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Potential of an Integrated Green Roof-Rainwater Harvesting System in Improving Stormwater Quality and Quantity

Pavinth Karnan[1,a], Badronnisa Yusuf [1,b*]

[1]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

Email: [a]212846@student.upm.edu.my, [b]nisa@upm.edu.my

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Abstract: Urban environments are increasingly challenged by flash flooding, water quality degradation, and pressure on potable water supply. This study investigated the performance of an integrated green roof-rainwater harvesting system aimed at improving both stormwater quality and runoff management. A laboratory scale model equipped with a rainfall simulator was designed and constructed to evaluate both the water retention capacity and rainwater quality enhancement. The system was tested using Philippine Grass, two types of main filter media (biochar and activated carbon), and two roof configurations (flat and sloped roof, 15° designs) across three different flowrates, comparing them to a conventional roof without substrates and vegetation. Rainwater samples before and after passing through the integrated model were analyzed for pH, TDS, COD, BOD_5, Fe, Zn, NH_3-N, total coliforms, and E. coli. The results showed that activated carbon improved rainwater quality by achieving up to 94% COD, 60% BOD_5, 100% ammonia nitrogen, 100% Fe, 100% Zn, and 88% total coliform removal, while biochar achieved up to 93% pH neutralisation and 73% TDS removal. *E. coli* was not detected in any sample. In terms of hydrological performance, the combination of a flat roof with activated carbon performed the best in terms of runoff reduction by retaining up to 42.1% of runoff. This study demonstrates that the integrated green roof-rainwater harvesting system with natural filter media enhances water quality and retention, supporting non-potable water reuse and urban flood mitigation.

Keywords: Green roof, rainwater harvesting, stormwater management, water quality, biochar, activated carbon

1. Introduction

As Malaysia's population is projected to surpass 40 million by 2050, the increasing demand for water has become an immense pressure [1]. Domestic water consumption in Malaysia has exceeded the WHO's recommended level of 165 liters per capita per day, reaching 245 liters per capita per day [2]. While Malaysia faces increasing water demand, it also struggles with a devastating recurring challenge: flooding. Flash floods are common in rapidly developing urban areas such as Kuala Lumpur, where natural landscapes have been remodelled into impervious surfaces, overwhelming drainage systems and damaging infrastructure [3]. These surfaces prevent water from naturally infiltrating into the soil, leading to excessive runoff that overwhelms drainage systems and causes flooding [3].

In response to these challenges of rising water demand and frequent flooding, integrating green roofs with rainwater harvesting systems offers a promising and sustainable solution. Green roofs consist of vegetation layers on rooftops, effectively capturing rainfall, reducing surface runoff and minimising the risk of flooding in urban areas [4]. By filtering sediments and pollutants, they also improve the quality of stormwater, ensuring cleaner water for reuse. Rainwater harvesting systems are designed mainly for stormwater management to store water for various non-potable activities such as irrigation and toilet flushing [5]. The integration of these two systems enhances their efficiency where green roofs could filter the stormwater before it enters the storage tanks of rainwater harvesting systems, reducing contamination and lowering the need for extensive water treatment [6]. This synergistic approach addresses both water demand and flood risk by harnessing the abundance of rainwater [7].

Despite the proven individual benefits of these systems, several research gaps remain. Rainwater harvesting systems can help collect and store rainwater, but the quality of harvested water is often a concern. Rainwater from roofs can pick up pollutants including dirt, heavy metals, and organic matter. Studies by Uddin et al. [8] and Shaheed & Mohtar [9] have shown that rooftop-harvested rainwater in Malaysia frequently contains elevated levels of COD, ammonia nitrogen, and microbial contaminants, primarily due to accumulation of bird droppings, dust, and debris on roof surfaces. Most existing rainwater harvesting systems are designed only to store water, not to improve its quality. As highlighted by Lani et al. [10], conventional systems lack integrated treatment components, resulting in harvested water that is typically suitable only for limited non-potable uses. Therefore, it is important to explore which substrate is most effective in improving water quality within an integrated green roof-rainwater harvesting setup.

**Corresponding author: [a]212846@student.upm.edu.my, [b]nisa@upm.edu.my*
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Apart from water quality, the quantity of rainwater harvested is influenced by the design of the roof. The slope of the roof affects how fast water runs off and how long it stays in contact with filter media. Lai et al. [11] investigated the effects of different roof slopes on rainwater quality and found that steeper slopes (30-45°) resulted in faster runoff and reduced contact time, potentially limiting treatment efficiency. Sloped roofs might cause water to flow too quickly, reducing treatment time, while flat roofs may allow more retention. Abdalla et al. [12] further confirmed that increased slope leads to decreased retention and detention performance. Hence, it is essential to determine which roof design, sloped or flat, works better for maximizing both filtration efficiency and volume of collected rainwater.

Moreover, while rainwater harvesting systems can help reduce water demand, they are not very effective in controlling stormwater or reducing floods on their own. Green roofs, on the other hand, can retain rainwater, delay runoff, and reduce flood risk. Studies by Chow et al. [4] and Cristiano et al. [13] have demonstrated that green roofs can achieve 50-70% runoff reduction under optimal conditions. However, as noted by Hamid et al. [14], the integration of green roofs with rainwater harvesting systems in Malaysia is still relatively new and not widely implemented. Most local studies, including those by Rahman et al. [15] and Tien and Yahya [16], have examined these systems separately. There is limited research on how these systems perform together, particularly in terms of pollutant removal, water retention, and flood control under different roof types and flowrates.

Therefore, this study aims to investigate the performance of various designs of integrated green roof-rainwater harvesting systems in terms of the quality and quantity of harvested rainwater. This research quantifies the effectiveness of different substrate materials, namely biochar and activated carbon, in removing pollutants from harvested rainwater, while also assessing the suitability of flat and sloped roof configurations based on both water quality improvement and runoff retention. Furthermore, the study compares the stormwater management performance of a standalone conventional rainwater harvesting system against the proposed integrated green roof-rainwater harvesting system to determine which approach offers superior hydrological and water treatment benefits.

2. Methodology

2.1 Overview

Fig. 1 shows a detailed outline of how the targeted objectives were achieved. It begins from the design of the green roof-rainwater harvesting system's model to how the rainwater was collected and tested.

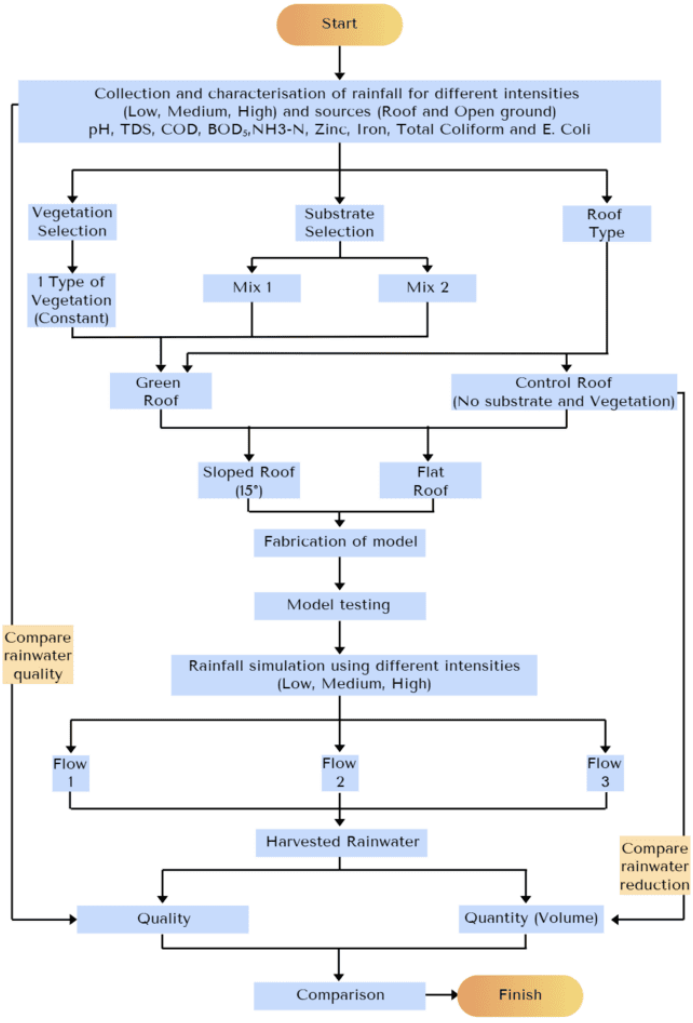

Fig. 1 – Flow chart of overall methodology

2.2 Location of Rainwater Samples Collection

Rainwater serves as the primary focus of this investigation, with samples collected from both open-air and roof runoff catchment systems in contrasting urban and suburban environments as depicted in Fig. 2. Ampang, Kuala Lumpur was chosen as the urban rainwater sample collection area due to its characteristic high-density development, featuring concentrated industrial zones and high traffic. Banting, Selangor represents the suburban environment with significantly lower population density.

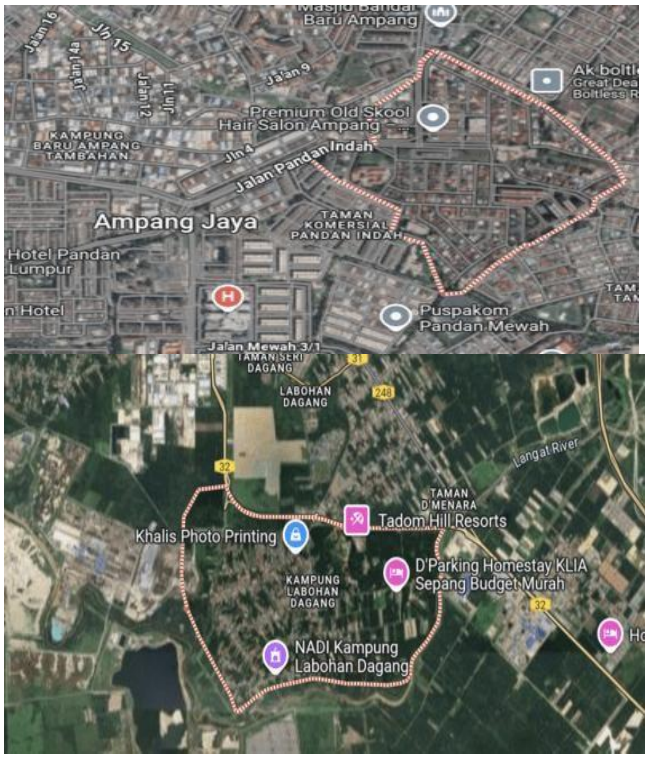

Fig. 2 - (a) View of Kampung Ampang Campuran, Kuala Lumpur (urban catchment); (b) Overview of Kampong Labohan Dagang, Banting (suburban catchment)

The collected rainwater was measured for its quality and then used to simulate the rainfall for this experiment.

2.3 Design of Integrated Green Roof-Rainwater Harvesting System Model

An integrated model was constructed to simulate a house with an adjustable roof so it could be either flat or sloped at 15° as illustrated in Fig. 3 - 6. The model dimensions are 1000 mm width, 1200 mm length, and 700 mm height. This model has a rainfall simulator attached, where the collected rainwater was pumped through it with three different flow rates: low (2.7 L/min), medium (3.0 L/min), and high (3.6 L/min).

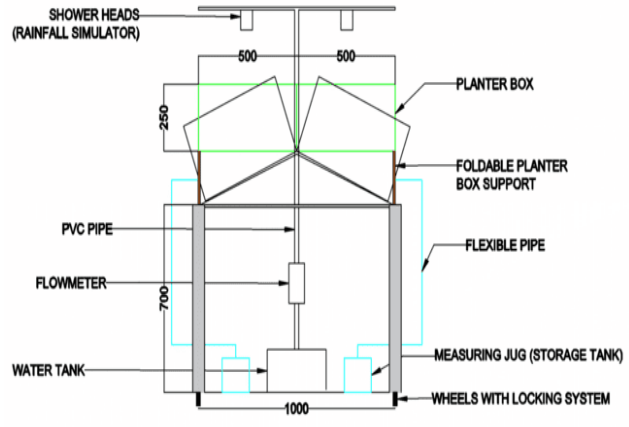

Fig. 3 – Front view

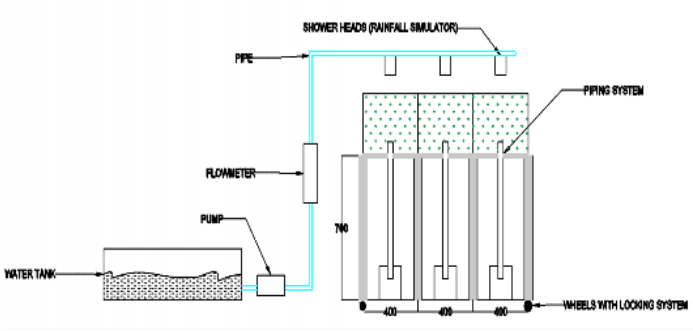

Fig. 4 – Side view

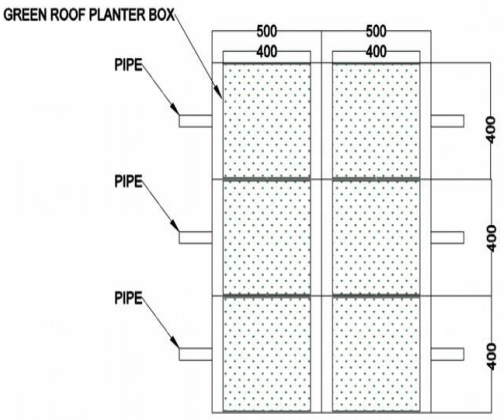

Fig. 5 – Top View

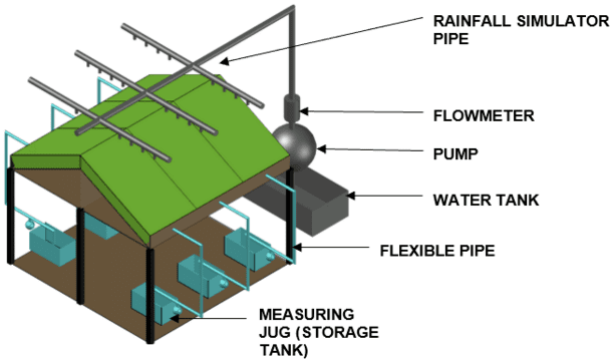

Fig. 6 – 3D view

The experimental green roof system comprised three planter boxes (400 mm × 390 mm × 250 mm). One planter box was designated as the control, representing a conventional roof without substrate or vegetation, while the remaining two were filled with distinct substrate compositions as illustrated in Fig. 7-8:

- **Box 1 (Conventional/Control):** An empty planter box acting as conventional roof without substrates and vegetation.
- **Box 2 (Biochar):** Filled with substrate mix of 30% biochar, 20% vermiculite, 20% perlite, 20% sand, and 10% compost, planted with Philippine Grass.
- **Box 3 (Activated Carbon):** Filled with substrate mix of 30% activated carbon, 20% vermiculite, 20% perlite, 20% sand, and 10% compost, planted with Philippine Grass.

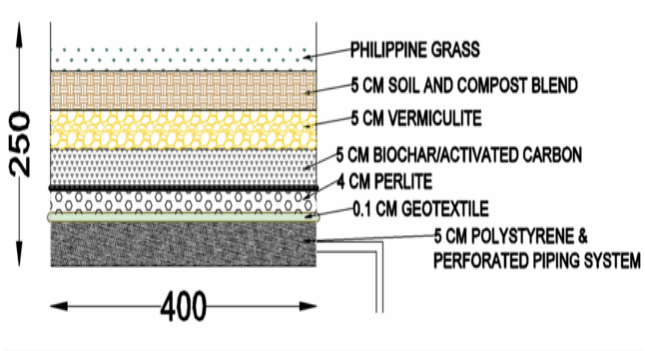

Fig. 7 – Schematic cross section of planter box



Fig. 8 - Three types of roofs, from left (conventional, Philippine grass with activated carbon and Philippine grass with biochar)

A perforated piping system was installed inside each box, with a geotextile layer placed on top to prevent substrate washout while allowing proper drainage and filtration. The simulated rainwater infiltrated through the planter boxes, then directed out through flexible pipes to measuring jugs for outflow volume measurements. The whole setup for the experiment is as shown in Fig. 9.



Fig. 9 – Integrated green roof-rainwater harvesting system with rainfall simulation

2.4 Water Quality Analysis

The study conducted comprehensive water quality assessment examining critical parameters to characterize the harvested rainwater. Samples from urban and suburban areas along with the rainwater before and after going through the integrated system were analysed for:

- pH and TDS: Measured using a calibrated multiparameter water quality meter.
- Chemical Oxygen Demand (COD): Analysed using the closed reflux method where potassium dichromate served as the oxidizing agent, and absorbance was measured using a spectrophotometer.
- 5-Day Biochemical Oxygen Demand (BOD_5): Determined by incubating samples in BOD bottles at 20°C for five days, after which the difference in dissolved oxygen levels was recorded.
- Ammonia Nitrogen (NH_3-N): Analyzed using the salicylic acid and cyanurate reagent method, with color intensity measured using a colorimeter.
- Iron (Fe) and Zinc (Zn): Concentrations measured using a colorimeter after adding specific reagents.
- Total Coliform and E. coli: Membrane filtration method used, with E. coli cultured on Eosin Methylene Blue (EMB) agar and total coliforms on nutrient agar, incubated at 37°C for 24 hours.

All analytical results were benchmarked against Malaysia's National Water Quality Standards (NWQS) to classify water quality and identify the most effective treatment approach.

3. Results and Discussion

3.1 Raw Rainwater Quality

Analysis of rainwater pH levels from urban and suburban catchments revealed slightly acidic values ranging from 5.01 to 6.93, with most samples classified as Class III based on NWQSM. Suburban showed slightly higher pH compared to urban in some cases. This anomaly can be attributed to industrial contamination, as factories located near the downstream of the suburban catchment area (Fig. 10), likely contributed to atmospheric pollution and subsequent acid deposition.



Fig. 10 – Steel processing factory near catchment area

TDS levels remained consistently low (3.5 to 35.9 mg/L), well within Class I standards. However, COD readings in rooftop samples were significantly higher, with values exceeding 100 mg/L (Class IV-V), indicating substantial organic contamination from roof surfaces. BOD_5 values were low (0.8-1.2 mg/L), within Class I-IIA.

Ammonia nitrogen concentrations in open areas were low (0.04-0.18 mg/L, Class I-IIA), while rooftop samples showed higher concentrations (0.11-0.57 mg/L, Class II-III). Iron and zinc concentrations remained well below NWQS limits (Fe <1.0 mg/L, Zn <0.4 mg/L).

Most critically, total coliform counts were extremely high, particularly in rooftop samples where values reached 1,490,000 CFU/100 mL (Class V). E. coli was completely absent in all samples. Based on the worst-performing parameters (total coliform and COD), all raw rainwater samples were classified as Class V, confirming that untreated rainwater requires significant treatment before any use.

3.2 Treated Harvested Rainwater Quality

Simulated rainfall experiments were conducted under three different flow rates (low, medium, and high) and two roof orientations (flat and sloped). The runoff passed through the respective media layers, and the harvested rainwater was analysed for the same parameters as those tested for the raw rainwater.

The quality of the pre-treated rainwater stored in the tank was compared with that of the post-treated rainwater collected after passing through the integrated green roof–rainwater harvesting system.

3.2.1 pH

Pretreated rainwater showed slightly acidic pH values, as shown in Fig, 11, (5.37 to 6.81, Class III). Both treatment media raised pH levels into Class II to Class I range (6.1-6.74). Biochar consistently outperformed activated carbon, achieving the highest pH values (up to 6.74 under medium flow on flat roofs). The conventional system showed minimal pH changes (5.76-6.04), confirming no buffering effect. Flat roofs generally facilitated better pH improvements due to longer water-media contact time.

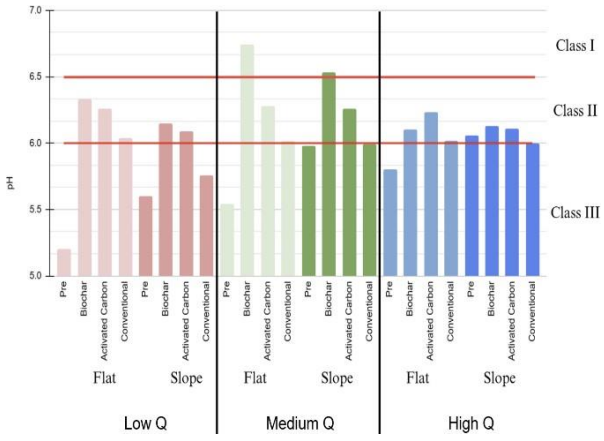

Fig. 11 - pH level of and NWQSM classification of treated harvested rainwater

3.2.2 Total Dissolved Solids (TDS)

Biochar emerged as the most effective medium for TDS reduction, achieving up to 73% reduction under medium flow on flat roofs as shown in Fig. 12. Activated carbon achieved 29-57% reduction. The conventional system showed minimal TDS reduction (4-48%). Flat roofs consistently outperformed sloped roofs across all flow rates and treatment types due to longer contact time and more uniform water distribution.

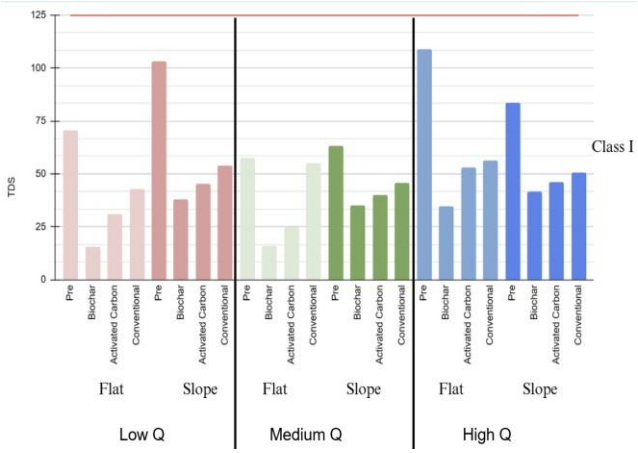

Fig. 12 - TDS level of and NWQSM classification of treated harvested rainwater

3.2.3 Chemical Oxygen Demand (COD)

Activated carbon consistently showed the highest COD removal, achieving 92-94% reduction across most conditions (Fig 13). Biochar closely followed with reductions of 80-95%. The conventional system showed minimal removal (5-62%) and often failed to reduce COD to acceptable levels. Activated carbon was less sensitive to flow dynamics, maintaining high performance even on sloped roofs.

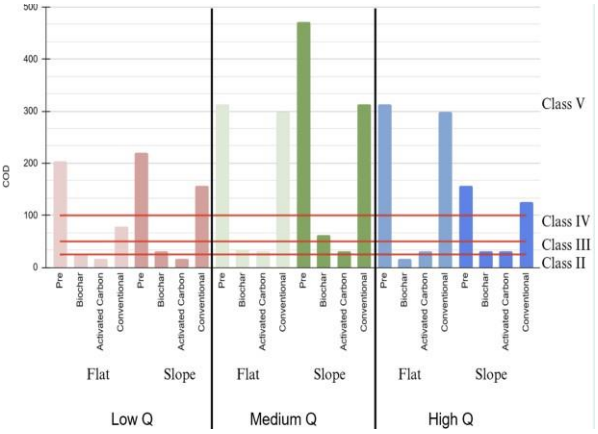

Fig. 13 - COD level of and NWQSM classification of treated harvested rainwater

3.2.4 5-Day Biochemical Oxygen Demand (BOD_5)

Both biochar and activated carbon effectively reduced BOD_5 values, achieving 53-60% removal under low and medium flows, bringing water into Class I as depicted in Fig. 14. Activated carbon performed better under high flow, maintaining 52% reduction on flat roofs. The conventional system showed poor results, with negative reductions in some cases, indicating possible contamination.

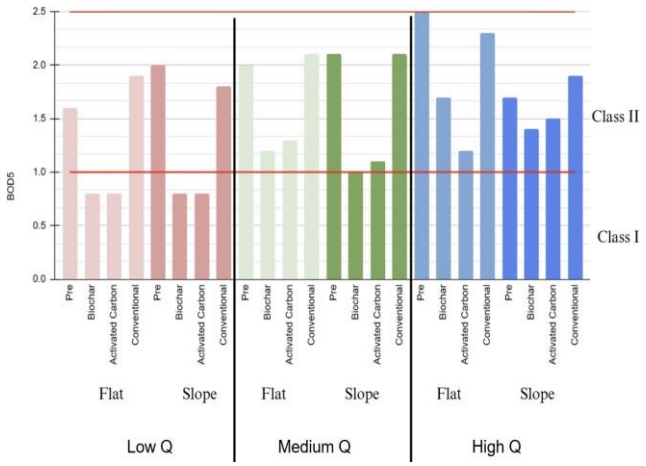

Fig. 14 - BOD5 level of and NWQSM classification of treated harvested rainwater

3.2.5 Ammonia Nitrogen (NH_3-N)

Fig 15 shows that activated carbon achieved 100% ammonia nitrogen removal under five of six conditions, meeting Class I standards throughout. Biochar also performed well with 67-93% removal, final values between 0.03-0.07 mg/L (Class I). The conventional system showed limited or negative removal effects.

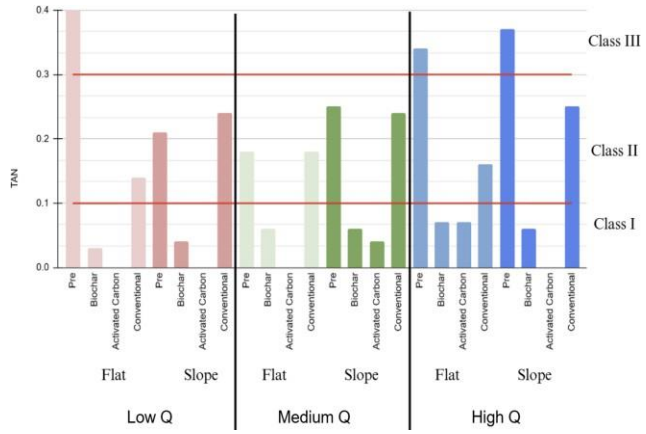

Fig. 15 - Ammonia nitrogen level of and NWQSM classification of treated harvested rainwater

3.2.6 Iron (Fe)

Activated carbon achieved up to 100% iron removal under low flow, flat roof conditions, maintaining high performance (94-95%) under medium and high flows (Fig. 16). Biochar demonstrated 76-89% reduction. Flat roofs generally supported better iron removal than sloped roofs for both media.

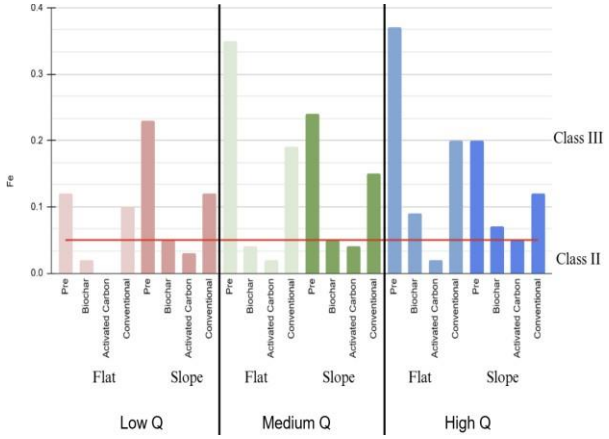

Fig. 16 - Iron level of and NWQSM classification of treated harvested rainwater

3.2.7 Zinc (Zn)

In Fig. 17, it is shown that activated carbon consistently achieved 95-100% zinc removal, bringing concentrations well below the Class II limit of 0.10 mg/L. Biochar achieved 67-89% removal. The conventional system failed to meet Class II standards in most conditions. Flat roofs demonstrated better performance than sloped roofs.

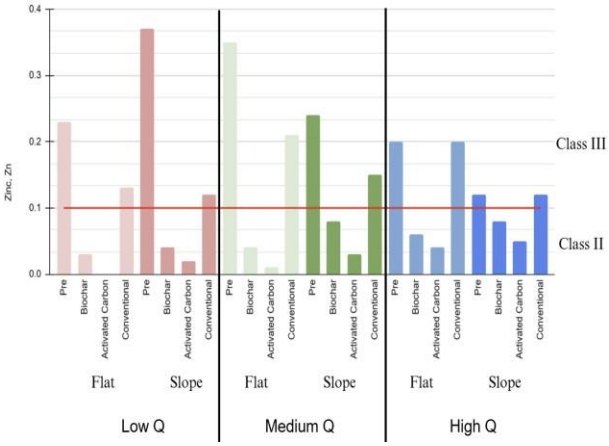

Fig. 17 - Zinc level of and NWQSM classification of treated harvested rainwater

3.2.8 Total Coliform

Activated carbon achieved the best total coliform reduction, up to 88% under low flow on flat roofs, often lowering values below the Class III threshold as shown in Fig. 18. Biochar showed 59-80% reduction. The conventional system was ineffective or counterproductive, with increases in microbial load in some cases (-83% to 34%). Flat roofs generally yielded better microbial reduction due to longer retention time.

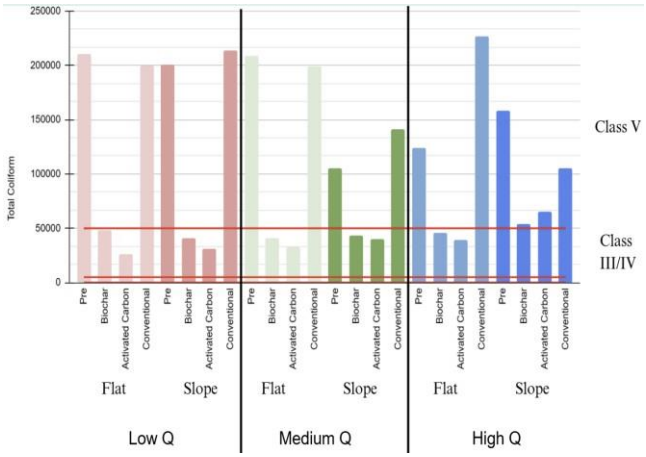

Fig. 18 – Total coliform level of and NWQSM classification of treated harvested rainwater

3.2.9 *Escherichia coli* (E. coli)

E. coli was not detected in any sample across all flow conditions, roof designs, and filter media, including both pre-treatment and post-treatment stages. This indicates minimal fecal contamination in the tested environment.

3.3 Summary of Treated Rainwater Quality

Table 1 summarises the overall quality classification of the treated rainwater following treatment through the integrated system. Green roof systems using activated carbon and biochar as filter media showed significant improvement on harvested rainwater over the conventional setup. On flat roofs, activated carbon achieved Class IIA water quality for most parameters. Biochar on flat roofs achieved Class III overall. Under sloped roof conditions, both systems were classified as Class III, primarily due to elevated total coliform counts. The conventional roof systems produced harvested rainwater within Class IV to Class V, driven by high COD and total coliform levels.

Table 1 – Overall quality classification of treated harvested rainwater

Parameter	Roof Type	Activated Carbon	Biochar	Conventional	Remarks
pH	Flat	Class IIA	Class IIA – III	Class III	All within acidic range; acceptable for non-potable use
	Sloped	Class IIA – III	Class III	Class III	Slight drop in sloped roof due to faster runoff
TDS	Flat	Class I	Class I	Class I	Very low; excellent in all cases
	Sloped	Class I	Class I	Class I	No major difference across roof types
COD	Flat	Class IIA	Class III	Class IV	Best removal with AC; biochar less effective at high flow
	Sloped	Class IIA – III	Class III – IV	Class IV – V	COD spikes under slope and flow, especially for conventional
BOD_5	Flat	Class I	Class I – IIA	Class IIA – III	All within safe range; AC consistently best
	Sloped	Class I – IIA	Class IIA	Class III	Sloped conventional drops to Class III
NH_3-N	Flat	Class I	Class II	Class III	Ammonia under control except in conventional setups
	Sloped	Class I – II	Class III	Class III	Faster flow limits contact time for biochar/conventional
Iron (Fe)	Flat	Class I	Class I – II	Class II	Excellent removal with AC and biochar
	Sloped	Class I – II	Class II	Class II	Minimal change due to roof type

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Zinc (Zn)	Flat	Class I	Class I – IIA	Class IIA – III	All within NWQS; AC gives Class I
	Sloped	Class I – IIA	Class IIA	Class III	Conventional exceeds 0.4 mg/L in some samples
Total Coliform	Flat	Class I – IIA	Class IIA – III	Class IV	Strong removal by AC; biochar drops with higher flow
	Sloped	Class IIA – III	Class III	Class IV – V	Worst in sloped conventional setup
E. coli	Flat	Class I	Class I	Class I	Undetected in all treated samples
	Sloped	Class I	Class I	Class I	No E. coli across any configuration

3.4 Volume of Harvested Rainwater

3.4.1 Low Flowrate

Fig. 19 shows that on flat roofs, the conventional system generated 27,000 mL runoff. Biochar collected 19,350 mL (28.3% retention), while activated carbon collected 17,000 mL (37% retention). On sloped roofs, conventional collected 29,100 mL, biochar 22,600 mL (22.3% retention), and activated carbon 18,650 mL (35.9% retention) as shown in Fig. 20. Green roof systems exhibited flatter, delayed runoff curves, indicating slower peak discharge.

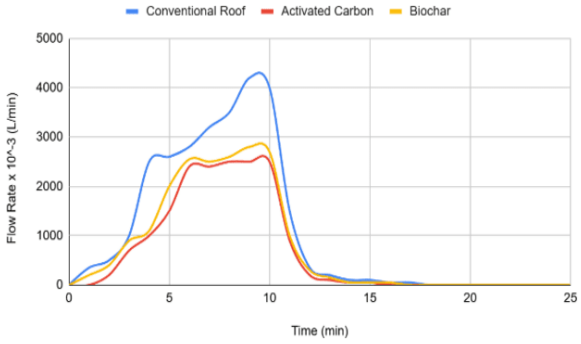

Fig. 19 - Flat Roof Under Low Flowrate

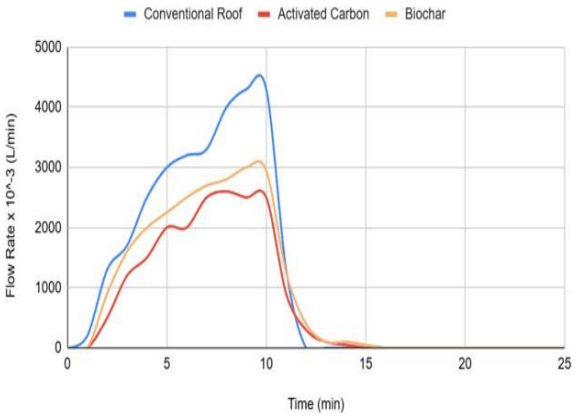

Fig. 20 – Sloped Roof Under Low Flowrate

3.4.2 Medium Flowrate

On flat roofs, conventional collected 30,000 mL, biochar 23,800 mL (20.7% retention), and activated carbon 20,050 mL (33.2% retention) as depicted in Fig. 21. On sloped roofs (Fig. 22), conventional collected 31,950 mL, biochar 25,150 mL (21.3% retention), and activated carbon 21,830 mL (31.7% retention). Green roof systems showed infiltration-related delay in outflow, continuing water release after rainfall stopped.

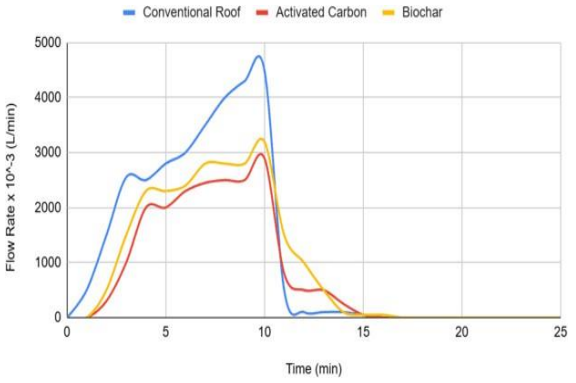

Fig. 21 - Flat Roof Under Medium Flowrate

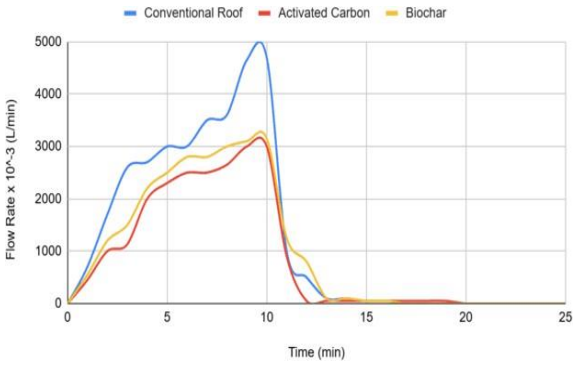

Fig. 22 - Sloped Roof Under Medium Flowrate

3.4.3 High Flowrate

As shown in Fig. 23, on flat roofs, conventional collected 37,250 mL, biochar 25,400 mL (31.8% retention), and activated carbon 21,550 mL (42.1% retention). Meanwhile Fig. 24 shows that on sloped roofs, conventional collected 36,350 mL, biochar 27,000 mL (25.7% retention), and activated carbon 23,700 mL (34.8% retention). Activated carbon on flat roofs achieved the highest water retention overall (42.1%).

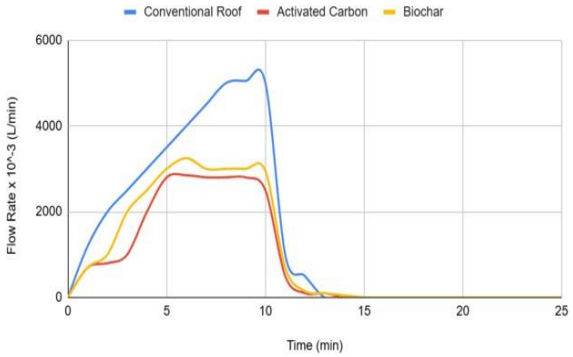

Fig. 23 - Flat Roof Under High Flowrate

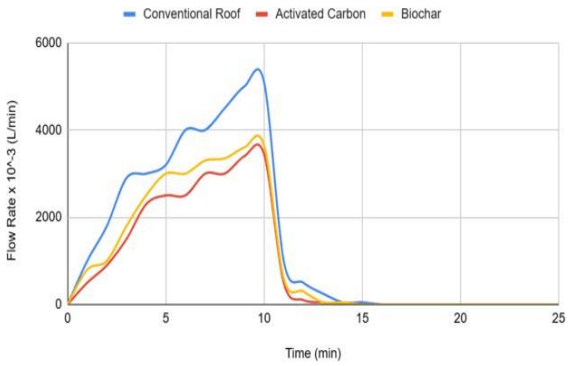

Fig. 24 - Sloped Roof Under High Flowrate

4. Conclusion

This research evaluated the performance of an integrated green roof-rainwater harvesting system using biochar, activated carbon, and a conventional roof setup under both flat and sloped roof designs across three flowrate conditions. Based on the methodology implemented and the analysis performed, the following conclusions are drawn:

i. The study confirmed that both biochar and activated carbon are highly effective in reducing pollutants, with activated carbon consistently showing higher removal efficiency across all parameters. Activated carbon improved rainwater quality by achieving up to 94% COD, 60% BOD_5, 100% ammonia nitrogen, 100% Fe, 100% Zn, and 88% total coliform removal, while biochar achieved up to 93% pH neutralisation and 73% TDS removal.

ii. The results showed that flat roofs performed better in terms of both pollutant removal and water retention, largely due to longer water contact time with the filter media but might increase loading to roof. The flat roof with activated carbon achieved the highest water retention (42.1% under high flow) and best overall water quality (Class IIA) which is suitable for livestock drinking and fishery purposes.

iii. The integrated green roof-rainwater harvesting system proved superior to conventional standalone systems for stormwater management. Green roof systems effectively delayed peak runoff and reduced discharge volume, demonstrating significant potential for urban flood mitigation while simultaneously improving harvested water quality for non-potable reuse.

This research contributes significantly to sustainable urban development by proposing a green infrastructure solution that simultaneously addresses stormwater quality, water scarcity, and urban flood risks. The integrated system reduces dependency on treated municipal water, improves water quality using eco-friendly materials, and enhances urban resilience by attenuating peak runoff.

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