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DESIGN AND DEVELOPMENT OF A GREEN ROOF SUBSTRATE FOR THE TROPICS

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ABSTRACT

Green roofs can be used as an effective climate change adaptation tool in South Asia. However, there is limited information on the type of substrate and the substrate depth best suited for extensive green roofs in this tropical climate. In this research, sixteen potential substrate mixtures were prepared using locally available materials and waste materials. The properties of these substrate mixtures were tested under laboratory and field conditions to identify the substrate mix best applicable for extensive green roofs for the tropical climate of Sri Lanka. Based on the results obtained from laboratory testing it was observed that substrate mixtures that contained coir and crushed recycled bricks displayed the properties most suited for a substrate in the tropical climate. Three different substrate depths (2.5cm, 5.0cm and 7.5cm) were also tested, in order to study their suitability for adequate plant development under tropical conditions. It was observed that the 2.5cm substrate depth had successful plant establishment and adequate plant coverage. Moreover, the 2.5cm depth substrate could be easily supported on an existing roof with little/no modifications. Therefore, for the tropical climate of Sri Lanka, a 2.5cm depth substrate composed of 10% compost, 5% coir, 5% rice husk, 40% sand and 40% crushed recycled bricks is recommended.

Keywords: *Green Roof Substrate; Substrate Depth; Tropical Climate*

1. INTRODUCTION

Green roofs have a great potential in South Asian countries such as Sri Lanka, where unplanned urbanisation has led to urban environmental issues such as urban flooding and heat islands (Vijayaraghavan & Raja, 2014). Green roofs can effectively mitigate these challenges and improve the urban micro-climate (Seyedabadi et al., 2021). However, despite this potential, the adoption of green roofs in these countries remains in its infancy (Dassanayake & Beneragama, 2011).

One of the major barriers to increasing the prevalence of green roofs in South Asia is the lack of local research and scientific data to evaluate their applicability to local conditions (Vijayaraghavan & Raja, 2014). Although green roofs have expanded beyond Europe in the recent decades, green roof research and implementation is still largely concentrated in the temperate regions (Blank et al., 2013; Lugo & Rullan, 2015).

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A green roof consists of a number of layers. Each of these layers should be carefully selected according to the location and climatic conditions (Shafique et al., 2018). Green roof components from temperate regions cannot be completely adopted to the tropical climate because of differences in climatic condition and building characteristics (Williams et al., 2010; Wong & Lau, 2013). As a result of the limited research on green roofs in the tropics, the components of a green roof suitable to these geographical locations have not yet been identified (Vijayaraghavan, 2016). Therefore, local research must be conducted to identify the components of the green roof that is best suitable for the tropical climate of South Asia.

The substrate is one of the key components of a green roof system (Ampim et al., 2010). It functions as a support system for the vegetation and provide the plants with sufficient access to nutrients, water and oxygen (Handreck & Black, 2010). Moreover, the substrate assists the vegetation to adapt to long-term growth on the harsh conditions of a rooftop (Xiao et al., 2014). In addition to plant growth, the type of substrate also influences the thermal performance, stormwater performance and sound insulation of the green roof system (Vijayaraghavan, 2016). Therefore, the substrate used in a green roof must be carefully selected as it is crucial for the success of the green infrastructure (FLL, 2008; Vijayaraghavan, 2016).

The US and German green roof guidelines recommends the use of 80-90% inorganic constituents in the green roof substrate (Vijayaraghavan, 2016). Sand, pumice, heat-expanded shale and scoria, perlite and vermiculite are some popular inorganic materials used in green roof substrates in temperate regions (Ampim et al., 2010; Johnston & Newton, 2004; Xiao et al., 2014). The remaining 10 - 20% v/v of the green roof substrate should be made up of organic components such as peat, coconut coir, composted green waste and composted saw dust (Emilsson & Rolf, 2005; Farrell et al., 2012; Vijayaraghavan & Raja, 2014; Xiao et al., 2014). However, majority of these organic and inorganic materials, which are popular green roof substrate constituents in the temperate climate, may not be available in South Asia. Moreover, the use of locally sourced materials can help to reduce the environmental and financial costs associated with transportation. Therefore, local research must be conducted to identify appropriate substrate mixes best suited for the local climate and geographical location (Dunnett & Kingsbury, 2004).

This research aims to identify the most suitable substrate mixture for extensive green roofs in the tropical climate of Sri Lanka. For this purpose, 16 different substrate mixes, made from locally available materials, were evaluated through field and laboratory investigations, to identify the substrate mixture best applicable for tropical conditions.

In addition to the substrate composition, the thickness of the substrate also has a significant impact on the performance of the green roof system. Plant establishment and survival, thermal performance, stormwater performance and the weight of the system are all reliant on the thickness of the green roof substrate (Dassanayake & Beneragama, 2011; Durhman et al., 2007; Getter et al., 2009b; Kok et al., 2015; Ondoño et al., 2016; Panayiotis et al., 2003; Rowe et al., 2006).

Although a substrate depth of 2 - 15 cm is recommended for extensive green roofs, the actual depth of the substrate must be established based on the local geographical and climatic conditions (Panayiotis et al., 2003). In general, as the substrate depth increases, the performance of the green roof system improves (Durhman et al., 2007; Papafotiou et al., 2013; Rowe & Getter, 2006; Thuring et al., 2010). However, as majority of the weight in a green roof comes from the substrate, a deeper substrate translates to a heavier system (Xiao et al., 2014). This is particularly problematic when retrofitting an existing building, as the current roof structure must accommodate the added weight of the green roof system. Therefore, it is essential to consider local building characteristics when deciding on the substrate depth. Hence the second half of this paper details the steps taken to identify a suitable substrate depth for extensive green roofs in Sri Lanka.

2. DEVELOPMENT OF THE GREEN ROOF SUBSTRATE

2.1 PREPARATION OF SUBSTRATE MIXES AND FACTORS CONSIDERED

The standards for developing green roof substrates are detailed in various literature and in the guidelines provided by German and US green roof standards. These desired properties of the green roof substrate are outlined in Table 1. In this study, the substrate was developed using these existing guidelines as the starting point and modifications were made where necessary to suit the local climatic conditions.

Table 1: Desired properties of the green roof substrate

Source	Water Holding Capacity	Wet Bulk Density	Dry Bulk Density	Air Filled Porosity	pH
(Chow et al., 2018)	39.4%	912 kg/m^3	431 kg/m^3	19.5%	-
German Green Roof Guidelines (FLL, 2008)	20 - 65 %	-	600 – 1200 kg/m^3	> 10%	-
(Johnston & Newton, 2004)	35 - 45%	-	-	15 - 25%	6
(Xiao et al., 2014)	40 – 60%	-	-	10 – 20 %	-
(ASTM International, 2015)	30 – 45%	-	-	> 20 %	6.5 – 8.5

It is not practical for one material to possess all the characteristics listed in Table 1. Therefore, the general practice is to prepare the green roof substrate by using a mixture of different materials, so that the substrate mixture meets the performance requirements detailed in Table 1 (ASTM International, 2015; Johnston & Newton, 2004).

When selecting different materials for the green roof substrate mixture it is recommended to incorporate local waste materials as it can help to increase the green rating of the building while decreasing the overall cost (ASTM International, 2015; Johnston & Newton, 2004; Nagase & Dunnett, 2011; Vijayaraghavan & Raja, 2014).

Majority of the load on a green roof result from the substrate. Therefore, the weight of the substrate must be kept as low as possible while still providing sufficient anchorage for plants (Vijayaraghavan, 2016; Xiao et al., 2014). For this purpose, US and Germany green roof guidelines recommends the use of 80% inorganic constituents in the green roof substrate (Vijayaraghavan, 2016). Therefore, in this study, 80% of the substrate composition consisted of inorganic materials. Recycled crushed bricks of 10 mm – 4.75 mm and sand of 2 mm – 0.475 mm were used as the inorganic materials. Brick waste is one of the most prominent wastes produced from the construction industry (Wong et al., 2018). Coarse materials such as crushed bricks have surface and internal pores which helps to improve the porosity, hydraulic conductivity and water storage capabilities of the substrate. Additionally, by incorporating crushed recycled bricks, the density of the substrate can be reduced while also decreasing the waste output from the construction sector (Johnston & Newton, 2004; Vijayaraghavan & Raja, 2014).

The green roof substrate should possess an adequate level of micro and macro-nutrients to promote plant growth (Vijayaraghavan, 2016). Therefore, organic constituents must be incorporated in to the substrate (Molineux et al., 2014; Nagase & Dunnett, 2011; Vijayaraghavan & Joshi, 2015). However, as the amount of organic material in the substrate increases, the stability of the substrate will be compromised. As the organic materials decompose, the substrate will shrink and compact, hindering healthy root growth (Nagase & Dunnett, 2011; Vijayaraghavan, 2016). The rate of decomposition of organic matter is higher in tropical countries such as Sri Lanka compared to countries in the northern hemisphere (Ampim et al., 2010). Moreover, under the tropical climate, a high organic content in the substrate can lead to excessive weed growth which will in turn increase the amount of maintenance required. Therefore, in tropical climates, careful consideration must be given to the quantity of organic matter utilised in the green roof substrate. According to literature, an organic content of 10 - 20% is recommended for warm humid climates (Friedrich, 2005). Considering the tropical humid climate of Sri Lanka, the organic content of the green roof substrate was fixed at 20%.

Compost, coir and rice husk were selected as the organic constituents of the substrate mix. Rice husk is an agricultural waste that is generated in large quantities in Sri Lanka (Rodrigo & Perera, 2011). Incorporating rice husk helps to reduce the density of the substrate while enhancing the aeration ability and water permeability (Xiao et al., 2014). Coir fibre is widely used in different climate regions to enhance the properties of the green roof substrate (Razzaghmanesh et al., 2014). Compost is a recycled material which can be produced locally (Graceson et al., 2014). It helps to provide the plants with nutrients and contributes positively to the green roof substrate due to its high air-filled porosity and water holding capacity (Raviv et al., 2008). However, compost in the substrate mix can lead to high concentrations of nitrogen in the green roof runoff (Hashemi et al., 2015). Therefore, according to recommendations of previous literature, the amount of compost used in the substrate mix was limited to 20% (Friedrich, 2005; Nagase & Dunnett, 2011; Toland et al., 2012)

By varying the composition of these organic and inorganic constituents, 16 potential substrate mixtures were prepared for testing. The substrate mixtures are given in Table 2.

Table 2: Substrate configurations

	Sample	Notation	Organic (20%)			Inorganic (80%)	
			Compost	Coir	Rice Husk	Sand	Brick
Series 1	1	S11	10%	5%	5%	40%	40%
	2	S12	10%	-	10%	40%	40%
	3	S13	10%	10%	-	40%	40%
	4	S14	20%	-	-	40%	40%
Series 2	1	S21	10%	5%	5%	80%	-
	2	S22	10%	-	10%	80%	-
	3	S23	10%	10%	-	80%	-

	Sample	Notation	Organic (20%)			Inorganic (80%)	
			Compost	Coir	Rice Husk	Sand	Brick
	4	S24	20%	-	-	80%	-
Series 3	1	S31	10%	5%	5%	50%	30%
	2	S32	10%	-	10%	50%	30%
	3	S33	10%	10%	-	50%	30%
	4	S34	20%	-	-	50%	30%
Series 4	1	S41	10%	5%	5%	30%	50%
	2	S42	10%	-	10%	30%	50%
	3	S43	10%	10%	-	30%	50%
	4	S44	20%	-	-	30%	50%

2.2 DETERMINATION OF THE PROPERTIES OF THE SUBSTRATE

The following properties were determined for each substrate mixture, under laboratory conditions, to determine its suitability as a green roof substrate for the tropics.

- Dry Bulk Density (DBD): The DBD was determined by oven drying a known sample volume at 105℃ for 2 hours. The resulting dry weight was used to calculate the DBD.
- Wet Bulk Density (WBD): The WBD was determined by saturating the samples in water for 24 hours and then allowing it to drain freely under gravity for 24 hours. The wet weight of the samples was measured and the WBD was calculated.
- pH: The soil samples were mixed with deionised water at 1:1 soil suspension ratio. The samples were then agitated in a shaker for 1 hour and was allowed to stand undisturbed for 1 hour. Then pH of the samples was determined by using a pH meter.
- Water Holding Capacity (WHC): Was determined as per the Percolation method.
- Air Filled Porosity (AFP): AFP was determined according to the Australian Potting Mix Standard (AS 3743-2003).

2.3 SELECTION OF A SUITABLE SUBSTRATE DEPTH

Three different substrate depths (2.5cm, 5.0cm and 7.5 cm) were tested, in order to study their suitability for adequate plant development under tropical conditions.

Sample plots of 40 cm x 30 cm were prepared for each of the thicknesses. The sample plots were filled with two substrate mixes selected based on the laboratory analysis detailed in 2.2. Using the plant selection matrix for the tropical climate developed by John & Halwatura (2022), *Alternanthera Sessilis* was selected as the vegetation layer for the evaluation. The plants were transplanted as plugs, 9 plants per plot. The sample plots were kept on a horizontal plane for 1 week until the roots had anchored to the substrate and was then transferred to a conventional sloped roof. The coverage and survival rate, under the three substrate depths, were monitored for 12 weeks to identify the most suitable substrate and the optimum thickness for the tropical climate. The percentage plant cover was measured using a grid (frequency-cover), weekly for 12 weeks. The survival rate of the plants was determined by visual assessment.

3. RESULTS AND DISCUSSIONS

3.1 LABORATORY ANALYSIS OF THE SUBSTRATE MIXTURES

Following sections presents the results of laboratory analysis of the substrate mixtures.

3.1.1 Wet and Dry Bulk Density

Figure 1 represents the dry and wet bulk density of the tested samples.

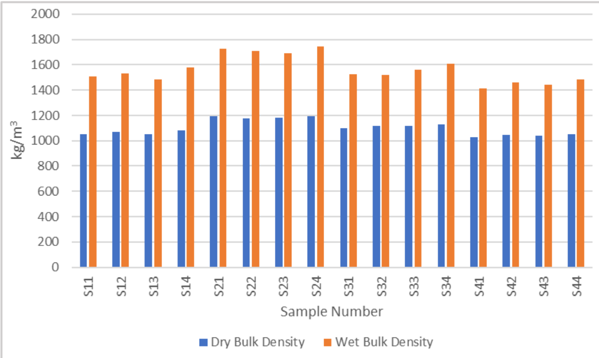

Figure 1: Dry and wet bulk density of substrate configurations

As expected, as the percentage of recycled crushed brick increased, the density of the substrate reduced. Majority of the load on a green roof result from the substrate. Moreover, during rainfall events the substrate can become saturated which can lead to an increase in the overall weight of the system. Most buildings are not designed to withstand heavy loads on the roof structure. Therefore, the WBD and DBD of a green roof substrate must be kept as low as possible (Vijayaraghavan, 2016; Xiao et al., 2014).

Additionally, the substrate used in a green roof should be sufficiently heavy to provide good anchorage for plants (Johnston & Newton, 2004). Lightweight substrates can be easily washed off or blown off. Therefore, according to the German Green Roof guidelines, the minimum permissible DBD of a green roof substrate is 600 kg/m^3. As shown in Figure 1, all substrate mixtures met this minimum performance requirement.

After conducting the WBD and DBD analysis, the samples were evaluated and ranked based on their suitability, as shown in Table 3. As previously mentioned, all substrate mixtures met the minimum DBD requirement. Therefore, in the ranking process, samples with lower wet and dry bulk densities were assigned higher ratings, given the importance of reducing the weight on the roof structure.

3.1.2 pH

The pH of the green roof substrate must be within the range that allows nutrient uptake by green roof plants (Beattie & Berghage, 2004; Friedrich, 2005). When tested for the pH, pH of all the substrate mixes were within the acceptable range given in Table 1.

3.1.3 Water Holding Capacity (WHC)

In extensive green roofs due to the shallowness of the substrate, and the extreme drought-like conditions that exist on a rooftop, especially in the tropical climate, the substrate tends to regularly dry out (Emilsson, 2006; Getter et al., 2009a; Vijayaraghavan, 2016). As the building acts as a barrier between the plant layer and the earth, there is no capillary rise of water from underground supplement the plant layer (Xiao et al., 2014). The WHC of the substrate enables the growth medium to store water thus enabling prolonged plant survival during periods of drought (Farrell et al., 2013; Graceson et al., 2014). Furthermore, the WHC of the substrate also affects the stormwater performance of the green roof system. Substrates with high WHC helps to retain water during rainfall events to delay the peak flow (Farrell et al., 2013; Vijayaraghavan, 2016). Therefore, according to the literature given in Table 1, the substrates used in a green roof must have a minimum WHC of 20%.

The WHC of the substrate mixtures are given in Figure 2a. All samples met the minimum requirement for WHC. As expected, the WHC of the samples increased with the increasing percentage of crushed bricks. This correlation can be attributed to the surface and internal pores present in crushed bricks which helps to retain water (Johnston & Newton, 2004; Vijayaraghavan & Raja, 2014).

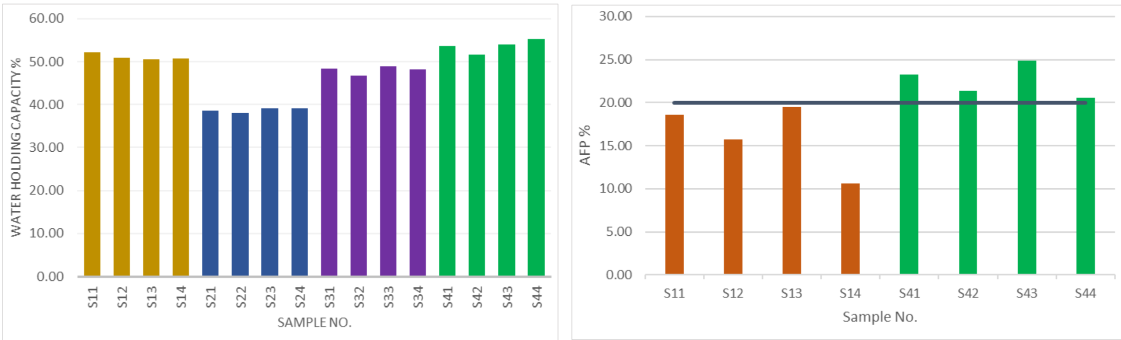

Figure 2: a) Water holding capacity b) Air filled porosity

A high WHC, within the guidelines given in Table 1, is recommended for green roof substrates used in the tropics (Vijayaraghavan, 2016). Therefore, when ranking the substrate mixtures by WHC, they were ranked in ascending order of their WHC as shown in Table 3.

3.1.4 Air Filled Porosity (AFP)

Oxygen diffusion through the substrate is an essential parameter for plant growth. Generally, in extensive green roofs, the shallowness of the substrate, limits the amount of oxygen diffused through the substrate. However, this can be addressed by incorporating coarse materials into the substrate mix. Coarse materials such a such as crushed recycled bricks, have surface and internal pores, which allow oxygen to be transported to the roots (Johnston & Newton, 2004). In addition to plant growth, a good AFP in the green roof substrate helps to minimises water logging and increases the ability of the substrate to act as an insulator (Saadatian et al., 2013). However, while a high AFP is always preferable, the AFP in the substrate should not exceed 20% (ASTM International, 2015; Chow et al., 2018; Xiao et al., 2014). This is because there is a significant correlation between the increase in AFP and a decrease in soil water content. Excessively high AFP can lead to water stress in the substrate, which can pose critical drawbacks, particularly in tropical countries like Sri Lanka. Therefore, maintaining an optimal balance in the substrate's AFP is essential.

Air-filled porosity was assessed only for Series 1 and Series 4 samples, as these substrate mixtures demonstrated the highest rankings following testing for wet and dry bulk density, pH, and WHC, as shown in Table 3.

The results of the AFP test are given in Figure 2b. As expected, the AFP increased as the fraction of crushed bricks increased. Series 4, which contained 40% crushed bricks, exhibited an AFP which exceeded the recommended 20%. As mentioned previously, a high AFP can negatively affect the water retention capabilities of the substrate. This holds particular significance in tropical climates, where consistent moisture availability in the substrate is crucial for plant growth. Therefore, the series 4 substrate mixtures, which had an AFP greater than the recommended 20% were thus rejected.

3.1.5 Ranking of the Substrate Mixtures based on Laboratory Testing

Following the analysis of wet and dry bulk density, WHC, and AFP, the 16 substrate mixtures were assessed and ranked based on their suitability, as given in Table 3.

Table 3: Ranking of substrate mixtures based on laboratory testing

Notation	DBD	WBD	WHC	AFP	Ranking
S11	13	11	13	15	52
S12	10	8	11	14	43
S13	11	13	9	16	49
S14	9	6	10	12	38
S21	2	2	2	N/A	6
S22	4	3	1	N/A	8
S23	3	4	4	N/A	11
S24	1	1	3	N/A	5
S31	8	9	7	N/A	24
S32	7	10	5	N/A	22
S33	6	7	8	N/A	21
S34	5	5	6	N/A	16
S41	16	16	14	0	46
S42	14	14	12	0	40
S43	15	15	15	0	45
S44	12	12	16	0	40

According to the ranking, the two substrate mixtures with the highest scores (S11 and S13) were chosen for further field investigations.

3.2 SELECTION OF A SUBSTRATE DEPTH FOR THE TROPICAL CLIMATE

3.2.1 Coverage

The percentage plant cover, measured weekly for 12 weeks, is given in Figure 3. As shown in Figure 3, deeper substrate depths showed a higher coverage in the initial weeks of the study. The deepest substrate depth, 7.5 cm, consistently showed the highest coverage throughout the study period. However, over time, the difference in coverage among different plot depths diminished, and by the end of the 12-week period, all plots achieved a coverage exceeding 50%.

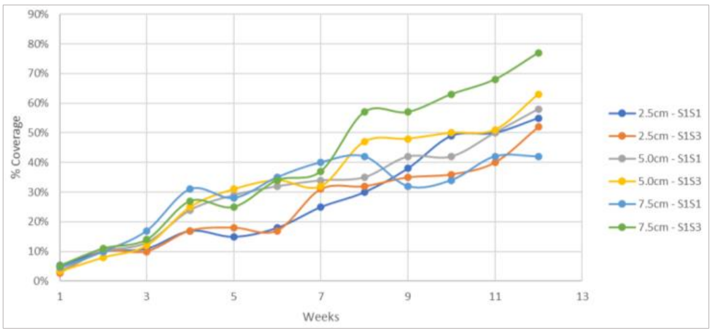

Figure 3: Percentage plant cover

It's worth mentioning that the *Alternanthera sessilis* planted in the 7.5 cm depth, specifically in the substrate S11, was affected by local pests towards the latter part of the study. Consequently, this led to a loss of coverage in that particular plot. However, aside from this isolated incident, there were no significant statistical differences observed in coverage between the S11 and S13 substrate mixes.

3.2.2 Survival Rate

Plant establishment was successful across all depths and in both substrate mixtures. All three substrate depths, 2.5 cm 5.0 cm and 7.5 cm, showed a 100% survival rate under both substrate mixtures, S11 and S13.

3.2.3 Weight of the System

Majority of the load on a green roof result from the substrate. Therefore, weight of the system is one of the key elements that must be considered when selecting a suitable substrate depth. The weight of the green roof system under each substrate type and substrate depth is given in Table 4.

Table 4: Weight of the system

Depth	Substrate	Weight of the System (kg/m^2)
2.5 cm	S1S1	28.26
2.5 cm	S1S3	28.19
5.0 cm	S1S1	56.51
5.0 cm	S1S3	56.37
7.5 cm	S1S1	84.77
7.5 cm	S1S3	84.56

According to the Department of Consensus and Statistics (2016), majority of the housing units in Sri Lanka (45.6%) are composed of Calicut tiled roofs. As such, existing roofing structures in Sri Lanka are typically designed to accommodate the average load of a Calicut tile, which is approximately 28kg/m^2.

The average weight of the system under a 2.5 cm substrate depth closely aligns with the weight of a Calicut tile. Therefore, a 2.5 cm depth can be supported on an existing roof with minimal/no modifications required. However, if the substrate depth is increased to 5.0 cm or 7.5 cm, the existing roof structure would need to undergo significant modifications to withstand the increased weight of the green roof system.

4. CONCLUSIONS

The substrate layer is one of the key components which affects the performance of the green roof system. The substrate used in a green roof must possess some unique properties. There is no universal green roof substrate and the most appropriate substrate mixture that suits the local climatic and geographical conditions must be selected based on local research (Ampim et al., 2010; FLL, 2008; Vijayaraghavan, 2016). This research aimed to identify the most suitable substrate mixture for an extensive green roof for the tropical climate of Sri Lanka. Sixteen (16) potential substrate mixtures were prepared using locally available materials including waste materials. The properties of these substrate mixtures were tested under laboratory and field conditions.

Based on the results obtained from laboratory testing it was observed that substrate mixtures that contained coir and crushed recycled bricks displayed the properties most suited for a substrate in the tropical climate. Hence, two substrate mixtures, S11 and S13, were selected for further field investigations.

In addition to the type of substrate, the depth of the substrate also affects the performance of the green roof system. The depth of the substrate must also be selected based on the local climate and geographical conditions. Within this study, three possible substrate depths (2.5cm, 5.0cm and 7.5cm) were investigated for their suitability for the tropical climate of Sri Lanka. Each substrate depth was prepared using the two selected substrate mixtures (S11 and S13) and field investigations were conducted.

The 2.5cm substrate depth showed successful plant establishment, with over 50% coverage and 100% survival rate, throughout the study period (12 weeks). Moreover, a green roof with a depth of 2.5cm can be readily supported on existing roof structures in Sri Lanka with minimal to no modifications required.

In field investigations, both substrate configurations (S11 and S13), displayed comparable performance for the same substrate depth. However, when considering the cost of the substrate, S11, which contains 5% coir and 5% rice husk proves to be more economical compared to S13, which contains 10% coir and 0% rice husk. This cost difference arises from the availability of rice husk as an agricultural waste, obtainable at no expense, while coir remains a relatively costly commodity.

Therefore, a 2.5cm substrate depth with 10% compost, 5% coir, 5% rice husk, 40% sand and 40% crushed recycled bricks can be recommended for the tropical climate of Sri Lanka.

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