The Hydraulic Performance of the Green Roofs by Using Banana Trunk Waste as the Material Layer

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ABSTRACT

Urbanization has increased the incidence of floods due to impermeable surfaces that prevent rainwater absorption, underscoring the necessity for effective stormwater management. Using green roofs, which include growth and other material layers, is an alternative solution. This research evaluates the hydraulic performance of green roofs incorporating banana trunk waste, a highly effective material due to its water absorption and retention properties in a drainage and filter layer, with the added support of PET bottle caps for lightweight structural applications. The study looks at the fibre model's peak flow reduction ranging from 61% to 77% and retention rate ranging from 64.75% to 79.47%, with the rainfall simulation carried out in low, moderate, and severe intensities, which are 10 mm/h, 30 mm/h, 60 mm/h, 180 mm/h, 350 mm/h and 550 mm/h. The research highlights the effectiveness of banana trunk waste and recycled materials, such as PET bottle caps, in enhancing the performance of green roofs to address waste disposal issues, while promoting circular economy systems.

Keywords: Green roof, rainwater, stormwater, hydraulic, banana trunk waste, retention rate, peak flow reduction, PET bottle caps, Axonopus compressus

INTRODUCTION

Urbanization and structural development have expanded, and the potential for higher risks of flash floods after heavy rainfall to drainage systems has posed several environmental and engineering issues. Thus, green roofs are a sustainable solution for flood rate control and urban water supply demand by retaining and slowing the release of water from rain [1]. Integration also contributes to the environmental and economic sustainability of green roofs, as banana trunk waste and PET bottle caps are considered unwanted waste. Banana trunk waste, generated from the lucrative banana industry in Malaysia, is a suitable resource because it is produced in a tropical climate that encourages the generation of significant amounts of waste [2]. Likewise, the recycled PET bottle caps, being lightweight and thermally insulating, contribute to the effectiveness of green roofs and simultaneously prevent PET waste from polluting the environment [3][4]. Both materials can be used in green roofs to enhance sustainable urban development targets for stormwater regulation, waste minimization, and the circular economy.

Green roofs are highly effective at reducing stormwater runoff and relieving strain in drainage systems. These are temporary storage before the stormwater outflow is directed to a drainage or catchment area [5]. The water retained in the system provides stormwater runoff retention capacity [6][7]. According to [8], the water storage capacity, or stormwater retention capacity, is closely related to rainfall intensity, and the capacity decreases during heavy storm events. Green roofs can effectively reduce stormwater runoff during storm events that happen less frequently (less than once every five years), for which the peak flow rate is predicted to reduce by

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between 19 and 50%. Azam compared a green roof system with a conventional roof to experimentally examine the peak flow reduction performance. The study used burnt-crushed coconut shells as a drainage layer and found that the green roof reduces stormwater runoff peak flow by 56-86% over the range of rainfall intensities [9].

MATERIALS AND METHODS

Methodology to investigate green roof performance in improving water runoff quantity. Two green roof models, a fiber model and a conventional green roof model, were constructed during the study period. Experiments on both models were conducted to determine the response of the green roof model in reducing the volume and duration of water runoff, as well as the rainfall depth and retention rate. The experiment was conducted over several months to compare the performance of the green roof model. A custom rainfall simulator was developed to simulate real-world conditions. A simulator with a nozzle system can apply water uniformly to the green roof model. The experiment consisted of six rainfall events, categorised into low, moderate, and high rainfall intensities. 10 mm/h represents the low, 30 mm/h for moderate, and 60, 180, 350, 550 mm/h for high rainfall intensity. The volumes of water runoff, retention rates, and times for water runoff delay were investigated for both models using six events. The experiment was conducted manually on-site using a flowmeter and rain gauge to collect the rainfall depth data. Peak flow and retention data were quantified using flow meters and drainage collection tanks. Observational studies were conducted to validate the proposed system for various rainfall intensities.

A. Green roof model layer

This study utilized a green roof model container in a small rectangular box measuring 300 mm in length and width and 200 mm in height, as seen in Fig 1. This compact size enables the effective simulation of small-scale green roof conditions while remaining easy to handle for research purposes. The total area of 0.09 m² provides a surface for vegetation and substrate within the green roof model. The materials selected for this study were chosen based on their environmental benefits, availability, and functional properties. Banana fibre was extracted through mechanical stripping, washed, and sun-dried to remove impurities. The dried fibers were then processed into non-woven mats for the filter layer using a needle-punching machine to ensure uniform thickness and durability. Meanwhile, the PET bottle caps were cleaned, perforated using the mechanical drill for the drainage layer, and assembled into bundles wrapped with banana fibers to enhance the structural shape and water flow. Lightweight and durable PET bottle caps in provide the supporting structure as a drainage layer, which leads to the reuse of plastic waste, thus reducing waste sent to landfills. This reduces plastic pollution and promotes circular economic practices [10]. The novel fibre bundle in Fig. 2, formed by firmly wrapping banana fibres around a central core, is a sustainable and biodegradable option for green roof systems. This distinctive design enhances water retention and drainage efficiency while maintaining structural integrity. The inherent characteristics of banana fibres and their sustainable origin establish this selection as an innovative alternative for promoting green infrastructure. The substrate layer used in this study is soil mixed with cocopeat to enhance the soil structure by storing moisture equivalent to 8-10 its times, facilitating proper drainage and aeration, promoting root development and preventing waterlogging [11]. Based on the Malaysian climate and green roof substrate, vegetation such as *Axonopus compressus* (cow grass) was used as a vegetation layer for its stress tolerance and ability to thrive in the Malaysian climate [12]. The full details of each layer are demonstrated in Fig 3 below.

Fig 1 The green roof model fiber

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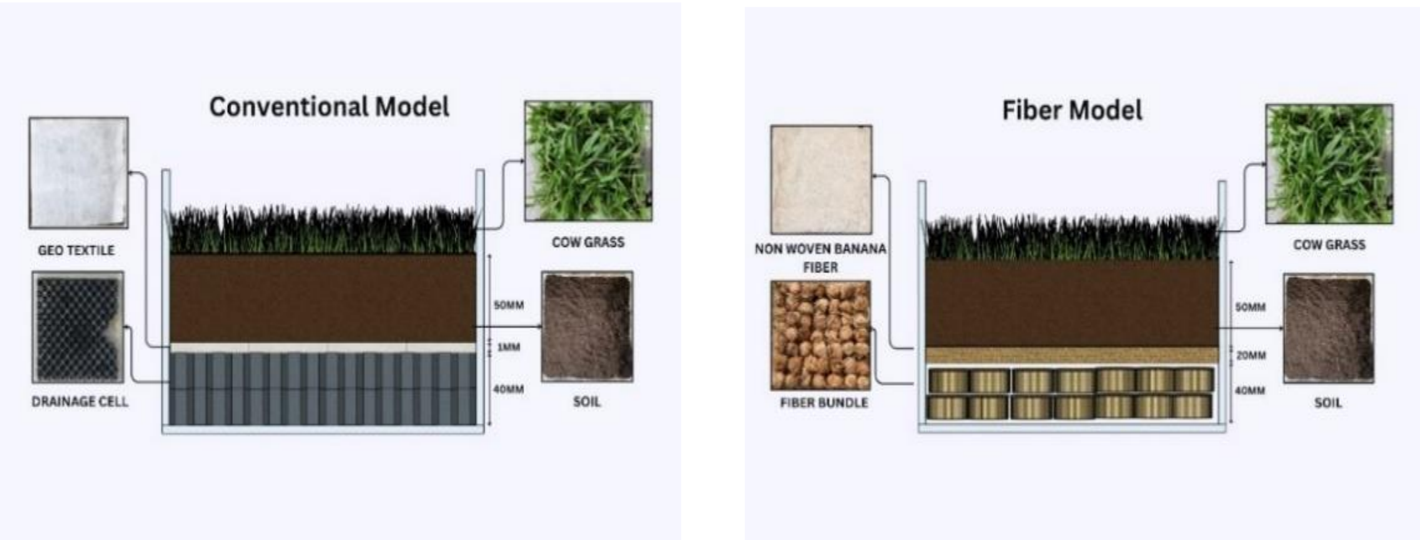
[1]

Fig 2 The fiber bundle



(a) **(b)**

Fig 3 The details of each layer for green roof models (a) Conventional model; (b) Fiber model

B. Site Testing

The rainfall simulator in Fig 5 was constructed using PVC pipes to support a water delivery system. The frame was rectangular, with horizontal pipes for stability and vertical supports. The water delivery system included nozzles for natural rainfall, adjustable valves, a flow meter, and a hose connector for consistent rainfall distribution. Hydrologic data collection utilized a green roof model with a base area of 0.09 m^2, measuring key parameters such as rainfall retention, runoff volume, and infiltration rate. A flow meter and manual measurements ensured data accuracy. The rainfall simulator was tested at six intensity levels (10, 30, 60, 180, 350, and 550 mm/h) using two sprinklers with one valve control. Data were recorded every minute over multiple trials. A digital flow meter, installed in a water pipe, provided discharge data for applications such as irrigation and industrial operations. The outflow from the green roof was also manually checked with a water container and stopwatch to determine the rainwater retention rate, thus supporting sustainable urban water management practices.

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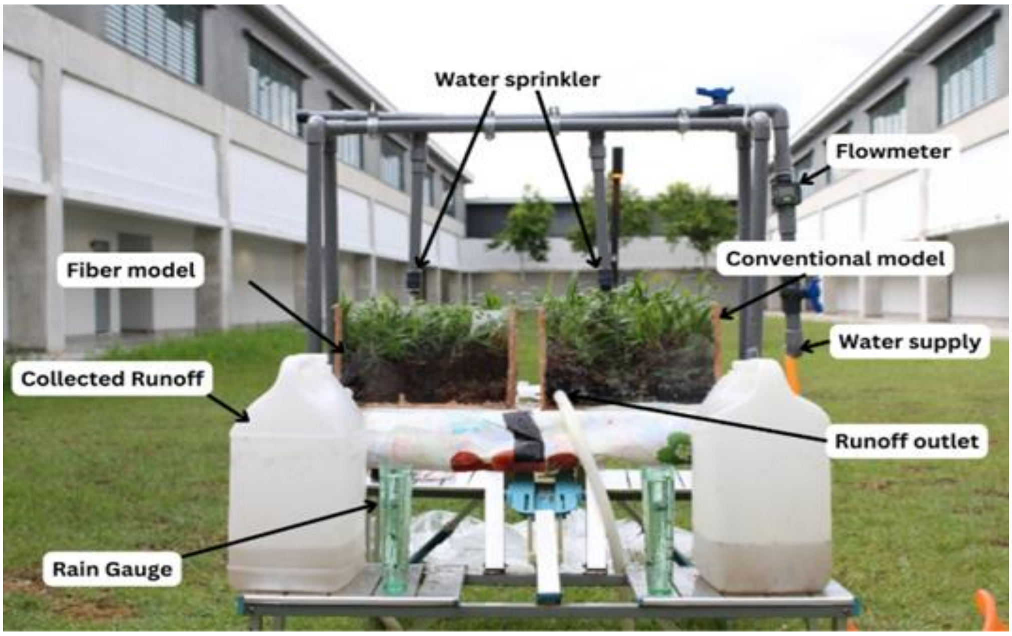

Fig. 5 The experiment setup

DATA COLLECTION

The hydrological and water quantity parameters of this study were meticulously gathered using a specially designed green roof model. The model simulated small-scale green roof conditions with a total base area of 90,000 mm² (0.09 m²). Key hydrological parameters, including rainfall retention, runoff volume, and infiltration rate, were measured to evaluate the model's performance under various conditions. Water quantity data were collected using a flowmeter and rain gauge to ensure accuracy and reliability. This comprehensive approach enabled a robust assessment of the capacity of green roofs to mitigate runoff and support sustainable urban water management.

A. Rainfall Intensity

Rainfall intensity functions are crucial for understanding and predicting precipitation patterns, which have significant implications for climate studies, urban planning, and flood management. If intensity is required, such as for drainage, the depth Pd (mm) is converted to an intensity I (mm/h) by dividing by the duration d in hours [13].

$$I = \frac{Pd}{d} \qquad (1)$$

B. Peak Discharge Estimation

The flow data from the flow meter were used to calculate the runoff coefficient (C) value as one of the rational method Equation (2) parameters. Average C values were used to predict the peak discharge of the green roof outflow [13].

$$Q = \frac{C.i.A}{360} \qquad (2)$$

Where,

Q = Peak flow (m^3/s)

C = Runoff coefficient

i = Average rainfall intensity (mm/h)

A = Drainage area (ha) (MSMA 1 Edition, 2012)

C. Runoff Coefficient (C)

The runoff coefficient (C) is an essential measure for assessing the hydrological efficacy of green roof, because it directly affects stormwater management techniques. It denotes the ratio of precipitation transformed into surface runoff, thereby offering insights into the effectiveness of green roofs in mitigating peak flows and controlling urban stormwater. A reduced runoff coefficient signifies an enhanced ability for rainwater retention and infiltration, which is crucial for reducing urban floods, enhancing water quality, and promoting sustainable drainage systems. By calculating the runoff coefficient, researchers and engineers can evaluate and enhance the design and efficacy of green roofs within urban hydrological systems [14].

$$C = \frac{\text{Total Runoff Volume}}{\text{Total Rainfall Volume}} \qquad (3)$$

C from MSMA 1 was used to choose C for the control, considering impervious roofs, concrete, and city areas. The C was 0.8 for 10, 30, 60, and 180 mm/h. At 350 and 550 mm/h, C was 0.9 because the rainfall intensity exceeded 200 mm/h.

D. Peak Flow Reduction

Equation (4) was applied to investigate the performance of green roofs in reducing the peak flow [16].

$$\text{Peak Flow Reduction (\%)} = \frac{(\text{Ccontrol} - \text{C green roof})}{\text{Ccontrol}} * 100\%$$

(4)

Control C is the estimation value from MSMA 1, which was applied to the control model. Green roof C comes from the calculation of (3).

E. Peak Flow Reduction

The runoff retention rate from green roofs in this study was calculated using equation (5) [15].

$$RR = \frac{(\text{RV} - \text{V})}{\text{RV}} * 100\% \qquad (5)$$

Where RR is the retention rate %, RV is the rainfall volume received by the green roof (L), and V is the runoff volume of the green roof (L) [16].

RESULTS AND DISCUSSION

Based on the findings from the experimental investigation of banana fibers as a drainage and filtration layer in green roof systems. This study aimed to evaluate the efficacy of banana fiber as an alternative to conventional materials, specifically examining its drainage efficiency, filtering capacity, and overall effect on the operation of green roofs. First, the physical and hydraulic characteristics of banana fibre were examined. Subsequently, the performance of green roof systems utilising banana fibre was compared with that of conventional systems in terms of water retention, filtration efficiency, and plant vitality. This section concludes with a discussion on the implications of the findings, emphasizing the potential of banana fiber as a sustainable and efficient component in green roof technology.

Peak Flow

The graph in Fig. 6 depicts the relative peak flows, m^3/s, of conventional green roofs against those of fibre-based green roofs at different rainfall intensities, ranging from 10 mm/h to 550 mm/h. At lower rainfall intensities (10 and 30 mm/h), both systems exhibited low peak flows, with only a slight difference between the two. The difference indicates a reasonably good performance in runoff management between the two systems. However, at a higher rainfall intensity of 60 mm/h, less peak flow resulted in a fibre-based green roof compared to its conventional counterpart, indicating that a fibre-based roof may provide better water retention and less runoff during modest rain. Peak flows increased with rainfall intensities of 188 and 350 mm/h in both systems; however, slight values were persistently lower in the fiber system, indicating a more pronounced ability to curb runoff in the case of severe rainfall events. Finally, the model demonstrated a higher peak flow at the highest rainfall intensity (550 mm/h) than the conventional system. This could be attributed to the saturated conditions of its banana fiber and PET drainage layers, which probably limit its ability to manage extreme runoff.

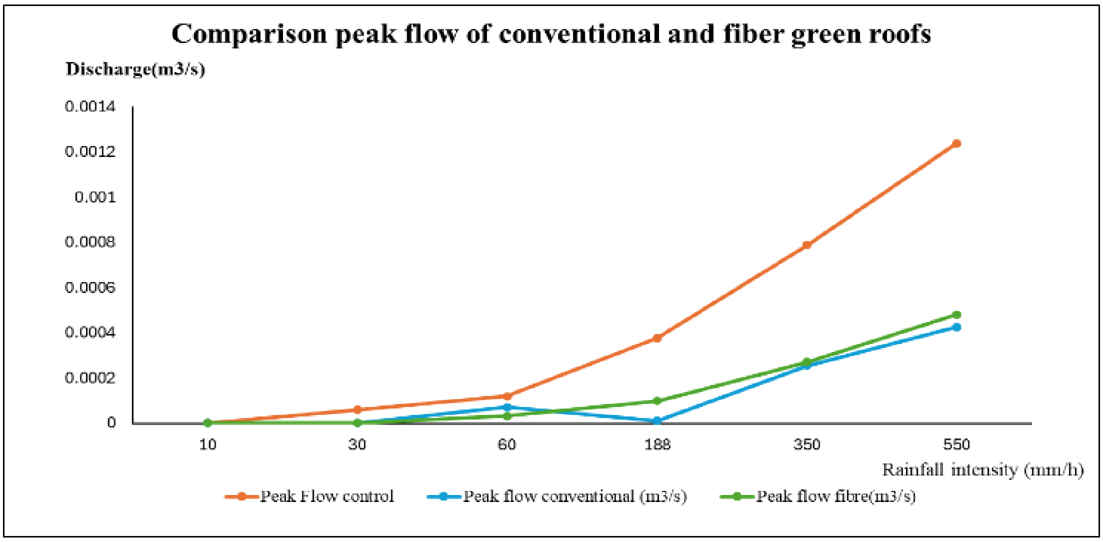

Fig 6 Graph of peak flow (m³/s) comparison between conventional and fiber green roofs.

Peak Flow Reduction

Green roofs with fiber materials reduce peak flow at low to moderate rainfall intensities better than conventional methods proven at Fig 7. For rainfall intensity of 10 mm/h, for instance, the fiber method yielded a 65% reduction in peak flow, whereas conventional methods gave a 60% reduction. The same trend held at 30mm/h and 60mm/h, where fiber methods reduced peak flow by 73% and 74%, respectively, which are approximately 8% more effective than conventional methods. Fiber green roofs have a 77% reduction compared with 72% for conventional methods, with the highest peak flow reduction at 188 mm/h. This trend was reversed as the intensity increased. At 350mm/h, conventional methods reduced peak flow by approximately 68%, marginally beating fiber-based green roofs with a reduction of 66% due to saturation in fiber model. At an intensity of 550mm/h, conventional methods reduced peak flow by 66%, whereas fiber based green roofs decreased peak flow by 61%. The bottom line shows that the fiber-based green roofs performed better for low to moderate rain intensity, and the conventional methods performed relatively better under extreme conditions. This study's results emphasize the correlation between rainfall intensity and the efficacy of green roofs. The results indicated that when rainfall intensity escalated, the attenuation of peak flow diminished. During intense rainfall events, the green roof system may fail to retain and absorb all the water, resulting in diminished peak flow decrease. The green roof system may reach saturation, resulting in water overflow and less absorption, hence decreasing its efficacy in mitigating stormwater runoff [17].

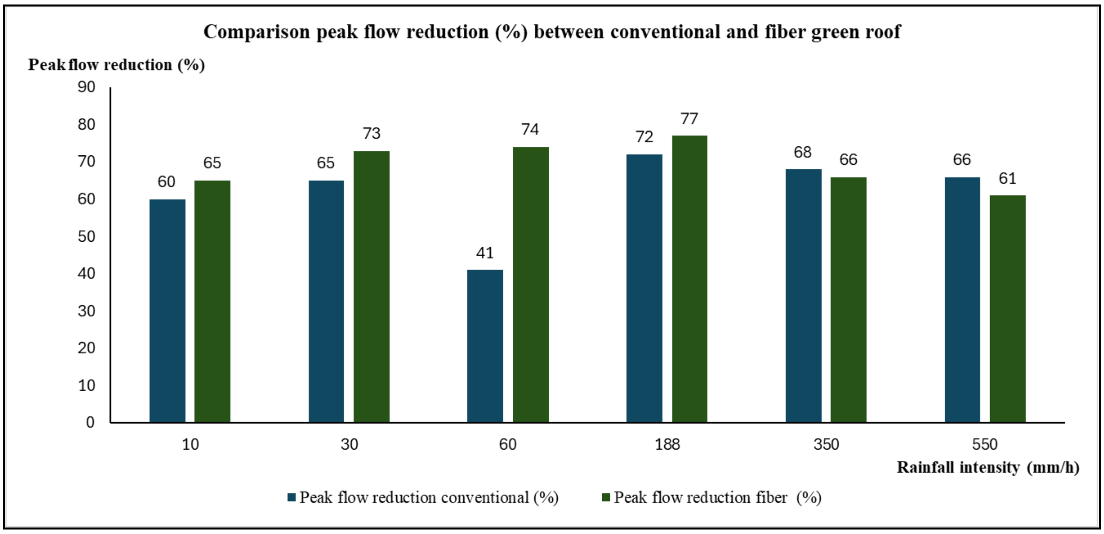

Fig 7 Graph of peak flow reduction (%) comparison between conventional and fiber green roofs.

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Previous studies have reported lower reductions in peak flow for conventional green roofs. For example, Romali observed a 41% reduction during a 100 mm/h event and 35% during a 150 mm/h event [9][18]. Azam reported reductions of 67%, 41%, and 24% for conventional green roofs at 125 mm/h, 200 mm/h, and 275 mm/h, respectively, whereas green roofs using recovered coconut fiber and crushed coconut shells achieved reductions of 86%, 72%, and 56% [14]. Ayub noted that peak flow decreases by 51% to 67% when using cow grass as a vegetative layer, aligning with reductions observed in typical green roofs in this study [19]. It can also be concluded that these materials are vital for the surface life of green roofs. The effectiveness of fibre-based green roofs can be explained by their higher water retention capacities and structural design, which were also aligned with the trend in studies that employed advanced biodegradable materials high in cellulose, particularly banana fiber. Fiber green roofs exhibited a distinctly beneficial behavior for retention, particularly during moderate to high rainfall intensities, attributed partially to the fiber materials' higher absorption and water-retention characteristics. A performance reduction of 550 mm/h implies limitations under severe rainfall conditions, possibly related to the saturation effects.

Rainwater Retention Rate

The graph in Fig 8 showed that the banana fiber showed higher water retention values for green roofs, especially within the range of lower rainfall intensities (between 10 mm/h and 30 mm/h). For example, at 10 mm/h, banana fiber shows improved water-holding capacity of 4% over the conventional (71.53% vs. 67.97%). This superiority becomes more apparent at 30 mm/h and 60 mm/h, whereby banana fiber was observed to enhance retention even more, especially at 60 mm/h (79.06% vs, 52.88% of the conventional). This creates the impression that the fibrous structural arrangement and the high absorbency of banana fiber are adequate in light or moderate rains due to constraining a pungent capillary action and moisture retention.

However, banana fiber performed poorly under extreme rainfall conditions (350–550 mm/h). At these rates, the water retention of banana fiber is approximately 4% less than the conventional. This downgrading performance is caused by the saturation of the fibers, which limits water retention and enhances general runoff. Conventional methods may also exhibit uniformity in performance under these conditions. This observation further elucidates the limitation of banana fiber under extreme rainfall conditions and highlights the need for complementary materials or additional measures to effectively counter high-intensity rain. It further displays the relevance of dual performance, rendering the selection of suitable materials for the expected rainfall intensity as hypothesized for the practical function of green roofs.

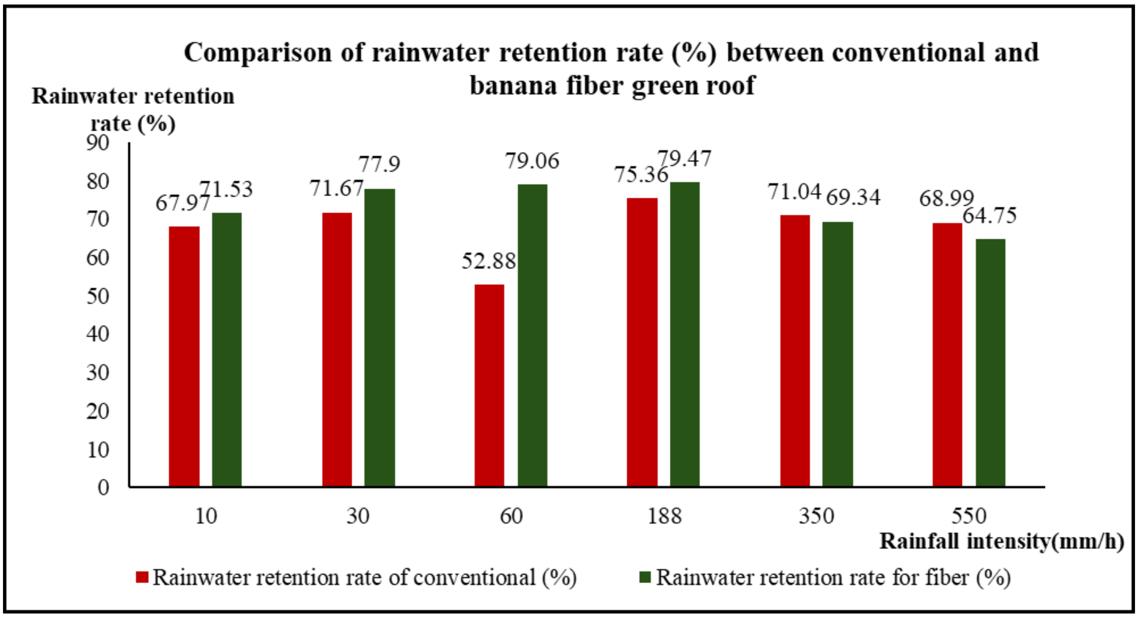

Fig 8 Graph of rainwater retention rate (%) comparison between conventional and banana fiber green roofs.

Banana fiber green roofs have superior rainfall retention compared to conventional green roofs from previous studies, retaining 71.53% to 79.47% rainfall, higher than the conventional green roofs, retaining 67.97% to 75.36%. It can thus be said that the banana fiber green roof is more effective in retaining runoff during

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moderate rainfall events. Its retention performance exceeds that of Wang [7], where a 59.9% maximum retention rate was reported for green roofs. Natural and biodegradable materials such as banana fibers for filter layers and fiber bundles for drainage layers contribute to this efficiency. Even under maximum rainfall intensities (188--550 mm/h), the fiber green roof can sustain high retention rates of 64.75% to 69.34%, thus outshining the studies conducted by R. Krishnan and H. Ahmad [20], which demonstrated reduced retention under equal conditions. Most notably, this retention ability, at a very high intensity of 550 mm/h, underlined the effectiveness of the green roof in managing stormwater and mitigating flooding within an urban context. The better performance through different intensities shows that the banana fiber green roof is a viable and sustainable option for urban stormwater management. It enhances the retention capacity, reduces urban runoff, and supports sustainable drainage systems. Both models were able to preserve plant growth conditions according to research by Vacari [21], the average annual rainwater retention rate for green roof was 59.7%. The correlation results showed that in such green roof conditions, retention capacities are affected by the intensity of rainfall and drain systems constructed. The study revealed that increasing rainfall amounts decreased the effective capacity retention due to system saturation, thus increasing the runoff coefficients. However, better drainage systems can see the opposite effect, allowing every system to retain more water and reduce the response time to intense rainfall, thereby slowly discharging water over a more extended period. This delayed selection allowed green roofs to control stormwater runoff rates effectively, particularly during peak times. By doing so, it provides an entire catchment for the last event. Critical to this finding is the more attuned drainage components for improving the green roof retention efficiency, particularly for areas with variable or unpredictable precipitation.

Runoff Coefficient

Rainfall intensity and runoff coefficients for conventional and fiber green roofs have inverse relationships. For instance, with low rainfall of 10 mm/h, runoff coefficients varied from 0.28 to 0.32, suggesting that effective rainwater retention exceeds 67.97%, as shown in Fig 9. Thus, green roofs effectively store large amounts of rainfall and reduce runoff. However, during 60 mm/h of rainfall, the general green roof was clogged and saturated, with a runoff coefficient of 0.5. In contrast, the fiber green roof maintained a lower runoff coefficient of approximately 0.3, showing better performance. For heavy rainfall (550 mm/h), the runoff coefficient rolls between 0.35 and 0.4, with retention rates lower than approximately 64-69%. This information indicates that green roofs are effective in stormwater management. However, their efficiency starts to wane with increasing rainfall intensity, thus underscoring the importance of proper drainage system selection that ensures its effectiveness under high rainfall. The results showed that with increased rain intensities, reduced runoff coefficients would lead to more significant peak flow reductions because the green roof systems could retain and manage the runoff water for the benefit of many. Peak intensity rainfalls that were notably higher than 350 mm/h feed the saturation thresholds of both models, reducing their efficiency in managing peak flows. The runoff coefficient, which represents the proportion of rainfall that causes surface runoff, revealed the relationship between the rainfall characteristics and the hydrological performance of the green roof.

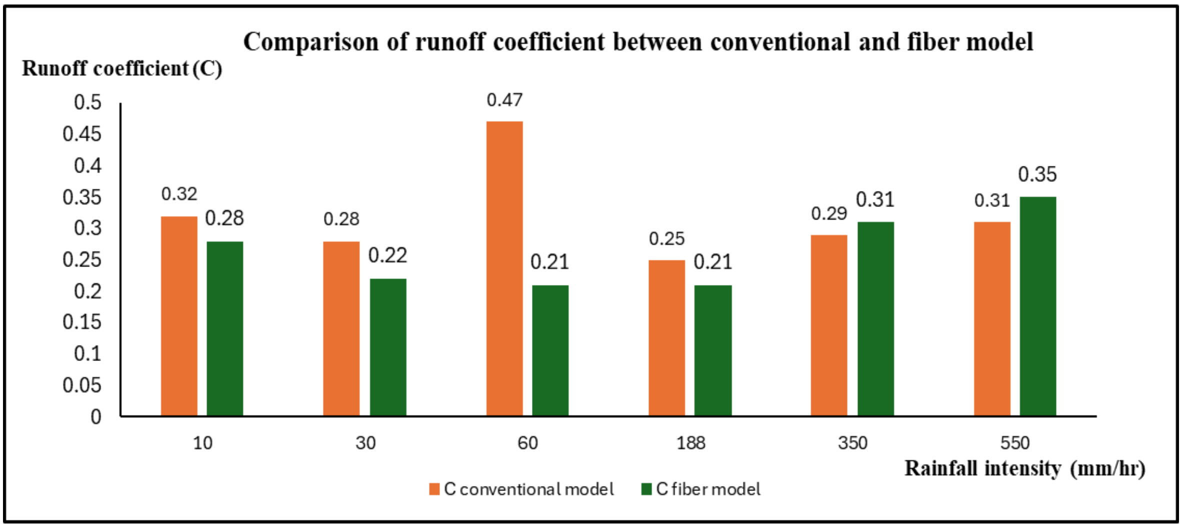

Fig 9 Graph of comparison of runoff coefficients between conventional and fiber models.

CONCLUSION

In conclusion, the current findings demonstrated that stormwater runoff could be improved when using a fiber green roof system since the fiber model achieved similarly lower peak flow compared with the conventional green roof. Hence, fiber green roofs may provide an alternative tool to consider when managing stormwater. The materials used for the four major components layers of the fiber green roof models would be suitable, especially for recycled waste, since the utilization of fiber bundles led to promising results. Overall, the green roof with conventional materials managed to decrease the peak flow in a range of 41 % -66 % and a retention rate of 75.36 %. Banana trunk waste has the potential as a green roof material to improve hydraulic performance, with peak flow reductions as high as 77 % and 79.47 % in retention rate compared to green roof with conventional materials.

Finally, the innovative aspect of this study is to consider tropical climates with intensive green roofs, which use banana trunk waste as a filter and drainage material for better stormwater management in Malaysia. The substrate particles did not clog the drainage owing to the nonwoven banana fiber filter layer. Fiber bundles showed similar drainage capabilities and water retention comparable to those found in conventional drainage layers. The experimental results showed peak flow reduction over varying rainfall intensities, significantly improving the performance at low to high events. Retention capability in the banana fiber system revealed the potential for using readily available agricultural waste to reduce flooding risks in cities, making more sustainable and environmental conservation practices possible. This could be an alternative method for replacing the synthetic materials conventionally used for sustainable urban development in Malaysia.

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