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The potential of coconut waste as green roof materials to improve stormwater runoff

Noor Suraya Romali *, Fatin Afiqah Binti Ardzu and Muhamad Nurfaizal Suzany

Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Tun Khalil Yaakob, 26300 Gambang, Kuantan, Pahang, Malaysia

*Corresponding author. E-mail: suraya@ump.edu.my

NSR, 0000-0001-5269-5818

ABSTRACT

Urbanization is one of the leading causes of urban flooding as rapid development produces more impervious areas in cities. The application of green roofs is regarded as an effective technology to minimize the adverse effects of urban development. The stormwater management capacities of green roofs have been extensively acknowledged, and they can retain rainfall and detain runoff. Nevertheless, Malaysia has experienced few green roof applications, and only limited literature is available concerning such topics. Additionally, the incorporation of waste and recycled material in green roof designs must be considered to ensure such projects benefit the environment as well as the economy. Therefore, the construction of a green roof utilizing recycled waste materials was attempted. An extensive green roof was constructed using beach morning glory and creeping ox-eye plants as vegetation layers, along with coconut waste, i.e., coconut fiber and coconut shell, as the medium for the filter and drainage layer, respectively. According to the results, the use of recycled coconut waste materials in the green roof operations reduced the peak flow by as much as 86%, while the use of commercial materials led to a reduction of 67%.

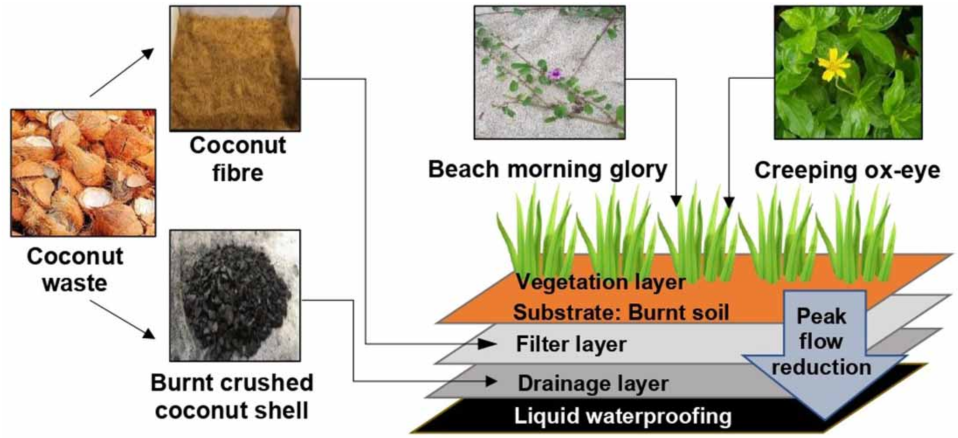
Key words: coconut waste, green roof, peak flow reduction, stormwater management

HIGHLIGHTS

The novelty of this study are:

- The utilization of coconut waste as the green roof materials.
- The production of burnt-crushed coconut shell as the drainage layer material.
- The use of coconut fiber to replace the non-woven geotextile used in the filter layer.
- A sustainable and economical green roof using a recycled waste material.
- Able to improve peak flow of surface runoff up to 86% reduction.

GRAPHICAL ABSTRACT



1. INTRODUCTION

When a region becomes more urbanized, impervious areas expand and the uses of urban land diversify in regard to hydrological and environmental practices (Lamera *et al.* 2014). Catchment permeability is reduced, resulting in surface type changes that diminish the water levels that flow into subsoils. Vegetation cover is generally lost when land use changes occur, which leads to the greater use of water because more of it evaporates. Urbanized areas often experience issues connected with the management of stormwater, such as floods in urban areas and polluted water (Ebrahimian *et al.* 2019; Shariat *et al.* 2019). More frequent floods, streambanks, and erosion are some of the effects of stormwater runoff, and these result directly from the surface runoff quantity changes that follow the expansion of impervious surface cover and the hydraulic expediency with which urbanization is associated (Moore *et al.* 2017).

Many efforts have been made to control and lessen the negative impacts of urbanization. The green roof is a type of best management practice capable of controlling overflow at the source by storing water in its various layers, deferring hydrological reactions, and restoring evapotranspiration (Kok *et al.* 2013). Cascone (2019) defined the structural basis of the green roof, which incorporates the installation of various layers (waterproofing, drainage, soil, and vegetation) above a standard roof. The extensive green roof and the intensive green roof are the two principal kinds (Kok *et al.* 2013, 2015; Krishnan & Ahmad 2014; Siew *et al.* 2019). An extensive system of roofing offers various benefits over an intensive system; for instance, the capital and maintenance costs are lower, and it requires less water. An extensive roof generally weighs very little but is very useful, particularly when it does not require supplementary support for the structure (Cascone 2019). Furthermore, installing large roofs is possible on larger slopes, while constructing them is technically straightforward and the methods are appropriate for a large roof. As a green roof covers a building with a living plant layer, this may assist in the mitigation of numerous urban hardscape issues because urban environments could then experience the natural cooling processes and water treatments generally found in less built-up zones (Özyavuz *et al.* 2015).

1.1. The benefits of green roofs to improve stormwater runoff

The adoption of green roofs has a positive impact on the environment, which can assist in the management of stormwater. The application of green roofs has the potential to reduce the peak flow of stormwater discharge by retaining rainfall using vegetation, substrate, and layered materials. These act as temporary storage before the outflow of stormwater is directed to a drainage or catchment area (Raimondi & Becciu 2021). The water retained in the system manages stormwater by providing runoff retention capacity (Kasmin *et al.* 2016; Zheng *et al.* 2021). According to Kok *et al.* (2015), the water storage capacity, or stormwater retention capacity, is closely related to the rainfall intensity and the capacity decrease during heavy storm events. Green roofs can effectively reduce stormwater runoff during storm events that happen less frequently (less than once every 5 years), for which the peak flow rate is predicted to reduce by between 19 and 50% (Fleck *et al.* 2022).

Loiola *et al.* (2019) compared a green roof system with a conventional roof, conducting an experiment to examine the volume retention performance. The study found that the green roof held 58% of the inflow water, resulting in a 12-min delay in the time runoff. Thus, the green roof system delayed the rainfall discharge, which decreased the chance of floods as the peak flow had been reduced. Moreover, the presence of plants in a green roof system led to increased stormwater retention. The water retention capacity for various plant species on wide green roofs ranged from 40 to 60% of total rainfall, with the green roof succeeding in retaining all minor rain occurrences of 10 mm. Meanwhile, the green roof retention ranged from 26 to 88% during 12 mm of rainfall (Li & Yeung 2014). Another study discovered a connection between climate differences and the retention capacity of green roofs when conducting observations in two different climates. The proportion of water retained ranged from 50 to 70% of total annual precipitation in Berlin, Germany. In contrast, the water retained was only 65% in Rio de Janeiro, Brazil as it has been influenced by high evapotranspiration rates. Two extensive green roofs were implemented in North Carolina, USA, both of which achieved a retention value of 64% of total rainfall. They also demonstrated drops in peak flow of more than 75% (Silva *et al.* 2019).

A previous study clearly showed that a green roof is one of the best practices for delaying the peak discharge time and attenuating the peak discharge volume (Liu *et al.* 2019). However, the performance of green roofs in terms of peak flow attenuation and delaying the start time runoff depends on the rainfall intensity, the green roof layer materials and thickness (Pęczkowski *et al.* 2018), as well as the types of plants used (Krishnan & Ahmad 2014). To sum up, green roofs contribute to the control of stormwater runoff by retaining or delaying stormwater runoff and reducing the risk of floods (Silva *et al.* 2019).

1.2. The challenges of implementing green roofs

Despite the extensive applicability of green roofs, their application in Malaysia is still limited. A number of major issues apply, including the fact that those monitoring green roof system construction operations are often lacking in technical capabilities (Shams *et al.* 2018) and costs can be high (Chow & Abu Bakar 2016; Hossain *et al.* 2019). The higher costs of maintaining and running a system during the construction work arise from the time-consuming need for maintenance activities that fulfill the aesthetic elements of the design. The costs of maintaining a system refer to those linked to the anticipated requirements during the system's life span. Traditional roofs last around 20 years, whereas green roofs last between 40 and 45 years. Complete renovations would be expected when these periods end. The maintenance of traditional coverings relates to repairing or replacing roof covering components, as well as potentially resolving the infiltration of water into the interior layers. Interventions related to other layers generally involve waterproofing sheaths, insulation layers, vapor barriers, and these are normally restricted to small roof surface sections. A well-executed roof may only require interventions sporadically. Furthermore, lacking suppliers who can supply products for green roof installation will lead to high maintenance costs.

Meanwhile, constructing green roof systems has always faced the issue that their installation in green buildings incurs high costs (Shams *et al.* 2018). Incorporating the construction of green roof systems into new buildings costs approximately 40–50% more. Malaysia has experienced problems with inexperienced contractors implementing green roof systems, as this may lead to budget overrunning and the improper installation of systems (Ismail *et al.* 2018). Investment costs are also greater, which is a major issue due to the higher expenditure required for green roof implementation. Moreover, suppliers are often unavailable, which can influence green building adoption as numerous countries have low demand for them (Chan *et al.* 2017). This issue is strongly associated with a local lack of technology related to green roofs because of the unavailability of green building material suppliers.

To summarize, the majority of countries make limited use of the green roof because the costs are high, non-renewable material use affects the environment, and formal green roof design, building, and maintenance methods are often lacking. However, green roof system construction has begun to witness recycled and reused materials being used in layers of drainage and substrates. Environmentally, technically, economically, and aesthetically, this may create advantages. It might also make possible the incorporation of waste into the production chain of construction, which would reduce the green roof costs connected with the substitution of reusable waste for commercial materials. The majority of researchers addressing recycled material use in green roofs have conducted hydraulic performance evaluations of the drainage and water retention capacities of the roofs, as well as comparing the growth of vegetation to that of a standard green roof system. Rubber crumbs (Perez *et al.* 2012; Solano *et al.* 2012; Vila *et al.* 2012), crushed porcelain and foamed glass (Matlock & Rowe 2016; Mert & Rowe 2016), and construction waste (Bates *et al.* 2015; Fan *et al.* 2020) are examples of the recycled materials that have undergone extensive research over the previous 10 years. Such studies have demonstrated the feasibility of employing such materials to replace those used in commercial green roof (CGR) systems.

1.3. The potential use of coconut waste as green roof materials

In the existing literature, numerous publications have shown how coconut waste could have different possible applications, as Table 1 shows. In particular, researchers have utilized coconut shell fibers in the production of textiles, certain biocomposites, panels to thermally and acoustically insulate buildings, and civil construction aggregates (Ferraz *et al.* 2011). On the other hand, green coconut shell has been used by Araújo De Almeida & Colombo (2021) as a substrate in a green roof system, combined with the humus produced from the vermicomposting process. The production of the residue of green coconut shell derives from the operations of agro-industries and consumer markets, which are linked to fresh or processed water and their derivatives. The composition of the residue is formed from cellulose (34%) and lignin (37%). The dimensions of green coconut shell residue mean it represents a large proportion of the annual production of waste.

Meanwhile, Alias *et al.* (2020) used two types of biocomposite materials – coconut fiber and rice husk – as additional materials in brick drainage systems to observe the best performance of water quantity and quality. They concluded that both materials showed potential for reducing the peak flow of stormwater, which the coconut fiber reduced by 5% and rice husk by 3% compared with the non-biocomposite brick. In addition, one characteristic of coconut fiber is porosity, which can increase the absorption of water. In terms of water quality, the rice husk and coconut fiber each had an alkaline pH, at 9.84 and 9.73, respectively. Both natural materials were able to reduce the total suspended solids (TSS) value to 5 mg/L, compared with the 20 mg/L from the benchmark test. For the total dissolve solids, the benchmark test recorded

Table 1 | The potential use of coconut waste in previous studies

Author	Type of coconut waste	Application
Fabbri *et al.* (2021)	Coconut fiber	Green roof insulation material made of coconut fiberboard
Araújo De Almeida & Colombo (2021)	Green coconut fiber	Combined with humus generated from the vermicomposting process for use as the green roof substrate
Alias *et al.* (2020)	Coconut fiber	Additional material for Integrated GSI (Green Stormwater Infrastructure) mortar brick use in a drainage system
Norhidayah *et al.* (2019)	Treated coconut fiber with sodium hydroxide (NaOH)	Combined with coconut shell in a mixture of porous asphalt
Lertwattanaruk & Suntijitto (2015)	Coconut fiber	Replacement materials in cement mortar mixture used for roof sheets
Brose *et al.* (2019)	Coconut husk fiber (coir)	Additional materials in cement for wall panels
Mintorogo *et al.* (2015)	Coconut fiber	Coconut fiber was laid on the surface rooftop slab
Iwaro & Mwasha (2019)	Coconut fiber	Implementation of coconut fiber in cavities of clay and concrete brick as insulation
Omar *et al.* (2020)	Coconut fiber	Use of 100% of coconut fiber as insulation ceiling board
Bolanos *et al.* (2021)	Coconut fiber (coir)	Additional material in mortar mixture for coating on a residential house

the highest value at 70 mg/L, followed by 40 mg/L for the rice husk. The lowest value was for the coconut fiber, at about 45 mg/L.

Porous asphalt mixture can use coconut shell as a substitute for aggregates and fiber as an additional material with better water permeability due to the higher air void values, which can help to minimize the clogging problem between the binders (Norhidayah *et al.* 2019). A study by Lertwattanaruk & Suntijitto (2015) used two different types of natural fibers – coconut fiber and oil palm fiber – as additional materials in cement mortar mixtures for roof sheets. The results showed that as the percentage of natural fiber replacement in the cement mortar increased, the percentage of porosity and water absorption increased. However, the coconut fiber could absorb more water as it has a higher porosity than oil palm fiber. The study also focused on the thermal conductivity of fiber cement mortars, in which both natural fibers were able to reduce the thermal conductivity to 66% due to their higher porosity. Brose *et al.* (2019) also used coconut fiber as an additional material in cement mixture to analyze the probability that natural fiber would reduce wall heat. It was discovered that compared with the control panel, the wall cement panel containing coconut fiber had better thermal insulation since the value of thermal conductivity achieved was 0.168 W/m K. Mintorogo *et al.* (2015) evaluated the thermal transfer performance of rooftop slab concrete with a coconut fiber cover. Significant differences were recorded for the surface temperatures of the bare concrete rooftop slab and the one with a coconut fiber cover, which were 33.2 and 28 °C for the daytime and 26.9 and 27.5 °C at night. The results showed that the rooftop slab covered with coconut fiber has better thermal insulation compared with the bare rooftop.

According to Iwaro & Mwasha (2019), coconut fiber reduces the energy consumption of a residential building while providing better thermal comfort as it minimizes the absorption of heat into the building. A study by Omar *et al.* (2020) proved that using natural fiber, i.e., coconut fiber, in a ceiling led to better heat transfer reduction results and did not harm the environment. The sample containing 1% of coconut fiber had a lower density, at 70.67 kg/m^3, compared with 99.56 kg/m^3 for the sample with 0% of coconut fiber. The material with a lower density had a higher probability of reducing heat transfer. Bolanos *et al.* (2021) used coconut fiber as an additional material in a mortar mixture based on Portland Cement for the coating façade of a residential building. The results showed that the mortar with additional coconut fiber reduced the temperature of an indoor room by a range of 0.5–1.5 °C and demonstrated excellent efficiency, with energy use reduced by 16%.

In conclusion, despite its benefits, especially in terms of stormwater management, the implementation of green roofs in Malaysia is still limited due to technical issues and high costs. Despite their limited use, some examples of green roof buildings in Malaysia are at Herriot-Watt University, Sime Darby Oasis, Damansara, and Putrajaya City Hall, Putrajaya. Hence, this study on green roofs is essential to encourage the utilization of the green roof concept and increase the number of green buildings in Malaysia. Furthermore, using recycled waste materials within more economically beneficial green roof systems is a positive step because this could make a contribution to the new green-focused endeavor of the Ministry of Energy, Green Technology and Water (KeTTHA), in which the use of recycled and waste materials is being promoted via the Green Building Index (GBI) and Green Technology Master Plan (GTMP) to ensure that buildings are more environmentally sustainable. As discussed in a previous section, the potential of coconut waste has been proven in many fields, so its utilization in green roof applications will be explored in this study. In addition, the influence of various factors such as the type of plant used and the intensity of rainfall on the performance of green roofs in reducing peak flow will also be observed.

2. MATERIALS AND METHODS

The investigation of the way green roofs performed in enhancing the stormwater runoff water quantity followed an appropriate methodology. This included designing a green roof system on a laboratory scale, utilizing coconut waste as the layers on the green roof, and observing the flow rate prior to and following the presentation of the green roof system.

2.1. Experimental set-up

The experiment required model prototypes built to a laboratory scale and was undertaken at the Hydraulic and Hydrology Laboratory, Faculty of Civil Engineering Technology, Universiti Malaysia Pahang. In the study, three green roof models have been assessed: two vegetated models that employed commercial (CGR) or recycled waste materials (RWGR), and a conventional model. The models are described in Table 2.

The model dimensions were 0.4 m × 0.4 m × 0.3 m, while the surface area of the roof was 0.25 m^2. Model A represents a conventional roof with no substrate and plants on the top and served as the control model. Two types of plants were used for the vegetated green roof (Model B and Model C), which is beach morning glory (*Ipomoea pes-caprae*) and creeping ox-eye (*Wedelia trilobata*). The selection of the plants is based on the study by Shahid *et al.* (2016) who suggested that the vegetation structure and leaf type with mat spreading characteristics like the creeping ox-eye are suitable for the green roof application as they can make a dense cover. Furthermore, a plant with the ability to tolerate high ambient temperatures like beach morning glory is recommended. As shown in Figure 1, the Model B design featured, from top to bottom, a vegetation layer of beach morning glory, a 50-mm deep layer of topsoil substrate, a filter layer of non-woven geotextile, a drainage cell, and a waterproofing layer of bitumen sealant.

Meanwhile, the Model C design for the green roof prototype using recycled waste contained five elements that are typically used, as Figure 2 illustrates. These were beach morning glory or creeping ox-eye as the vegetation layer, a 40-mm deep layer of burnt soil substrate, a 30-mm deep filter layer of coconut fiber, a 30-mm deep drainage layer of burnt-crushed coconut shell,

Table 2 | Green roof model description

Model	Description
A	Conventional roof (control)
B	Green roof with commercial materials (CGR)
C	Green roof with recycled waste materials (RWGR)

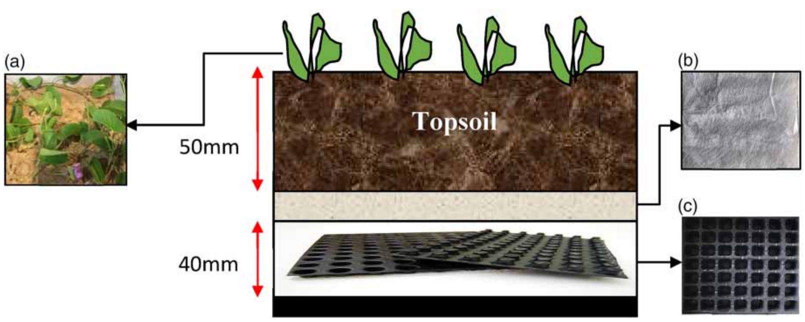


Figure 1 | Commercial green roof model (CGR) with (a) beach morning glory, (b) non-woven geotextile, and (c) drainage plate.

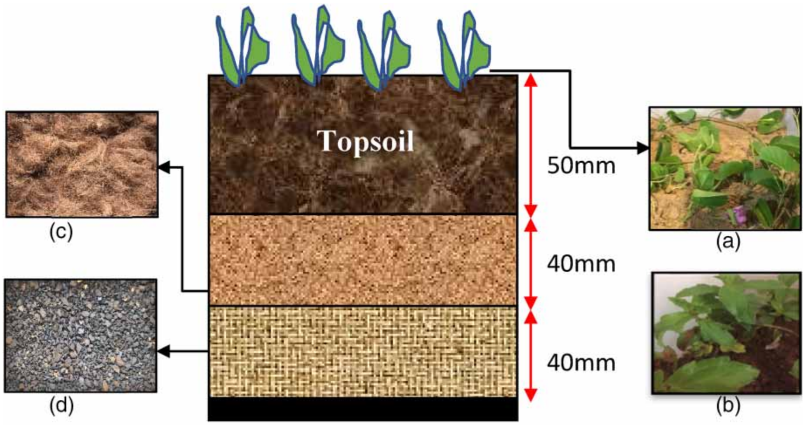


Figure 2 | Recycled waste green roof with (a) beach morning glory, (b) creeping ox-eye, (c) coconut fiber, and (d) burnt-crushed coconut shell.

and a waterproofing layer of bitumen sealant. Soil medium losses and runoff were prevented by placing a filter membrane between the medium (soil) and the layer for drainage.

A pipe was connected to the roof to allow the flow of water to the measuring cylinder to calculate the discharge (m^3/s) of the stormwater passing through. A discharge (m^3/s) vs time (s) hydrograph was plotted to observe how the models performed in terms of improving stormwater runoff. In addition, the peak flow reduction percentages were calculated using Equation (1).

$$\frac{Q_{p\,\text{without green roof}} - Q_{p\,\text{after green roof}}}{Q_{p\,\text{without green roof}}} \times 100 \qquad (1)$$

2.2. Data collection

Two series of data collection were conducted to evaluate the effectiveness of coconut waste as a green roof material to improve the stormwater quantity. The first data collection (Series 1) was undertaken to evaluate the effectiveness of the recycled waste green roof (RWGR) compared with the conventional roof, as well as observe how using different types of plants affected the performance of the green roof. Meanwhile, the latter (Series 2) was undertaken to investigate the advantage of using coconut waste compared with CGR materials. The performance of Series 1 was observed in five events – Event 1, Event 2, Event 3, Event 4, and Event 5 – with a 10-min design storm applied for each event. Different rainfall intensities were applied for each event, as shown in Table 3.

Meanwhile, Table 4 shows the characteristics of Series 2, which involved three events: Event 1, Event 2, and Event 3. Their rainfall intensities were 125, 200, and 275 mm/h, respectively. The adopted intensity of 125–275 mm/h was chosen considering the commonly used value applied by other studies (Kok *et al.* 2015; da Silva *et al.* 2020). However, higher intensities were applied in Series 1 to investigate the effects of intensities on the ability of the green roof system to retain rainwater. The storm event was simulated using a rainfall simulator in the Hydraulic and Hydrology Laboratory.

Table 3 | Green roof simulated rainfall event for Series 1

Event	Rainfall intensity (mm/h)
1	180
2	300
3	350
4	450
5	550

Table 4 | Green roof simulated rainfall event for Series 2

Event	Rainfall intensity (mm/h)
1	125
2	200
3	275

2.3. Production of burnt-crushed coconut shell for the drainage layer

The recycled waste material used for the drainage layer was coconut shell. The raw coconut had to be processed before being placed in the green roof system. Six stages were involved in processing the coconut shell, as shown in Figure 3. The raw material (coconut shell) was collected from the local market. After removing the coconut shell from the husk, it underwent a washing and cleaning process. Before the heating and activation process, the coconut shell was air-dried under direct sunlight. Next, the coconut shell was burned to activate the carbon. As soon as the burnt coconut shell had been crushed, it was sieved using a 2–5 mm sieve.

3. RESULTS AND DISCUSSION

3.1. Performance of green roof with different plants

The 10-min storm simulation produced discharges that were observed for Events 1, 2, 3, 4, and 5. These are represented, respectively, in the hydrographs given in Figure 4(a)–4(e). As shown in the hydrographs, the discharge values reduced when using the RWGR model which, in comparison to the control model, experienced a lower peak flow. From Figure 4(a), the RWGR (9×10^{-6} m^3/s) flow was lower than that of the control model (15×10^{-6} m^3/s). The same trend of results can be observed in Figure 4(b)–4(e). They show that the beach morning glory managed to retain stormwater.

Table 5 shows the peak flow reduction percentages for the green roofs with beach morning glory and with creeping ox-eye. The comparison is illustrated in Figure 5. Event 1 appeared to lead to the greatest reduction in flow since the green roof featuring beach morning glory managed a 38% peak flow decrease. Regarding Event 2, the same green roof performed well again, since the 36% reduction in flow was greater than the reduction rate of 28% achieved with the green roof that used creeping ox-eye. Events 3, 4, and 5 were observed to produce similar outcomes, whereby the reduction percentages recorded by the green roof featuring beach morning glory were greater than those produced when using the green roof with creeping

Figure 3 | The production of burnt-crushed coconut shell.

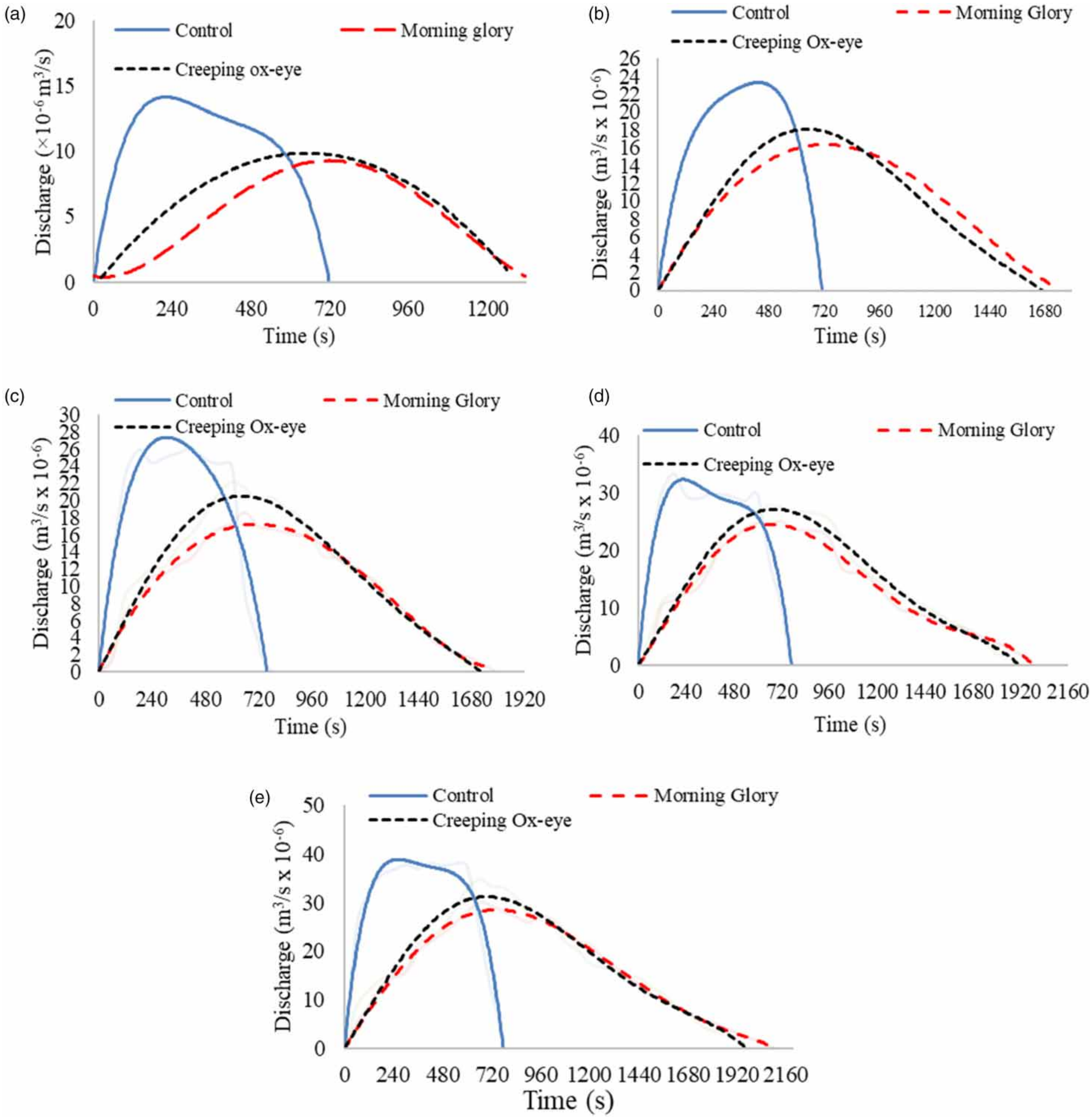


Figure 4 | Peak flow comparison for control and RWGR models for rainfall intensities of (a) 180, (b) 300, (c) 350, (d) 450, and (e) 550 mm/h.

ox-eye. The respective rates for the three events were 35, 31, and 26%, compared with 24, 23, and 18%. Furthermore, Event 1 (180 mm/h intensity) to Event 5 (550 mm/h intensity) appeared to indicate that the green roof reduction percentages decreased when the intensity of rainfall increased.

3.2. Performance of RWGR vs CGR

The discharge values observed during the 10-min rainfall simulation for Series 2, including Events 1, 2, and 3, are shown in Figure 6(a)–6(c), respectively. The hydrograph compares the peak flows of the conventional roof (control) and those of the green roofs with commercial materials (CGR) and recycled waste materials (RWGR). The results indicate that the green roof with recycled waste materials (RWGR) showed the best potential for reducing the peak flow, compared with the CGR. The

Table 5 | Peak flow reduction (Series 1)

	Peak flow reduction (%)	
Intensity (mm/h)	**Morning glory**	**Creeping ox-eye**
180	38	31
300	36	28
350	35	24
450	31	23
550	26	18

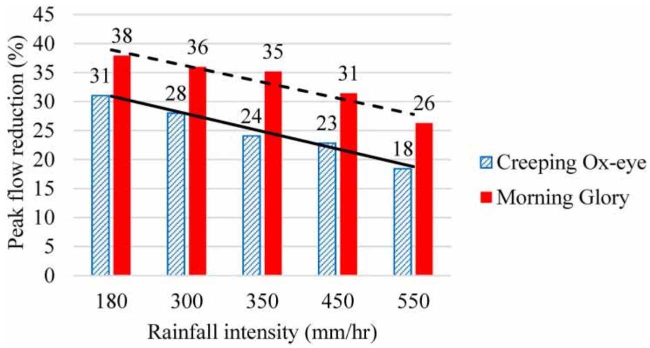


Figure 5 | Peak flow reduction for morning glory and creeping ox-eye per rainfall intensity.

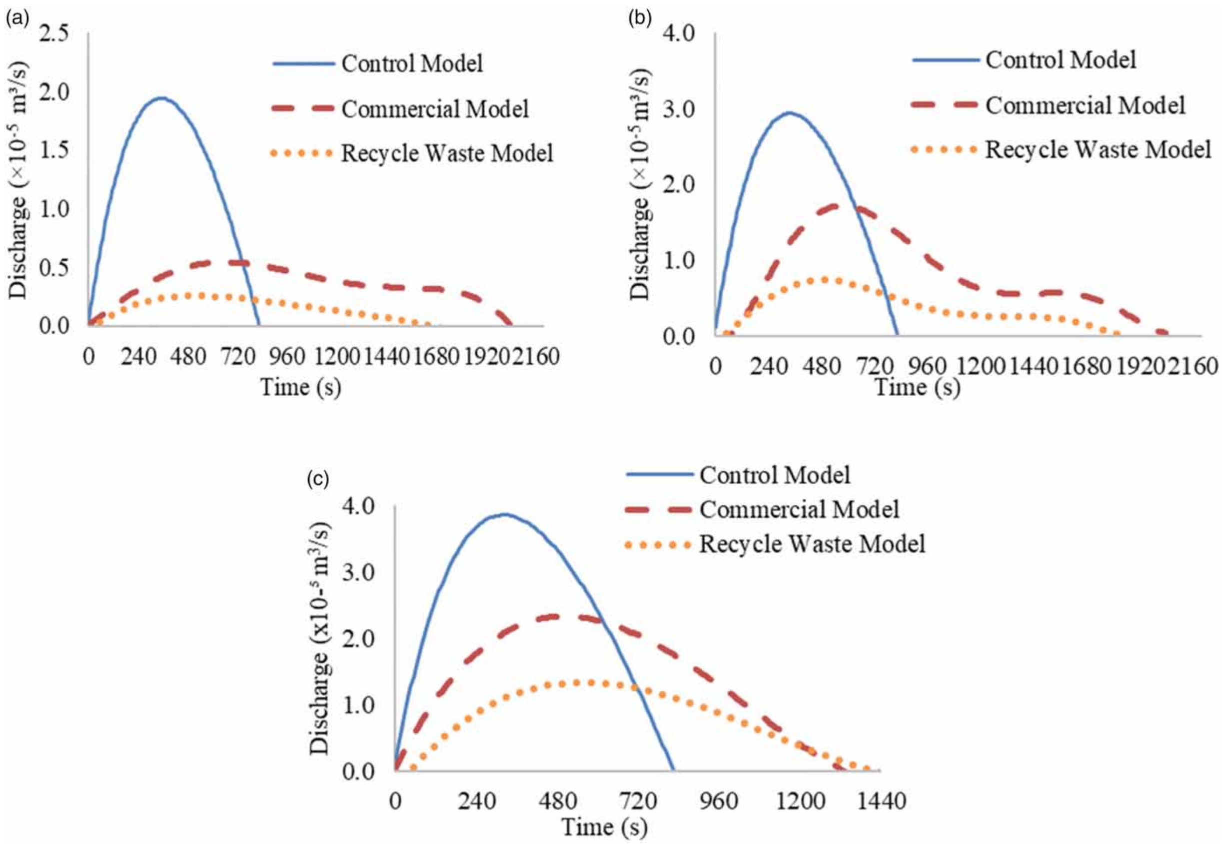


Figure 6 | Comparison of peak flows for control, commercial, and recycled waste green roof models for rainfall intensities of (a) 125, (b) 200, and (c) 275 mm/h.

control model recorded the highest peak flows, which were 1.83×10^{-5} m^3/s for Event 1, 2.70×10^{-5} m^3/s for Event 2, and 3.63×10^{-5} m^3/s for Event 3.

As Figure 6(c) illustrates, at 1.60×10^{-5} m^3/s, the RWGR led to a lower peak flow than the CGR, whose value was 2.75×10^{-5} m^3/s. As predicted, similar results can be observed in Figure 6(b) and 6(a), whereby the peak flow of the RWGR (0.75 and 0.25×10^{-5} m^3/s) was lower than that of the CGR (1.60 and 0.60×10^{-5} m^3/s), respectively. In conclusion, the hydrological performance of the green roof improved significantly when using recycled waste materials, in this case, burnt-crushed coconut shells and a filter of coconut fiber.

Table 6 shows the peak flow reduction percentages for green roofs with commercial materials (CGR) and recycled waste materials (RWGR). Figure 7 compares the peak flow reductions of the CGR and RWGR. The results revealed that the CGR could reduce the peak flow reduction of stormwater runoff, recording reductions of 67, 41, and 24%. However, the performance of the RWGR was better, with peak flow reductions of 86, 72, and 56% for the events using coconut waste, compared with the CGR materials. The findings validated the high potential of RWGR to make hydrological stormwater improvements. In Event 1 (125 mm/h intensity), the RWGR performed the best, whereby the peak flow was reduced by 86%, from 1.83×10^{-5} to 0.25×10^{-5} m^3/s. This result is in accordance with the results obtained in Series 1 in which the green roof system recorded a better performance in terms of reducing the stormwater quantity during rainfall of lower intensity.

4. DISCUSSION

The green roof is an innovative and sustainable solution to traditional roofing systems that offers numerous environmental benefits. One aspect that is crucial for green roof performance is the use of appropriate filters and drainage layers. In this discussion section, we will explore the results of our study on the use of recycled waste materials, specifically coconut waste, as a filter and drainage layer in green roof systems. We will also explore how different plant species impact green roof performance. Additionally, we will discuss the inverse relationship between rainfall intensity and green roof performance and its impact on the overall efficiency and longevity of the green roof system. Through this discussion, we aim to provide a comprehensive understanding of the factors that contribute to green roof performance and offer insights for future research and design considerations.

In this study, the filter layer was changed from geotextile to coconut fiber, and the drainage layer was changed from a commercial drainage plate to burnt-crushed coconut shells. The results showed that green roofs using recycled waste materials, such as coconut waste, were able to significantly improve the performance of the roof in reducing stormwater runoff

Table 6 | Peak flow reduction (Series 2)

	Peak flow reduction (%)	
Intensity (mm/h)	**Commercial green roof**	**Recycled waste green roof**
125	67	86
200	41	72
275	24	56

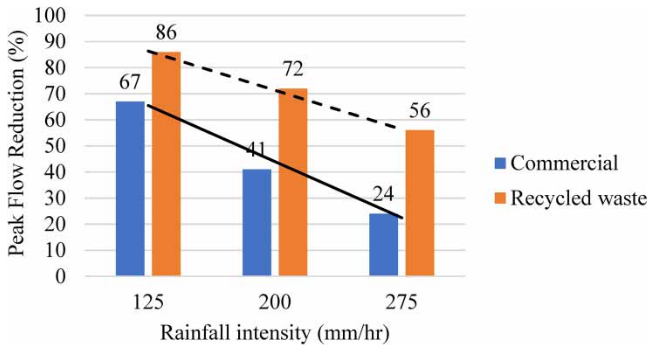


Figure 7 | Percentages of peak flow reductions for commercial green roof (CGR) and recycled waste green roof (RWGR) per rainfall intensity.

compared with conventional green roof systems that use commercial materials. The filter layer, made of coconut fiber, was able to effectively retain and filter water, allowing for more water to be absorbed by the roof and reducing the amount of runoff. The use of burnt-crushed coconut shells in the drainage layer improved the overall water management of the green roof system, as the shells were able to provide a porous and permeable surface for water to flow through, reducing the risk of saturation and water damage.

In comparison, commercial green roofs using geotextile and commercial drainage plates were able to reduce the peak flow of stormwater runoff by 24–67%, while green roofs using recycled waste materials, specifically coconut waste, were able to reduce the peak flow of stormwater runoff by 56–86% with different rainfall intensities applied. These results indicate that recycled waste materials, such as coconut waste, can provide a more effective and sustainable solution for filter and drainage layers in green roof systems.

Furthermore, plants play a critical role in the performance of green roofs, as they provide numerous benefits, including reducing stormwater runoff, improving air quality, and providing insulation and cooling. In this study, two types of plants were used to assess their impact on green roof performance: beach morning glory (*Ipomoea pes-caprae*) and creeping ox-eye (*Wedelia trilobata*). The results revealed that the choice of plant species can have a significant impact on green roof performance where green roofs with creeping ox-eye showed a peak flow reduction range between 18% and 31% during the five simulated rainfall intensities. On the other hand, green roofs with morning glory showed a higher percentage of peak flow reduction, with a range of 26–38%. These results suggest the ability of beach morning glory to reduce stormwater runoff is better than creeping ox-eye. Beach morning glory, with its deep roots and dense foliage, is able to absorb and retain more water compared with creeping ox-eye. The dense foliage also provides additional insulation and cooling, improving the overall performance of the green roof system. On the other hand, creeping ox-eye, with its shallow roots and less dense foliage, may not retain as much water as morning glory, but its ability to spread and cover a large area may still contribute to the overall reduction in stormwater runoff.

The results of this study also highlight the relationship between rainfall intensity and green roof performance. The results revealed that as rainfall intensity increased, the reduction of peak flow decreased. For green roofs using creeping ox-eye, the reduction of peak flow decreased from 31% to 18% as the rainfall intensity increased from 180 to 550 mm/h. For green roofs using beach morning glory, the reduction of peak flow decreased from 38 to 26% for the same increase in rainfall intensity. Similarly, for green roofs using CGR materials, the reduction of peak flow decreased from 67 to 24% as the rainfall intensity increased from 125 to 275 mm/h. For green roofs using recycled waste materials, the reduction of peak flow decreased from 86 to 56% for the same increase in rainfall intensity.

These findings suggest that the performance of green roofs may be inversely proportional to rainfall intensities which agrees with the study by Krishnan & Ahmad (2014) and Kok *et al.* (2015), who recorded that an event involving a higher rainfall intensity reduced the least stormwater. This is because, during high intensity rainfall events, the green roof system may not be able to retain and absorb all the water, leading to a reduction in peak flow reduction. The green roof system may become saturated, leading to water overflowing and not being absorbed, reducing its effectiveness in reducing stormwater runoff. The inverse proportionality between green roof performance and rainfall intensity highlights the importance of considering the local climate when designing and constructing green roofs. Green roof designers and builders should consider the average rainfall intensity and frequency of high intensity events in their area when selecting and designing the green roof system. This information can be used to optimize the design of the green roof system, ensuring that it can effectively reduce stormwater runoff even during high intensity rainfall events.

In summary, the use of recycled waste materials, such as coconut waste, as a filter and drainage layer in green roofs can have a positive impact on the overall performance of the roof in reducing stormwater runoff. These materials offer a more sustainable, cost-effective, and environmentally friendly solution compared with commercial materials, and their use should be considered in future green roof design and construction. In addition, the choice of plant species can greatly impact the performance of green roofs in reducing stormwater runoff. Morning glory and creeping ox-eye showed different peak flow reductions during the five simulated rainfall intensities, highlighting the importance of selecting the appropriate plant species for green roof design and construction. It is important for future research to continue to examine the impact of different plant species on green roof performance and to develop guidelines for selecting the most effective vegetation for specific green roof applications. Furthermore, the performance of green roofs may be inversely proportional to rainfall intensities, with higher rainfall intensities leading to a reduction in peak flow reduction. It is important for future research to continue to examine this relationship and to develop guidelines for optimizing the design of green roofs for different rainfall intensities and climates.

5. CONCLUSION

In conclusion, the current findings demonstrated that stormwater runoff could be improved when using a green roof system since the vegetated green roof achieved a lower peak flow compared with the conventional roof. Hence, green roofs may provide an alternative tool to consider when managing stormwater. The materials used for the five major component layers of the green roof models would be suitable, especially for recycled waste green roofs, since the utilization of the coconut waste led to promising results, as follows:

i. Overall, the green roof with commercial materials managed to decrease the peak flow in a range of 24–67% compared with the conventional roof.
ii. Coconut waste has the potential as a green roof material to improve hydrological performance, with peak flow reductions as high as 86% compared with those of a CGR (24–67%).
iii. Using the green roof system with beach morning glory led to higher peak flow reduction percentages in comparison to using the green roof featuring creeping ox-eye. The green roof system using beach morning glory performed better, with reduction percentages as high as 38% compared with the roof with creeping ox-eye, the rate of which was 31%.
iv. The peak flow reduction percentages for the green roof decreased with higher levels of rainfall intensity.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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