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Rice husk and thermal comfort: Design and evaluation of indoor modular green walls

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ABSTRACT

Green walls are vertical greening structures where varied plant species grow. They are conceived as a form of urban landscape and have numerous environmental, social and economic benefits. In fact, these structures have positive effects on air quality, thermal and acoustic insulation, microclimate, psychophysical well-being and urban design. In the framework of thermal comfort, several studies demonstrated the potential of green walls to improve indoor thermal comfort and reduce heat flows through the wall of buildings.

This research evaluates the thermal efficiency of two modular green walls that present an alternative substrate as growing medium. This substrate is composed of loam soil and rice husk, an agricultural organic waste derived from the rice milling process. The choice of rice husk is inspired by principles of circular economy in order to reduce the environmental impact and costs of the substrate used in greening applications. The alternative substrate was compared with expanded clay aggregate, used for plant cultivation in living walls, and the analysis was divided into two phases. Firstly, field experiments were carried out on three plant species (*Chlorophytum*, *Dieffenbachia* and *Spathiphyllum*) to evaluate the efficacy of these substrates to grow plants. The efficacy of the substrate was evaluated through the measurement of the concentration of chlorophyll, the determination of the growth index of plants and a qualitative observation of the root development. Secondly, two modular green walls with varied substrates and plants were designed and tested from the point of view of the thermal comfort, using the open source software TerMus-G. After the transmittance value was obtained as output for each green wall module, the heat flow and the relative variation were calculated and compared to the indoor supporting walls.

This article presents a valid methodology approach to evaluate the efficiency of green walls substrate and its thermal performance. This methodology differs from those found in scientific literature and represents a valid alternative.

The present research demonstrates the ability of designed modules and, more generally, of indoor green walls to increase thermal insulation without causing condensation. Furthermore, the investigation shows a positive contribution both in winter and in summer. Finally, the use of this undervalue by-product rice husk mixed with loam soil shows to be appropriate for green wall application, providing better performance than the expanded clay in terms of thermal comfort and plant growth rate. Moreover, its use as substrates should further improve the ecological footprint of green vertical structures and reduce costs.

1. Introduction

Green walls are vertical systems on which a selection of plant species are grown and they can be generally divided into green façades and living walls (Manso and Castro-Gomes, 2015). Green façades are usually built with limited selection of climbing plants growing directly against the wall or indirectly on a support system (Vox et al., 2018). Instead, living walls are generally more complex and present a supporting structure on which the growing medium is placed (Gunawardena and Steemers, 2019a, 2019b). These structures are divided into modular or continuous and allow a more uniform vegetation growth (Perini et al., 2013), but may require frequent irrigation and supply of nutrients.

In recent years, green spaces have decreased in urbanized areas due to the excessive exploitation of the land and the exponential increase of concrete structures (Liberalesso et al., 2020). However, this trend is currently reversing due to the implementation of sustainable development policies (Liberalesso et al., 2020). In this context, green walls are assuming a dominant role in the design, construction and recovery of

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buildings or districts, contributing to the sustainability of urban and suburban areas (Francis and Lorimer, 2011; Liberalesso et al., 2020).

Conceived as a form of urban landscape, green walls improve its aesthetic value. They also provided multiple associated environmental, social and economic benefits (Manso et al., 2021). Some of these benefits are improving air quality (Pettit et al., 2019), increasing urban biodiversity (Madre et al., 2015), absorbing noise (Gunawardena and Steemers, 2019a), influencing the urban microclimate (Xing et al., 2019), improving psychological well-being and social relationship (McCullough et al., 2018).

In the framework of thermal comfort, several studies demonstrated the potential of green walls to improve building energy efficiency (Manso et al., 2021; Mazzeo and Kontoleon, 2020). Green walls and, in particular, plant coverage improve indoor thermal comfort in summer and winter, and reduce heat flows through the wall of buildings (Yoshimi and Altan, 2011). This reduction corresponds to a lower annual energy consumption for heating and cooling (Yoshimi and Altan, 2011). This effect depends on a number of factors such as the climatic zone and season (Pérez et al., 2014), the orientation of the wall (Mazzeo and Kontoleon, 2020), the type of substrate (Hunter et al., 2014), the plant species used (Libessart and Kenai, 2018) and the percentage of wall covered by plant materials (Widiastuti et al., 2020).

This study evaluates the thermal efficiency of two modular green walls that present an alternative substrate as growing medium. Rice husk, an agricultural organic waste derived from the rice milling process, was selected to be tested as alternative cultivation substrate. The choice of this material is inspired by principles of circular economy in order to reduce the environmental impact and costs of the substrate used in greening applications. Rice husk can be reused in numerous fields due to its multifaceted characteristics (Bodie et al., 2019). In the context of green walls, this agricultural organic waste has already shown to be appropriate for growing plants if associated with coconut fibre (Rivas-Sánchez et al., 2019; Rivas Sánchez et al., 2018) or perlite, river sand and peat (Dede et al., 2019).

Section 2 illustrates the different stages and tools adopted in the research, while Section 3 describes the results obtained testing rice husk as an alternative substrate from the point of view of plant health and thermal efficiency. Finally, a Conclusions Section underlines the advantages of green walls using rice husk and suggests some future research perspectives.

2. Materials and methods

In the present project rice husk was tested in a mixture with loam soil (1/3 rice husk and 2/3 loam soil). The husk-soil ratio refers to results obtained by Zanninelli (2015). The rice husk/loam soil substrate was compared with expanded clay aggregate, used for plant cultivation in living walls (Pérez-Urrestarazu et al., 2019), and the analysis was structured into two main stages. Firstly, field experiments were carried out on three plant species (*Chlorophytum*, *Dieffenbachia* and *Spathiphyllum*) to evaluate the efficacy of these substrates to grow plants. Substrate efficacy was evaluated through the measurement of the concentration of chlorophyll, the determination of the growth index and a qualitative observation of the root development. Secondly, two modular green walls with varied substrates and plants were designed and tested from the point of view of the thermal comfort, calculating the transmittance through the open source software TerMus-G. After the transmittance value was obtained as output for each green wall module, the heat flow and the relative variation were calculated with respect to the indoor supporting walls considered.

The two modular green walls were designed without plastic materials widely used in vertical greening application (Manso and Castro-Gomes, 2015), because these materials gradually release microplastics in cultivation substrates affecting negatively plants health and growth (De Souza Machado et al., 2019).

2.1. Substrates and health status of plant species

Performances of expanded clay aggregate and rice husk mixed with loam soil were compared following these considerations. *Chlorophytum*, *Dieffenbachia* and *Spathiphyllum* were cultivated in both substrates and into two types of vase, rectangular and round, to simulate different structures and consequently evaluate the response of the three plant species to different rooting conditions. Plants were watered at varying intervals according to the substrate humidity and to the environmental conditions, with a quantity of water equal to 22.5 cl at each time. Moreover, liquid fertilizer was applied to plants cultivated in the expanded clay substrate through fertigation, due to the lack of nutrients. Specifically, the fertigation was carried out adding 20 g of liquid fertilizer for green plants in two litres of water.

Starting from the transplant day, the plants response was tested for a period of 134 days (89 for the *Spathiphyllum)*, measuring the chlorophyll concentration and the leaf length twice a week. The *Spathiphyllum* was inserted 45 days later following the negative response of *Dieffenbachia*.

The chlorophyll concentration and the leaf length were also performed on the reference samples represented by three plants, one per each species, cultivated in the plant nursery substrate. The chlorophyll measurement was performed through a non-destructive method using the Apogee Mc-100 (Apogee Instruments Inc, 2019.) optical manual meter. The optical techniques provide a relative indication of leaf chlorophyll concentration, measuring the ratio of radiation transmittance from two wavelengths of radiation through plant leaves (Parry et al., 2014). The Apogee Mc-100 meter is normally used in agriculture to estimate the plant health by determining the concentration in μmol of chlorophyll per square meter of leaf (https://www.apogeeinstruments.com). In particular, its concentration can give an evaluation of the stress condition of plant species due to the lack of nutrients, insufficient water supply and adverse climatic conditions (https://www.apogeeinstruments.com).

The leaf length was used to quantify plants growth rate through the determination of the growth index. The growth index (GI) was calculated by comparing the difference between the first (S_{i-1}) and last (S_i) measurements with the time elapsed between them (T), through the following formula.

$$GI = \frac{S_i - S_{i-1}}{T}$$

Length measurements were always taken on the same three leaf replicates per each plant using the same procedure in order to not affect the growth index.

Finally, at the end of the field experiments, the response of the three plant species to different rooting conditions was estimated, removing the plants from pots and carrying out a qualitative and comparative evaluation. A number of parameters, such as length, volume, density and distribution, were considered during the observation of the root system.

2.2. Thermal efficiency

Green walls thermal efficiency is influenced by four main mechanisms: the interception of solar radiation by the vegetation (shadow effect), the thermal insulation provided by vegetation and substrate, the evaporative cooling due to the evapotranspiration process and the protection from wind action (Cascone et al., 2018). However, the shadow effect and the evaporative cooling could be assumed to be minimal in the calculation of the thermal performance of an indoor green wall (Gunawardena and Steemers, 2019b). While regards the wind action in indoor environment, Gunawardena and Steemers (2020) highlights a dominant daytime downward flow generated by the vegetation surface that encourages the formation of a microscale centripetal thermal system. This flow were not considered in the present study, although it may partly affects the heat flow given its capacity to present thermal sensation and

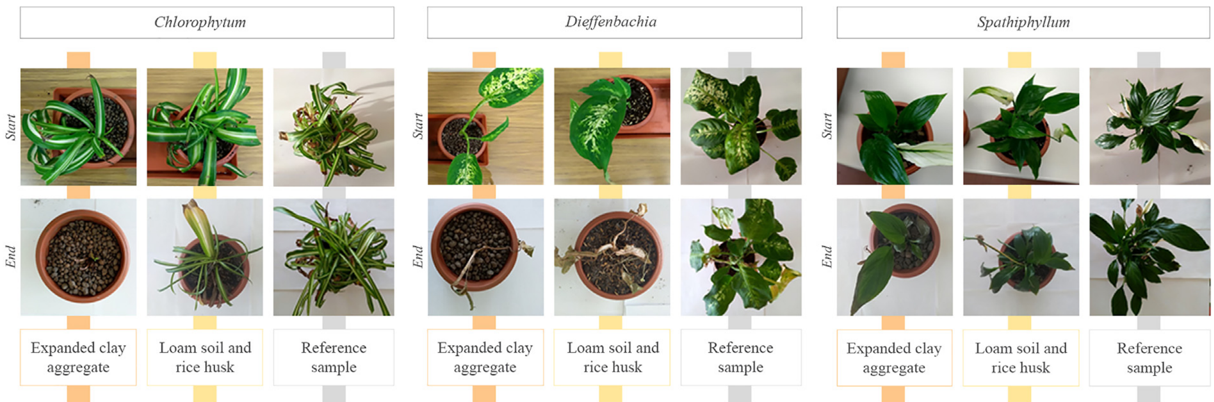

Fig. 1. Chlorophytum, Dieffenbachia and Spathiphyllum (round vase) at the beginning and at the end of the experiment for the two evaluated substrates and for the reference sample.

diversity to occupants (Gunawardena and Steemers, 2020). Therefore, in order to calculate the heat exchange of the two designed modular green walls, the only contribution of thermal insulation was considered. The calculation was performed through the opensource TerMus-G software[1] provided by the Acca software. This software allows to calculate the thermal transmittance of a multilayer wall and check the interstitial condensation using the Glaser diagram. The calculation was carried out considering the housing of the two modules on the perimeter wall and on the internal partition, in winter and summer conditions. The two modules and supporting walls present the following stratigraphy:

- Module 1: (i) external structure in aluminium (thickness 1 mm) of 50x50x15cm, (ii) culture substrate, (iii) natural felt (thickness 3 mm), (iv) aluminium lid 50x50x0.1cm with 4 holes of Ø10 cm and (v) plant species.
- Module 2: (i) external wooden structure of 50x15x20cm (wood thickness 10 mm), (ii) bituminous waterproof layer (thickness 1 mm), (iii) culture substrate, (iv) natural felt (thickness 3 mm) and (v) plant species.
- Perimeter wall: (i) external plaster (thickness 1 mm), (ii) hollow bricks (thickness 120 mm), (iii) air, (iv) fiberglass insulation panel (thickness 6 mm), (v) hollow bricks (thickness 250 mm) and (vi) gypsum plaster (thickness 1 mm).
- Internal partition: (i) internal plaster (thickness 2 mm), (ii) hollow bricks (thickness 120 mm) and (iii) internal plaster (thickness 2 mm).

At first the stratigraphy of the two modules was reconstructed on the TerMus-G software, defining the characteristics of the materials, such as dimensions, thermal conductivity and water vapor diffusion resistance factor. The three plant species and the alternative substrate were not present in the database of the software and they were defined analytically or through literature review. As for the plant species, their thickness was assessed on the basis of the reachable height, the thermal conductivity value was assumed to be 0.15 W/mK as expressed by Yi et al. (2019) and the water vapor diffusion resistance factor was set equal to 1 since air is the material that controls the plant layer (Lambers and Oliveira, 2019). As for the alternative substrate, the thermal conductivity (λ) was assumed equal to 0.042, considering the individual conductivity values ($\lambda_{loam\ soil} = 0.028$, $\lambda_{rice\ husk} = 0.07$) and the ratio of loam soil (2/3) and rice husk (1/3), while the water vapor diffusion resistance factor was provided by the software.

Subsequently, the software TerMus-G returned as outputs the transmittance values of the two modular green walls in the different conditions, i.e. supporting walls, periods, substrates and plant species). These transmittance values were used to calculate the amount of heat that crosses the wall per unit of time and surface. Finally, the heat variation was calculated with respect to the supporting wall.

3. Results and discussions

3.1. Substrates and health status of plant species

Plants health status and consequently the efficacy of investigated substrates as growing media were assessed using the chlorophyll concentration, the leaf length measurements and a qualitative observation of the root development. Fig. 1 shows the three plant species, cultivated in the round vase, at the beginning and at the end of the experiment.

The chlorophyll concentration and the leaf length values were graphed over time and related to the irrigation or fertigation carried out during the sampling period. Trends were evaluated considering first individual plants, then the comparison of the three plant species according to the growing medium and finally the comparison of growing medium for individual plant species. Trends of chlorophyll concentration for the three plant species, according to the two selected substrates and to the reference sample, were reported in Fig. 2.

While, Table 1 shows the Grow Index of the three plants species for the two substrates analysed and the reference sample.

At the end of the field experiments, 8 out of 15 plants survived and specifically, one *Spathiphyllum* in the expanded clay aggregate, two *Spathiphyllum* and two *Chlorophytum* in the rice husk/loam soil substrate, and the three plants in the reference sample. Based on survival rate, photographs, trends and values obtained, it is possible to draw up the following considerations on the two substrates (expanded clay and rice husk mixed with loam soil) and on the three plants species analysed (*Chlorophytum*, *Dieffenbachia* and *Spathiphyllum*). Firstly, all three plant species were demonstrated to be dependent by irrigation or fertigation, regardless of the substrate. Chlorophyll content is mostly influenced by water provision in *Chlorophytum* and *Dieffenbachia*. Secondly, *Dieffenbachia* (i) presents the most variable chlorophyll concentration trend throughout the sampling period and it (ii) is no longer present at the end of the measurement period (plants grown in both substrates are dead). Thirdly, *Chlorophytum* presents higher growth rate than other two plant species in the two selected substrates and in the reference sample. Fourthly, all plants cultivated in the alternative substrate present higher survival rate (66.6%) than those grown in expanded clay substrate (16.6%). Lastly, a similar roots development was noticeable for plants cultivated in the same substrate but placed in square or round vases. However, observing the roots of the remaining plants, it is possible to see

[1] https://www.acca.it/.

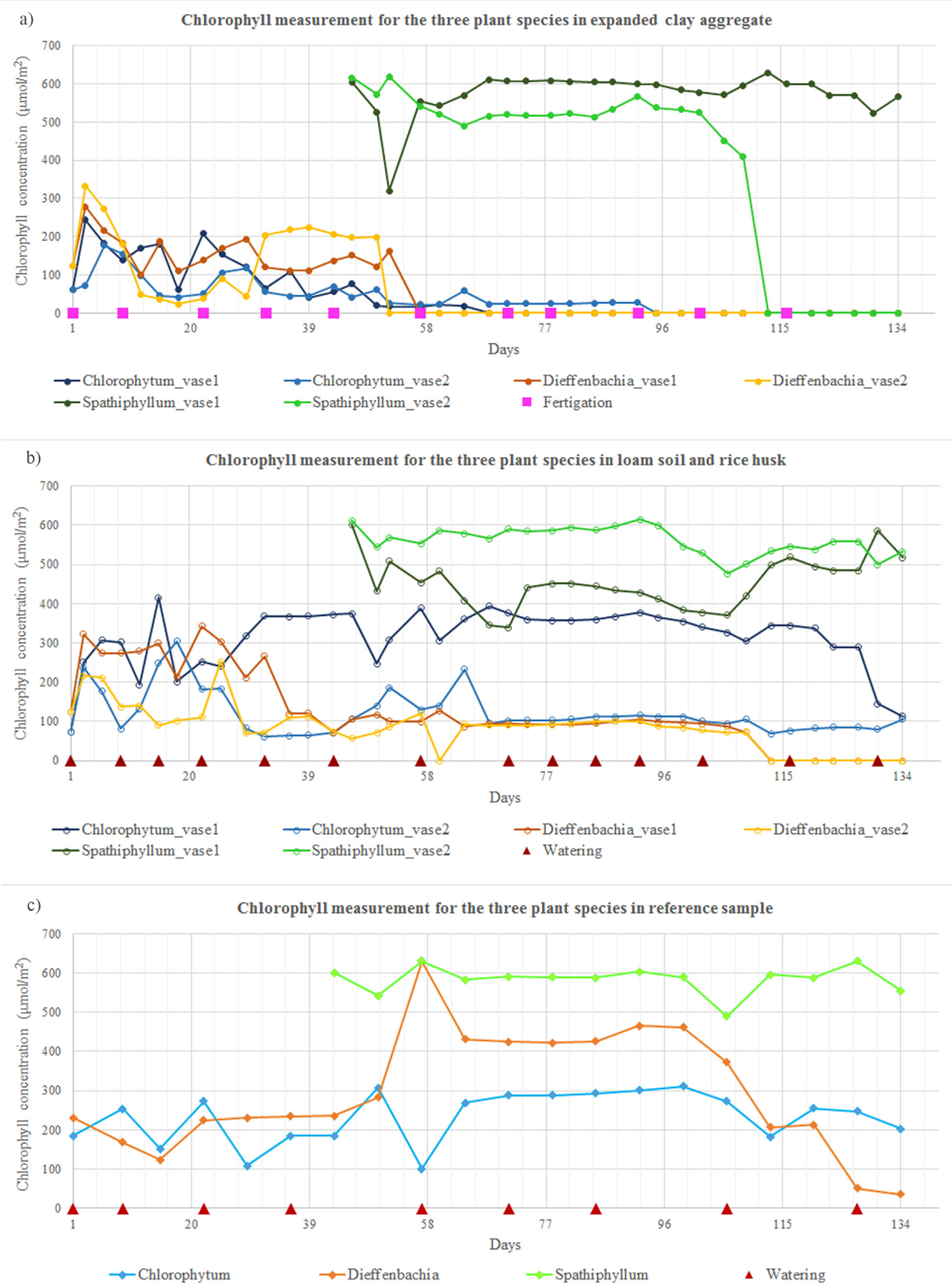

Fig. 2. Chlorophyll measurement of the three plant species in the expanded clay aggregate (a), in the rice husk mixed with loam soil (b) and in the reference sample (c).

Table 1
Grow Index of the three plants species for the two substrates evaluated and the reference sample. If the plant died before the end of the experiment, the partial GI was calculated.

Substrate	Species	Vase	Sample times (gg)	Grow Index		Result
				(cm/d)	(%)	
Expanded clay aggregate	*Chlorophytum*	1	29 out of 134	0.155 GI partial	15.5 GI partial	Dead
		2	43 out of 134	0.079 GI partial	7.9 GI partial	Dead
	Dieffenbachia	1	15 out of 134	−0.011 GI partial	−1.1 GI partial	Dead
		2	18 out of 134	−0.012 GI partial	−12.2 GI partial	Dead
	Spathiphyllum	1	89 out of 89	0.013	1.3	Live
		2	61 out of 89	0.005 GI partial	0.5 GI partial	Dead
Loam soil and rice husk	*Chlorophytum*	1	134 out of 134	0.072	7.2	Live
		2	134 out of 134	0.041	4.1	Live
	Dieffenbachia	1	113 out of 134	−0.011 GI partial	−1.1 GI partial	Dead
		2	106 out of 134	−0.001 GI partial	−0.1 GI partial	Dead
	Spathiphyllum	1	89 out of 89	0.008	0.8	Live
		2	89 out of 89	0.010	1	Live
Reference sample	*Chlorophytum*	–	134 out of 134	0.034	3.4	Live
	Dieffenbachia	–	135 out of 134	0.011	1.1	Live
	Spathiphyllum	–	136 out of 134	0.016	1.6	Live

Table 2
Transmittance values obtained with TerMus-G, the heat flow and variation calculated with respect to the host wall (Perimeter wall and internal partition).

Period	Supporting wall	Module	Substrate	Plant species	T1 (°C)	T2 (°C)	Thickness (mm)	Transmittance (W/m^{2}K)	Heat flow (W/m^2)	Variation (%)
Wintertime	Perimeter wall	–	–	–	20	−8	490	0.299	8.372	–
	Perimeter wall	Module 1	Expanded clay aggregate	*Dieffenbachia*	20	−8	930	0.156	4.368	−47.82
				Spathiphyllum	20	−8	880	0.164	4.592	−45.15
				Chlorophytum	20	−8	830	0.174	4.872	−41.81
			Loam soil and rice husk	*Dieffenbachia*	20	−8	930	0.130	3.640	−56.52
				Spathiphyllum	20	−8	880	0.136	3.808	−54.52
				Chlorophytum	20	−8	830	0.142	3.976	−52.51
		Module 2	Expanded clay aggregate	*Dieffenbachia*	20	−8	994	0.144	4.032	−51.84
				Spathiphyllum	20	−8	944	0.151	4.228	−49.50
				Chlorophytum	20	−8	894	0.159	4.452	−46.82
			Loam soil and rice husk	*Dieffenbachia*	20	−8	994	0.114	3.192	−61.87
				Spathiphyllum	20	−8	944	0.119	3.332	−60.20
				Chlorophytum	20	−8	894	0.124	3.472	−58.53
Summertime	Perimeter wall	–	–	–	20	24	490	0.299	−1.196	–
	Perimeter wall	Module 1	Expanded clay aggregate	*Dieffenbachia*	20	24	930	0.156	−0.624	−47.83
				Spathiphyllum	20	24	880	0.164	−0.656	−45.15
				Chlorophytum	20	24	830	0.174	−0.696	−41.81
			Loam soil and rice husk	*Dieffenbachia*	20	24	930	0.13	−0.520	−56.52
				Spathiphyllum	20	24	880	0.136	−0.544	−54.52
				Chlorophytum	20	24	830	0.142	−0.568	−52.51
		Module 2	Expanded clay aggregate	*Dieffenbachia*	20	24	994	0.144	−0.576	−51.84
				Spathiphyllum	20	24	944	0.151	−0.604	−49.498
				Chlorophytum	20	24	894	0.159	−0.636	−46.82
			Loam soil and rice husk	*Dieffenbachia*	20	24	994	0.114	−0.456	−61.87
				Spathiphyllum	20	24	944	0.119	−0.476	−60.20
				Chlorophytum	20	24	894	0.124	−0.496	−58.53
–	Internal partition	–	–	–	20	12	160	1.981	15.848	–
	Internal partition	Module 1	Expanded clay aggregate	*Dieffenbachia*	20	12	600	0.280	2.240	−85.87
				Spathiphyllum	20	12	550	0.308	2.464	−84.45
				Chlorophytum	20	12	500	0.344	2.752	−82.64
			Loam soil and rice husk	*Dieffenbachia*	20	12	600	0.205	1.640	−89.65
				Spathiphyllum	20	12	550	0.220	1.760	−88.89
				Chlorophytum	20	12	500	0.238	1.904	−87.99
		Module 2	Expanded clay aggregate	*Dieffenbachia*	20	12	664	0.242	1.936	−87.78
				Spathiphyllum	20	12	614	0.264	2.112	−86.67
				Chlorophytum	20	12	564	0.289	2.312	−85.41
			Loam soil and rice husk	*Dieffenbachia*	20	12	664	0.169	1.352	−91.47
				Spathiphyllum	20	12	614	0.179	1.432	−90.96
				Chlorophytum	20	12	564	0.191	1.528	−90.36

that the *Spathiphyllum* presents less root development in the expanded clay rather than in the alternative substrate. Moreover, the alternative husk rice/loam soil substrate presents the critical issue of rice grains and fragment germination during the test period, with and without plant cultivation. However, rice plantlets die after about two weeks from germination due to the lack of water provision.

3.2. Thermal efficiency

The TerMus-G software allows to assess the thermal efficiency of indoor walls and to evaluate interstitial condensation, highlighting the riskiest months.

Values of transmittance, heat flow and its variation with respect to the supporting wall are showed in Table 2. This data referred to the winter and summer period.

Results demonstrate the ability of the designed modules and, more generally, of the indoor green walls to increase thermal insulation in winter and in summer periods without causing condensation. In particular, it should be noted that:

- the application of a green module on the internal partition or on the perimeter wall leads to a reduction in the heat flow per unit of time and surface, in winter and summer period. The heat variation ranges from −41.8% to −61.87% with respect to the perimeter wall and it ranges from −82.64% to −91,47% with respect to the internal partition.
- the wooden module (module 2) obtained the best values in terms of the quantity of heat exchanged, both for different supporting walls and periods. In particular, the maximum reduction in the amount of heat per unit of time occurs with the application of the alternative substrate.
- the alternative substrate guarantees a lower heat dispersion than commercial substrate consisting of expanded clay aggregate. In the case of internal partition, the maximum variation obtained for rice husk/loam soil substrate is −91.47% (wooden module) compared with −87,78% for the expanded clay aggregate, while in the case of perimeter wall it is −61.78% (wooden module) compared with −51,84% for the expanded clay. This result is closely due to the different conductivity values of the two substrates (0.04 W/mK for the rice husk/loam soil and 0.08 W/mK for the expanded clay aggregate).
- the amount of heat obtained for the three plants species is similar. However, the *Dieffenbachia* guarantees greater thermal efficiency than the other two plant species because it occupies a greater layer than the other two. This plant reaches a greater height.

4. Conclusions

This paper illustrated the potential of rice husk as growing medium in modular green walls. This agricultural organic waste derived from the rice milling process. It resulted suitable for the growth of plants and showed a better performance than expanded clay aggregate. The results of this investigations show that plants cultivated in the rice husk/loam soil substrate present higher survival rate and better root development than those grown in expanded clay substrate. However, this alternative substrate may not be suitable for the growth of all species of plants, as shown by the poor response of *Dieffenbachia*. In terms of thermal efficiency, the findings of this investigation confirm those of earlier studies that demonstrate the potential of green walls to improve the thermal performance of buildings (Manso et al., 2021; Mazzeo and Kontoleon, 2020). Moreover, the dependence of this effect by the type of substrate (Hunter et al., 2014) is noticeable. The alternative substrate presented in this paper provides better results than commercial substrate consisting of expanded clay aggregate. The values of transmittance, heat flow and its variation with respect to the supporting walls show a lower heat dispersion in the application of the alternative substrate, due to the different conductivity values of the two substrates. The approach used in the analysis of substrates and in the calculation of the thermal performance differs from those found in scientific literature and represents a valid alternative methodology. However, the application of TerMus-G in the calculation of the thermal performance has a limit, because it does not permit to totally consider the effects of vegetation on indoor environment comfort. In fact, this application takes into account the covering percentage of the plant foliage (Kontoleon and Eumorfopoulou, 2010) but it does not consider that the vegetation increases the night-time indoor temperatures in summer and obstructs daytime solar heating in winter (Yoshimi and Altan, 2011). This limit could be passed with a *in situ* further investigation in order to obtain quantitative data to compare and validate TerMus-G results and to verify the vegetation effects.

Overall, rice husk is a yet under-valued by-product for rice. In the context of indoor green walls, the use of rice husk represents a valid alternative to commercial substrates due to its efficiency in terms of cultivation and energy. Moreover, its use as substrates further improve the ecological footprint of green vertical structures.

Future developments should consider the life cycle assessment (LCA) of the alternative substrate and compared it to other commercial solutions. The LCA would allow to evaluate the environmental impact of rice husk and demonstrate its sustainability as substrate. In the field of vertical greening structures, LCA is implemented to promote sustainable design and construction (Oquendo-Di Cosola et al., 2020; Ottelé et al., 2013). Consequently, substrates with low environmental impact are one of the aspects to considered as part of the sustainable strategies for the design of these systems.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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