Developing a low-cost thermally insulated ceiling sheet system using coir fibre

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Abstract

Recent research has shown that ceilings play a significant role in enhancing thermal comfort and indoor air quality within the built environment, particularly in tropical climates. However, this can result in excessive energy consumption as traditional methods struggle to maintain a comfortable temperature indoors. To address this issue, the objective of the research was to develop a cost-effective, thermally insulated ceiling sheet system that reduces the operational energy required for temperature control and ensures consistent temperatures within enclosed spaces. The researchers devised an insulation panel using readily available natural fibers, specifically coconut coir, which possesses excellent insulation properties. The proposed system was modeled and compared with two other scenarios: Calicut roofing without any insulation and Calicut roofing with Expanded Polystyrene Insulation (EPS). The results of the study demonstrated that the single-layer insulation system achieved a remarkable 65% reduction in temperature variation when compared to the traditional roofing system. These findings highlight the efficacy of the proposed low-cost, thermally insulated ceiling sheet system in improving indoor thermal comfort and reducing energy consumption for temperature regulation in tropical climates.

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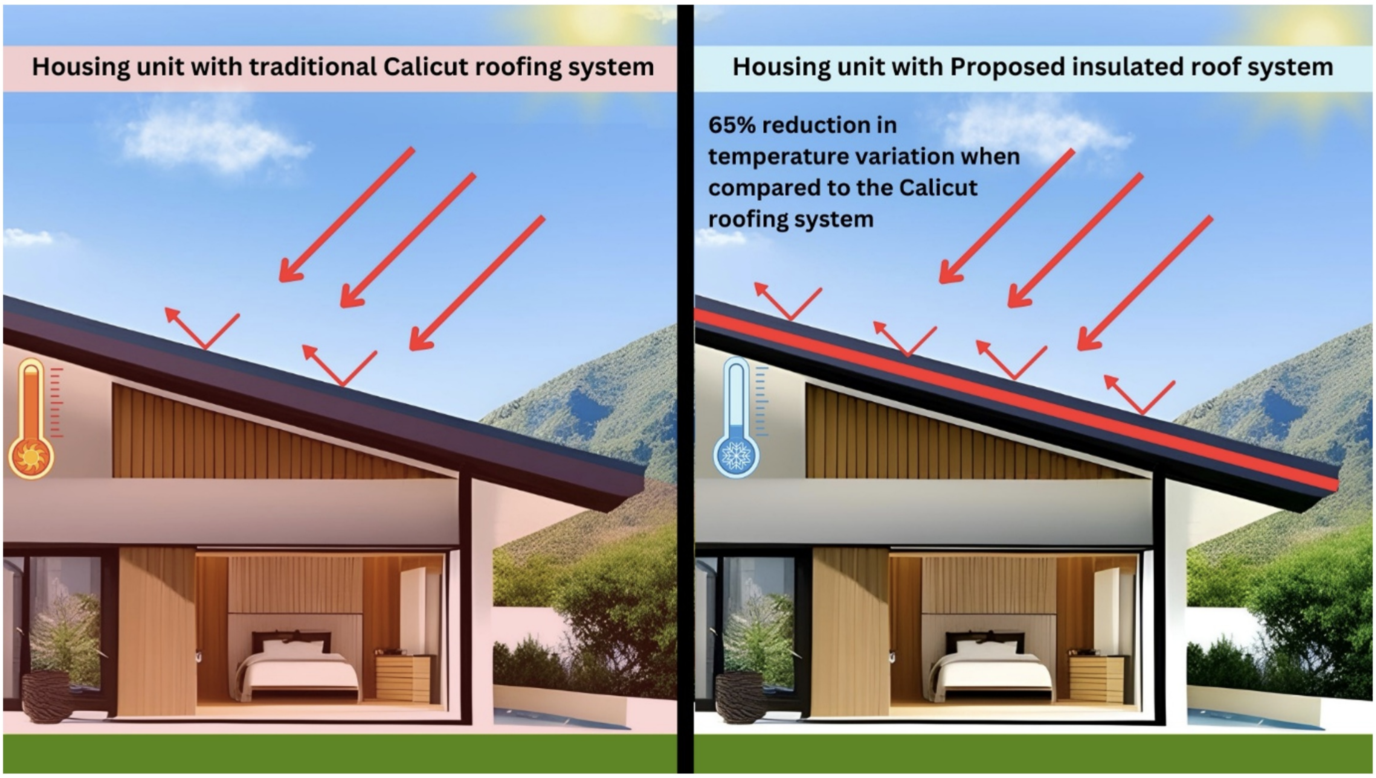
Graphical Abstract



1. Introduction

Countries like Sri Lanka endure tropical climates with greater humidity levels and lesser seasonal temperature variance because of their proximity to the equator. Most Asian countries with similar climatic conditions are rapidly developing countries that struggle with problems, including an energy crisis and a lack of suitable lands for building constructions [1],[2].Due to the damages imposed through this development, global warming is rising at an alarming rate and has emerged as one of the earth's key concerns [3]. The world seems to be on a path to experience even catastrophic consequences from global warming, including glacier melting and a rapid rise in sea level, abnormal precipitation, hurricanes and storms, floods, and droughts as the impacts of global warming persist even if scientists and researchers work to discover solutions [4],[5]. In the 1960s, the United States experienced an average of two heat waves per year, but in the 2010s, that number increased to more than six [6]. Since 1981, the warming rate has been estimated at 0.18°C per decade, making global average temperatures in 2021 1.04°C higher than in the pre-industrial era. Recent studies have shown that if required measures to address global warming are not taken, the earth's surface temperature will rise by 1.1-6.4 °C by the end of the twenty-first century [7]. The cost of energy consumption to cool buildings in tropical countries is increasing due to the development in living standards and deterioration of the thermal quality due to climate change and urbanisation. Various architectural and natural "passive techniques" such as insulation, shading and orientation are available to reduce energy consumption costs. Insulating the walls and roof of a building can significantly reduce the energy consumption of heating and cooling. Insulation thickness is inversely proportional to the building's energy needs. However, the thickness is directly proportional to the initial cost. Therefore, all these parameters must be considered to obtain a maximum economic benefit when using thermal insulation technology.

The climate and heat transfer coefficients of roofs and ceilings not only have a significant impact on the energy consumption and thermal comfort of cold buildings. It contributes significantly to the roof and heat island phenomenon, where the roofing system contributes approximately 70% of the total heat gain inside a building [8], [9]. The simple one-room, two-story houses are mostly built with pitched roof systems. Most pitched roofs are built without insulation, and attics can be ventilated or unventilated. However, unventilated attic floors are more likely to be built. Commercial buildings such as shops, office buildings, hotels, and apartments are built with air-conditioned flat concrete roof systems. Occupied dwellings and active buildings have a high demand for air-conditioning energy, so a suitable roof system should consider the issues of global warming and sustainable construction [10],[11]. Sustainable roofing technologies can contribute to reducing the energy consumption cost of buildings and the resulting implications for heating and cooling energy use [12]. Since the roofing system is the fundamental element of sheltering construction from changing weather conditions, it should have strength, wind resistance, water repellence, fire endurance, and insulation properties. Consequently, individuals are looking for passive cooling alternatives, including roofing and ceiling systems, to conquer the thermal discomfort due to global warming.

Recently, researchers are focused on finding an alternative thermal insulating material for buildings using different kinds of plant residue fibres. Natural materials, including wood, straw, sheep's wool, fibres – hemp, and cork, are the most used in traditional construction materials as thermal insulating materials [13],[14]. For example, coir fibre, cotton, bamboo, banana, palm, flax, pineapple, hemp, and sisal, identified as waste or low-cost materials, have been investigated for construction materials [15]. Coir fibres are abundant in many tropical countries such as Bangladesh, India, Indonesia, Malaysia, Sri Lanka, Thailand, Vietnam, etc. [16],[17]. In the agricultural sector, around 12% is counted for coconut (Cocos nucifera) cultivation and produces about 2500-3000 million coconut fruits per year, according to Sri Lankan Export Development Board records [18]. In 2014, it was stated that the production of coir fibre was around 150,400 tonnes in Sri Lanka [18], nearly 90% of the world's coir production. 33-35% of the coconut fruit consists of the husk, the remaining 30% as fibres and 70% as the pith. This coir fibre content is a crucial by-product of coconut processing, as a significant amount of coir fibre is discarded while consuming coconut nuts. Therefore, coir fibres in bulk amounts are being produced as waste at both domestic and industrial levels in Sri Lanka. Thus, coir fibres could be considered a highly suitable material to investigate the suitability of these fibres for roofing element manufacturing and their usefulness for heat insulation as it can be easily found out of all the significant Agro-plant residues in Sri Lanka [19], [20]. Thus, this study is focused on developing a low-cost thermally insulated ceiling sheet system using coir fibre for building construction as a passive cooling alternative.

2. Materials and Methods

The most important aspect of an insulation system lies within its insulation material. Insulation materials have more significant potential for reducing carbon emissions when compared with other building components. Therefore, selecting an insulation material with better performance is essential. Although there are many insulation materials, natural insulation materials such as straws, wool, and hemp were found to be the ideal products for sustainable construction practices. For tropical countries, coconut coir fibre was found to be the perfect natural insulation material due to its availability. Hence, the study considered coconut coir fibre for the proposed system (Fig.1).

The proposed insulation system mainly consists of a 2.59mm aluminium sheet and coconut coir fibre layer. Initially, adhesive was applied on top of the aluminium sheet, and sieved coconut coir fibre (passing through a 2.36mm sieve) was distributed evenly on the sheet and pressed the components together. In contrast, the adhesive is still wet (heat-resistant adhesive was used as an intermediate layer to bond both materials). 1mm (dia.) wire mesh and framework were used to strengthen the insulation panel furthermore (Fig.2).

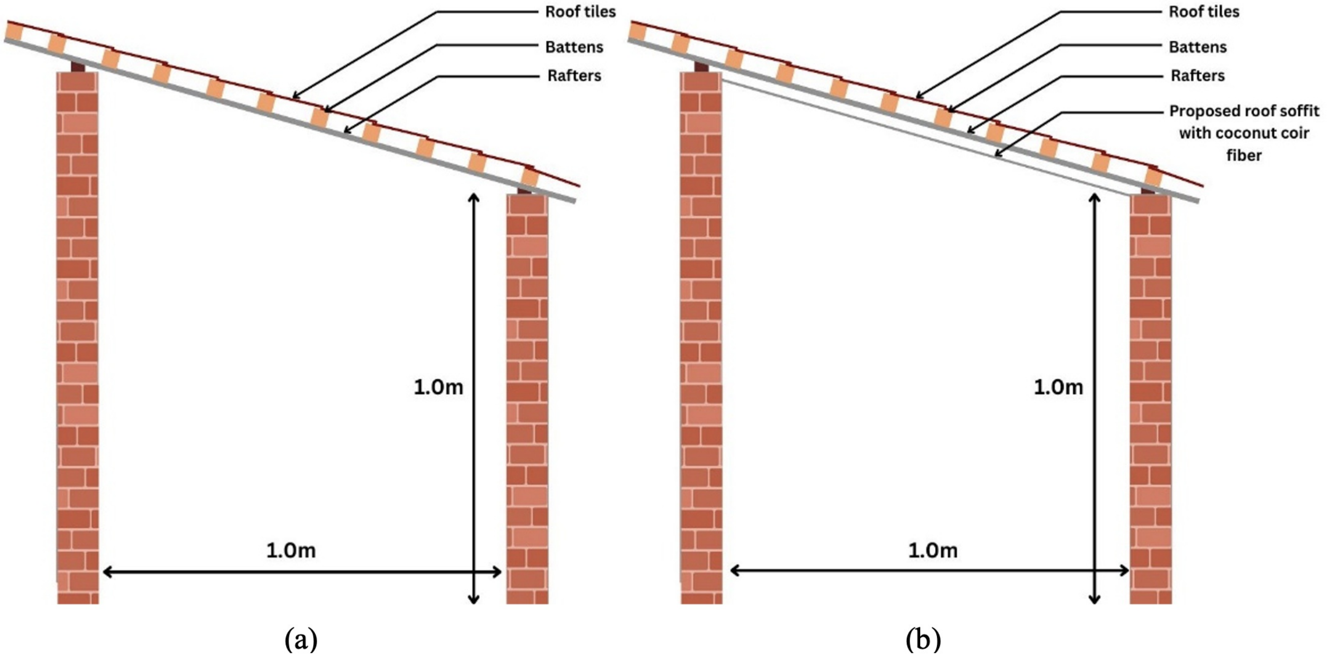


Fig. 1. Schematic view of the traditional Calicut roof tile system (a) with proposed system (b)

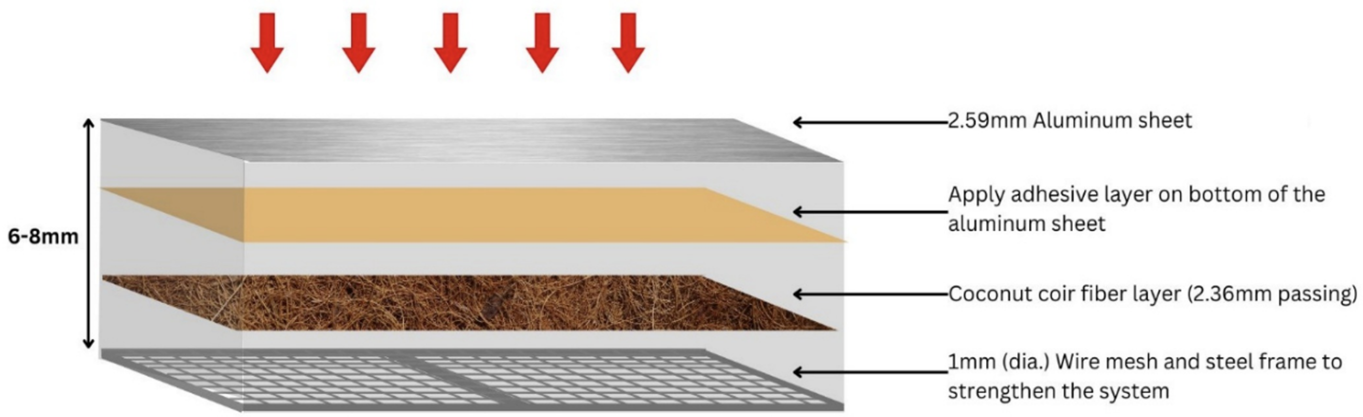


Fig. 2. The main components of the proposed insulation system, designed to address heat transfer from the top surface.

2.1. Simulation

Table 1 Performance variations for three different roofing systems

Roofing system	Decrement factor	Time lag
Calicut roofing without insulation	0.988373640	0 hours
Calicut roofing with EPS insulation	0.337434776	2 hours
Calicut roofing with single coir fibre insulation	0.635432665	1 hour

The proposed system was modelled using DesignBuilder software. Performance variations for three different roofing systems (i., Calicut roofing without any insulation, ii. Calicut roofing with Expanded Polystyrene Insulation (EPS) and iii. Calicut roofing with proposed insulation) were evaluated (Table 1).

2.2. Construction

Two identical 1.0m x 1.0m x 1.0m physical models were constructed with Calicut roofing systems (one model as the controller to mimic the actual scenario and the other model to test the proposed systems' thermal performance). Insulation panels were installed at the roof soffit level, facing the aluminium sheet to the exterior surface (the reflective surface is outward).

Fig. 3. Installing steps of the insulation system (a) fixed to the framework (b) placing the insulation to the roof, reflective side is facing outward (c) final models, controlled physical model and the insulated physical model.

3. Results and Discussion

GL820 Midi Data Logger was used to get uninterrupted thermal readings for seven consecutive days in March 2022. Average hourly thermal readings for 24 hours were then obtained with minimum deviations. It was identified that the traditional Calicut tile roofing system and thermal reading for the rooftop level and the roof soffit level are similar. The peak rooftop temperature was determined as 48.62^{0}C. However, there was a significant temperature difference between the roof soffit (peak roof soffit temperature of 47.90^{0}C) and the ambient room temperature (peak temperature of 32.15^{0}C) (Fig.

4).

The insulated roofing system consists of a single coir fibre layer that shows significant temperature loss between the rooftop and the soffit level, which is nearly the ambient room temperature (32.55⁰C and 32.15⁰C, respectively) (Fig. 5).

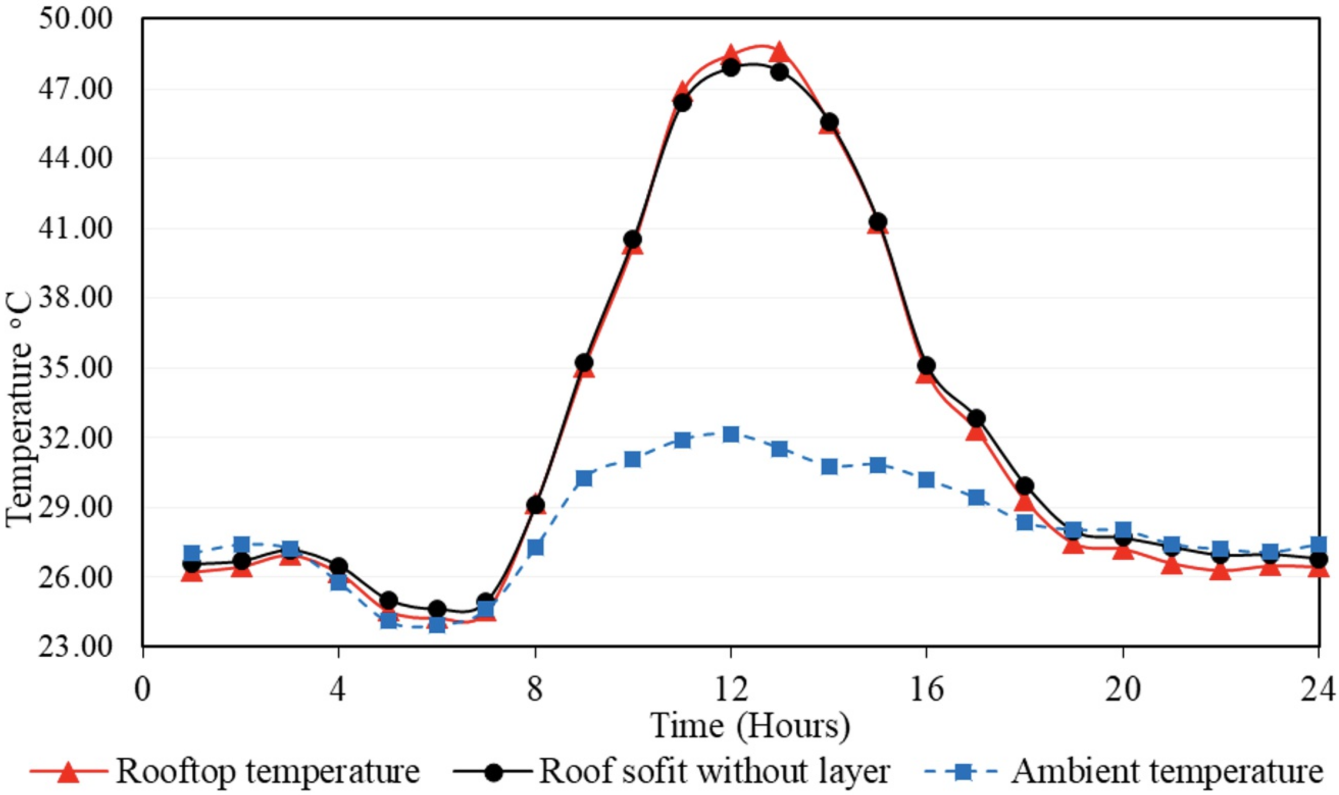


Fig. 4. Temperature variation of traditional Calicut roofing system

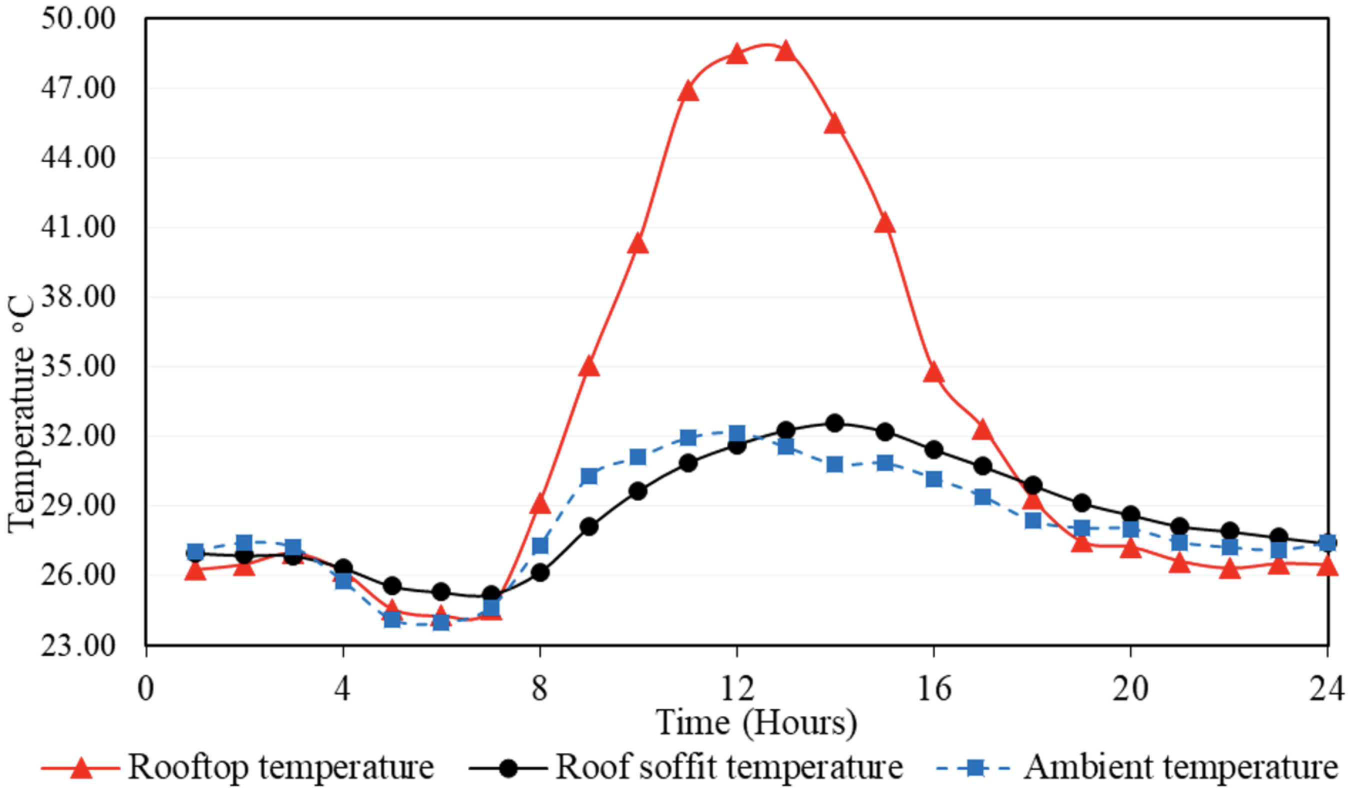


Fig. 5. Temperature variation on proposed new system (single layer) for Calicut tile roof

4. Conclusions

In conclusion, the preliminary study of the low-cost insulation system utilizing coconut coir fibre has demonstrated significant temperature reduction in the roof soffit of dwelling units in tropical countries. The use of locally available and cost-effective insulation materials, such as coconut coir fibre, holds promise for developing an affordable insulation solution. The findings of this study indicate that a single coir fibre insulation panel can achieve a remarkable 65% reduction in temperature. However, further investigations are necessary to explore the potential benefits of employing multiple insulation panels and determining the optimal void gap between them. Such studies will enable the development of a cost-efficient system that combines effective energy reduction with affordability. It is important to note that this study focused specifically on the Calicut roofing system, considering the climate conditions of a tropical country. Future research should expand the scope to encompass various roofing systems and different climate conditions, to assess the adaptability and performance of the proposed insulation system.

Furthermore, there is potential for the application of this method in vertical systems, such as wall panels and wall insulation. Exploring these possibilities will contribute to the broader implementation of the low-cost insulation system across different areas of a building, further enhancing energy efficiency and thermal comfort. In summary, the preliminary study highlights the potential of the low-cost insulation system utilizing coconut coir fibre. Continued research and development in this field will enable the creation of cost-effective and sustainable insulation solutions for tropical regions, benefiting both the environment and inhabitants of dwelling units.

Statements & Declarations

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Author Contribution

All authors contributed to the study conception and design. Rohantha Rukshan Jayasinghe and Anura Ruwansiri De Silva performed material preparation, constructed the models, and conducted data collection and analysis. The first draft of the manuscript and simulation work were conducted by Rohantha Rukshan Jayasinghe and Krishani Rukmali Jayasingha. Wasudha Prabodhani Abeyrathna and Rangika Umesh Halwatura provided comments on previous versions of the manuscript and assisted in its refinement. All authors have read and approved the final manuscript.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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