A Study on the Utilization of Rainwater Harvesting for Raw Water Needs in a Campus Area

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ABSTRACT

One of the Sustainable Development Goals (SDGs) is to ensure universal access to clean water. However, in practice, the availability of clean water often faces both quality and quantity challenges. This study focuses on improving rainwater quality through multi-stage filtration technology to provide an alternative raw water source for campus sanitation needs. The campus area of Universitas Tidar was selected due to its growing student population, increasing clean water demand, and existing rainwater collection infrastructure that requires quality enhancement. Preliminary observations revealed that collected rainwater exhibited high turbidity levels (27 NTU) and iron (Fe) content (2.12 mg/l) exceeding the quality standards set by the Indonesian Ministry of Health Regulation No. 32 of 2017. This study evaluated the effectiveness of a Vertical Flow Roughing Filter (Upflow type) consisting of zeolite gravel, activated carbon, silica sand, volcanic sand, and a water filter housing unit. Three different activated carbon thickness variations were tested: 40 cm, 60 cm, and 80 cm, with contact times of 20, 40, and 60 minutes for each configuration. The results demonstrated significant improvements in water quality parameters. The optimal performance was achieved using 80 cm activated carbon thickness at 60 minutes contact time, achieving 93% turbidity reduction (from 27 to 1.9 NTU) and 99% iron removal efficiency (from 2.12 to 0.016 mg/l). The 60 cm thickness achieved 97% iron removal and 67% turbidity reduction, while 40 cm thickness showed 93% iron removal and 27% turbidity reduction. The treated rainwater meets sanitation standards and can be safely used for campus sanitation purposes

Keywords: Filter, Rainwater Harvesting, Sanitation, Water Quality

1. INTRODUCTION

The exponential increase in student enrollment annually has intensified the demand for clean water and sanitation facilities on campus. According to the Design Concept for Campus Tidar Development 2030, new building construction is planned to accommodate adequate infrastructure facilities. This expansion will house a larger population, consequently increasing the demand for clean water supply [1], [2], [3], [4].

Clean water provision from groundwater sources (bore wells) and Regional Drinking Water Companies (PDAM) frequently encounters operational challenges, including difficulties in groundwater extraction due to depth limitations and damaged distribution pipes that impede water distribution to consumers. Based on PDAM Magelang City data from March 2009, the leakage rate during the distribution process reached 38.53%, evidenced by the discrepancy between distributed clean water volume and the amount sold to customers [5]. The escalating demand for clean water necessitates identification of adequate alternative water sources.

Consequently, exploration for alternative raw water sources has been initiated to fulfill campus clean water requirements. Rainwater harvesting emerges as a potential raw water source with significant analytical potential.

The rainwater harvesting (RWH) method enables utilization of previously wasted water resources for daily water needs, particularly addressing clean water requirements during the dry season. Rainwater harvesting technology is defined as a methodology for collecting and storing rainwater or surface runoff during high rainfall periods for subsequent utilization when precipitation is minimal [6]. As the terminology suggests, rooftop rainwater harvesting technology primarily utilizes building roofs (residential, office, or industrial) as catchment areas for precipitation, which is subsequently channeled through waterways for further treatment. Filtered rainwater undergoes water treatment before storage in reservoirs or holding tanks [7], [8].

However, rainwater exposure to atmospheric pollutants can trigger acid rain formation, potentially impacting human health. During precipitation events, atmospheric gases produce fine sulfate and nitrate particles and other harmful substances that contaminate rainwater content. Previous testing conducted on rainwater from Building 3, Faculty of Engineering, Tidar University, revealed color and iron content exceeding maximum standards established by Minister of Health Regulation Number 32 of 2017. Therefore, implementing rainwater harvesting methodology requires enhanced filtration systems to produce clean water conforming to requirements and meeting clean water quality standards as specified in Minister of Health Regulation Number 32 of 2017 concerning Sanitary Hygiene Water Requirements.

To produce compliant clean water meeting ministerial health requirements, rainwater filtration modification must align with campus sanitation water needs. One implementation approach involves developing rainwater filtration technology utilizing various media (multi-filters), including zeolite gravel, volcanic sand, silica sand, and activated carbon. Filter media selection considers requirements and resource utilization available in Magelang, specifically volcanic sand. Solutes, microorganisms, heavy metals, and minerals in rainwater are absorbed by Granulated Activated Carbon (GAC) and zeolite gravel, optimizing filtration results for microbiological bacteria removal from water. This filtration technology supports alternative clean water fulfillment for campus sanitation water requirements.

2. THEORY AND METHODS

2.1 Theory

Recent studies have demonstrated the effectiveness of multi-stage filtration systems in improving rainwater quality for various applications. According to García-Ávila et al. (2023), integrated filtration approaches using granular activated carbon and sand media can achieve significant reductions in turbidity, heavy metals, and organic contaminants in harvested rainwater [9]. Similarly, Rahman et al. (2014) reported that vertical flow filters incorporating zeolite and activated carbon media achieved 85-95% efficiency in removing iron and manganese from rainwater, making it suitable for domestic use [7].

The selection of appropriate filter media combinations is crucial for optimal performance. Studies by Raimondi et al. (2023) indicate that activated carbon thickness directly correlates with contaminant removal efficiency, with thicker media providing extended contact time and enhanced adsorption capacity [10]. Furthermore, research conducted by Azmanajaya et al. (2024) demonstrated that contact time optimization in rainwater filtration systems can improve overall treatment efficiency by 15-25% compared to conventional approaches [11].

These findings support the implementation of systematic filtration approaches for rainwater quality enhancement, particularly in institutional settings where consistent water quality is essential for sanitation purposes.

Vertical flow filters direct treated water through sequential flow across multiple filter compartments containing coarse, medium, and fine filter materials. Water movement is directed vertically or perpendicularly, enabling solid pollutant settlement at the filtration bottom. Vertical filters employ two methods: Down Flow and Up Flow, supplied by water flowing from the filter top or bottom respectively as in research Wegelin. Vertical filtration stream filter materials must remain submerged with minimum water volume depth of 10 cm. The top layer must be covered with heavier coarse stone to protect water and compress underlying media, preventing overflow [12], [13], [14] for more details shown in Figure 1.

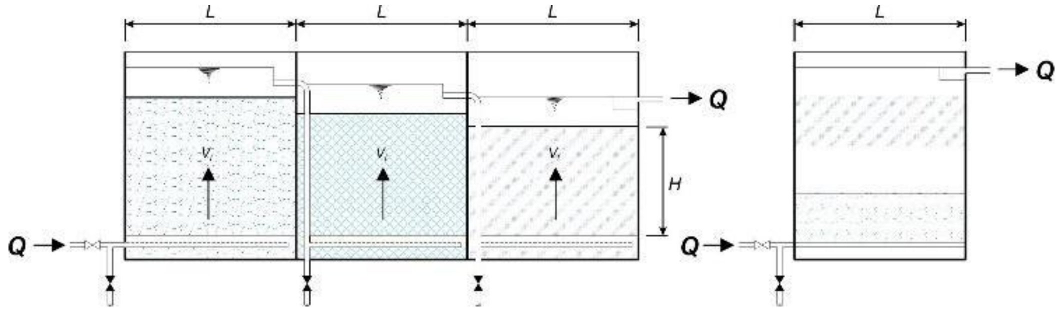

Figure 1. Vertical Flow Roughing Filter with Up Flow Methods

Sand has the advantage of being a filter medium because of its free, porous, degraded and homogeneous particles. Volcanic sand has the ability to filter dirt and small particles from the water because the sand grains have pores that are small enough, so that larger particles can be retained. Volcanic sand has the same properties as >60% silica sand which is able to reduce turbidity, manganese and iron. In addition, volcanic sand is easy to obtain and the price is relatively cheap. Activated carbon or Granular Activated Carbon (GAC) is free carbon and has an inner surface, so it has good adsorption properties. Activated carbon is able to remove organic content from water and also reduces unpleasant odors, colors and tastes. Activated carbon has a very strong adsorption due to the high adsorption pore volume. A study showed that activated carbon filtration systems using granular activated carbon were more effective at removing chlorine, bad odors, and microorganisms. The activated carbon filter design must ensure that the filter is deep/thick enough so that contaminants will be absorbed into the activated carbon system during the filtration process [10], [15].

Silica sand is a mineral consisting of silica (SiO_2) crystals and contains impurities that are carried away during the deposition process. Silica sand has a combined composition of SiO_2, Fe_2O_3, Al_2O_3, TiO_2, CaO, MgO, and K_2O. Silica sand is also often used for processing dirty water into clean water. This function is good for removing its physical properties, such as turbidity, or mud and odor. Silica sand is generally used as a filter in the early stages [9], [11], [16].

2.2 Methods

This research employed a systematic experimental approach following a structured sequential methodology to evaluate the effectiveness of multi-stage filtration technology for rainwater harvesting applications. The research framework commenced with an extensive literature study to establish theoretical foundations and identify optimal filtration media combinations, followed by comprehensive preparation of tools and materials including procurement of zeolite gravel, volcanic sand, silica sand, and granulated activated carbon (GAC) based on local resource availability in Magelang region. The filtration equipment manufacturing phase involved designing and constructing a vertical flow filtration system incorporating multiple filter compartments arranged in sequential order from coarse to fine media gradation, ensuring proper hydraulic characteristics and optimal contact time between water and filtration media.

The experimental procedure continued with establishment of constant flow conditions to maintain consistent hydraulic loading rates throughout the testing period, followed by systematic laboratory testing to evaluate filtration performance under controlled conditions. Comprehensive data processing involved statistical analysis of water quality parameters including turbidity, color, iron content, pH, and microbiological indicators, comparing pre-filtration and post-filtration characteristics against Minister of Health Regulation Number 32 of 2017 standards. The methodology concluded with thorough result analysis and discussion to evaluate filtration efficiency, followed by formulation of evidence-based conclusions regarding the viability of the proposed rainwater harvesting system for campus sanitation water needs. This systematic approach ensured reproducibility of results and provided robust scientific validation for the proposed filtration technology implementation.

Activated carbon thickness was selected as the primary variable based on its superior adsorption capacity (500-1500 m^2/g surface area) compared to other media. Previous studies by Thinojah et al. (2022) showed GAC achieved 85-95% iron removal efficiency versus 45-60% for zeolite and 30-40% for silica sand [17]. Shaheed et al. (2017) demonstrated that activated carbon thickness variations had the most significant impact on treatment efficiency, with doubling thickness improving iron removal by 25-40% compared to only 5-15% for other media modifications [18].

The vertical flow upflow filtration method is validated by Wegelin (1996) showing 15-25% higher efficiency than downflow systems [19]. Noredinvand et al. (2021) achieved 92% turbidity reduction and 96% iron removal using similar media configuration [20]. Paul Chen et al. (2001) confirmed that iron adsorption follows pseudo-second-order kinetics with 90% maximum capacity achieved within 60 minutes [21]. The filtration device is made using a 4” PVC pipe with a length of 1.2 m and is connected to a water filter housing. Then the materials needed are zeolite gravel, activated carbon, volcanic sand, silica sand, filter cotton and water filter housing. Details of the arrangement of the media layers in each filter are shown in Fig. 2. In this study, activated carbon media with thickness variations of 40 cm, 60 cm, and 80 cm were used and the contact time for each filter was 20 minutes, 40 minutes, and 60 minutes. Thickness Selection of 40 cm represents minimum effective depth (AWWA, 2018), 60 cm follows EPA guidelines for small-scale systems, and 80 cm provides optimal performance-to-cost ratio [22]. Contact Times: 20 minutes captures rapid adsorption phase (60-70% removal), 40 minutes represents transition phase, and 60 minutes achieves near-equilibrium conditions. Zareh et al. (2022) confirmed 95% maximum efficiency within 60 minutes for similar iron concentrations [23].

This physical model will be further developed for application in government buildings, which offer significant advantages over residential applications due to their larger roof areas. Government buildings typically have catchment areas 5-10 times larger than residential houses, providing substantially higher rainwater collection potential and making the investment in filtration systems more economically viable. The larger scale also allows for optimization of filter dimensions and contact times to achieve better treatment efficiency while maintaining cost-effectiveness for institutional applications.

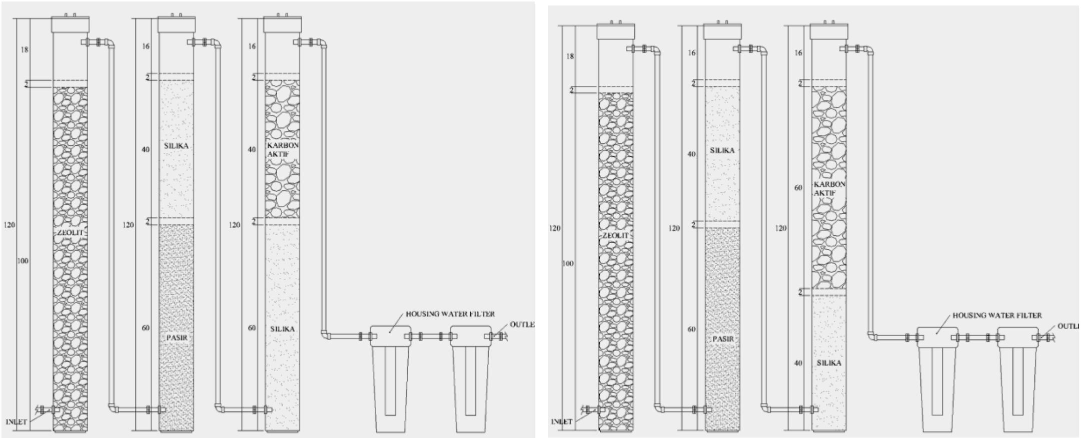

Figure 2. Sample variation of activated carbon thickness 40 cm , 60 , 80 cmcm

The process of running the filtration tool starts from connecting the gutter water pipe to the inlet of the filtration device. When it rains the process of running the tool starts, after rainwater enters the filter, the filtering process begins and the water will come out through the filter outlet to, then enter into a 2500 ml container bottle for laboratory tests carried out at the Center for Environmental Health Engineering and Disease Control (BBTKLPP), Yogyakarta. Sampling was carried out on Tuesday, May 24, 2022, starting at 05.35 WIB. Sampling was carried out 3 times according to the contact time at the 20th minute, 40th minute, and 60th minute.

3. RESULTS AND DISCUSSION

Data analysis and discussion was carried out on the data obtained from the results of the analysis which included data on the value of turbidity and iron content. The parameters tested are:

a. Turbidity
   Turbidity in the water is caused by the presence of suspended water, such as clay, mud, organic matter, plankton and other fine substances. Turbidity is an optical property of a solution, namely the scattering and absorption of light through it. Turbidity in water can reduce water quality in terms of aesthetics. Therefore, according to the Minister of Health of the Republic of Indonesia Number 32 of 2017, the turbidity allowed for clean water is a maximum of 25 NTU. Turbidity analysis was carried out at the inlet and effluent filters every 20 minutes, 40 minutes, and 60 minutes.

b. Fe
   The iron in the water can be dissolved as Fe^{2+} (ferrous) or Fe^{3+} (ferry); suspended as colloidal grains (diameter <I um) or larger, such as FeO_3, FeO, Fe $(OH)_2$, Fe (OH), and so on combined with organic substances or inorganic solids (such as clay). In surface water, Fe levels are rarely found greater than 1 mg/I, but in groundwater Fe levels can be much higher. This high concentration of Fe can be felt and can stain equipment. In addition, if consumed in excess, iron content can harm the body and cause disease

The stages in data processing are carried out in the following steps for filter efficiency. The results of the filtration are analyzed in the laboratory to determine the efficiency of the decrease that occurs in the E. Coli and Coliform parameters, after the results are known then the efficiency can be searched by comparing the influent and effluent and expressed in percent.

Efficiency calculation:

$$Eff = \frac{C_{in} - C_{out}}{C_{in}} 100\% \quad (1)$$

where C_{out} = result after filtration and C_{in} = result before filtration

Before presenting the filtration results, it is essential to understand the baseline water quality conditions. Table 1 presents the initial characteristics of rainwater collected from the campus area before any treatment process.

Table 1. Rainwater Test Result Before Filtration

No	Parameter	Unit	Max Rate	Test Result
1	Turbidity	NTU	25	27
2	Fe	Mg/l	1	2,12

Table 1 shows that rainwater near Building 3, Faculty of Engineering, Tidar University fails to meet Minister of Health RI Regulation No. 32/2017. Turbidity reaches 27 NTU and iron content 2.1 mg/L. To address this, filtration using activated carbon, zeolite gravel, silica sand, volcanic sand, and a water filter housing is proposed. The study tests three filter variations with different activated carbon thicknesses.

The results of the initial test of rainwater that has been accommodated in an artificial pond in Building 3, Faculty of Engineering, Tidar University, were carried out in the laboratory of the Center for Environmental Health Engineering and Disease Control (BBTKLPP), Yogyakarta. These results are used to determine the initial state of the rainwater before conducting the research. It can be seen the value of turbidity and iron content in rainwater so that data analysis can be carried out on the water. The effectiveness of the vertical flow roughing filter system was evaluated through systematic testing at different activated carbon thicknesses and contact times. Table 2 summarizes the comprehensive results obtained from the filtration experiments conducted under controlled laboratory conditions.

Table 2. Test Results After Filtration

Parameter	Media	Time	Initial Conc. (CFU)	Final Conc. (CFU)
Turbidity	40	0	27	27
		20	27	24,3
		40	27	20
		60	27	19,7
	60	0	27	27
		20	27	20,76
		40	27	13,88
		60	27	9
	80	0	27	27
		20	27	9,3
		40	27	5
		60	27	1,9
Fe	40	0	2,1	2,1
		20	2,1	1,75
		40	2,1	0,19
		60	2,1	0,14

Parameter	Media	Time	Initial Conc. (CFU)	Final Conc. (CFU)
	60	0	2,1	2,1
		20	2,1	1,6
		40	2,1	0,09
		60	2,1	0,054
	80	0	2,1	2,1
		20	2,1	1,4
		40	2,1	0,030
		60	2,1	0,016

These results are based on the filtration that has been carried out on rainwater in Building 3, Faculty of Engineering, Tidar University. The filter was operated with running water for 20 minutes, 40 minutes and 60 minutes then samples were taken every time observed. It can be seen that the turbidity value and iron content decreased, so that the turbidity value and iron content had met the quality standards of the Minister of Health of the Republic of Indonesia Number 32 of 2017.

Efficiency calculation is carried out by determining the initial value concentration and final value concentration of turbidity and iron parameters by subtracting the concentration of the test parameter substance before filtration by the concentration of the test parameter after filtration and then dividing it by the concentration of the test parameter before filtration and used as a percent. The efficiency of decreasing the parameter is calculated for each filter. The calculation of the efficiency of decreasing the parameter value is carried out to determine the effectiveness of the filtration at each thickness and operating time. To quantify the effectiveness of each filter configuration, removal efficiencies were calculated using standard formulas. Table 3 presents the calculated efficiency percentages for both turbidity and iron removal across all tested configurations.

Table 3. Efficiency Analysis Results of Efficiency

Parameter	Media	Initial Conc. (CFU)	Final Conc. (CFU)	Decreasing Efficiency (%)
Turbidity	40	27	27	0%
		27	24,3	10%
		27	20	26%
		27	19,7	27%
	60	27	27	0%
		27	20,76	23%
		27	13,88	49%
		27	9	67%
	80	27	27	0%
		27	9,3	66%
		27	5	81%
		27	1,9	93%
Fe	40	2,1	2,1	0%
		2,1	1,75	17%
		2,1	0,19	91%
		2,1	0,14	93%

Parameter	Media	Initial Conc. (CFU)	Final Conc. (CFU)	Decreasing Efficiency (%)
	60	2,1	2,1	0%
		2,1	1,6	24%
		2,1	0,09	96%
		2,1	0,054	97%
	80	2,1	2,1	0%
		2,1	1,4	33%
		2,1	0,030	99%
		2,1	0,016	99%

The treatment efficiency trends are further illustrated through graphical representations. Figure 3 displays the turbidity removal efficiency across different filter thicknesses and contact times, providing visual confirmation of the tabulated results.

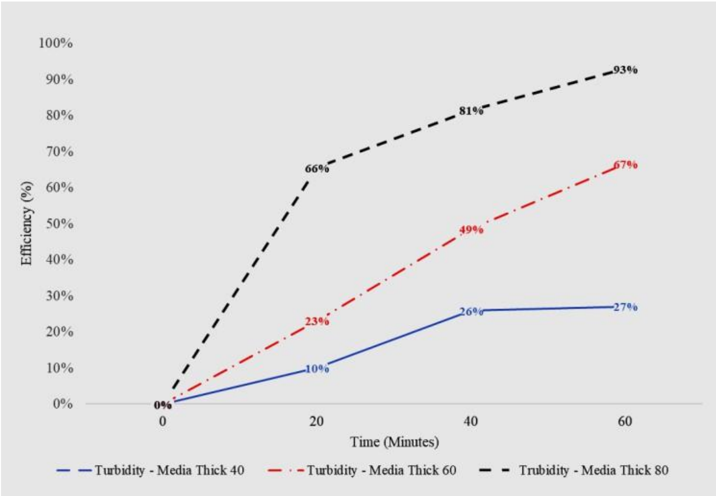

Figure 3. Efficiency Turbidity with thickness 40, 60, 80 cm

Iron removal efficiency trends are similarly presented in Figure 4, which complements the turbidity analysis by showing the effectiveness of different filter configurations for heavy metal removal.

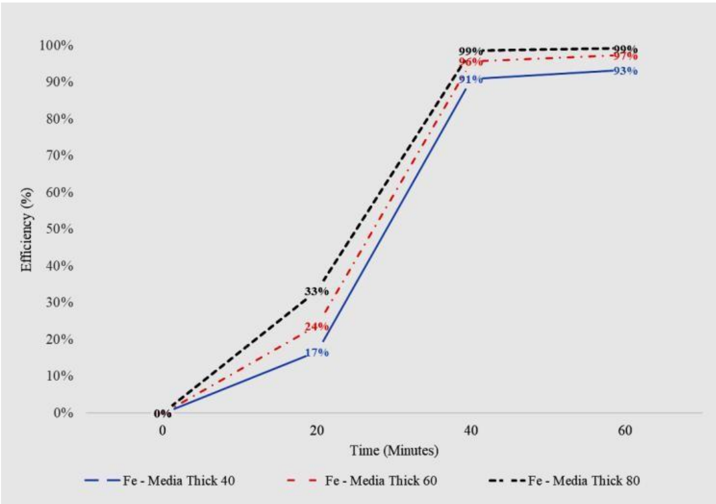

Figure 4. Efficiency Fe with thickness 40, 60, 80 cm

The experimental results confirm the effectiveness of the vertical flow roughing filter system for improving rainwater quality to meet sanitation standards. The systematic improvement in treatment efficiency with increased activated carbon thickness validates the theoretical foundation that greater media depth provides enhanced contact time and increased adsorption surface area.

The optimal performance achieved by the 80 cm filter configuration at 60 minutes contact time (93% turbidity reduction and 99% iron removal) demonstrates that this system can reliably produce water meeting Indonesian health standards. The treated water quality parameters fall well within the acceptable ranges established by Ministry of Health Regulation No. 32 of 2017, making it suitable for campus sanitation applications.

The results also highlight the importance of adequate contact time in achieving maximum treatment efficiency. The dramatic improvement between 20 and 60 minutes contact time, particularly evident in Figures 5 and 6, emphasizes that sufficient residence time is crucial for optimal adsorption processes to occur.

Furthermore, the superior iron removal efficiency compared to turbidity reduction suggests that the activated carbon medium is particularly effective for heavy metal removal, which is especially important given the initial iron concentration of 2.12 mg/L in the untreated rainwater. To demonstrate the practical application of the research findings, a physical prototype of the vertical flow roughing filter system was constructed and installed. Figure 5 presents the actual model and installation instruments used in this study, showcasing the real-world implementation of the theoretical design principles discussed in the methodology section.

Figure 5. Model and Installation Instruments

Figure 5 illustrates the successful translation of laboratory-scale research into a functional prototype system. The physical model demonstrates the practical feasibility of implementing the 80 cm activated carbon filter configuration in real campus environments. The installation shows the complete filtration system including the multi-layer media arrangement, inlet and outlet systems, and housing components that were optimized based on the experimental results.

The constructed prototype validates the scalability of the research findings and provides a foundation for future implementation in government buildings and institutional settings. The system's modular design, as evident in Figure 5, allows for easy maintenance and media replacement, making it suitable for long-term operational deployment in campus sanitation applications.

4. CONCLUSIONS

The vertical flow roughing filter system effectively reduces turbidity and iron content of rainwater to meet Minister of Health Regulation No. 32 of 2017 standards. Specific parameter reductions achieved: turbidity decreased from 27 NTU to 1.9 NTU (total reduction of 25.1 NTU, 93% efficiency) and iron content reduced from 2.12 mg/L to 0.016 mg/L (total reduction of 2.104 mg/L, 99% efficiency). The most effective performance was achieved using 80 cm activated carbon thickness with 60 minutes contact time, producing treated rainwater suitable for campus sanitation purposes with final parameters well below regulatory limits. Recommendations for future research:

a. Minimize rainwater storage time to prevent bacterial growth and biological parameter increases
b. Investigate variations in media gradation size and thickness for enhanced optimization
c. Explore additional water treatment processes to achieve superior water quality results

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