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Experimental Study of the Thermal Behavior of a Watercress Planted Roofed Cubic Cell to be Watered with Domestic Wastewater

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Authors' contributions

This work was carried out in collaboration among all authors. Authors DM and IAFAR designed the study, performed the statistical analysis, wrote the protocol and the first draft of the manuscript. Authors DM and HTR managed the analyses of the study and the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

One of the virtues of watercress is its ability to grow in wastewater. This work aims at experimentally studying the thermal behavior of a watercress planted roofed cubic cell. To do this, the temperatures of various components of the cell and the solar radiation received by this cell were measured in order to compare the watercress roof performance with that of the conventional concrete roof. Then, the influence of the opening applied on the door of the studied cell was analyzed. As results, the fluctuation amplitude of the indoor ambient temperature of the concrete roofed cell is wider than that of the green roofed cell. Moreover, the last opening applied to the facades of the cell was the optimum area that the ambient temperature indoor was more attenuated. The LAI's crop was worth 1.2. In addition, the low value of the canopy apparent thermal conductivity revealed that this layer plays a role of thermal insulation. The rooftop greening allows energy savings of about 85%

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compared to the consumed energy with conventional roofing. An extension of this work could be the energy performance analysis of a system using renewable energy for pumping domestic wastewater produced in or around green roofed housing.

Keywords: Green roof; energy performance; watercress; wastewater; LAI.

1. INTRODUCTION

Green roof is a natural air conditioning for improving the indoor and outdoor thermal environment of buildings [1]. This technique involves planting vegetation on the roof. In addition, green roof includes energy conservation through the insulation of buildings thus improves and reduces the abundant consumption of energy [2-3]. Generally, green roof consists of four main components which are the plants forming the canopy layer, the soil or substrate for vegetal growth, the insulating membrane, and the support [4-5]. Compared to conventional roof, the implementation of green roof reduces air pollution, noise and water storm [6]. Thanks to the presence of plants grown on the roof, it avoids the abundant emission of carbon dioxide by photosynthesis phenomenon [7].

Green roofs are differentiated according to the size of the plants that make up the canopy. The extensive green roof can support herbaceous plants with a soil layer less than 20cm while the intensive green roof can withstand large shrubs and trees with plant growth soil between 20 and 30cm thick [5].

Domestic wastewater comes from the kitchen, shower, sink, washing machines, and toilet. It can be stored in the roof and reused to water the vegetation. The drainage water that passes through green roofs can be collected again and can also be reused [8]. By the action of plant growth soil, green roof contributes to the purification of wastewater by filtration of the organic elements that they contain.

Several experimental studies on thermal behavior of green roofs were carried out. Har'el et al. [8] conducted the comparison between gray and tap water and coal ash versus perlite on the growth of two plant species on green roofs, namely: convolvulus mauritanicus and phyla nodiflora. The development of these plants, the quality of the drainage water, the electrical conductivity and the quality of the substrate were measured.

Susana et al. [9] conducted an experimental and analytical study of the potential of green roofs for the regulation of the Mediterranean-continental urban microclimate by choosing grass, tree and alfalfa plant species. Measured variables were radiative wave fluxes, latent heat fluxes, and surface, wall, and wall base temperatures.

The thermal performance of an extensive green roof in the Mediterranean region was studied by Piero et al. [10]. They planted on its roof the genera dianthus grantiano politanus, carpobrotus edulis and cerastium tomentosum. A weather station was used to measure ambient air temperature, relative humidity, wind speed and direction, precipitation, atmospheric pressure, solar radiation, and thermal infrared radiation from the sky.

For experimental observations and monitoring of the amount of water and the quality of the response of a green roof to storms, Corey et al. [11] grew on the upper layer of the extensive green roof six types of native sedum (Sedum reflux, Sedum sexangulare, Sedum acre, Sedum kamschaticum, Sedum spurium "Fuldaglut", and Sedum album). Precipitation amount, stormwater runoff, dissolved organic carbon concentrations, total nitrogen and phosphorus concentrations were determined.

Chagolla et al. [12] conducted a study on the effect of irrigation on the experimental thermal performance of a green roof in a semi-hot climate in Mexico. Five types of plants from the Crassulaceae family were selected: Sedum Adolphi, Echeveria Prolifica, Aeonium Subplanum, Crassula Ovata and Sedum Makinoi. A weather station located on the experimental site was used to measure temperature, humidity, wind speed, precipitation, heat flow and water volume.

Chemisana and Lamnatou [13] selected two species of Mediterranean plants: Gazania rigens Compositae (Asteraceae) and Sedum clavatum Crassulaceae for developing their experimental systems, green photovoltaic roofs, at the University of Lleida, Spain, while measuring three parameters such as temperature, effective irradiation, and wind speed.

Morau et al. [14] conducted a study evaluating the performance of green roofs for the thermal protection of buildings in Reunion Island. It consists in evaluating the green roof effect on the changes of temperature and heat flux during the summer season while using as plant species Plectranthusneochilus, Kalanchoethyrsiflora and Sedum reflex. It was concluded that rooftop greening enables to reduce indoor temperature and conductive heat flux through roofs.

Heim et al. [15] use two species of plants such as Festuca rubra and Sedum acre in their experiment for studying the effects of substrate depth. It included four different substrate depth treatments: three homogeneous treatments,15 cm, 10 cm, and 5 cm and one heterogeneous treatment, wherein half of the substrate had a depth of 5 cm, and the other half a depth of 15 cm (henceforth, the 5/15 cm treatment). As a result, soil depth heterogeneity could allow coexistence of species associated with different conditions for longer than homogeneous conditions.

Zhang et al. [16], by using twenty-eight species of plants (18 non-succulent forbs and 10 succulents), carry out an experiment which shows sustainable extensive green roof without irrigation in a temperate monsoonal climate is realizable. While deeper substrate, at least 15 cm deep, could facilitate the survival and performance of plants, substrate moisture content was more significant for the survival of plants in the dry and cold winter.

Mesocosms, Centaurea jacea, Dianthus carthusianorum, Hylotelephium maximum, Lotus corniculatus, Koeleria pyramidata plants are used by Dusza et al. [17] to assess how green roof design impacts their attractiveness to pollinators. To conclude, plant-pollinator interactions on green roofs are modulated by substrate type, substrate depth and plant community.

The twelve species plants were chosen by Nagase et al. [18], such as: Armeria maritima, Leontodon hispidus, Prunella vulgaris, Silene uniflora, Sedum acre 'Minor', Sedum album 'Coral Carpet', Sedum rupestre, Sedum spurium 'Coccineum', Anthoxanthum odoratum, Festuca ovina, Koeleria macrantha, Trisetum flavescens to investigate the influence of plant species and plant diversity on the amount of water runoff from a simulated green roof. The result shows the amount of water runoff from Sedum spp. was higher than that from bare ground. However, species richness did not affect the amount of water runoff.

Gong et al. [19] were chosen four species: Sedum lineare Thunb., Sedum spurium 'Coccineum', Sedum aizoon L. and Sedum spectabile to make a comparison of the growth status, rainfall retention and purification effects of different green roof. This study showed the growth status of these plants was great; the vegetation coverage was more than 95% in summer; and the average retention rates of Sedum spectabile, Sedum lineare Thunb, mixed plants, Sedum aizoon L. and Sedum spurium 'Coccineum' were 90.98% and 91.38%, 88.51%, 83.42% and 84.17%, respectively.

Meetam et al. [20] assessed the suitability of ten groundcover plants in a tropical area using quantitative physiological parameters of plants, including relative water content, stomatal opening rate, maximum quantum yield of photosystem and soil moisture, and leaf surface temperature, and found among ten plants that S. portulacastrum and C. repens are able to drought tolerance.

At the present state of our knowledge, no work on the green roof has yet been done using watercress as a plant species forming the canopy. The present work aims at experimentally studying the thermal behavior of an extensive green roofed cubic cell using watercress watered with domestic wastewater. The experiment was carried out close to the campus of the University of Antananarivo, Madagascar. A number of parameters such as the temperatures of the studied cell components, the relative humidity of the indoor air underneath the green roof and the solar radiation are measured in order to analyze and the conductive heat flux is calculated by using the Fourier's law for the conductive heat transfer, on the one hand, the thermal behaviors of the watercress planted roofed cubic cell while being compared to the conventional roofed cell, and on the other hand, the influence of the openings applied to the door of the studied green roofed cell. In addition, the importance of saving energy related to this type of green roof is also studied.

2. MATERIAL AND METHODS

2.1 Location of the Site and Description of the Watercress Planted Roofed Cubic Cell

The study site is located in Ankatso, Antananarivo, Madagascar, with an elevation of

1299m, latitude -18.8 °, longitude 47.48 °, and time zone +3. The studied cubic cell is 1m side, 0.22m thick brick wall, mortar coated inside and outside, and 0.07m thick concrete slab roofing. Its wooden door is 0.01m thick, 0.96m high and 0.55m wide. In addition, two openings were applied to the wall and the door of the cell, and represent 0.56% of the total area of the inside facade. A one-meter square edge was built above the support to enclose the soil on which watercress should grow whereas a pipe was installed for allowing the runoff of extra wastewater to the outside. For economic reasons, during some days preceding the study of the green roof cell, series of measurements on the cell covered only by a concrete slab, considered in the present study as forming the conventional roof, were carried out before adding the soil and planting the watercress. This plant was used since it grows in wet soil irrigated by domestic wastewater stream [21]. In this study, wastewater from dishwashers is collected and used to water by hand the watercress. The average thickness of the watercress canopy layer is 0.05 m or 1.97 in while that of the plant growth soil is 0.03 m. The green roof is here an extensive green roof type.

In order to facilitate the flow of air from outside to inside and vice-versa, a number of openings were applied to the door and the wall of the cell. To analyze the effects of these openings on the studied cubic cell indoor ambient temperature, the area of the opening applied to the door was changed successively to represent about 0.56%, 2.42%, 4.41% and 6.47% of the internal facade of the cell. More precisely, the considered door opening areas are as follows: a) 0.09m by 0.125m, b) 0.15m by 0.55m, c) 0.30m by 0.55m, and d) 0.45m by 0.55m. Figure 1 presents the photos of the conventionally roofed cubic cell (a) and the watercress planted roofed cubic cell (b) while thermal properties of materials used for building the studied cubic cell are summarized in Table 1.

2.2 Instrumentation and Experimental Procedures

In Madagascar, the February and March months are included in summer season. As there was only one cell, we first conducted the convectional rooftop experiment. It was only after that the study of the green roof was started. Comparative studies are possible insofar as we count what the roof receives from the outside compared to what it emits, that is to say, the energy balance which enable us to assess the energy saving.

The adopted experimental protocol can be divided into three different parts such that part 1 consists in measuring the temperatures, the indoor air humidity, and the global solar radiation related to the conventional roofed cell (see Fig. 1.a) from February 21st, 2018 at noon through February 24th, 2018 at noon. The conductive flux is obtained by using the Fourier relation for the heat transfer to the level of the roof made of concrete. To do this, the pyranometer was placed outside the cell while five temperature probes were placed as follows: one outside the cell for taking the outside ambient temperature, one on the concrete slab roof, one on the ceiling, another one inside the cell and the last one on the cell floor.

More precisely, a Kypp & Zonen SP-Lite pyrometer connected, via a USB 2.0 A to B cable for the printer, to a National Instrument USB-6008 device was used for measuring global solar radiation received by unit area of the cubic cell roof. It has a temperature range from -40 to 80°C, a sensitivity of 73 µV per $W.m^{-2}$, a spectral range of 400 to 1100 nm, a typical output signal for atmospheric application ranging from 0 to 100 mV and maximum radiation of 2000 $W.m^{-2}$.

Table 1. Thermal properties of materials used for building the studied cubic cell [22]

Material	Density ($kg.m^{-3}$)	Thermal conductivity ($W.m^{-1}.K^{-1}$)	Heat capacity ($J.kg^{-1}.K^{-1}$)
Reinforced concrete	2350	2.3	1000
Brick	1850	1.15	1634
Mortar	1900	1.3	1000
Fireboard	435	0.11	1600

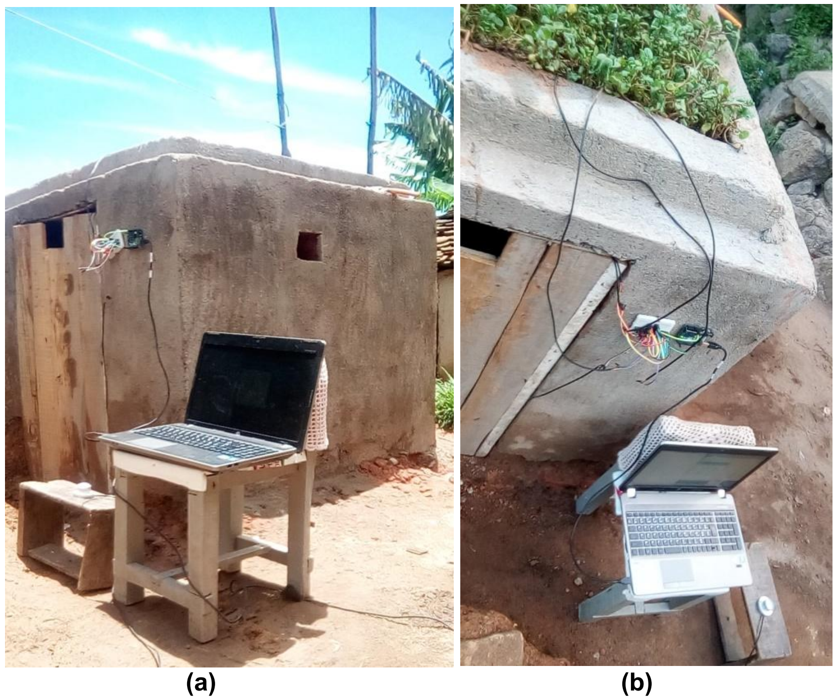
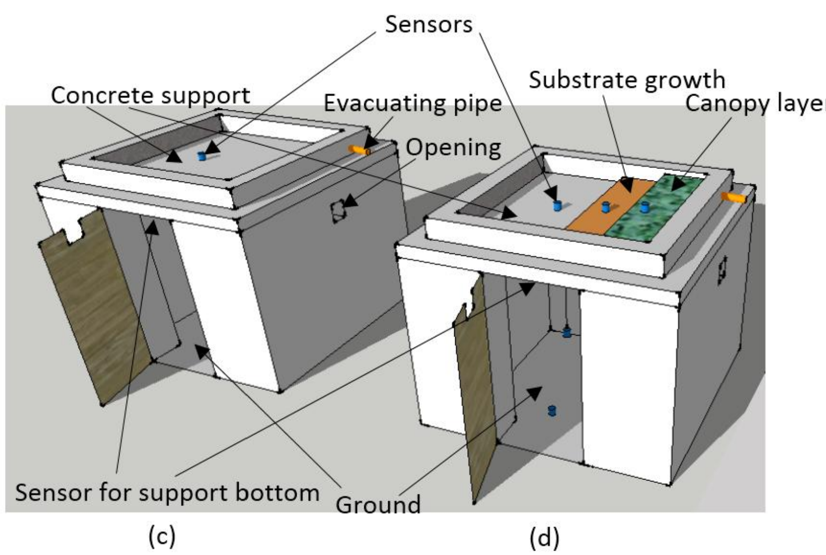


Fig. 1. Photos of the two compared roofs (a) conventional roofed cell; (b) Watercress planted roofed cell; (c) and (d) positions of sensors on these compared rooftops



Besides, Testo 410-2, which is equipped with an anemometer, a thermometer and a hygrometer, was employed to measure the wind speed, the ambient air temperature and relative humidity; its anemometer can measure wind speed ranging from 0.4 to 20 $m.s^{-1}$ while its operating temperature ranges from -10 to 50 ° C and its hygrometer ranges from 0 to 100%; its autonomy is about 60 h while its measurement rate is 0.5 s. Apart from the measurement of ambient air temperature, DS15B20 digital temperature sensors in the form of probes connected with an Arduino Uno board using male-male wires were used for the measurement of temperatures. This probe has an operating temperature ranging from -55°C to +125°C and is accurate within ± 0.5 °C in the range between -10 °C and + 85 °C; the data pin of the probe is connected to the power supply with a resistance of 4.7kΩ. Figure 1.c and 1.d indicate the positions of sensors on these compared rooftops.

As for part 2, the previously stated parameters were still measured but this time the measurements are related to the watercress planted cubic cell (see Fig. 1.b) during the period between February 27th at 11am and March 2nd, 2018 at noon; the provisions of the measuring apparatus expressed in part 1 were not changed; however, two other complementary temperature probes were laid on the watercress leaves and on the growth soil top surface.

In part 3, the area of the opening applied to the door was daily varied for three days (March 14th, 15th and 16th, 2018 from 8am to 16pm) and the opening during February 28 th, 2018 from 8am to 16pm was considered as the initial opening area. Meanwhile, the same measurement procedure as in part 2 was performed but only during the day (excluding night). This part allows analyzing the effect of the door opening area change on the thermal environment inside the studied cell.

2.3 Calibration of Data Processing

The use of the GPExp tool [23] under Matlab enabled us to eliminate all absurd points that are not compatible with all the data of the experiment. So, all the data measured was calibrated with this tool.

2.4 Calculation of the Leaf Area Index of the crop LAI

Watercress was considered like a grass so that the formulation recommended by Jensen et al. [24] can be used for computing the Leaf Area Index (LAI) of this plant:

$$LAI = 0{,}61\ h_C \tag{1}$$

where h_c denotes the crop height and is equal to 1.97 inches for clipped grass less than 6 inches tall.

2.5 Calculation of the Average Apparent thermal Conductivity of the Watercress Canopy Layer

While using Fourier's law [25] governing the heat transfer by conduction, the experimental value of the average apparent thermal conductivity $\langle h_{can} \rangle$ of the watercress canopy layer can be determined as follows:

$$\langle h_{can} \rangle = \frac{\langle w_{can} \rangle \langle \phi_{calc} \rangle}{S_{can} \langle T_{leaf} - T_{soil} \rangle} \tag{2}$$

in which $\langle w_{can} \rangle$ represents the average thickness of the canopy layer (m), $\langle \phi_{calc} \rangle$ is the average conductive heat flux crossing the watercress canopy layer (W.m^{-2}), S_{can} is the horizontal cross section of the watercress canopy layer (m^2), and $\langle T_{leaf} - T_{soil} \rangle$ denotes the average value of the difference between the watercress and the vegetated soil top face temperatures (K).

2.6 Determination of Energy Saved Due to Rooftop Greening

The energy consumption per area unit for both cooling and heating was evaluated. It is directly related to the quantity of heat flux entering or leaving through the roof support and which can be written as follows [1]:

$$\varphi = \frac{1}{R}(T_s - T_{in}) \tag{3}$$

where, φ is the heat flux entering or outgoing through a unit area of the roof support (W.m^{-2}), T_s and T_{in} are the temperatures of the support top face and the indoor air respectively, R is the bulk thermal resistance of the roof support (K.m^2.W^{-1}) which is given by:

$$R = \frac{L_s}{\lambda_s} + \frac{1}{h_{in}} \tag{4}$$

in which, h_{in} is thermal convective coefficient between the support bottom and the indoor air (W.m^{-2}.s^{-1}), L_s and λ_s are the thickness (m) and thermal conductivity (W.m^{-1}.s^{-1}) of the support.

To investigate the energy performance of both roof types, we followed the same method as proposed by Jacquet [26]. Indeed, a positive value of heat flux φ represents an entry of heat through the roof (thus a need for cooling) while a negative value of heat flux represents a loss of heat through the roof (thus a need for heating).

To present the demand for energy necessary to mitigate the heat flux crossing the roof, we assume that a system of cooling and heating with a 100% yield will consume, to ensure a constant indoor air temperature, the same number of kilowatt-hour that the energy which entered or left the cell through the roof and for the same period of times. So, for a given day, for example, if it was entered 2 (kWh) through the support, we would assume that 2 (kWh) were spent by the cooling system to keep constant the indoor air temperature. Similarly, if 1.2 (kWh) were lost through the roof for the same day, we assume that 1.2 (kWh) were spent by the heating system to preserve a constant indoor air temperature.

Thereafter, the instant heat flux being calculated for each time step, the daily number of kilowatt-hour entering and outgoing per area unit through the supports of both roof types can be computed by integrating the heat flux versus time curve; in other words, calculating the surface bounded by the abovementioned curve and the time-axis. As heat fluxes are calculated with sufficiently small time step, the sum of kilowatt-hour obtained over 24 hours can be obtained by means of rectangular method, that is, the sum over 24 hours of the product of the instant flux value (kW) and the time step (h). Then, the difference between consumption energy quantities respectively related to the ordinary roof and the green roof represents the saved energy.

3. RESULTS AND DISCUSSION

3.1 Results Related to Concrete Slab Roofed Cubic Cell (Conventional Roof)

Fig. 2 shows the fluctuations of the outside ambient temperature T_{out}, the temperature of the ceiling $T_{ceiling}$, the ambient temperature reigning inside the cell T_{in} , and the indoor floor temperature T_{floor}, as well as the temperature of the conventional roof top face T_{troof} of which evolution is very notable while approximately ranging from 15.43°C to 55.85°C due to the high thermal conductivity of the concrete slab. This enormous progressive change is therefore one of the causes that entail the rise or fall of the heat flux inside the cubic cell. As for the fluctuation amplitude of the ceiling temperature $T_{ceiling}$, it peaks at 37.23°C and reaches a minimum value of about 18.62°C. On the other hand, the change of the cell indoor floor temperature T_{floor} is almost constant compared to those of the others while only varying between 19.68 °C and 22.87 °C.

As can be seen from Fig. 3, the evolution curves of indoor and outdoor ambient temperatures (T_{in} and T_{out}), conductive heat flux and solar radiation agree well. Indeed, globally, as the solar radiation increases, the conductive heat flux and the two ambient temperatures increase. Moreover, the solar radiation and the conductive heat flux are both close to zero at night; the solar radiation ranging from 1.59 Wm^{-2} to 913.1 W.m^{-2} while the conductive heat flux varying between 0 W.m^{-2} and 506.8 W.m^{-2}. In other words, the solar radiation fluctuation controls the change of the conductive heat flux. This explains that the conductive heat flux crossing the reinforced concrete roof is a part of the global solar radiation that is absorbed by the concrete.

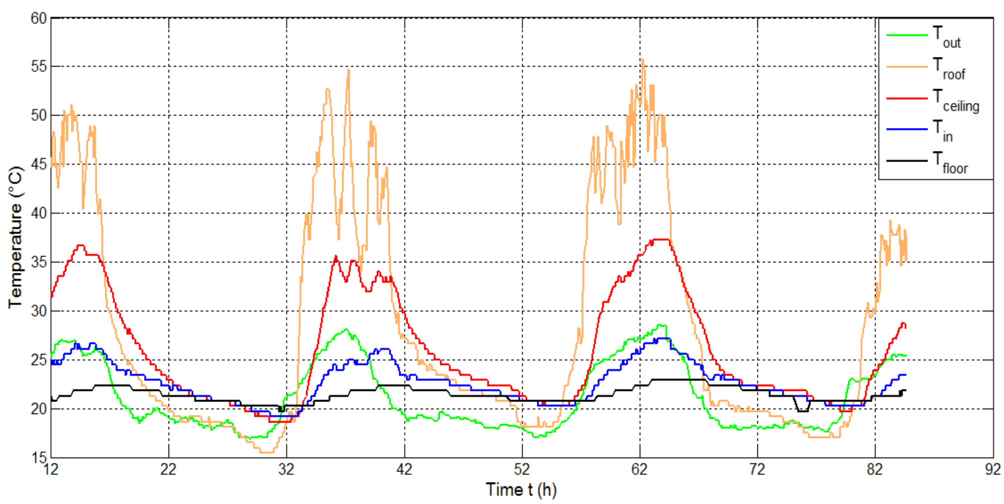


Fig. 2. Temperature changes recorded from 21 February at noon to 24 February 2018 at noon for conventional roof

With regard to the indoor and outdoor ambient temperatures (T_{in} and T_{out}), there is no much difference between their variations in the daytime while there is in the night period. Indeed, during the diurnal period, this difference is only about 3°C whereas in night period, it becomes a little larger with a value of 5°C. In fact, it is the conductive heat flux that significantly influences the thermal change in the cubic cell.

3.2 Results Related to Watercress Planted Roofed Cubic Cell (Green Roof)

Fig. 4 shows the variations of the outdoor ambient temperature $T_{(out,g)}$, the temperature of the watercress leaves T_{leaf}, the plant growth soil top face temperature T_{tsoil}, the support top face temperature $T_{tsupport}$, the support bottom face temperature $T_{ceiling}$, and the indoor ambient temperature of the vegetated roofed cell $T_{(in,g)}$ as well as its indoor floor temperature T_{floor} from February 27 at 11am to March 2, 2018 at noon.

The fluctuation amplitude of the top face temperature of the watercress leaves is relatively large as it varies in a wide temperature range from about 15.96 °C to about 43.08 °C. With respect to the watercress growth soil top face temperature, its fluctuation is a little attenuated, on the first hand, by the shading given by the overall surface of the watercress leaves, and on the other hand, by the renewal of wastewater used for watering the canopy. It is worth noting

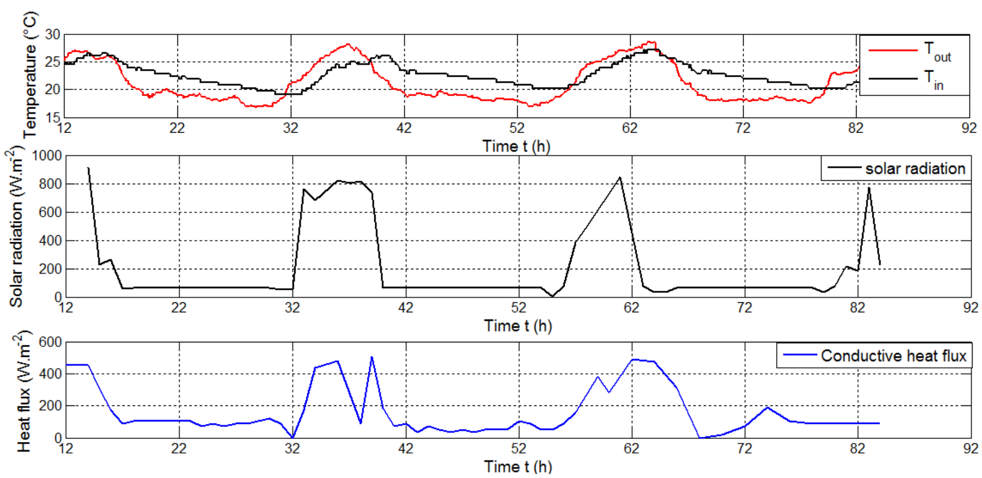


Fig. 3. Trends in variation of indoor and outdoor ambient temperatures, conductive heat flux, and solar radiation over time for conventionally roofed cubic cell

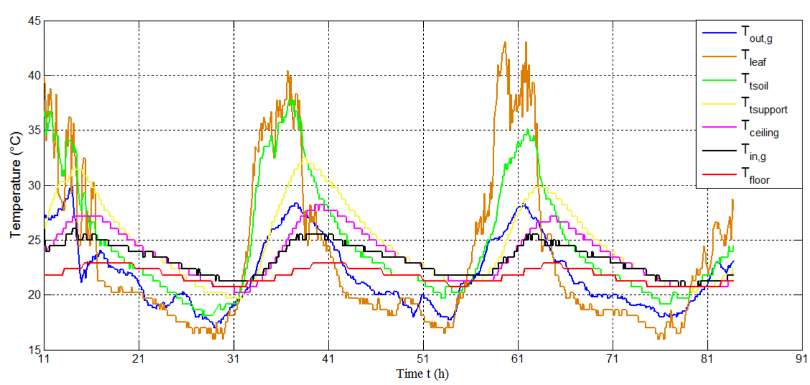


Fig. 4. Temperature changes recorded from February 27 at 11am to March 2, 2018 at noon for watercress roof

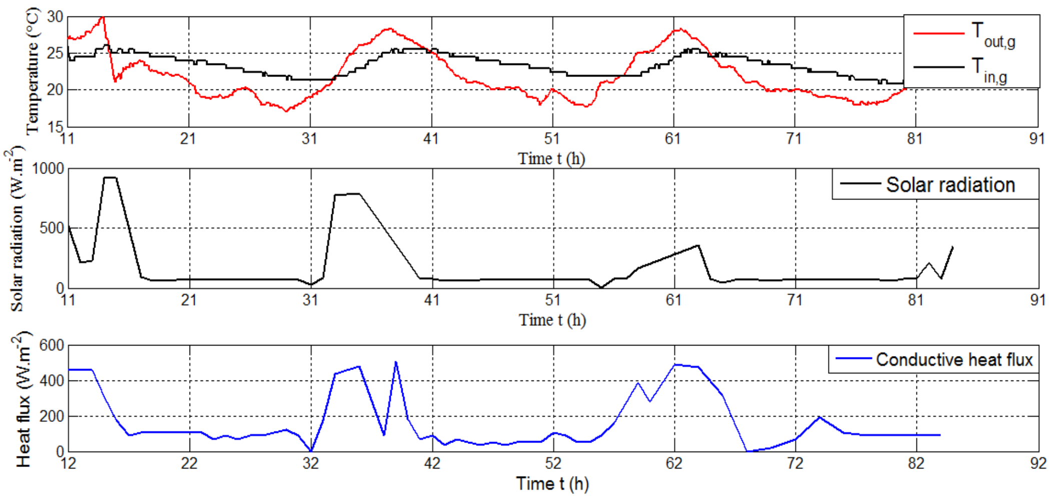


Fig. 5. Trends in variation of indoor and outdoor ambient temperatures, conductive heat flux, and solar radiation over time for watercress planted roofed cubic cell

that, for the present study, the renewal of wastewater was done manually using a plastic bucket and such watering operation was repeated each time the water flowing on the green roof is exhausting. In addition, it can also be seen in Fig. 4 that the presence of vegetation on the roof attenuates the fluctuation of temperatures of some elements of the green roofed cell. This concerns more precisely the temperatures of the studied cell elements which are located from its support upper face $T_{tsupport}$ to its indoor floor T_{floor}.

As can be seen from Fig. 5, the outside ambient temperature $T_{(out,g)}$ range from 17 °C to 29.7°C while that of the indoor ambient temperature $T_{(in,g)}$ ranges between 20.74 °C and 26.06 °C. During daytime and night period, there is always a difference between the abovementioned two temperatures. This shows that the existence of the canopy and the soil layers enables to decrease the cell conductive heat flux during the diurnal period and to increase it during the night period. Indeed, in the night period, $T_{(out,g)}$ is constantly lower than $T_{(in,g)}$ while the opposite occurs during the daytime. Similarly, to the case of reinforced concrete slab roofed cell, it is the variation of the conductive heat flux that directly causes the evolution of the environment inside the watercress roofed cell. However, for the green roof case, the conductive heat flux ranges from 0W.m^{-2} and 139.8W.m^{-2} whereas the solar radiation varies between 5.22 Wm^{-2} and 913.1 W m^{-2}.

3.3 Comparison of Thermal Performance between Conventional Roofed Cell and Green Roofed Cell

As it can be seen from Figs. 2 and 4, the fluctuation of the indoor ambient temperature of the watercress planted roofed cell is more attenuated than that of the non-vegetated roofed cell as the existence of the canopy and soil layers on the roof slows the gradual decrease and increase of the conductive heat flux, and stabilizes the internal thermal environment of the cubic cell. In addition, the renewal of the wastewater irrigation of the plant makes it possible to change the thermal conductivity of the plant support. In contrast, for the case of conventional roof, the reinforced concrete slab directly receives the solar radiation which results enormous maximum values of the conductive heat flux. Accordingly, the indoor air conditioning of watercress planted roofed cell is more livable than that of the conventionally roofed cell.

3.4 Calculation of the Average Apparent Thermal Conductivity and the LAI of the Watercress Canopy Layer

The computed average conductive heat flux crossing the watercress canopy layer $\langle \phi_{calc} \rangle$ equals 42.36 W while the average temperature difference $\langle T_{leaf} - T_{soil} \rangle$ is equal to 3.07 °C and the average thickness and the horizontal cross section area of the canopy layer are equal to 0.05 m and 1 m^2 respectively, it follows from the use of equation (2) that the average apparent thermal conductivity of the watercress canopy layer is about 0.69 $W.m^{-1}.K^{-1}$. Such low thermal conductivity value means that the watercress canopy layer constitutes a thermal insulator for the studied cubic cell and attenuates therefore the conductive heat transfer from the outside to the inside and vice versa. This layer subsequently plays a very important role in improving the thermal comfort inside the cubic cell.

By using the equation (1), the value of the crop's LAI equals 1.2. This value is one of the parameters which reduce the variation of heat flux through the roof as LAI is included in convective heat transfer, shading and evapotranspiration.

3.5 Energy Saving

Using the method presented in section 2.6, the average daily air conditioning consumed energy relative to the cubic cell with conventional roof is 2.2 kWh per unit area while that with watercress roof is only 0.33 kWh per unit area. The difference between these two values therefore gives a daily saved energy value of the order of 1.87 kWh per unit area.

3.6 Financial Savings Achieved Due to Watering with Wastewater

According to Pradhan et al. [27], for the green roof, some plants need a lot of water to survive and can consume daily a volume of water ranging between 0.5 and 20 L per m^2 of roofing. Besides, it was reported in [28] that the required water volume for watering lawns ranges between 20 and 25 L per m^2 of roofing.

Referring to the watering of the green lawn roof vegetation with tap water, the proposed solution would thus achieve at least a financial saving of around 22 Ariary (1 Ariary equals US$ 0.00028 approximately) per day per square meter of the green roof, knowing that Madagascar the cost of one cubic meter of drinking water is worth 1 155 Ariary [29]. It is worth noting that this estimate does not include the environmental costs associated with the purification and distribution of drinking water used for irrigating the green roof as it is supposed to be irrigated with domestic wastewater.

4. CONCLUSION

This experimental analysis allowed us studying the thermal behavior of watercress planted roofed cubic cell. The chosen plant species has various virtues including the possibility of using wastewater for watering. Though most of the employed measurement devices are simple and not costly, the present study enabled to compare the thermal behaviors of the conventionally roofed cell and the green roofed cell. Moreover, the present study was extended by analyzing the influence of the openings applied to the cell door.

It follows from the obtained results that the performance of the watercress planted roofed cell is better compared to the conventionally roofed cell. Indeed, the canopy and the plant growth soil layers can reduce the conductive heat flux and reduce therefore the fluctuation amplitude of the indoor temperature range. For the green roof, the indoor ambient temperature ranges between 20.74°C and 26.06 °C while that related to the conventionally roofed cell ranges between 19.15 °C and 27.13 °C. The thermal environment inside the green roofed cell is then found more stable.

The rooftop greening allows energy savings of about 85% compared to the consumed energy with conventional roofing.

This work also showed that due to the low average value thermal conductivity of the watercress canopy, it plays the role of thermal insulator. An extension of this work could be the study of the energy performance of a system using renewable energy for pumping domestic wastewater produced in or around green roofed housing.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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