September 1 2024 to November 1

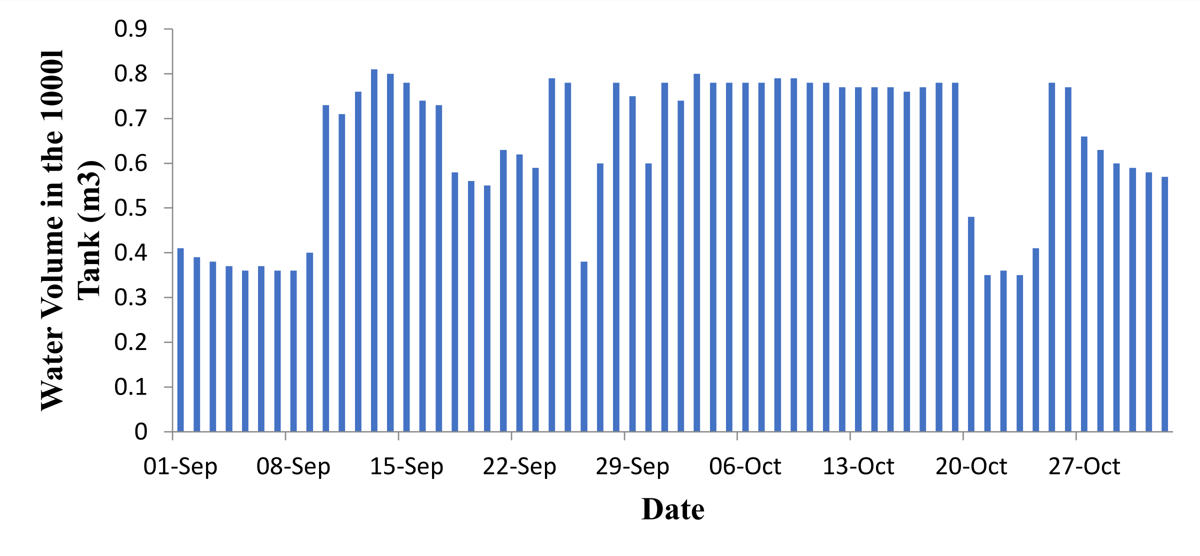

Figure 12: Variation in Water Volume for the 1000ℓ Water Tank from September 1 2024 to November 1 2024

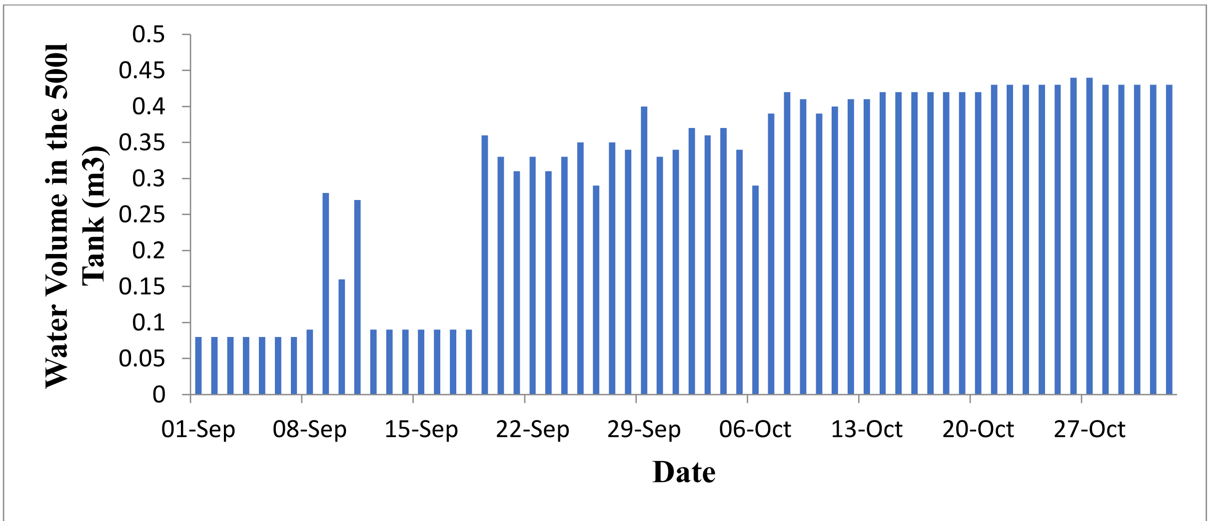

Figure 13: Variation in Water Volume in the 500ℓ Water Tank from September 1 2024 to November 1 2024

pH Variations

The pH levels of the harvested water ranged from 6.35 to 7.08, remaining within WHO's potable water standard of 6.5 to 8.5. However, a slight decrease in pH was observed after heavy rainfall, suggesting dilution effects from roof contaminants. The pH trend over time is presented in Figure 14.

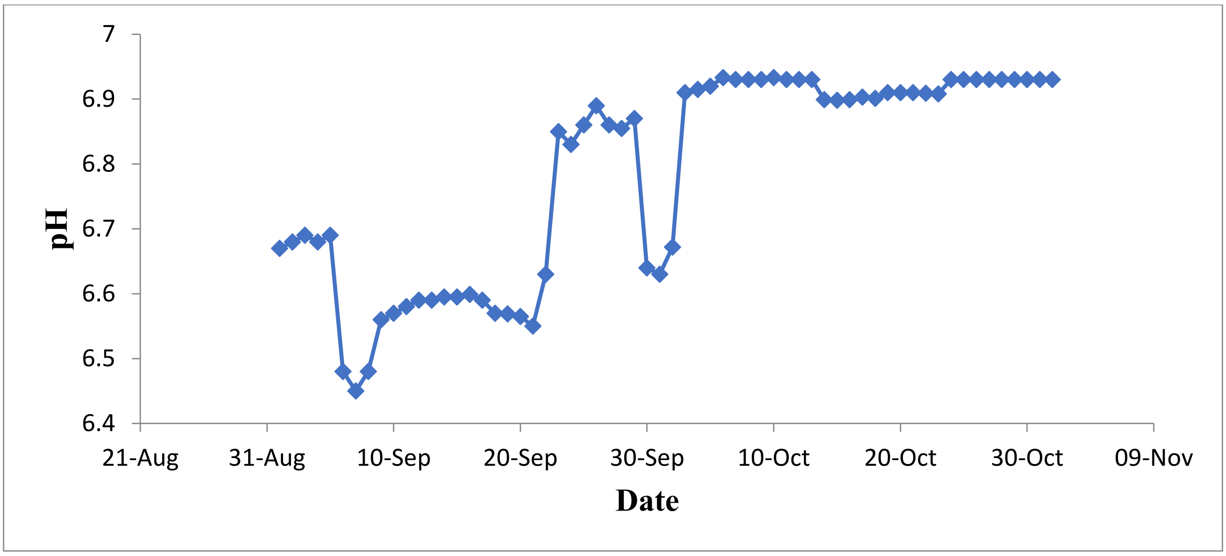

Figure 14: Variation in pH in the Smart Rainwater Harvesting System from September 1, 2024, to November 1, 2024

Turbidity Trends

Turbidity values ranged from 38.71 to 94.93 NTU, far exceeding the WHO standard of ≤5 NTU. Spikes in turbidity were recorded immediately after rainfall, indicating an influx of suspended particles and debris. Figure 15 shows the turbidity trends over time.

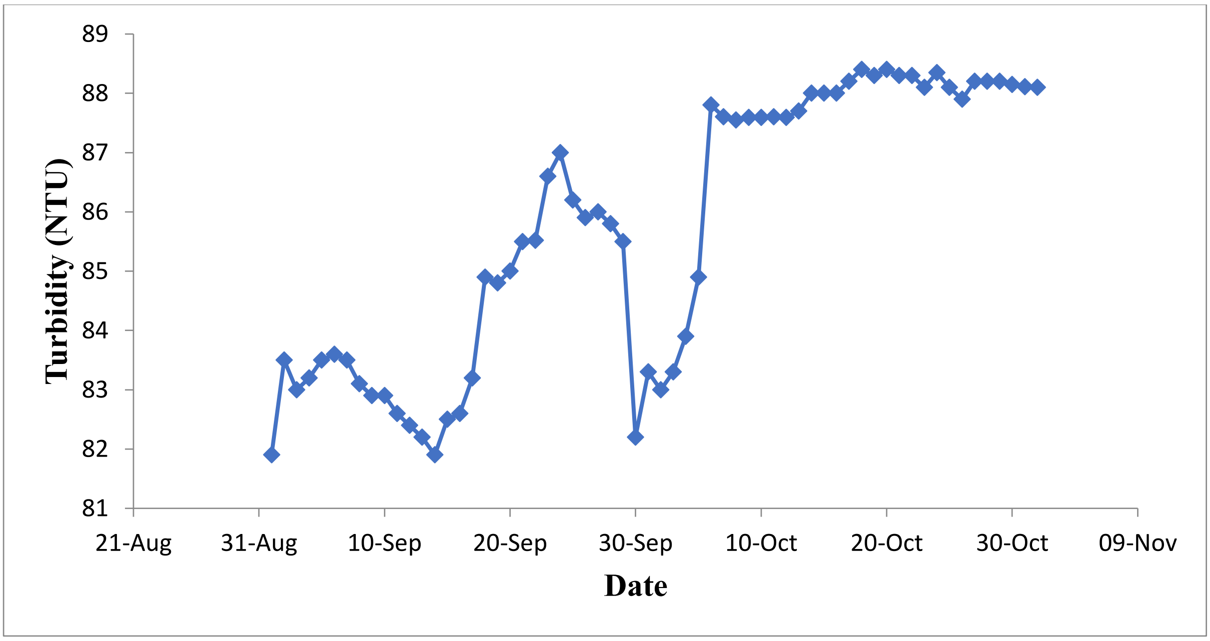

Figure 15: Variation in Turbidity from the Harvested Rainwater from September 1, 2024, to November 1, 2024

The Correlation between Water Level on pH and Turbidity

Higher water levels led to more stable pH values, as observed after heavy rainfall events when dilution effects neutralized acidity. However, a correlation coefficient of 0.2651 was obtained between water level and pH, which indicates a weak positive linear relationship. This means that as the water level increases, the pH also increases slightly, as visually represented in Figure 16. A correlation coefficient of −0.144 was obtained between water level and turbidity, which indicates a very weak negative linear relationship. This implies that as the water level increases, turbidity slightly decreases, as visually represented in Figure 17. Figure 18 illustrates the overall trend between water level, pH, and turbidity.

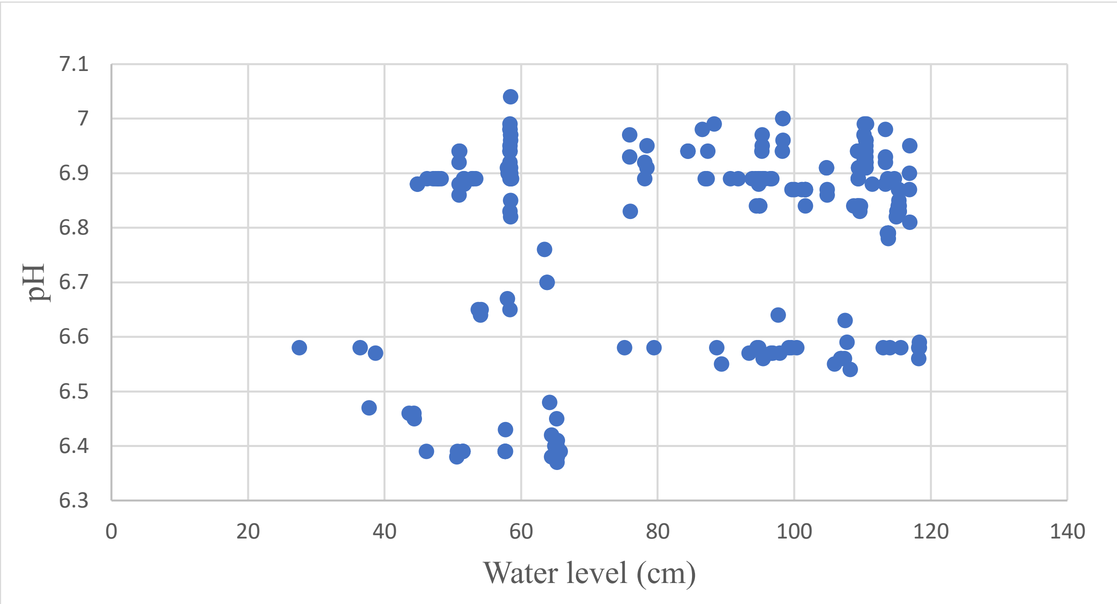

Figure 16: Scatter Plot of Water Level vs. pH

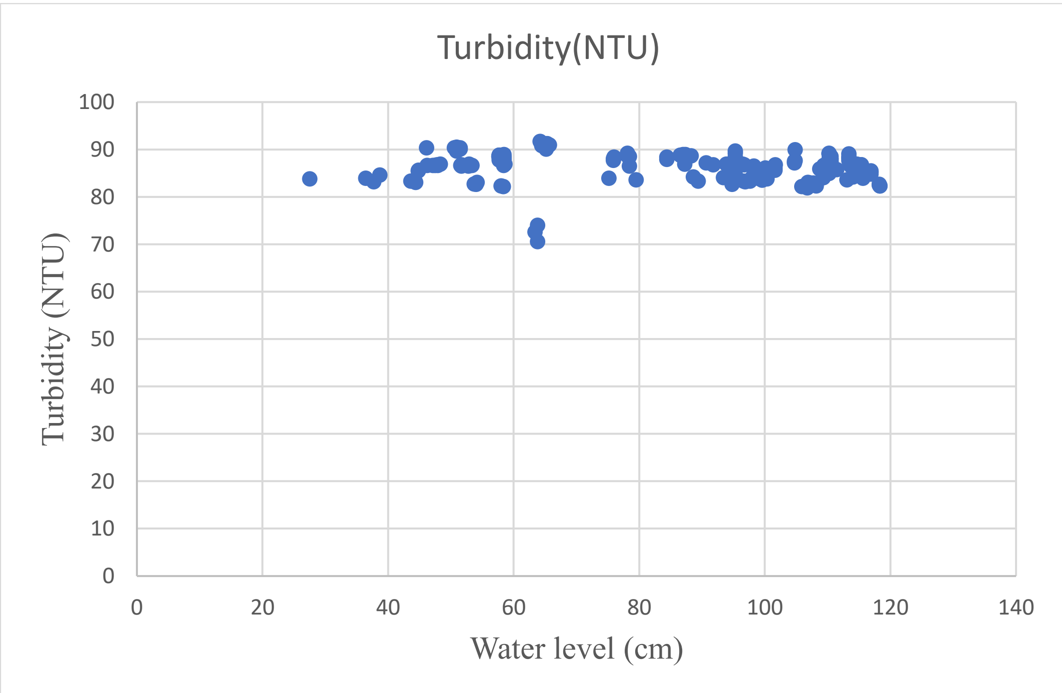

Figure 17: Scatter Plot of Water Level vs. pH

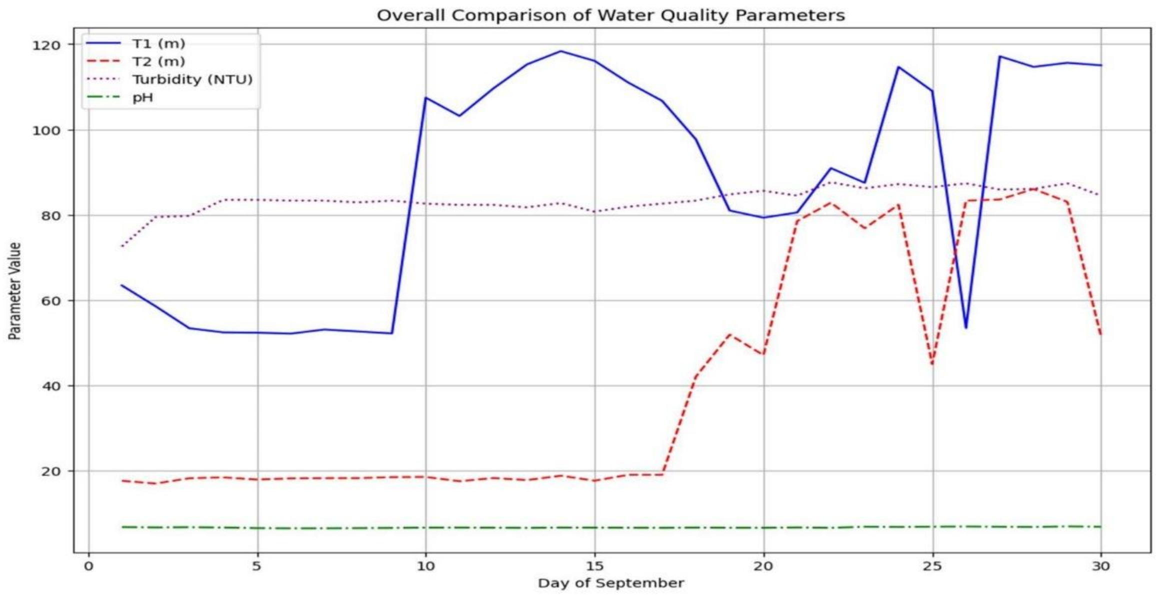

Figure 18: Overall comparison of water quality parameters

The smart rainwater harvesting system allowed for the successful collection and storage of rainwater while monitoring water quality in real time. The integration of smart devices allowed for automated tracking of water levels, pH, and turbidity, ensuring efficient water usage and reducing wastage. The water level variations observed in the 1000ℓ and 500ℓ tanks were consistent with rainfall patterns, confirming that the system effectively captured and stored rainwater during peak rainfall events. The 1000ℓ tank showed a sharp increase in water levels during heavy rainfall, such as on September 10, 2024, when levels rose from 0.579m to 1.05m. The pH levels of the harvested water were within WHO's safe drinking water range (6.5–8.5), demonstrating that rainwater acidity was not a major concern. However, slight pH fluctuations after rainfall events indicate that contaminants from the roof surface may temporarily alter water chemistry. This supports the findings of Despins *et al*. (2009); and Olaoye and Olaniyan (2012), who emphasized the impact of roof material on harvested rainwater quality. The study by Olaoye *et al*. (2018) on the potability of rainwater collected in the Oluyele industrial area, Ibadan, also revealed pH values ranging from 6.6 to 6.9, all within the observed values in this study.

A major concern in this study was the high turbidity levels recorded, which exceeded the WHO's maximum permissible limit (≤ 5 NTU). The turbidity spikes observed after rainfall events (e.g., October 9, 2024, reaching 87.5 NTU) suggested that roof runoff carries suspended particles. This aligns with research by Ahmed *et al*. (2011), who found that rainwater harvested from rooftops often contains sediments and organic matter, necessitating additional filtration before usage. However, it is expected that turbidity levels in harvested rainwater will reduce after the water has passed through the carbon filter. In comparison to traditional rainwater harvesting systems, the smart system demonstrated clear advantages in efficiency and automation. Traditional systems often experience water overflow, inadequate filtration, and a lack of real-time monitoring (Coombes and Barry, 2008). In contrast, the smart system's automation features allowed real-time adjustments, preventing wastage and optimizing water use.

A key limitation observed was the inability of the system to fully remove turbidity. Despite carbon filtration between tanks, turbidity values remained above WHO's standards, suggesting that additional filtration mechanisms (e.g., UV sterilization or advanced filters) are required. Future studies should explore microbial contamination levels, as Salih *et al*. (2024) highlighted the potential for pathogen presence in WEE

CONCLUSION AND RECOMMENDATION

The smart rainwater harvesting system successfully integrated smart devices to monitor water levels, pH, and turbidity in real time, ensuring efficient water collection and quality assessment. Over the two-month study period, the system harvested a total of 854,610 litres of raw rainwater, of which 408,050 litres were filtered and stored in the 500ℓ tank. The system's daily filtered water output of 306 litres met the water demand for a 10-person workforce, validating its effectiveness in optimizing water usage.

The pH of the harvested water ranged from 6.35 to 7.08, aligning with WHO's recommended standard of 6.5–8.5 for potable water. However, turbidity values ranged from 38.71 to 94.93 NTU, which exceeds the WHO's permissible limit of ≤5 NTU, indicating the need for additional filtration. Additionally, higher water levels were associated with turbidity spikes due to increased sediment from roof runoff, while pH remained stable during high water levels, demonstrating a dilution effect on acidity. The smart system demonstrated superior performance by automating storage management and reducing overflow losses. However, turbidity remained a challenge, necessitating further improvements in filtration and treatment mechanisms.

Results indicated that integrating an advanced filtration system, such as UV sterilization or membrane filtration, is necessary to reduce turbidity levels to the WHO's permissible standard (≤5 NTU), ensuring safer water for broader applications. Results indicated that expanding the roof catchment area from 534 m² to 1,150 m² could potentially increase the annual rainwater yield from 854,610 litres to approximately 1,837,875.5 litres, which demonstrates improvement in water for larger-scale usage.

CONCLUSION AND RECOMMENDATIONS

The smart rainwater harvesting system successfully integrated smart devices to monitor water levels, pH, and turbidity in real time, ensuring efficient water collection and quality assessment. Over the two-month study period, the system harvested a total of 854,610 litres of raw rainwater, of which 408,050 litres were filtered and stored in the 500ℓ tank. The system's daily filtered water output of 306 litres met the water demand for a 10-person workforce, validating its effectiveness in optimizing water usage.

The pH of the harvested water ranged from 6.35 to 7.08, aligning with WHO's recommended standard of 6.5–8.5 for potable water. However, turbidity values ranged from 38.71 to 94.93 NTU, which exceeds the WHO's permissible limit of ≤5 NTU, indicating the need for additional filtration. Additionally, higher water levels were associated with turbidity spikes due to increased sediment from roof runoff, while pH remained stable during high water levels, demonstrating a dilution effect on acidity. The smart system demonstrated superior performance by automating storage management and reducing overflow losses. However, turbidity remained a challenge, necessitating further improvements in filtration and treatment mechanisms.

Results indicated that integrating an advanced filtration system, such as UV sterilization or membrane filtration, is necessary to reduce turbidity levels to the WHO's permissible standard (≤5 NTU), ensuring safer water for broader applications. Results indicated that expanding the roof catchment area from 534 m² to 1,150 m² could potentially increase the annual rainwater yield from 854,610 litres to approximately 1,837,875.5 litres, which demonstrates improvement in water for larger-scale usage.

REFERENCES

Amarachukwu, E., Evuti, A.M., Salam K. A. and Silas, S. S. (2020), "Determination Of Waste Generation, Composition And Optimized Collection Route For University Of Abuja Main Campus Using "Myrouteonline" Software". Scientific African 10 e00569. www.elsevier.com/locate/sciaf. P. 1 – 10.

Ahmed, W., Gardner, T., and Toze, S. (2011). Microbiological quality of roof-harvested rainwater and health risks: a review. *Journal of Environmental Quality*, *40*(1), 13–21. https://doi.org/10.2134/jeq2010.0345

Bhallamudi, Murty and Philip, Ligy. (2023). Sustainable management of water. 10.2166/9781789063714_0003.

Campisano, A., and Modica, C. (2012). Optimal sizing of storage tanks for domestic rainwater harvesting systems in Sicily. *Resources, Conservation and Recycling*, 63, 9-16.

Coombes, P. J., and Barry, M. E. (2008). The effect of selection of time steps and average assumptions on the continuous simulation of rainwater harvesting strategies. *Water Science and Technology*, 58(1), 117–124.

Despins, C., Farahbakhsh, K., and Leidl, C. (2009). Assessment of rainwater quality from rainwater harvesting systems in Ontario, Canada. *Journal of Water Supply: Research and Technology—AQUA*, 58(2), 117–134.

Fewkes, A., and Butler, D. (2000). Simulating the performance of rainwater collection and reuse systems using behavioural models. *Building Services Engineering Research and Technology*, 21(2), 99–106.

García-Ávila, F., Guanoquiza-Suárez, M., Guzmán-Galarza, J., Cabello-Torres, R., and Valdiviezo-Gonzales, L. (2023). Rainwater harvesting and storage systems for domestic supply: An overview of research for water scarcity management in rural areas. *Results in Engineering*, 18(2590-1230), 101153.

Ghodsi, S.H.; Zhu, Z.; Matott, L.S.; Rabideau, A.J.; Torres, M.N. (2023) Optimal Siting of Rainwater Harvesting Systems for Reducing Combined Sewer Overflows at City Scale. *Water Res*. 2023, 230, 119533.

K, Gowtham and John, Dr. (2024). SMART IRRIGATION SYSTEM USING IOT. IARJSET. 11. 10.17148/IARJSET.2024.11617.

Monteiro, M.; Matos Silva, C.; Shetty, N.; Wang, M.; Elliott, R.; Culligan, P. (2022) Examining How a Smart Rainwater Harvesting System Connected to a Green Roof Can Improve Urban Stormwater Management. *Water* 2022, 14, 2216

Okoye, C. O., Solyalı, O., and Akıntuğ, B. (2015). Optimal sizing of storage tanks in domestic rainwater harvesting systems: A linear programming approach. *Resources, conservation and recycling*, 104, 131-140.

Olaoye, R. A., and Olaniyan, O. S. (2012). Quality of rainwater from different roof materials. *International journal of Engineering and Technology*, 2(8), 1413-1421

Olaoye, R.A., Coker, A.O., Sridhar, M.K. and Adewole, E.M. (2013). Examining the Effectiveness of Rainwater Collection Systems in a Nigerian Leper Colony Using the Behavioural Model, *ARPN Journal of Engineering and Applied Sciences*, 8 (1): 1-8.

Olaoye, R.A., Oladeji, O.S., Olaniyan, .O.S.and Salawu, A. M. (2018). Potability of Harvested Rainwater in Oluyole Industrial Area of Ibadan, Southwestern Nigeria, *LAUTECH Journal of Civil and Environmental Studies*, LAUJOCES**,** 1 (1): 67 – 74,

Palla, A.; Gnecco, I. (2022). On the Effectiveness of Domestic Rainwater Harvesting Systems to Support Urban Flood Resilience. *Water Resour. Manag*. 2022, 36, 5897–5914.

Pushpa Rani, Katari and Srija, Krishna and Jyothianvitha, A. and Ashasri, M. and Mamatha, I. and Rajesh, G.. (2021). Rain Water Harvesting for Smart Water Management Using IoT. 475-478. 10.1109/ICICCS51141.2021.9432365.

Raimondi, A., Quinn, R., Abhijith, G. R., Becciu, G., and Ostfeld, A. (2023). Rainwater Harvesting and Treatment: State of the Art and Perspectives. *Water*, 15(8), 1518. https://doi.org/10.3390/w15081518

Ross, T.T.; Alim, M.A.; Rahman, A. (2022). Community-Scale Rural Drinking Water Supply Systems Based on Harvested Rainwater: A Case Study of Australia and Vietnam. *Water* 2022, 14, 1763.

Salih, Z. R., Toma, J. J., Aziz, A. H., Hassan, T. M., Aziz, F. H. (2024). Evaluation of Rainwater Quality in Some Polluted Locations within Erbil Province. *Polish Journal of Environmental Studies*, 33(2), 1839-1848.

Sazakli, E., Sazaklie, E., and Leotsinidis, M. (2015). Rainwater harvesting: from ancient Greeks to modern times. The case of Kefalonia Island. *International Journal of Global Environmental Issues*, 14(3-4), 286-295.

Singh, M., and Ahmed, S. (2021). IoT-based smart water management systems: A systematic review. Materials Today: *Proceedings*, 46, 5211-5218.

Sunkpho, J., and Ootamakorn, C. (2011). Real-time flood monitoring and warning system. *Procedia Engineering*, 8, 354-358. doi:10.1016/j.proeng.2011.03.063

Van der Sterren, M., Rahman, A., and Dennis, G. R. (2012). Quality and quantity monitoring of urban rainwater harvesting systems in Australia. *Water Science and Technology*, 66(1), 77–84.

Ward, S., Memon, F. A., and Butler, D. (2010). Harvested rainwater quality: The importance of appropriate design. *Water Science and Technology*, 61(1), 79–86.

Appendix 1: Table showing the Descriptive Statistics of the Measured Properties of the Harvested Water in the Smart Storage System

Parameter	Mean	Minimum	Maximum	Range	Median	Standard Deviation
Water Level (1000ℓ tank) (m)	85.60	3.60	130.00	126.4	88.81	25.77
Volume of Water Collected (1000ℓ Tank) (m^3)	0.59	0.03	0.90	0.87	0.62	0.18
Water Level (500ℓ tank) (m)	58.15	0.00	90.00	90.00	80.17	30.92
Volume of Water Collected (500ℓ Tank) (m^3)	0.28	0.00	0.44	0.44	0.39	0.15
Ph	6.75	6.35	7.08	0.73	6.82	0.17
Turbidity (NTU)	85.57	38.71	94.93	56.22	85.76	2.54

Appendix 2: Computer Code

```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <SD.h>
#define TRIG1 2  // Ultrasonic sensor for top tank
#define ECHO1 3
#define TRIG2 4  // Ultrasonic sensor for lower tank
#define ECHO2 5
#define TURBIDITY_SENSOR A0  // Turbidity sensor connected to analog pin A0
#define PH_SENSOR A1         // pH sensor connected to analog pin A1
#define SD_CS 10             // Chip select pin for SD card module

LiquidCrystal_I2C lcd(0x27, 16, 2);
File dataFile;
float readUltrasonic(int trig, int echo) {
  digitalWrite(trig, LOW);
  delayMicroseconds(2);
  digitalWrite(trig, HIGH);
  delayMicroseconds(10);
  digitalWrite(trig, LOW);
  long duration = pulseIn(echo, HIGH);
  float distance = duration * 0.034 / 2; // Convert to cm
  return distance;
}

void setup() {
  Serial.begin(9600);
  pinMode(TRIG1, OUTPUT);
  pinMode(ECHO1, INPUT);
  pinMode(TRIG2, OUTPUT);
  pinMode(ECHO2, INPUT);

  lcd.begin();
  lcd.backlight();

  if (!SD.begin(SD_CS)) {
    Serial.println("SD card initialization failed!");
    lcd.setCursor(0, 0);
```

```
    lcd.print("SD Init Failed");
    return;
  }
  Serial.println("SD card initialized.");
  lcd.setCursor(0, 0);
  lcd.print("SD Ready");
  delay(2000);
  lcd.clear();
}

void loop() {
  float topTankLevel = readUltrasonic(TRIG1, ECHO1);
  float lowerTankLevel = readUltrasonic(TRIG2, ECHO2);

  int turbidityValue = analogRead(TURBIDITY_SENSOR);
  float pHValue = (analogRead(PH_SENSOR) * 5.0 / 1023.0) * 3.5; // pH scaling factor

  Serial.print("Top Tank Level: ");
  Serial.print(topTankLevel);
  Serial.println(" cm");

  Serial.print("Lower Tank Level: ");
  Serial.print(lowerTankLevel);
  Serial.println(" cm");

  Serial.print("Turbidity Sensor Value: ");
  Serial.println(turbidityValue);

  Serial.print("pH Value: ");
  Serial.println(pHValue);

  Serial.println("------------------------");

  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("T1:"); lcd.print(topTankLevel); lcd.print("cm");
  lcd.setCursor(0, 1);
  lcd.print("T2:"); lcd.print(lowerTankLevel); lcd.print("cm");
  delay(2000);

  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Turb:"); lcd.print(turbidityValue);
  lcd.setCursor(0, 1);
  lcd.print("pH:"); lcd.print(pHValue);
  delay(2000);

  dataFile = SD.open("sensor_data.txt", FILE_WRITE);
  if (dataFile) {
    dataFile.print("Top Tank Level: "); dataFile.print(topTankLevel); dataFile.println(" cm");
    dataFile.print("Lower Tank Level: "); dataFile.print(lowerTankLevel); dataFile.println(" cm");
    dataFile.print("Turbidity: "); dataFile.println(turbidityValue);
    dataFile.print("pH Value: "); dataFile.println(pHValue);
    dataFile.println("------------------------");
    dataFile.close();
  } else {
    Serial.println("Error opening file");
  }
  delay(2000);
```