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Assessment of Rainwater Quality from Rainwater Storage in Ende, East Nusa Tenggara Province, Indonesia

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ABSTRACT

Using rainwater as an alternative water source requires careful attention to its quality, particularly in simple storage systems. This study aims to analyze changes in the physical, chemical, and microbiological quality of rainwater stored in a tank over a specified period, as well as the effects of maintenance practices on rainwater harvesting systems. The research methodology involved collecting samples of untreated rainwater and rainwater stored in a tank over four weeks. Physical parameters analyzed included color, turbidity, and total dissolved solids (TDS); chemical parameters included pH; and microbiological parameters included total coliforms and *Escherichia coli*. The results indicate that poor roof surface and gutter system cleanliness led to increased turbidity and noticeable changes in rainwater color. Following roof and gutter cleaning, improvements in the physical quality of the stored rainwater were observed. However, an anomaly in turbidity occurred during the third week, reaching 52 NTU. TDS values decreased throughout the storage period, while the pH of the rainwater remained within a neutral range. From a microbiological perspective, the concentrations of total coliforms and *E. coli* decreased significantly over the storage period, presumably due to limited nutrient availability and unfavourable environmental conditions for bacterial growth. The boiling process was effective in reducing bacterial concentrations; however, total coliforms and *E. coli* were still detected at levels of 11 CFU/100 mL and 4.4 CFU/100 mL, respectively. These findings demonstrate that stored rainwater requires further treatment prior to use, particularly for potable purposes.

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1. Introduction

Rainwater is one of the sources of raw water for a clean water supply derived from surface water [1]. The use of rainwater is common in regions experiencing water scarcity during the dry season. Rainwater harvesting can be considered relatively simple and accessible to most communities, as rainwater falling on rooftops is collected through gutters, conveyed by pipes, and subsequently stored in tanks. Typically, the tank inlet is equipped with a water filter to prevent debris and sediment from entering the storage tank, as well as a water purification unit to ensure the collected water meets the required quality standards for a clean water supply [2].

Many countries have utilized rainwater as a source of raw water to meet clean water demands. One country that has extensively adopted rainwater not only as a raw water source but also for potable purposes is Australia [3]. Most regions in Australia have introduced regulations or policies promoting rainwater harvesting, primarily to reduce dependence on centralized water supply utilities. This approach is critical given that Australia is one of the driest continents on Earth, with continuously increasing air temperatures that have led to widespread depletion of surface water and groundwater resources. For example, the state of Queensland enforces regulations requiring new residential buildings with roof areas of at least 100 m^2 to install rainwater harvesting systems with a minimum storage capacity of 5 kL.

Related studies on the use of rainwater as a raw water source have also been conducted in Jordan, a country that experiences severe water scarcity during the dry season [4]. These studies demonstrated that approximately 15 m^3/year of rainwater can be harvested from a single household roof in Jordan, equivalent to about 5.6% of the total domestic water supply in 2005, which largely depended on groundwater resources. In most regions of the American continent, rainwater is primarily used for non-potable purposes, such as hygiene activities (toilet flushing, laundry, and irrigation), with limited use for drinking water. This is because rainwater collected from rooftops and stored in ponds or tanks requires appropriate treatment before use for potable purposes [5].

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Rainwater has also been utilized as a source of raw water in several regions of Indonesia. A study conducted by Krisnayanti *et al*. [6] in Kupang Town demonstrated that the minimum rainwater storage capacity, calculated using the water balance method, ranges from 26.59 to 44.10 m³ per household. This capacity was shown to reduce reliance on the municipal water supply (PDAM) by 30.57% and to significantly decrease household expenditures on clean water. Another study by Purwantoro *et al*. [7] in Panggang District, Gunungkidul Regency, examined patterns of household water resource utilization and estimated the appropriate size of rainwater harvesting systems. The results indicated relatively high rainfall conditions, with five dry months and six wet months annually. The required storage volume was determined by multiplying daily water demand by the duration of the dry season. The potential volume of harvestable rainwater was estimated by multiplying the effective roof catchment area by the average monthly rainfall and the runoff coefficient of the roofing material.

The quality of rainwater as a raw water source for a clean water supply generally complies with the standards stipulated in the Indonesian Ministry of Health Regulation (Permenkes) No. 32 of 2017; however, most measurements of rainwater quality indicate a tendency toward acidic pH values that do not meet the prescribed quality standards [8–10]. According to Maryono [11] , the acidic nature of rainwater in Indonesia is mainly due to high atmospheric carbon dioxide concentrations, which react with water vapor to form carbonic acid, a weak acid. Rainwater with a pH range of 5.0 to 6.0 is generally considered safe for use and poses no significant health risks. Nonetheless, bacterial contamination remains a critical concern, requiring appropriate treatment before it can be used for clean water purposes [12,13].

Hamilton *et al*. [12] identified several factors influencing the presence of bacteria in rooftop-harvested rainwater storage tanks, including meteorological factors (wind direction and speed), catchment location, climatic conditions, organic matter accumulation in gutters, the presence of animal feces or animals around the roof area, water volume and retention time within the tank, as well as the condition of the roof and storage system. In addition, the presence of *Escherichia coli* in untreated rainwater is presumed to be associated with bioaerosol events, in which pathogenic microorganisms attached to aerosol particles are deposited with rainfall. Rahayu *et al*. [14] reported that *E. coli* is a member of the coliform group of bacteria that can survive and persist in the digestive tracts of humans and animals. The growth and survival of *E. coli* are strongly influenced by environmental conditions, including temperature, pH, and osmotic pressure. The optimal temperature for *E. coli* growth is approximately 37 °C, with a minimum generation time (doubling time) of about 30 minutes. *E. coli* is also capable of surviving under acidic conditions, within a pH range of 2.5 to 4.6.

This study aims to analyze changes in the physical, chemical, and microbiological quality of rainwater stored in a tank over a specified period, and to evaluate the effects of maintenance practices on the rainwater harvesting system. The research process began with the collection of samples of untreated rainwater and rainwater stored in the tank, followed by an assessment of roof and gutter conditions, the implementation of cleaning procedures for the rainwater harvesting system, and periodic monitoring of water quality through physical, chemical, and microbiological parameter testing throughout the storage period.

2. Methodology

2.1 Tools and Materials

A simple rainwater storage installation requires a set of materials designed to ensure the effective collection, conveyance, and storage of rainwater. The main component is a 1,300-liter storage tank that serves as the reservoir for roof runoff. Rainwater is collected through 6-inch gutters equipped with gutter outlets and gutter guards, allowing for controlled flow while minimizing the entry of large debris such as leaves and twigs.

The water conveyance system employs PVC pipes with varying diameters 4 inches, 2 inches, and ¾ inch adjusted to meet the required flow rate and pressure at different sections of the system. Larger-diameter pipes are used in the upstream section to accommodate relatively high runoff discharge, after which the pipe size is gradually reduced using reducing sockets from 4 inches to 2 inches and from 2 inches to ¾ inch. Pipe fittings, including 2-inch elbow (L) joints and 2-inch tee (T) joints, are utilized to control flow direction and branching, allowing the installation configuration to be adapted to site-specific conditions.

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Flow regulation and the use of harvested rainwater are facilitated by installing valves and ¾-inch faucets, enabling users to control outflow from the storage tank according to demand. In addition, a plastic float ball combined with a wire is used as a preliminary filter (pre-filter) to retain floating debris before the water enters the tank. The integration of these components results in a rainwater harvesting system that is simple, cost-effective, and easy to implement, while still supporting water conservation efforts and sustainable water resource management. The rainwater storage system was installed in Kota Raja Subdistrict, Ende Utara District, at coordinates 8.836498° S, 121.6479562° E. The installation of the rainwater harvesting system is shown in **Fig. 1**.

Figure 1. Rainwater Harvesting System

2.2 Research Methods

Data analysis methods were applied to evaluate changes in rainwater quality across the collection, conveyance, and storage processes within the rainwater harvesting (RWH) system. The initial stage involved planning the installation of the RWH system by considering roof conditions, gutter configuration, rainwater flow direction, and storage tank capacity, ensuring that the system adequately represented actual rainwater utilization practices. Subsequently, the RWH system was installed at the predetermined location in accordance with the planned design, ensuring consistent rainwater collection and conveyance throughout the observation period.

Water sampling was conducted in stages to capture variations in rainwater quality at each process phase. The samples included rainwater collected prior to roof contact, rainwater after runoff from the roof surface, and rainwater stored in the RWH system. Sampling of stored rainwater was carried out periodically from the first to the fourth week of storage to observe changes in water quality resulting from storage processes, sedimentation, and potential contamination. All samples were collected following standard water sampling procedures to minimize contamination and ensure analytical accuracy. The rainwater samples analyzed comprised untreated rainwater (R0), roof-runoff rainwater (R1), first-flush rainwater collected in a 1 m pipe (RX), and rainwater stored in a tank (R2). Following the sampling process, water quality testing was conducted weekly over four weeks after a rainfall event, during which no additional rainwater entered the storage system. This approach enabled the isolation of external variables and allowed for a focused assessment of the natural purification processes occurring within the tank until the water quality met the established clean water standards.

All water samples were analyzed at the Regional Health Laboratory of Ende Regency using standardized water quality testing methods. The analyzed parameters included physical, chemical, and microbiological indicators, and the results were compared with relevant water quality standards. The test results were analyzed descriptively and comparatively to assess differences in water quality across

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process stages and changes over the storage period. Based on these analyses, recommendations were formulated regarding the suitability of harvested rainwater for non-potable domestic use, as well as the potential development of additional treatment systems to enable safer, more sustainable use of rainwater.

3. Results and Discussion

During the first rainfall event, rainwater samples were collected and analyzed at the Regional Health Laboratory of Ende Regency. The results of the water quality analysis are presented in **Table 1**. The findings indicate that all tested rainwater samples failed to meet the required standards for color, turbidity, total coliforms, and *Escherichia coli*. Rainwater that had passed over the roof exhibited total dissolved solids (TDS) values exceeding the permissible limits, whereas rainwater collected prior to roof contact showed TDS concentrations below 300 mg/L. The observed deterioration in rainwater quality can be attributed to several factors.

First, the poor condition of the roof surface and gutters, which conveyed rainwater into the storage tank, significantly affected water quality. Prolonged periods without rainfall following system installation led to the accumulation of leaf litter on the roof and in the gutters. Rainwater mixed with decaying leaves led to increased turbidity and noticeable changes in water color. Turbidity is closely associated with suspended and dissolved solids, while water color is related to TDS, suspended solids, and turbidity levels. Elevated TDS values are influenced by the presence of dissolved organic and inorganic compounds, as well as plankton or microorganisms in the water [15]. High concentrations of total coliforms and *E. coli* may result from bacterial contamination originating from roof surfaces or leaf debris, as well as from bioaerosol deposition processes [12]. The condition of the roof prior to cleaning is shown in **Fig. 2**, while a representative sample of water collected from the storage tank is presented in **Fig. 3**.

Figure 2. The condition of the roof prior to cleaning

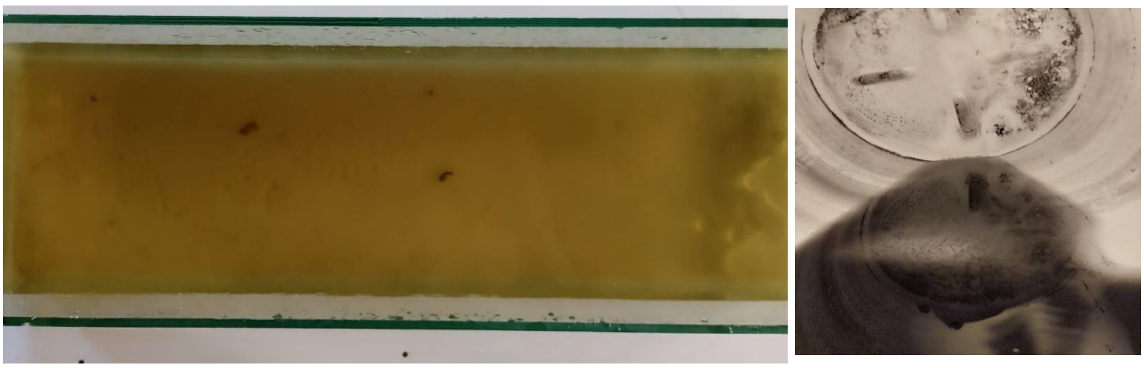

Figure 3. Rainwater from the storage prior to cleaning

Second, the quality of untreated rainwater samples may be poor, depending on the timing of the rainfall event and the environmental sanitation conditions at the sampling location. Precipitation patterns play a critical role in determining water quality within storage tanks. Short-duration rainfall events often result in higher concentrations of dissolved substances because of their limited volume. In contrast, prolonged precipitation results in significant dilution, lowering the overall concentration of dissolved materials [16, 17]. Maryono *et al*. [11] suggested that rainwater should be collected only after the first 5–10 minutes of a rainfall event. The initial runoff, commonly referred to as the "first flush," is believed to have inferior quality due to mixing with atmospheric pollutants and airborne particles. It should be noted that the rainwater samples analyzed in this study were collected from the first rainfall event following the installation of the rainwater harvesting system.

Subsequently, the roof and gutter system were cleaned, and overhanging branches were trimmed to reduce the accumulation of leaf debris on the roof and in the gutters, which could obstruct the flow of rainwater into the storage tank. The rainwater storage tank was also cleaned to prevent contamination from previously stored water. Rainwater harvesting was then conducted during the subsequent rainfall event, and the collected water was stored for four weeks to assess changes in rainwater quality during storage. Rainwater was collected from a single rainfall event only and was not supplemented by subsequent rainfall. Water quality testing was carried out at the beginning of the first week (R4), the second week (R5), the third week (R6), and the fourth week (R7) of storage. The cleaned conditions of the roof, gutters, storage tank, and the outflow from the cleaned storage tank are presented in **Fig. 4**.

Figure 4. Condition of the roof, the storage tank after cleaning, and the condition of the water inside the storage tank

The results of the water quality analysis are presented in **Table 2**. The findings indicate an increase in color intensity in rainwater stored in the rainwater storage tank. As discussed previously, water color is closely associated with dissolved solids, suspended solids, and turbidity. Based on the cross-sectional configuration of the installed rainwater harvesting system, rainwater enters the storage tank from the roof located above the tank, while water intended for use is withdrawn through a tap positioned near the bottom of the tank. The observed increase in color in stored rainwater may be attributed to particles, chemical compounds, bacteria, plankton, or even algae that enter the tank with the rainwater.

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Table 1 Rainwater quality prior to roof cleaning

No	Location		Parameter										
	Latitude	Longitude	Sample Code	Odor	Taste	Color (TCU)	Turbidity (NTU)	Temperature (⁰C)	TDS (mg/L)	pH	Salinity (mg/L)	Total Coliform (CFU/100 mL)	E. coli (CFU/100 mL)
1	-8,8365	121,648	R0	Odorless	Tasteless	28	12	24⁰C	75	7,9	0	>2400	120
2	-8,8365	121,648	R1	Odorless	Tasteless	26	30	24⁰C	320	7,9	0	>2400	150
3	-8,8365	121,648	R2	Odorless	Tasteless	24	34	25⁰C	380	7,8	0	>2400	210
4	-8,8365	121,648	RX	Odorless	Tasteless	46	52	24⁰C	230	7	0	>2400	210

Table 2 Rainwater quality following roof cleaning

No	Location		Parameter										
	Latitude	Longitude	Sample Code	Odor	Taste	Color (TCU)	Turbidity (NTU)	Temperature (⁰C)	TDS (mg/L)	pH	Salinity (mg/L)	Total Coliform (CFU/100 ml)	E. coli (CFU/100 ml)
1	-8,8365	121,648	RX2	Odorless	Tasteless	115	10	24⁰C	41	7,3	0	>2400	240
2	-8,8365	121,648	R3	Odorless	Tasteless	0	0	23⁰C	16	7,6	0	>2400	240
3	-8,8365	121,648	R4	Odorless	Tasteless	0	0	23⁰C	21	7,4	0	>2400	240
4	-8,8365	121,648	R5	Odorless	Tasteless	25	2	28,9⁰C	11	7,6	0	93	7,5
5	-8,8365	121,648	R6	Odorless	Tasteless	30	52	27⁰C	17	7,5	0	28	11
6	-8,8365	121,648	R7	Odorless	Tasteless	70	2	28⁰C	9	7,8	0	11	7
7	-8,8369	121,6515	RP	Odorless	Tasteless	0	0	24⁰C	21	7,8	0	>2400	240

The color value of rainwater during the first week of storage complied with the Indonesian Ministry of Health Regulation (Permenkes) No. 2 of 2023, whereas the values measured in subsequent weeks exceeded the prescribed standard. The trend in changes in rainwater color is illustrated in **Fig. 5**.

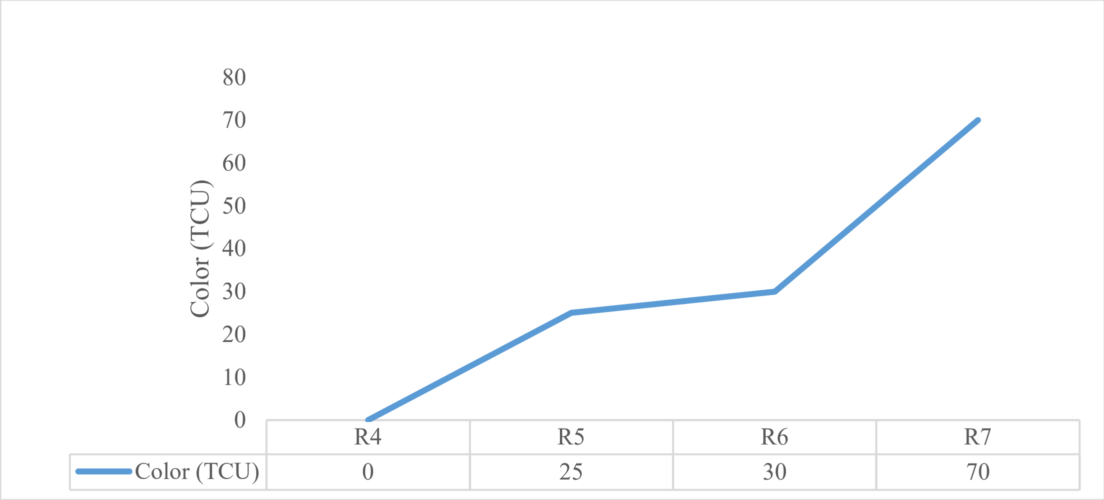

Figure 5. Color of rainwater in the storage tank from week 1 to week 4

Rainwater turbidity may originate from total suspended solids (TSS) or particles transported from the roof into the storage tank. Turbidity levels in the rainwater storage tank showed an anomaly in the third-week sample, when turbidity increased sharply to 52 NTU. This unusually high value may have resulted from sampling error, such as disturbance of the tank prior to sampling. Such a disturbance could resuspend settled particles at the bottom of the tank, temporarily increasing turbidity. Dispersion in water can explain the increase in suspended particles and turbidity within a storage system. Dispersion refers to the movement of particles within a fluid from their initial positions to new locations [18]. Larger particles tend to move more rapidly than smaller particles, and the type of fluid also influences the rate of particle transport in water [19].

Particles carried into the tank with rainwater may originate from an unclean metal roof or poorly maintained gutters. These particles are initially transported from the water surface toward the bottom of the tank, where they gradually settle over time. Consequently, water stored in the tank over a given period will contain particles that slowly sediment to the bottom. Turbidity in stored rainwater increases with the presence and resuspension of suspended particles within the storage system. Turbidity values during the first, second, and fourth weeks of storage complied with the Indonesian Ministry of Health Regulation (Permenkes) No. 2 of 2023, whereas the sample collected in the third week exceeded the allowable standard. The turbidity results are presented in **Fig. 6**.

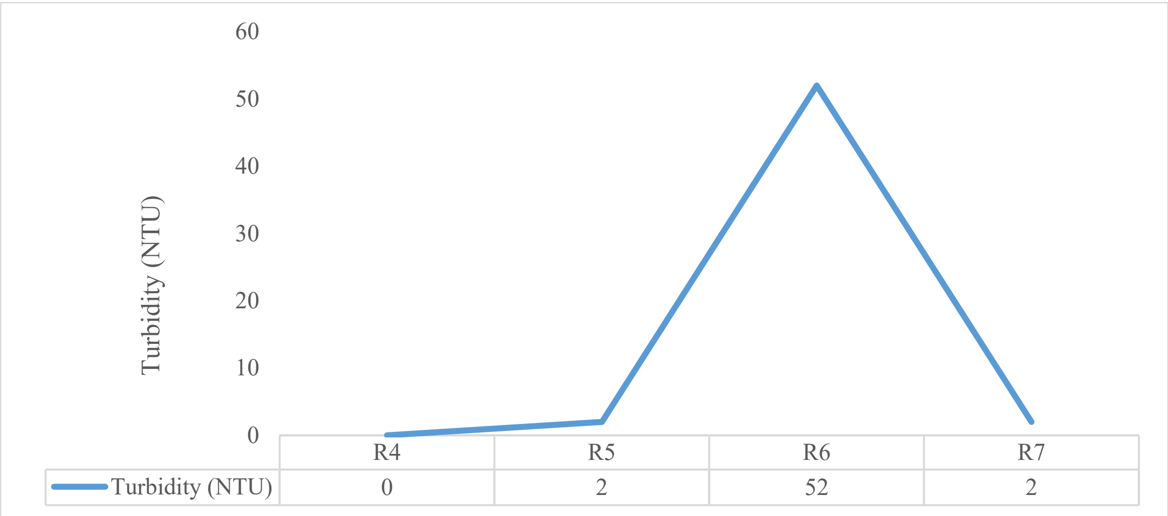

Figure 6. Turbidity of rainwater in the storage tank from week 1 to week 4

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The total dissolved solids (TDS) values of rainwater stored in the rainwater harvesting tank decreased over the storage period. TDS in stored rainwater may originate from dissolved particles leached from galvanized or metal roofing materials, as well as from residual debris on the roof that is transported and dissolved during rainfall events. Previous studies have shown that roof material quality significantly influences the quality of rainwater collected in storage systems, with chemical parameters—particularly metal concentrations—being the most affected. Galvanized or zinc roofs tend to leach more particles into rainwater compared to clay tile roofs [20]. Furthermore, rainwater collected from corroded roofs exhibits higher TDS values than rainwater harvested from non-corroded roofing surfaces [21].

Therefore, both roof cleanliness and roof material type should be carefully considered in rainwater harvesting applications. The use of appropriate roofing materials combined with regular roof maintenance can substantially improve the quality of stored rainwater. In addition, the surface of the storage material and its placement close to sunlight support the growth of biofilms and trigger the release of organic substances, which cause fluctuations in the TDS of the water [22, 23]. All measured TDS values from the first to the fourth week of storage complied with the Indonesian Ministry of Health Regulation (Permenkes) No. 2 of 2023. The TDS results are presented in **Fig. 7**.

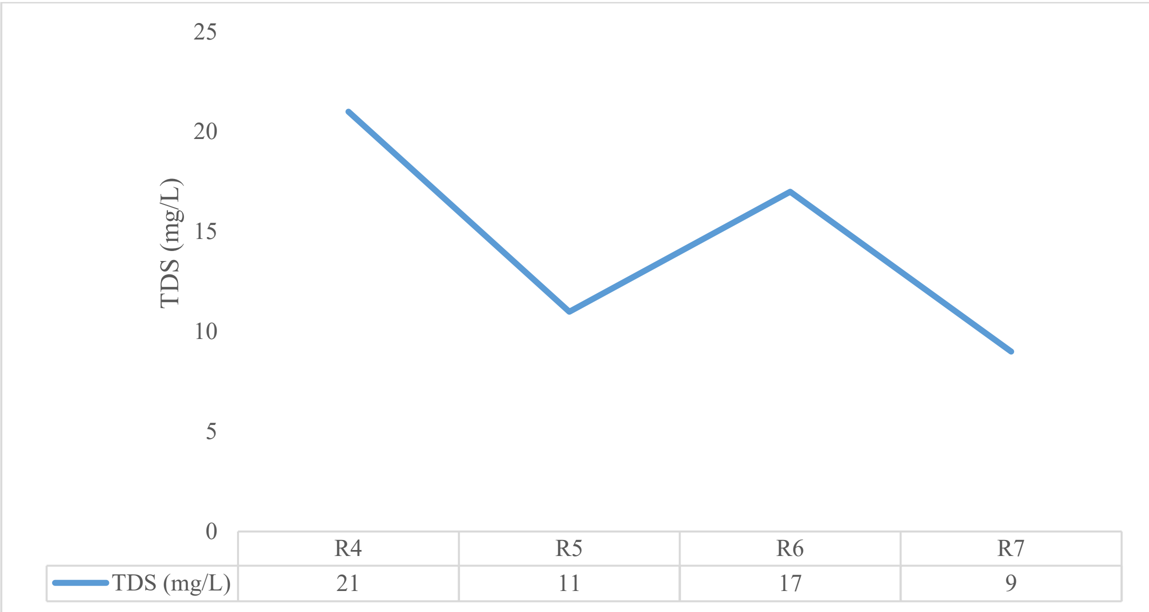

Figure 7. TDS of rainwater in the storage tank from week 1 to week 4

The pH values of the stored rainwater remained within normal conditions, approximately neutral at pH 7. According to the Indonesian Ministry of Health Regulation (Permenkes) No. 2 of 2023, acceptable pH values for water quality range from 6.5 to 8.0. The measured pH values of rainwater samples from the first to the fourth week of storage ranged from 7.4 to 7.8, indicating compliance with the established standard. An increase in water pH may be attributed to changes in dissolved carbon dioxide (CO_2) concentration, as lower CO_2 levels result in higher [24]. Furthermore, the type of storage tank material, such as plastic, can alter the water's pH due to the leaching of chemical additives and the influx of carbon dioxide from the air [22, 25]. The pH variation over the storage period is illustrated in **Fig. 8**.

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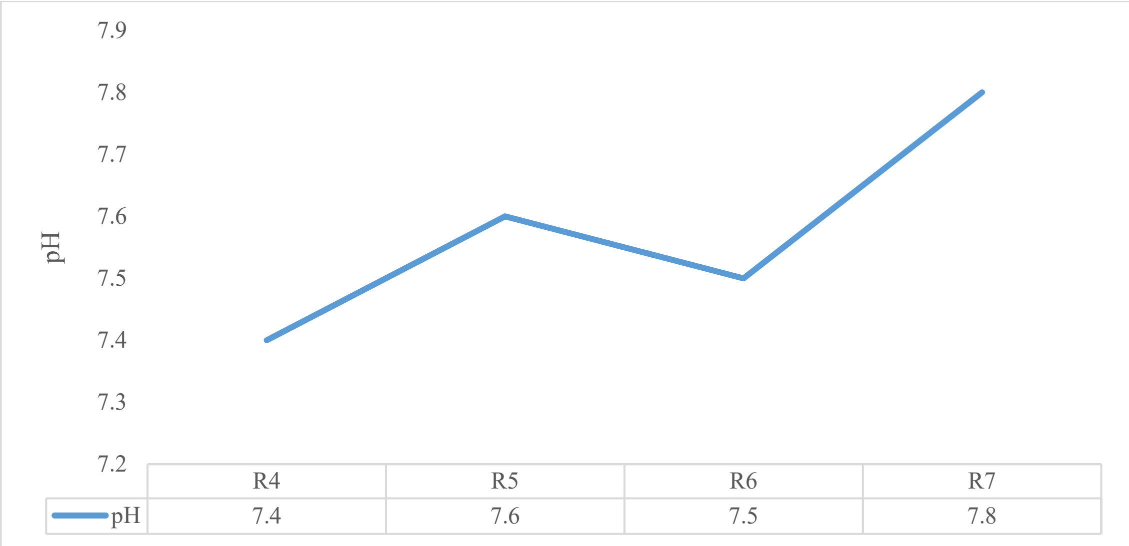

Figure 8. pH of rainwater in the storage tank from week 1 to week 4

Bacteria present in rainwater stored in rainwater harvesting tanks may originate from roof cleanliness, the presence of insects or birds around the roof area and surrounding environmental sanitation conditions that allow aerosol deposition near the [12, 26]. Rainwater samples collected after roof contact (R3) and first-flush rainwater captured in the initial collection pipe (RX2) exhibited high abundances of total coliforms and *Escherichia coli*. These conditions indicate that the rainwater stored in the tank originated from runoff passing through surfaces that served as potential bacterial reservoirs. The concentrations of total coliforms and *E. coli* in the storage tank at the beginning of the first week of sampling (R4) were identical to those measured in rainwater from the first roof runoff and the first-flush sample collected in the pipe.

In addition, rainwater samples collected directly from rainfall near a livestock enclosure without roof contact (RP) also showed high abundances of total coliforms and *E. coli*. This finding suggests that aerosol deposition events can also significantly influence rainwater quality. Over the 4-week storage period, total coliform and *E. coli* concentrations in the rainwater storage tank declined substantially. The trends in bacterial reduction are presented in **Fig. 9** and **Fig. 10**. Previous studies have reported that *E. coli* concentrations in surface water can decrease by up to 50% within 1.5 to 3 days, while total coliform concentrations decrease by 50% within approximately 0.9 days [27]. These reductions may be attributed to decreases in temperature, limited availability of organic carbon in the water, and variations in sunlight intensity, which affect bacterial survival.

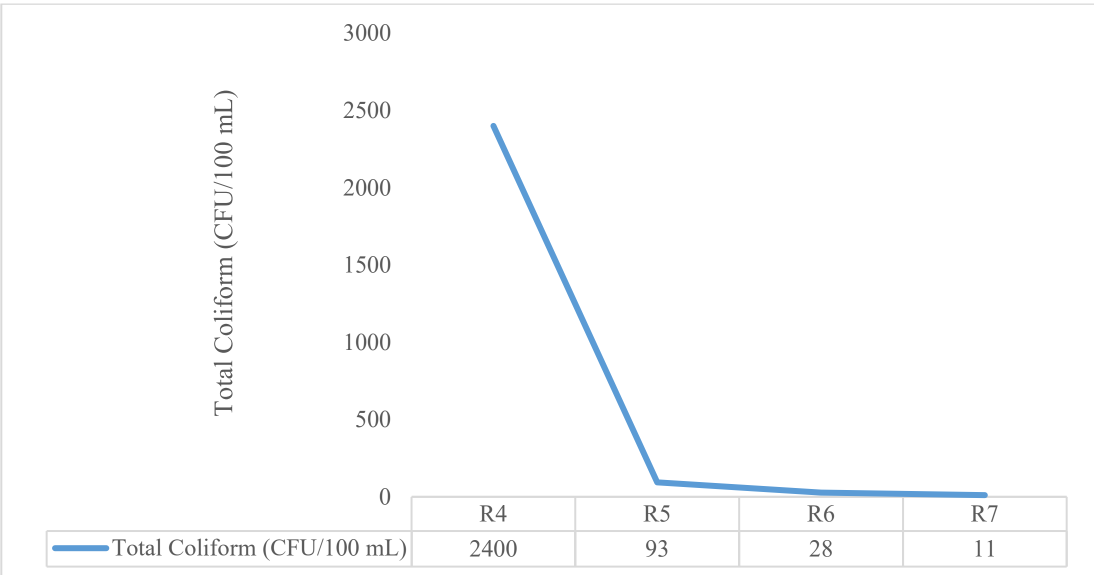

Figure 9. Total Coliform of rainwater in the storage tank from week 1 to week 4

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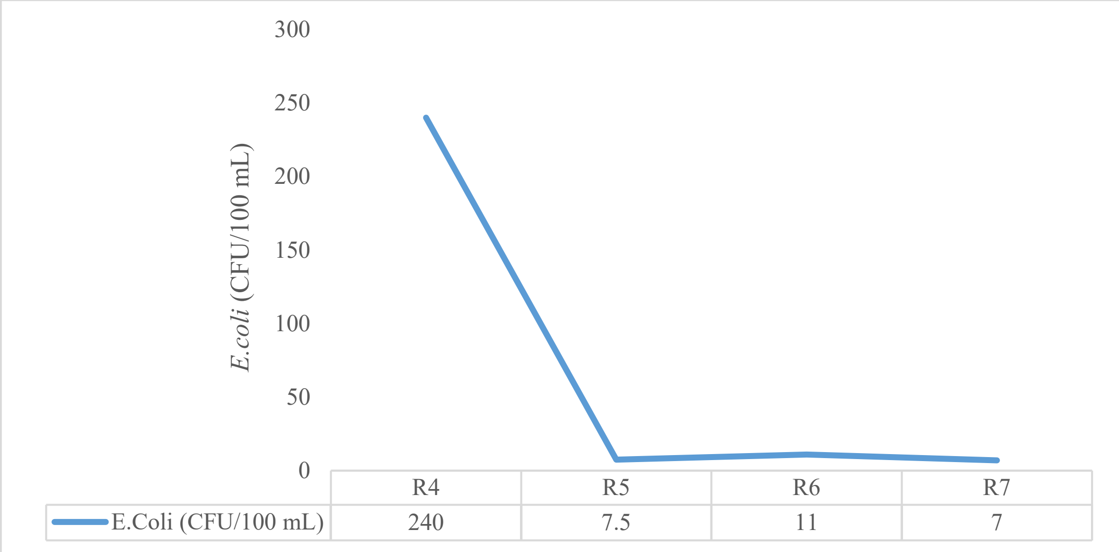

Figure 10. *E. coli* of rainwater in the storage tank from week 1 to week 4

The decrease in total coliforms and *E. coli* concentrations in stored rainwater may also be associated with limited nutrient availability and unfavorable environmental conditions within the storage system. Such conditions may induce bacterial dormancy or inactivity. Dormancy is defined as a physiological state in which bacterial cells remain viable and metabolically active but are unable to grow under prevailing environmental conditions [28]. A study by Gao *et al*. [29] from Harvard University found that, to survive harsh environmental conditions, bacteria may enter a dormant state by forming spores and developing protective layers around the cell. This protective structure enables bacteria to survive in nutrient-free environments and protects them from cellular damage caused by extreme temperatures, ultraviolet radiation, harsh chemicals, and antibiotics. However, when spores detect favorable environmental conditions and nutrient availability, they can shed their protective layers and reactivate metabolic activity. The spores referred to in this context are endospores, which function as bacterial survival mechanisms under extreme and unfavorable conditions rather than as part of vegetative growth or genetic reproduction processes [30].

Dormant bacteria exhibit greater antibiotic resistance than metabolically active bacteria. Following antibiotic exposure, dormant bacteria may resuscitate and resume growth when environmental conditions become favorable and sufficient nutrients are available. Dormant bacteria are difficult to detect using conventional laboratory microbiological techniques because, during dormancy, bacterial cells often undergo morphological changes from rod-shaped to coccoid forms. Actively detectable bacteria are typically rod-shaped. Moreover, during dormancy, bacteria lose intracellular components such as proteins and other molecules essential for routine cellular functions, including respiration and metabolism, making them less detectable through standard microbiological assays [28], [31].

This study did not measure water temperature within the storage tank or quantify nutrient availability in the stored rainwater to assess correlations with bacterial dormancy directly. Instead, the study further examined changes in the quality of stored rainwater following boiling treatment (RB) using a household electric water heater. The boiled rainwater sample was collected at the beginning of the second week of storage. The results showed that, although the rainwater had been boiled, total coliforms and *E. coli* were still detected at concentrations of 11 CFU/100 mL and 4.4 CFU/100 mL, respectively. Prior to boiling, the rainwater contained 93 CFU/100 mL of total coliforms and 7.5 CFU/100 mL of *E. coli*. Heating is one method that can damage bacterial DNA, leading to bacterial inactivation or death [32]. Previous studies have reported that bacteria generally cannot survive heating at 75 °C [33] and *that E. coli* is inactivated at approximately 70 °C [34]. However, these studies were conducted under sterile laboratory conditions rather than in household settings. Therefore, the persistence of *E. coli* in boiled rainwater samples may be attributed to environmental hygiene conditions or contamination associated with the boiling container itself. The thermal resistance of total coliforms and *E. coli* warrants further investigation to better their survival under extreme temperature conditions. Such studies could provide valuable recommendations for the effectiveness of conventional rainwater treatment methods, such as boiling, in ensuring safe water use.

4. Conclusion

Based on the study results, the physical and chemical parameters of rainwater stored in the storage tank were strongly influenced by roof conditions, gutter cleanliness, rainfall timing, and surrounding environmental hygiene. The presence of organic debris, such as leaves and twigs, on the roof and in the gutters was shown to contribute to increased turbidity and changes in rainwater color. Maintenance measures, including roof and gutter cleaning and vegetation trimming around the building, were effective in improving the physical quality of rainwater through natural sedimentation during storage. In addition, the chemical characteristics of the stored rainwater remained relatively stable, with pH values within the neutral range and a decreasing trend in dissolved substances, suggesting water quality stabilization during storage.

From a microbiological perspective, the stored rainwater still showed potential contamination indicators, although their abundance tended to decrease with more extended storage. This reduction is likely influenced by limited nutrient availability and unfavorable environmental conditions within the storage tank, causing bacteria to enter a dormant state. Nevertheless, the detection of bacteria even after heat treatment indicates that boiling alone does not fully guarantee the microbiological safety of harvested rainwater. Therefore, rainwater stored in tanks still requires additional treatment before use, particularly for drinking, to ensure it is safe and compliant with health standards.

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