

Evaluating thermal performance of experimental building solutions designed for livestock housing: the effect of greenery systems

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Abstract. The thermal performance of a greenhouse-type building provided with a living plant canopy was evaluated in Northern Italy during summer. Four reduced scale buildings with different types of covering were tested. The first type was the reproduction of a gable roof covered with 40 mm-thick sandwich panels (SAND), a widespread solution for dairy barns in temperate climates, used as control. Two roofs were reproductions of a Venlo-type greenhouse covered with a 0.2 mm-thick transparent EVA film equipped with either a reflective shading screen with 70% shading level (TRA+SHA) or with a living plant canopy (TRA+PLA). The last type of roof consisted of the living plant canopy alone (PLA). Plant canopies were made up of climbing plants (*Trachelospermum jasminoides*) with an average LAI of 1.39 m² m⁻².

Data were analysed with mixed linear models for repeated measures. Fixed effects tested were roof type and the interaction of roof type and time of the day. Internal temperature in TRA+SHA (22.60 °C) was higher than PLA (21.28 °C; $p > 0.001$), SAND (21.53 °C; $p = 0.026$) and TRA+PLA (21.68 °C; $p = 0.036$), with no significant differences among the latter three. Differences were larger during the hottest hours of the day (from 09:00 till 17:00) while, during the night, internal temperature did not differ among types of roof.

Results indicate that greenhouse-type buildings with conventional shading systems may not be adequate for housing livestock in warm climates. However, the employment of greenery systems such as a plant canopy may effectively reduce internal temperature. Further research is deserved to develop suitable building solution for livestock farming.

Key words: livestock housing, greenhouse, green roof, greenery systems, thermal performance.

INTRODUCTION

Heat stress in livestock housing is a major concern and, since the global temperature is likely to increase (IPCC, 2013), the magnitude of this issue will continue to grow. In dairy cows, heat stress can compromise milk production and reproductive performance, modify behavior, cause serious health problems and even lead animals to death (Jordan, 2003; West, 2003; Vitali et al., 2009; Tao & Dahl, 2013). In many cases, natural ventilation alone is not adequate to support the high production level of modern dairy cows (Berman et al., 1985; Armstrong, 1994). For this reason, several studies have been focused on active cooling techniques such as water sprinkling, forced ventilation and evaporative cooling even though their application considerably increases energy

consumption (Ecim-Djuric & Topisirovic, 2010; Barbari et al., 2011; Legrand et al., 2011; Honig et al., 2012).

In the last years, significant efforts have been made to improve energy efficiency in the building sector (Týbl & Kic, 2016). Researches on residential and commercial buildings showed that there are many passive solutions which can reduce the energy requirement for cooling purposes. The use of various types of plants as part of the building enclosure has been shown to improve its thermal performance (Saadatian et al., 2013; Pérez et al., 2014). Due to their capacity to intercept solar radiation, plants provide effective shade but, due to evapotranspiration, they also have an air-cooling effect (Jaffal et al., 2012). Both roofs and walls can be provided with vegetation. These techniques are commonly known as green roofs and green façades.

Green roof mainly refers to a roof covered with herbaceous and/or woody plants which are planted in a layer of soil or other growing medium. Many studies have been focused on thermal performance of these systems. In a literature review, Saadatian et al. (2013) found that green roofs can absorb 60% of the solar radiation and decrease the surface temperature of the roof up to 60 °C, thus reducing the internal building temperature up to 20 °C and the cooling load by 32 to 100%. In term of economics, Blackhurst et al. (2010) reported that green roofs can be an economical option in the long term but their initial cost is three to six times higher than a conventional roof.

Green façades are vertical greenery systems that involve virtually any way to set plants in a building façade or wall. Traditionally, green façades consist of climbing plants or shrubs which grow directly along building walls or along supports such as frames and wires. In warm temperate climate, green façades can reduce the external surface temperature of the building façade wall by 12 to 20.8 °C in the summer period and by 5 to 16 °C in autumn, with a reduction in energy consumption for cooling between 5% and 50% (Pérez et al., 2014).

Planting and growing trees near the building is another simple and effective mean of reducing building solar loads and thermal regulation requirements in summer. Tree shade can decrease wall surface temperatures by up to 9 °C and external air temperatures by up to 1 °C (Berry et al., 2013). Balogun et al. (2014) found that tree shade sensibly lessens the energy requirement for cooling in a school building. Since greenery systems have the potential to improve the thermal performance of buildings and decrease the energy consumption for active cooling they could be profitably employed in dairy barns. However, literature about the use of these passive systems in livestock housing is almost lacking.

Another solution that has been spread in recent years is the use of greenhouse-type structures for livestock housing (Galama et al., 2011). Greenhouses typically have automatic vents and shading systems which appear to allow a better control over the internal microclimate compared with traditional shelters (Sethi & Sharma, 2007; Vanthoor et al., 2011). Moreover, greenhouses are considered to provide a more natural environment for the cows mainly due to improved natural lighting. Natural lighting also contributes in drying and thus reduces the amount of bedding materials needed, especially during winter (den Hollander, 2014). The use of greenhouse-type buildings for housing dairy cows is mostly spread in temperate areas with moderate summer temperatures. In warmer climates, the characteristics of the materials typically used for greenhouse cladding could pose challenges in keeping adequate internal temperature during summer months.

According to the information available, greenery systems for buildings and greenhouse-type structures can have a role in future development of housing systems for dairy cows. Although there are some issues concerning their employment, they have the potential to lower production costs, improve animal welfare and reduce environmental impact of dairy farming. Despite that, literature about the use of these solutions in housing for dairy cows and other livestock is still sparse. The aim of this study is to evaluate the effect on internal temperature of different roof configurations combining greenery systems and greenhouse-type coverings in warm weather conditions.

MATERIALS AND METHODS

The research was carried out by comparing the thermal performance of 4 different types of roof. Four identical reduced-scale buildings were built (Fig. 1). Each one was 2 m long, 1 m wide and 1 m high. Experimental buildings had a wooden-frame structure made up of 40 x 40 mm timbers. Floor and curtain walls were built using 40 mm thick polystyrene sheets. To allow natural ventilation, a 1 m x 0.33 m opening was created in both sidewalls of the experimental buildings. Since all the buildings were oriented with the ridge running East-West, the opening of the South sidewall was provided with a sloped overhang shading made up of a reflective cloth (ILS 70 F Revolux, Svensson, Kinna, Sweden). One of the four types of roof was applied to each experimental building.



Figure 1. A view of the experimental site with the reduced-scale buildings (originally 6 structures were built but 2 of them were excluded from the study).

The first type of roof was the reproduction of a gable roof with continuous ridge vent, which is a widespread solution for dairy barns in temperate climates and was used as control. The covering consisted of sandwich panels (SAND) with 40 mm-thick polyurethane foam core and 2mm-thick aluminum skins. The thermal transmittance (U) of the panels used in SAND was $0.54 \text{ W m}^{-2} \text{ K}^{-1}$ (Isocop Granite, Isopan, Verona, Italy). To assess performance of different greenhouse-type coverings, 2 roof frame structures that reproduced the shape of a Venlo greenhouse with fixed continuous ridge vents were assembled using 40 x 40 mm timbers. Both greenhouse-type roofs were covered with a 0.2 mm-thick transparent EVA film (PATILUX, P.A.T.I., Treviso, Italy) but were equipped with different internal shading systems. The first consisted of a single shading screen with 70% shading level (TRA+SHA). The screen had an open structure to allow

ventilation and its top surface was reflective (ILS 70 F Revolux, Svennson, Kinna, Sweden). The second greenhouse-type roof was provided with a living plant canopy (TRA+PLA). The plant canopy was made up of a metal net that sustained climbing plants trained and tied to create a consistent layer. Eight potted Star Jasmine plants (*Trachelospermum jasminoides*) were used. The pots had a capacity of 4 l each and were fixed to the metal net along the sidewalls of the experimental building. To keep the plants alive and physiologically active during the test, they were irrigated by an automatic drip system which was set to deliver 0.05 l h⁻¹ in each pot. In order to evaluate performance of the plant canopy alone, it was also applied to an experimental building with a completely open roof (PLA). Cross sections of experimental buildings with the different types of roof are reported in Fig. 2.

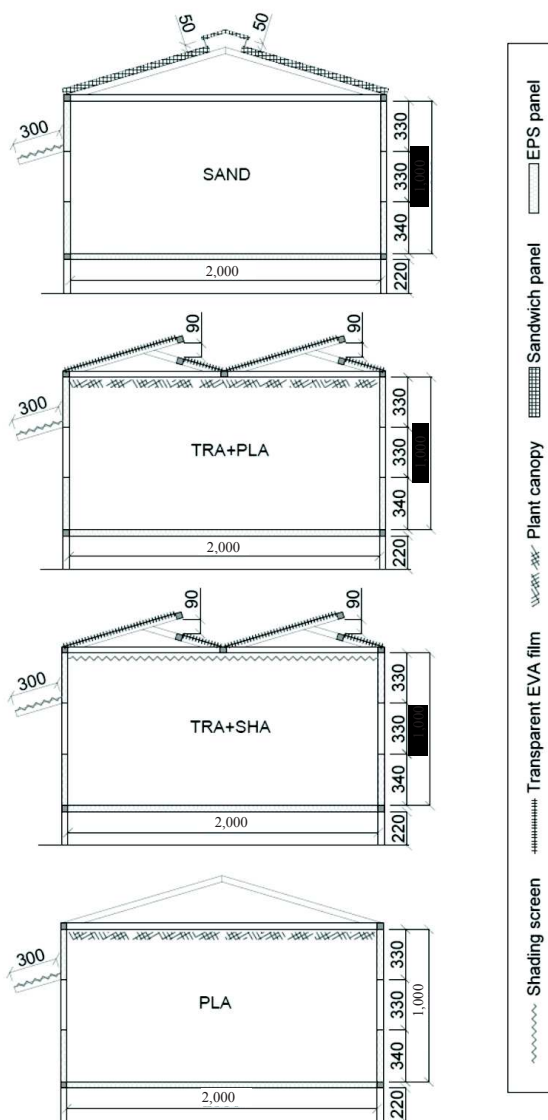


Figure 2. Cross sections of the reduced-scale buildings with the different types of roof tested (dimensions are in mm).

To evaluate the shading level of the plant canopy, the leaf area index (LAI) was measured (Jonckheere et al., 2004). Ten plants were randomly selected among those available and the number of leaves per plant was counted. Twenty randomly selected leaves were plucked from all the plants available to evaluate their dimensions. To determine the leaf's area, length and width, a photo of leaves on graph paper was taken. Leaves were kept flat by placing a glass above them. The pictures were then imported in AutoCAD (Autodesk, San Rafael, California, USA) and scaled using the paper grid as reference. The leaf area was measured using a minimum of 20 points to better approximate the round perimeter. The LAI was calculated by multiplying the average one-sided leaf area by the average number of leaf per plant and by the number of plant used in each canopy. The value obtained was then divided by the internal area of each experimental building. The thickness of the plant canopies was measured in 5 randomly selected points.

To avoid any external source of shading, all the experimental buildings were placed in a field with no trees or constructions nearby and at a minimum distance of 4 m among them. In the experimental area, grass was mown before the beginning of the trials. During the whole experiment, dry bulb temperature was measured outside and inside the experimental buildings. The probe for external temperature was placed 1 m above the ground while the probes for internal measurements were placed inside each experimental building at 0.1 m above the floor. The external probe was provided with a radiant screen. All the sensors used in the experiment were Pt100 resistance thermometers (DMA672-1, Lsi Lastem, Milan, Italy) and they were connected to a 16-bit data logger (E-log, Lsi Lastem, Milan, Italy). Both internal and external temperatures were recorded continuously every 15 minutes. Trials were carried out in Mantua (Italy) during August 2013 (13-27/08/2013). Experiment lasted 15 days but 2 days had to be removed from the data set due to a technical issue with data recording. Final data set included observations collected over 13 full days.

Statistical analysis

Statistical analysis was carried out using R (R Core Team, 2016). Data collected at 15-min intervals were averaged to obtain hourly observations. Descriptive statistics for external air temperature during the experimental period and plant canopy characteristics were computed. Results are reported in text as mean \pm SD. A mixed model for repeated-measures was built to assess the effect of different types of roof on internal air temperature, which was the response variable. Roof type and the interaction of roof type by time of the day was included as fixed effects. Day was included as random repeated effect. An autoregressive (ar1) correlation structure was used to take into account for autocorrelations of subsequent observations. Model was fitted with ML. Normality and homoscedasticity of variance were visually evaluated using residual plots. Least squares means and SEM were computed and reported in text and figures as LSmeans \pm SEM. Tukey's method was used for pairwise comparisons of LSmeans. Significance of differences was declared at $P < 0.05$ while a tendency was reported at $P < 0.10$.

RESULTS

During the whole experimental period (13-27/08/2013) weather was predominantly sunny. The average, maximum and minimum temperatures were 21.96 °C, 33.15 °C and

11.87 °C, respectively. Highest air temperatures were recorded during the day at 16:00-17:00 while lowest occurred at 5:00-6:00, just before sunrise (Fig. 3).

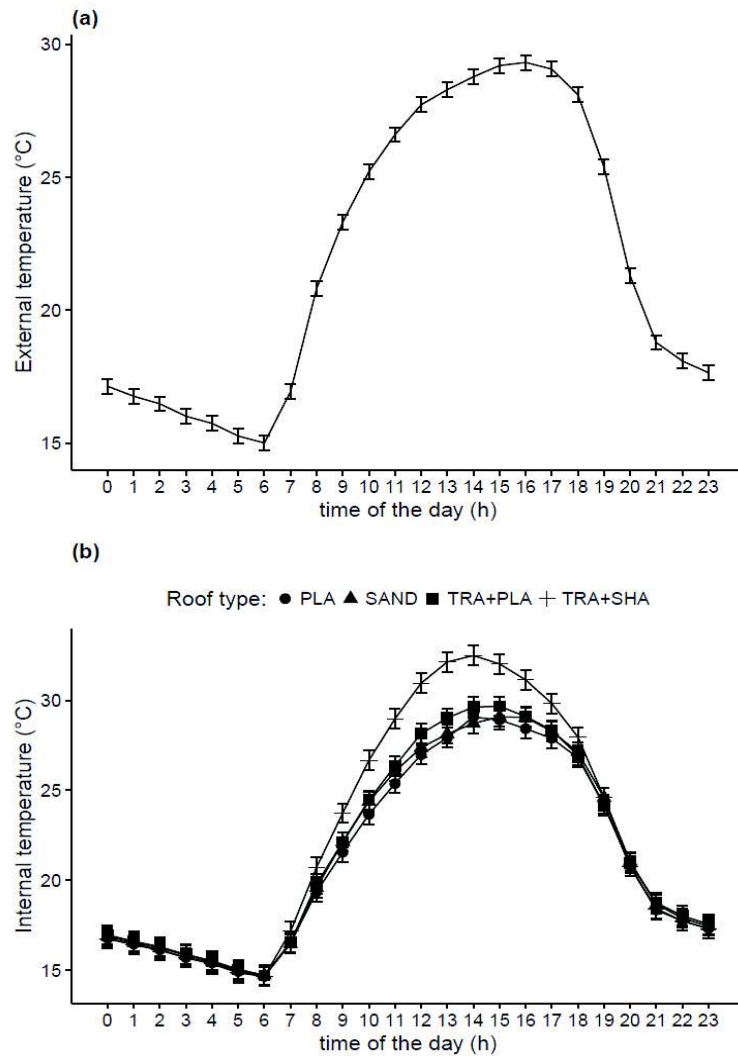


Figure 3. External temperature (a) and temperature measured inside the reduced-scale buildings provided with different roof types (b).

Plant canopy

Plants used in the present study (*Trachelospermum jasminoides*) to make the canopies had 484 ± 91 leaves. Since the area of the experimental building was 2 m^2 and 8 plants were used in each canopy, average leaf density was estimated to be $1,936 \text{ leaves m}^{-2}$. Leaves were $57 \pm 6 \text{ mm}$ long and $19 \pm 4 \text{ mm}$ wide. The one-sided area of a single leaf was $720 \pm 166 \text{ mm}^2$. On average, the LAI of the plant canopies used in this study was $1.39 \text{ m}^2 \text{ m}^{-2}$. The vegetation layer was $6.1 \pm 5.6 \text{ cm}$ thick.

Roof type

Mixed model analysis indicated that both the main effect of roof type and the interaction of roof type by hour of the day significantly affected internal air temperature. Temperature in TRA+SHA (22.60 °C) was higher than PLA (21.28 °C; $p > 0.001$), SAND (21.53 °C; $p = 0.026$) and TRA+PLA (21.68 °C; $p = 0.036$), with no significant differences among the latter three. Interaction with hour of the day showed differences that were larger during the hottest hours of the day while, during the night, internal temperature did not differ among types of roof. During the interval from 9:00 and 17:00, the roof with TRA+SHA configuration produced significantly higher temperature than PLA, SAND and TRA+PLA (Fig. 3). During the same period, no significant differences were detected among PLA, SAND and TRA+PLA, even though PLA tended to have the numerically lowest internal temperature. During the remaining parts of the day (from 00:00 to 08:00 and from 18:00 to 23:00) all roof types produced similar internal temperatures with no significant differences.

DISCUSSION

External air temperature measured during the course of the experiment can be considered representative of the summer period in Northern Italy and potentially reduce welfare and performance of dairy cows as well as other farm species, such as swine and poultry (Jordan, 2003; West, 2003; Barbari & Sorbetti Guerri, 2004; Cândido et al., 2015; Santos et al., 2015). The experimental buildings with greenhouse-type coverings and artificial shading net (TRA+SHA) had higher internal temperature than all other configurations tested. During the hottest period of the day, the difference between TRA+SHA and SAND reached 3.4 °C. Results indicate that, in hot weather conditions, the use of conventional greenhouses, if applied for livestock housing, could result in increased heat stress. However, it has to be considered that cladding materials used in this study were not specifically developed to reduce thermal load. Researches on greenhouse cooling techniques showed that by employing semi-transparent or reflective materials the internal temperature can be reduced (Kumar et al., 2009; Lamnatou & Chemisana, 2013). On the other hand, a semi-transparent cladding would limit heat gain also during winter when, in the case of livestock housing, it would be useful to dry the bedding and reduce its consumption (Leso et al., 2013; den Hollander, 2014).

Temperatures inside the buildings with plant canopies (PLA, TRA+PLA) did not differ from that measured in SAND, despite they were not provided with any insulating material. These results confirm that plants have the capacity to effectively reduce the thermal load of buildings in hot weather conditions. Although difference was not statistically significant, the roof type made up of the plant canopy alone (PLA) produced the lowest internal temperature among all types of roof tested. That was probably due to the open structure of the plant canopy, which may result in a higher air exchange rate. The type of greenery system used in this experiment was not properly a green roof nor a green façade since it was horizontal but there was not a continuous layer of growing medium on the roof (Saadatian et al., 2013; Pérez et al., 2014). For this reason, findings obtained in the present study cannot be directly compared with those reported in most of the relevant literature. Nevertheless, Koyama et al. (2014) used a greenery system for similar purposes. They examined a technique to cool a livestock building by covering its south wall and roof with kudzu vine (*Pueraria lobata*). Findings shown that the internal

temperature of a building with 43.9% plant coverage was 3.44 °C lower than that in a bare one. They also found that temperature reduction increased with the percentage of building covered.

In many researches regarding greenery systems for energy saving in buildings, characteristics of the vegetation, such as plant species, canopy density and fractional coverage, have been regarded as the most significant parameters affecting thermal performance (Dvorak & Volder, 2010; Cameron et al., 2014). In the present study, the percentage of the roof surface covered by plants was not measured directly. However, it can be considered to be almost fully covered, since canopies were specially prepared by tying plants to form a uniform and consistent layer. The LAI of the canopies was 1.39 that also indicates a complete covering, though many studies on green roofs and green façades reported higher LAI (Kumar & Kaushik, 2005; Hunter et al., 2014). Higher LAI are also typical for many other planted environments. In forests the maximum LAI varies from 6 to 8. In agricultural fields LAI varies from 2 to 4 for annual crops with a mean LAI for grassland of 2.5 (Asner et al., 2003) According to the information available, increasing LAI in greenery systems for energy saving in buildings would result in improved thermal performance (Jaffal et al., 2012).

Results obtained in the present study showed that, in hot weather conditions and high sun load, providing greenhouses with plant canopies allows obtaining the same internal temperature as with traditional insulated coverings. The plant tested in the present study (*Trachelospermum jasminoides*) is evergreen and was selected for its wide availability and relatively low cost. However, using deciduous plants as shading in greenhouse-type buildings designed for livestock housing could really allow maintaining an adequate temperature during summer and benefit from direct solar radiation during winter. In order to fully evaluate costs and benefits of this kind of housing systems for dairy cows and potentially other farm species, future studies should be carried out during a year round period. Afterwards the trials could be replied in real-scale buildings with animals inside.

Both deciduous and evergreen plants should be taken into account as well as semi-transparent cladding materials. Furthermore, the ventilation properties of a plant canopy would deserve further investigation. Encouraging results obtained with PLA led to think a roof combining plant canopy with retractable roof systems may provide adequate temperature during hot weather and improve natural ventilation.

CONCLUSIONS

Results confirm that the employment of climbing plants as part of the building enclosure improves its thermal performance and has the potential to reduce energy consumption for cooling purposes. In hot weather conditions, greenhouse-type covering provided with plant canopies had the same internal temperature as an insulated roof. Compared with an artificial shading net, plant canopy produced a significantly lower internal temperature.

Outcomes of the present study suggest that greenery systems for energy saving in buildings and greenhouse-type structures can have a role in future development of housing systems for dairy cows and other farm species. Further studies could be required to verify the environmental conditions in real-scale livestock buildings with animals kept inside.

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