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Bamboo Fibre as a Green Roof Material Layer to Improve Stormwater Quantity

Nurul Natasha Mohd Zaidi[1], Nur Aini Mohd Arish[1]*

[1] *Faculty of Engineering Technology*
Universiti Tun Hussein Onn Malaysia (UTHM), 84600 Pagoh, Johor, Malaysia

*Corresponding Author: nuraini@uthm.edu.my
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Abstract

Rapid urbanization in Malaysia has increased stormwater runoff and urban floods, requiring long-term management solutions. While green roof systems have gained widespread adoption in advanced countries, their implementation in Malaysia faces perceptual and practical barriers, limiting the application of research findings. Green roofs present substantial benefits, including mitigating the urban heat island effect, improving stormwater management and reducing pollution. This study investigates using bamboo fibre as a green roof material layer to enhance stormwater quality control. The innovation uses bamboo fibre, which is strong, absorbs moisture, and is eco-friendly, along with recycled PET bottles to reduce plastic waste and improve green roofs. Two green roof models were constructed: a conventional model and an enhanced model utilizing bamboo fibers and PET bottles as a drainage layer based on the fibre bundle concept and filter layer using a concept non-woven bamboo fibre. Rainfall intensities were categorized as low (10 mm/h), moderate (34-47 mm/h), and high (>67 mm/h). A rainfall simulator was employed to evaluate the models hydrological performance, focusing on runoff retention rate, peak flow reduction and runoff coefficient. Experimental results revealed that the bamboo fibre-enhanced green roof , combined with PET bottle caps in the drainage layer, outperformed the conventional model by achieving a stormwater retention rate up to 61% under high rainfall intensities. These findings highlight the effectiveness of integrating bamboo fibre and recycled PET materials in optimizing green roof systems. This study demonstrates the potiental of bamboo fibre as an innovative and renewable material for stormwater management, promoting sustainable urban development and advancing eco-friendly construction practices.

1. Introduction

Urbanization has rapidly expanded, creating challenges such as pollution, loss of green spaces, and climate changes impacts. In Malaysia, these issues are urgent, as urbanization outpaces environmental protection [1]. Green roof systems, which are popular in developed countries, help reduce the urban heat island effect, manage stormwater, and mitigate high temperatures [2]. However, their adoption in Malaysia faces obstacles, including limited practical applications of research [1]. Exploring the potential of green roofs in rapidly urbanizing regions such as Malaysia is essential. Research underscores the importance of green roofs in addressing environmental issues. These systems use substrates of organic materials, such as grass charcoal and peat, for nutrient and water storage, and inorganic materials for support and drainage [2]. Fiber-based materials have gained attention for their contribution to green roof performance, particularly in stormwater management. Previous studies have demonstrated the hydrological benefits of green roofs in terms of runoff retention and peak flow reduction. [3] reported that coconut fiber as drainage layer reduced peak flow by 56%-86% under rainfall intensities of 125 mm/h to 275 mm/h. Additionally, Hoong Kok et al. (2015), found that geotextile TS500 reduced peak discharge by up to 47%. Runoff retention rates also vary significantly based on the materials used. Studies have shown that retention rates of 73.8%-84.2% for small rainfall events, while storm events showed retention rates ranging from 33.0% to 55.3% [4]. PET bottle caps have also been investigated for their potential as drainage materials in green roof systems demonstrate better water retention compared to commercial green roof drainage layer [5]. PET bottle caps retained up to 9.8 L/m2 of water compared to 7.1 L/m2 for commercial systems. Their use addresses plastic waste issues while enhancing green roof hydrology, making them a sustainable alternative for drainage layers. Bamboo fiber, known for its eco-friendliness and water absorption, is an ideal addition for stormwater management [6]. It has the capability to decrease runoff coefficient and hold considerable amounts of stormwater, improving green roof hydrology. Nevertheless, issues such as modifying materials to fit local circumstances and improving the durability of bamboo fiber must be tackled [7]. This study introduces the novel concept of a fiber bundle, where bamboo fiber is wrapped around PET bottle caps to optimize water flow and retention within the drainage layer. The study conducted by [8] showed that fiber bundles made from plastic, hemp, and cotton ropes enhanced seepage performance and increased drainage efficiency. This study explored integration bamboo fiber and PET bottle caps into green roof systems to enhance sustainability in Malaysia, it hypothesizes that these materials to improve stormwater management, reduce environmental impacts, and contribute to resilient urban infrastructure. By evaluating their performance, this research aims to propose innovative solutions for sustainable urban development in Malaysia.

2. Materials and methods

Two green roof models were constructed: a conventional system and a bamboo fiber system as illustrated in figure 1. The bamboo fiber was used as a filter and drainage layer, incorporating concept fiber bundles using a PET bottle cap and bamboo fiber. In addition, non-woven bamboo fibers used as the filter layer. Both models were tested under simulated rainfall intensities categorized as low (10 mm/h), moderate (30-47 mm/h) or very heavy (> 67 mm/h). The experiment was conducted at the Water Resource Engineering Technology Laboratory at the Universiti Tun Hussein Onn Malaysia (UTHM). These setups were placed side by side to compare the efficiency of green roofs with and without bamboo fiber.

Fig. 1: Both model green roof in this study *(a) conventional green roof (b) bamboo fibre green roof*

2.1 Green roof physical model

The physical model of the green roof consists of a rectangular box measuring 300 mm x 300 mm x 200 mm [9]. The box was designed to accommodate multiple layers that look similar to a green roof system, such as vegetation, substrate, filter, and drainage layers. Each model included outlets for runoff measurements, and a water collection system was installed at the base to determine stormwater retention and flow rates. Figure 2 illustrated the green roof system with a rainfall simulator for both systems with detailed measurements. A rainfall simulator was installed above the model to simulate controlled rainfall events. Figure 3 illustrates a rainfall simulator setup with labeled components to evaluate the performance of the green roof systems. The setup included a sprinkler to simulate rainfall, a flow meter to measure the water input (water in), and two test beds: one for a conventional green roof and the other for a fiber -based green roof. Water exiting the system (water- out) was collected in containers placed below each test bed to compare water retention and runoff between the two types of green roofs. The green roof model was constructed with four essential layers, each serving a specific function to enhance stormwater management, as shown in Figure 4, which illustrates the details of each layer with different thicknesses. The vegetation layer (a) utilized cow grass (Axonopus compressus), selected for its resilience to environmental stress and efficient water absorption properties [10]. Below this substrate layer (b), with a thickness of 50 mm consisted of a lightweight organic mix soil, designed to support plant growth while retaining moisture and minimizing the overall weight of the roof structure [11]. The filter layer (c), as shown in figure 5 (b), featured non-woven bamboo fiber with a thickness of 1mm, manufactured using a machine needle-punched process. This layer effectively prevents fine particles from entering the drainage system, ensuring smooth water flow and reducing clogging risks [12]. Finally, the drainage layer (d), with a thickness of 40 mm, incorporated PET bottle caps wrapped in bamboo fiber and referred to as fiber bundles to enhance water storage and flow capabilities. Figure 5 (a) illustrates the arrangement of PET bottle caps wrapped with bamboo fiber (fiber bundle) within the container green roof system. In this model, the filter layer material for conventional green roofs, used a geotextile with thickness of 1mm and conventional drainage layer, which used a drainage cell with a thickness of 40 mm. This innovative combination of layers worked to optimize stormwater retention, reduce runoff, and improve the overall hydrological performance of the green roof system under varying rainfall intensities.

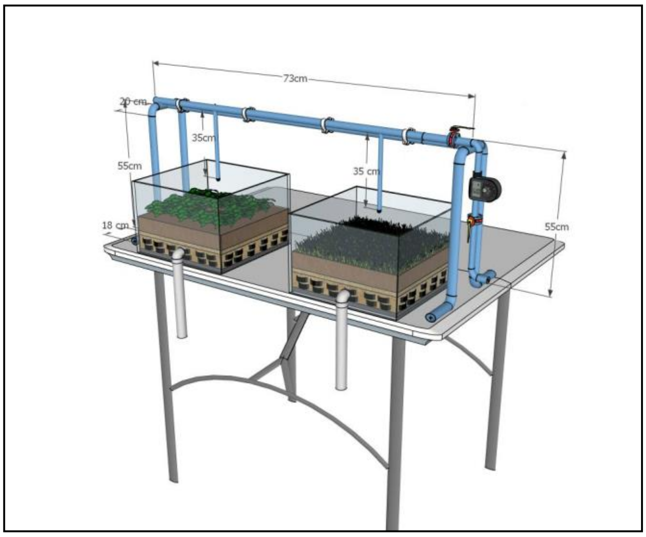

***Fig. 2*: Green roof system sketch using Sketchup**

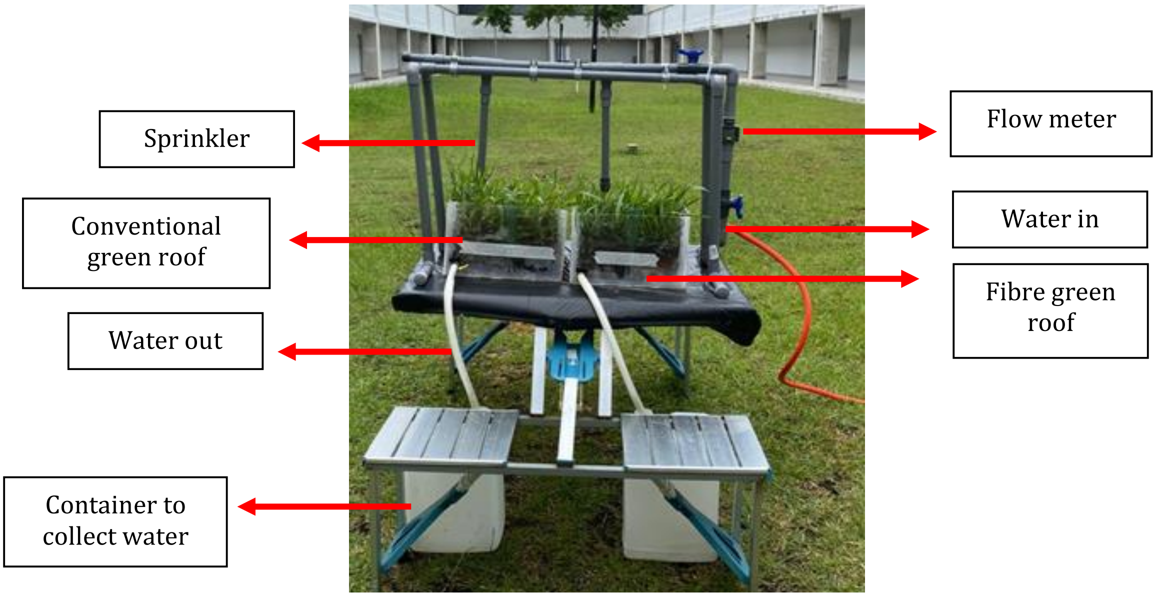

***Fig. 3*: Rainfall simulator with label for each component**

a) Vegetation Layer: Cow Grass (Axonopus Compressus)
b) Substrate Layer: Organic mix soil
c) Filter Layer: Non-woven bamboo fiber
d) Drainage Layer: Pet bottle cap and bamboo fiber (fiber bundle concept)

***Fig. 4*: Green roof module layer for fibre**

(a) (b)

Fig. 5: Material layer for green roof *(a) arrangement of fibre bundle; (b) non-woven bamboo fibre*

2.2 Data collection

The data collection process of this study focused on evaluating the hydrological performance of green roof systems, specifically conventional and bamboo fiber green roofs, under various rainfall conditions. Hydrological parameters such as the runoff retention rate, runoff coefficient, and peak flow reduction were measured using an integrated water collection system and outlet points for runoff analysis. These measurements provided critical data to compare the efficiency of bamboo fiber as a green roof material layer against conventional systems in managing stormwater.

2.2.1 Runoff retention rate calculation

Runoff water was collected from the storage tanks connected to the model outlet. The runoff retention rate data were calculated using Equation 1

$$\text{Runoff Retention Rate} = \frac{Volume_{in} - Volume_{out}}{volume_{in}} \text{ x } 100\% \qquad (1)$$

Where,

$Volume_{in}$ = Volume of rainfall entering the system (Liters)

$Volume_{out}$ = Volume of runoff water that exits the system (Liters)

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2.2.2 Peak flow reduction calculation

Data were analyzed to determine the reduction in peak flow achieved by the bamboo fiber green roof system compared to the conventional model by using the calculation in Equation 2

$$\text{Peak Flow Reduction} = 1 - \left(\frac{C_{\text{green roof}}}{C_{\text{conventional}}}\right) \times 100\% \tag{2}$$

$C_{green\ roof}$ = Runoff coefficient of green roofs (conventional or fiber).

$C_{conventional}$ = Runoff coefficient for the conventional system assumed 0.8 and 0.9 based on MASMA 1st edition for low and high rainfall intensity.

2.2.3 Runoff coefficient calculation

The runoff coefficient (C) was calculated for each rainfall intensity using the formula in Equation 3

$$C = \frac{Volume\ of\ Runoff}{Volume\ of\ Precipitation} \tag{3}$$

Volume of runoff = total volume of water that flows across the surface of the land as runoff after a rain event
Volume of precipitation = total amount of water entering the system through rainfall over a specific area

3. Result and discussion

This section presents the hydrological performance outcomes of the green roof systems, focusing on parameters such as runoff retention rate, runoff coefficient and peak flow reduction. The results compare the efficiency of the bamboo fiber-enhanced green roof system to a conventional system under varying rainfall intensities.

3.1 Runoff retention rate

The runoff retention rate was evaluated for the conventional and bamboo fiber green roof systems. Figure 6 illustrates the graph for runoff retention rate for conventional and bamboo fiber systems. The bamboo fiber green roof consistently outperformed the conventional system, achieving retention rates of 68.12% under low rainfall intensity (10 mm/h), 68.75 % under moderate intensity (30 mm/h), 63.43% under high intensity (450 mm/h). In comparison to the conventional system, it showed lower retention rates, ranging from 37.5% -67.26% as rainfall intensity increased. According to a study by [4], small rainfall events (<10 mm/h) can retain 73.8%-84.2% while high intensities (> 50.0 mm/h) can retained 33.0%-55.3%. The superior performance of the bamboo fiber system is due to its high-water absorption and storage capacity, which effectively reduces runoff by retaining a larger portion of rainfall, even under extreme conditions. The sudden decrease in runoff retention observed at 360 mm/h can be attributed to the green roof system reaching its saturation point. As highlighted in a study by [13], when green roofs are exposed to prolonged or high -intensity rainfall events, they gradually lose their ability to retain water caused to substrate saturation. These results highlight the system's effectiveness in stormwater management by mitigating runoff generation across various storm scenarios.

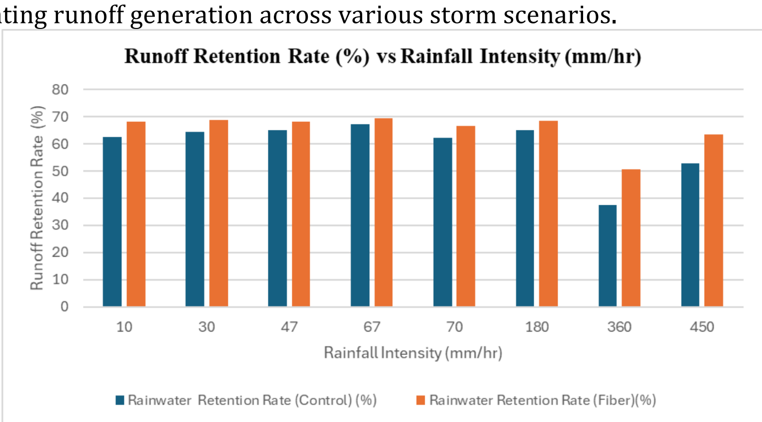

Fig. 6: Comparison of runoff retention rates for both green roof systems

3.2 Peak flow reduction

The peak flow reduction was analyzed for both the conventional and bamboo fiber green roof system under varying rainfall intensities as illustrated in Figure 7. The bamboo fiber green roof achieved a higher peak flow reduction, of 60% under low rainfall intensity (10 mm/h), 61% under moderate intensity (30 mm/h), and 59% under high intensity (450 mm/h). When rainfall intensity exceeds the storage capacity, such as during a 360 mm/h storm, the system's ability to retain water is severely reduced. Under such conditions, the substrate and plant layers that are intended to absorb and temporarily store precipitation get saturated fast [14]. As a result, water retention declines, and an excess rainwater leaves the retention layers and flows straight into the drainage system. This causes a rapid increase in the runoff, which increases the peak flow. For example, study by [3], which stated it can reduce 86% using recycled waste such as coconut fiber, at higher intensity (125 mm/h) compared to the commercial green roof, which can reduce peak flow almost 67%. Another reference can related with this findings is the study by [15] stated can reduced peak flow around 47.3% at the high intensity (59.9 mm/h). In comparison, the conventional system showed lower reductions, averaging approximately 30%- 59% across all conditions. These results confirm that the bamboo fiber system's enhanced capability to mitigate peak flow effectively reduces the impact of intense storm events and improves urban stormwater management.

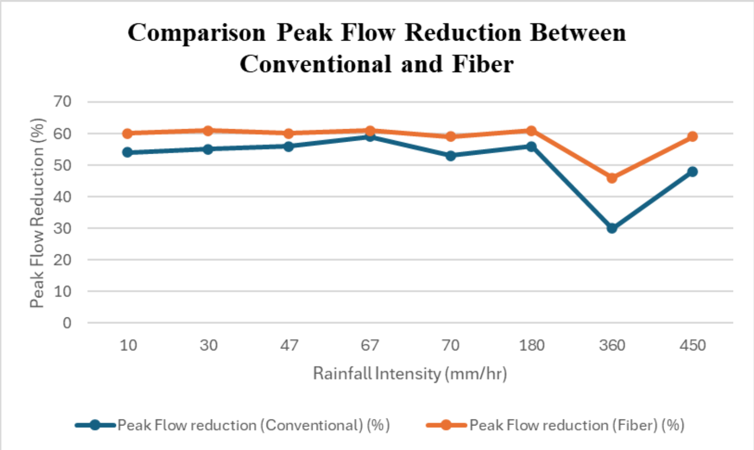

Fig. 7: Comparison of peak flow reduction between conventional and fiber green roofs.

3.3 Runoff coefficient

Figure 8 illustrates a comparison of the runoff coefficient for both systems. The runoff coefficient was measured for both conventional and bamboo fiber green roof systems under various rainfall intensities. The graph demonstrates a positive relationship between rainfall intensity and runoff coefficient, with higher rainfall intensities leading to greater runoff coefficients for both roof systems. This relationship arises because increased rainfall intensity reduces the infiltration capacity of the roof systems, leading to more surface runoff. For the conventional green roof system, the runoff coefficient was 0.37 at a low rainfall intensity of 10 mm/h and increased to 0.47 at a high rainfall intensity of 450 mm/h. This indicates the limited water retention capacity of the conventional green roof system, particularly under heavy rainfall conditions. Supporting research, such as Paus et al, 2024), highlights that conventional systems often struggle to retain stormwater during high intensity rainfall events due to rapid saturation. In contrast, the bamboo fiber green roof system achieved lower runoff coefficient starting at 0.31 for moderate rainfall intensity (30 mm/h) and peaking at 0.47 under extreme rainfall intensity (450 mm/h). These results emphasize the superior stormwater retention capability of bamboo fiber systems, which outperformed the conventional systems across all tested conditions. Additionally, the saturation threshold effect is evident in the data. At lower rainfall intensities, the difference in runoff coefficients between the two systems is smaller, but as rainfall intensity increases, the bamboo fiber green roof demonstrates its ability to delay saturation and reduce runoff more effectively. [17] also observed that green roofs, particularly fiber-based ones, perform better at retaining water during moderate to high-intensity storms, highlighting their ability to manage stormwater sustainability. In summary, the bamboo fiber green roof system exhibits significantly better performance in reducing runoff generation compared to conventional systems.

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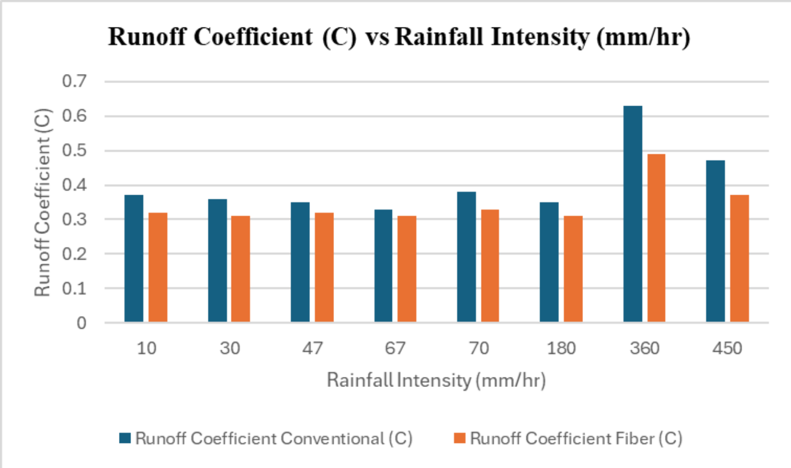

Fig. 8: Comparison of runoff coefficients between conventional and fiber green roofs.

4. Conclusion

The integration of bamboo fiber into green roof systems presents a viable solution to urban stormwater challenges. This innovative approach not only reduces flood risks but also aligns with sustainable development goals by utilizing renewable and recycled materials. The experimental results highlight the effectiveness of the fiber bundle concept, where bamboo fiber is innovatively wrapped around PET bottle caps to enhance green roof performance. This design significantly improved the system's hydrological functionality. The fiber bundle concept demonstrated superior water flow and retention capacity, achieved up to 69% runoff retention, reduced the runoff coefficient to as low as 0.31, and delivered peak flow reductions of up to 61% under high rainfall intensities. The use of PET bottle caps in the drainage layer further improved water flow and storage capacity, supporting the overall functionality of the system. Compared to the conventional drainage layers, this innovative approach maximized water retention and minimized runoff, highlighting its potential to improve green roof systems in urban areas. Future research should focus on the durability and aging of bamboo fiber under varying environmental conditions such as investigating the long-term exposure to moisture, UV radiation, and microbial activity that affects bamboo fiber structural integrity and hydrological performance. Treatments to improve bamboo fibers resistance to rot and fungus might be evaluated to ensure long-term performance. Other than that, the scalability of fiber bundle integration should be tested in larger green roof installations across diverse urban environments, including high-rise buildings, industrial zones, and residential areas. This will help in determining the possibility of increasing system capacity while keeping performance in terms of runoff retention, peak flow reduction and capacity to bear load.

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Author Contribution

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