



Solar thermo-visual gain optimization of a building using a novel proposed nature-based green system

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Abstract

Nearly buildings consume 40% of the world's total energy. With the constant push to reduce energy consumption in buildings, a novel nature-based system is proposed for use in buildings. This novel solution is a controllable system that could control solar heat gain, solar illuminance while enhance urban green space and produce local organic vegetables with low water consumption. To assess the system performance, a paired comparison was made in two similar rooms, one with the novel system installed outside its window and the second as the control treatment. The experimental results show that the maximum recorded indoor air temperature and solar thermal gain reductions due to the system installation were 2.9 °C and 61%, respectively. However, it could also decrease useful daylight illuminance up to 22.9%. Therefore, to achieve a stable optimum thermo-visual comfort, the room indoor temperature reduction and useful daylight illuminance were optimized using NSGA-II (Elitist Non-dominated Sorting Genetic Algorithm). The novel system and building nexus provides optimum thermo-visual comfort and approximately 8 kg m⁻² per month organic vegetables for building residents. Finally, we proposed a performance flowchart for the transient control of the passive cooling and the natural daylight illumination of the room.

Keywords Building · Urban greenery · Useful daylight illuminance · Vertical green system · Solar heat gain

List of Symbols

<i>B</i>	Window width
<i>I</i>	Illuminance level/lux
<i>k</i>	Thermal conductivity/W (m K) ⁻¹
<i>t</i>	Time/s
<i>T</i>	Temperature/°C
<i>V</i>	Velocity/m s ⁻¹
<i>x</i>	Displacement/m

Subscripts

av	Available
ave	Average
max	Maximum
Opt	Optimum

Greek symbol

ρ	Density/kg m ⁻³
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Abbreviations

GH	Green house
LAI	Leaf area index
O.F	Objective function
PCR	Plants coverage rate
PDR	Plant displacement ratio
PED	Peak electrical demand
TCR	Total coverage rate
UDI	Useful daylight illuminance
VGS	Vertical green system

Introduction

Due to the expansion of industries and cities, the need for sustainable energy has increased. Applying consumptions management is one way to get out of the current situation. Several experimental and numerical studies have been published to provide strategies to manage energy consumption. About 40% of the world's total energy consumption relates to buildings [1]. Accordingly, appropriate consideration of energy in the construction industry leads to practical steps

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to achieve green low-energy buildings. The Heating, ventilation, and cooling (HVAC) systems account for 38% of total residential building energy consumption [2]. In this sector, preventing energy waste is one of the essential strategies to optimize energy consumption [3].

In this regard, researchers presented various plans to reduce energy waste by building boundaries and eliminating executive shortcomings. The use of natural solutions has been evaluated in many studies to decrease buildings' energy consumption. Applying plants in various ways, including vertical green systems (VGSs), is one of these methods. Based on the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommendation in Standard 62.2-2016, and Shao et al.'s research results [4], 100-plant-scale vertical farming in an average of 30 m² residential building with two occupant can reduce ventilating energy consumption at least 12.7%. The vertical green systems have widely been used in buildings: from highly engineered structures to the case where climbing plants are attached directly to the walls [5].

The VGSs energy-saving potential has been investigated in numerous numerical [6–9] and experimental [10–15] studies in different climate regions and building orientations [16]. Based on these papers, VGS helps to reduce a building energy consumption in four different ways. Firstly, it acts as a natural canopy against solar thermal radiation; secondly, as an insulator [17]; thirdly, as an evaporative cooler; and fourthly, as a wind blockage [18].

The evaporative cooling of the plant leaves and the substrate is significant. Many parameters, such as plant type, substrate type [1], planting method, and leaf size can affect the evaporative cooling capacity of VGSs. Perini et al. [19] stated that VGSs are natural canopies due to the reduction of building surface temperature compared to control ones. Perez et al. [20] experimentally showed that VGS has high protection against sunlight in the eastern, southern, and western views of the Mediterranean climate. They concluded that green facades could reduce the heat gain of the building drastically.

The effect of VGSs on the building-affected surface temperature was evaluated in some papers. Djedjig et al. [21] examined the thermal effect of a green wall system installed in four different directions of an office building during the summer over nine days. Evaluation results showed that the green wall reduced the outside surface temperature by an average of 1.3 °C. Pérez et al. [22] evaluated the effect of VGSs leaf area index (LAI) on building-affected surface temperature in a Mediterranean continental climate region in Spain. They believed that in addition to the fact that plants can play the role of thermal insulation in summer, they could also reduce heat loss in winter. The experiment results indicated that the LAI and the building facade orientation influenced on VGSs

energy saving amount. Hoelscher et al. [23] conducted an outdoor experiment in the summer on three different facades of a building in Berlin, Germany. Their scholar findings showed that the walls' surface temperature with green cover was up to 5.75 °C lower than the bare wall. In addition, the temperature of the inner wall showed a decrease of 1.7 °C during the night. In this regard, Olivieri et al. [24] have compared the thermal performance of two different vertical green coating systems. The evaluation results confirmed the high potential of these systems for energy saving. In several experiments, the indoor air temperature has been selected as a study parameter. Price et al. [25] evaluated the cooling ability of green walls. Their research indicated that the wall and indoor air temperature were minimized using VGS. Chen et al. [18] examined the effect of opening greening design on building indoor temperature. The selected plants were growing in pots. According to the results, the cooling effect of plants was about 1 °C. Haggag et al. [26] examined the use of green facades to reduce heat gain in indoor spaces in a high heat load climate. They claimed that the green façade could reduce the peak indoor temperature of summer daytime.

About 50% of the buildings' energy losses are through windows and doors. The effect of using the green solution in front of windows has been examined in some studies [25, 27]. The plants were attached permanently in front of the window in some related research works. As a result, they act as a barrier to light and heat even in cold and dark seasons like autumn and winter. Recently, Ren et al. [28] studied the impact of using window gardens on the passive cooling of buildings. They declared that a smart window garden would be a suitable potential for use in subtropical regions.

Movable plants ideas were developed in some valuable research works [29, 30]. However some of the existing ideas, due to the presence of soil in the system, impose an extra load (density of plant soil is an average of 1400 kg m⁻³) on the building structure. In addition, movable systems must be as light as possible to move with little power. Furthermore, the roots must move along the bed to minimize plant shock. Therefore, the only possible way is to use a soilless planting system, for example, a hydroponic system.

Reviewing the above papers demonstrates that about 40% of the world's total energy consumption is related to buildings and windows have a significant effect on indoor temperature and energy consumption in different climate regions. Moreover, using plants on the buildings' surface as a green façade or in front of the windows seems to reduce the energy consumption of the building.

However, the use of these methods has one or more of the following deficiencies:

- In some cases, deciduous plants were applied that lose their capabilities in some seasons [10];

- Sometimes, heavy (substrate) VGSs were used which impose an extra load on building structure [28];
- Some window VGSs were not movable [27, 28];
- In some cases, the plants were exposed to outside uncontrolled weather conditions [6–15] which causes vegetables damage;
- The window systems mainly were non-controllable ideas [29, 30];

There was still a research gap and practical need for the construction and application of a novel building integrated system. Such a system, in addition to being a natural solar heat gain control system, would be more sustainable if it is an organic farm to produce food for the building residents and works as a natural daylight control curtain. The novelty of the manuscript lies in design, development, and optimization of a novel multipurpose building integrated nature-based system. The novel system and building nexus provides optimum thermo-visual comfort and organic vegetables for building residents, while it provides a one side thermal barrier for the plants.

Materials and methodology

Study area

In this study, the city of Mashhad was selected to conduct the experiments. This city is located at 36.31° North latitude and 59.53° East longitude at 1037 m above sea level and has a cold semi-arid climate (Köppen: BSk) with hot summers and cold winters. The system structure was fabricated, and installed at the Ferdowsi University of Mashhad.

In residential buildings in Iran, most buildings have only south-facing and north-facing windows. Based on the results of previous research [20], in the northern hemisphere, south wall receives more sunlight; thus, we select the south wall to install the system. The system was placed in front of the window of the building rather than the entire façade.

Experimental investigation

The proposed system dimensions were 2.1 m × 0.55 m × 1.2 m. It included the framework, plant cultivation sites, displacement, irrigation, rainwater collection, measuring, and control subsystems. The system's set-up is illustrated in Fig. 1. Plant cultivation site consisted of three moving pipe bases (NO. 5), each consisting of three rows of pipes with a 30 cm distance. The pipes (NO. 6) were U-shaped and made of PVC material. Inside the pipes, the cocopeat-perlite mixture was used as a hydroponic substrate for the plants. The pipes were equipped with a filter with a circular 1 mm fine steel mesh and a drainpipe to collect excess water inside the main pipe and transfer it to the tank. Each pipe contained four holes having 0.06 m diameter and 0.144 m distance for inserting the hydroponic pots. The PVC pipes are situated on the stepped manner base to prevent shading the upper rows on the lower ones and sunlight directly exposure to the lower plants. The transparent parts were made of polycarbonate (PC) (NO. 1) and poly methyl methacrylate (PMMA) (NO. 2) sheets. The system was covered with PC on side faces, and the front side was covered with a combination of PC and PMMA sheets. The displacement subsystem consisted of two DC (Direct Current) electrical motors, a power supply, gear racks, and pinions. The recirculating irrigation subsystem included three pumps, one air pump, and three water tanks (NO.7). This subsystem works for 20 s at eight time intervals every 1.5 h during daytime. The control subsystem

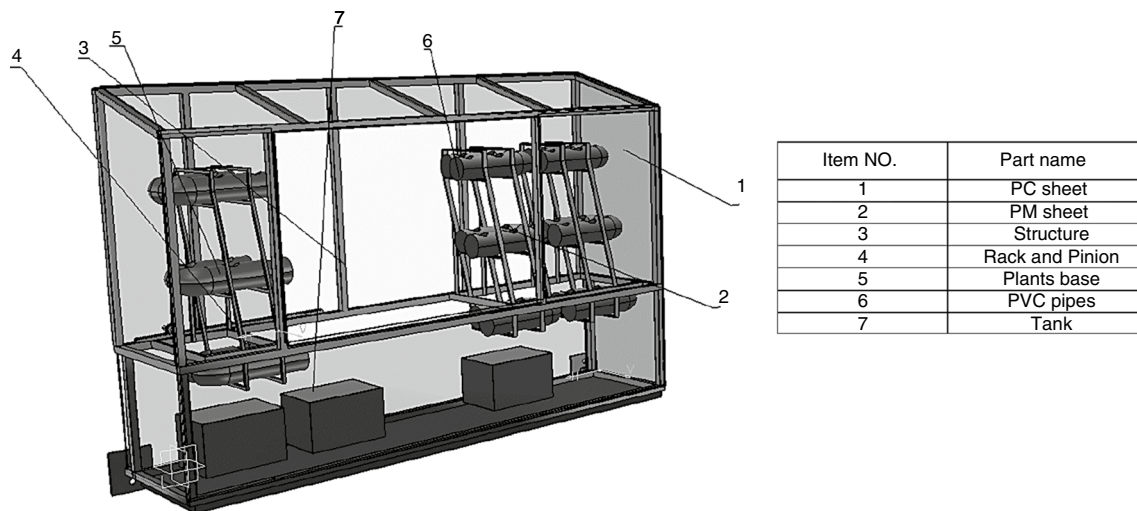


Fig. 1 Set-up of the novel system

could control irrigation times and frequencies, exposure times and frequencies, and movement of plant cultivation sites. The measurement and control subsystem included the thermocouples, digital timers, time counters, data loggers, etc. The rooms' indoor air temperature, the system air temperature, and the ambient air temperature were recorded every 5 min. The rooms' indoor air temperature were measured with thermocouples type K, which situated at same height in the middle of the rooms. The sensors were protected from solar radiation exposure. The details of the measuring apparatuses (Fig. 2) are as Table 1. The accuracy of experimental results depends on the accuracy of the individual measuring apparatuses. Based on Table 1, the total

uncertainty of the experiments were estimated to be 2.34%. In the experiment, two varieties of lettuce (Batavia lettuce and Romaine lettuce) were cultivated in the system.

The system provides some features simultaneously that will be mentioned below:

- Enable low-mass soilless farm by using a hydroponic system;
- It is an enclosed system; the only access to the system is through the window.
- Plants enable a natural indoor air purifier by consuming CO₂ and releasing oxygen [31];

Fig. 2 Some of the used measurement apparatus. **a** thermometer; **b** humidity meter; **c** PAR meter; **d** Lux meter



Table 1 The measuring apparatuses characteristics

Parameter	Measuring equipment	Range	Accuracy
Temperature	Thermocouple type K + Thermometer	- 50.0 to 999.9 °C	± (0.4% + 0.5) °C
Temperature	IR camera	- 20.0 to 120.0 °C	± 1% or 1 °C
Relative Humidity	Humidity meter	0.0 to 100.0%	± 0.1 RH
Illuminance level	Lux meter	0–99,999 Lux	± 3 Lux
PAR	PAR meter	0–1000 μmol m ⁻² s ⁻¹	± 1 μmol m ⁻² s ⁻¹

- It was an indoor available neat organic food production without using pesticides and chemical fertilizers;
- The system was portable, enable to carry to another place or building;
- It was movable and fully mechanized. The vertical farm had the ability of horizontal movement in front of building wall and window when necessary;
- Sustainable because of using recycled material in the construction of the system. The electrical motors were the remaining parts of a junk car, and used plastic bottles were used to fabricate the rain gutter;
- Enable Low energy consumption (passive cooling and food mile transportation [32]); Moreover, the pumps, the DC motors, and the control system cumulative electricity consumption were about 0.12 kWh, every 24 h.
- Reliable, the system, due to the use of three utterly separate irrigation subsystems, even if two pumps fail, it can continue to work with minimum capacity.
- Using PMMA to cover the system face parallel to the window. The thermal and mechanical properties of PMMA are as follows:

Low-mass ($\rho_{\text{glass}} = 2500 \text{ kg m}^{-3}$, $\rho_{\text{PMMA}} = 1180 \text{ kg m}^{-3}$), higher light transmission (PMMA=0.92), and lower thermal conductivity in comparison with glass ($k_{\text{PMMA}} = 0.17 - 0.25 \text{ W (m K)}^{-1}$, $k_{\text{glass}} = 0.55 - 1.4 \text{ W (m K)}^{-1}$), scratch and shatter-resistant, more Hydrophobic (PMMA water contact angle $= 72^\circ$, uncoated glass water contact angle $\sim 55^\circ$), and non-toxic.

Curtains have added for a time when residents want to grow plants such as *Peperomia obtusifolia* that may damage by intense sunlight. Some mentioned features would be discussed in detail in following sections. To investigate the system's performance, two rooms with the same dimensions ($3 \text{ m} \times 1.7 \text{ m} \times 2.5 \text{ m}$) and completely similar conditions in terms of orientation, sealing, and insulation were used. The rooms were located on the second floor of a building of 7 m in height. Each room had one south-facing window ($1.2 \text{ m} \times 0.9 \text{ m}$). The window-to-wall ratio was 0.21. The windows had double clear (3 mm + 6 mm air gap) glazing with PVC frame. Before installing the vertical farm in front of the plant room window, to validate the comparing results, the rooms' indoor temperatures measured and compared for two days (Fig. 3). As can be seen in this figure, the results of the test rooms were in good agreement. Furthermore, the maximum deviation is $\pm 0.4 \text{ }^\circ\text{C}$.

After justifying the rooms' thermal behavior, the novel system installed in front of the window of one of the test rooms (Fig. 4). As seen in Fig. 5, the vertical farm had the ability to horizontal movement when necessary, for example, to allow sunlight to enter the room at cloudy days. The displacement subsystem could enable horizontal velocity of $V = 0.05 \text{ m s}^{-1}$ manually or automatically.

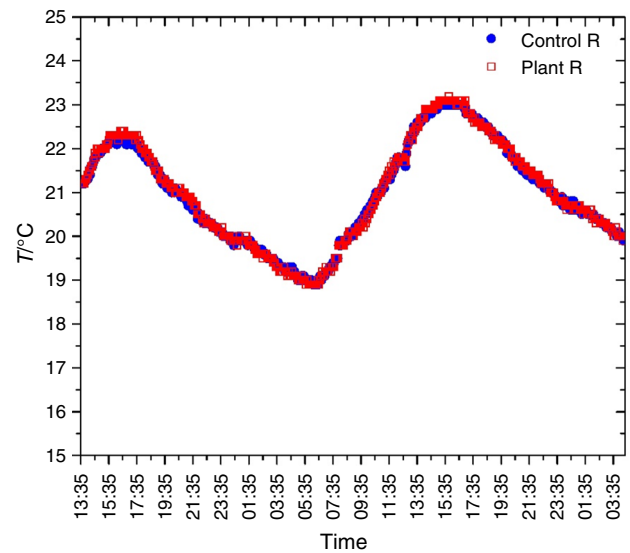


Fig. 3 Verification of the measurements

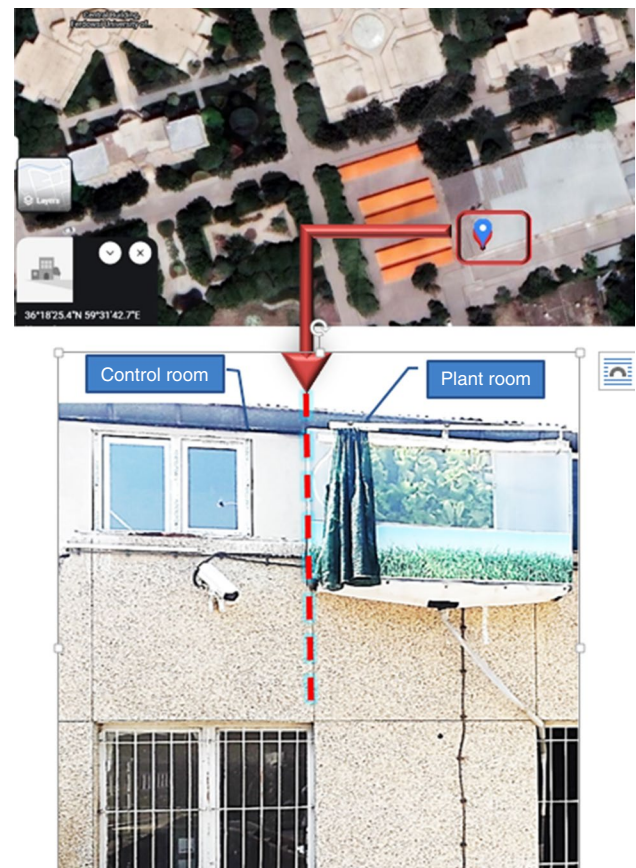


Fig. 4 The test rooms

In some previous research works, the concept of leaf area index (LAI) used to characterize the potential of the VGSs as a passive cooling system. Therefore, in current

Fig. 5 The horizontal movement of the vertical farm on a cloudy day allows sunlight to enter the room



research in order to study the effect of the plants density on energy-saving ability of the plants, the LAI will be calculated indirectly using Eq. (1) [22].

$$LAI = \frac{-\ln\left(\frac{PAR_{\text{below}}}{PAR_{\text{above}}}\right)}{0.9} \quad (1)$$

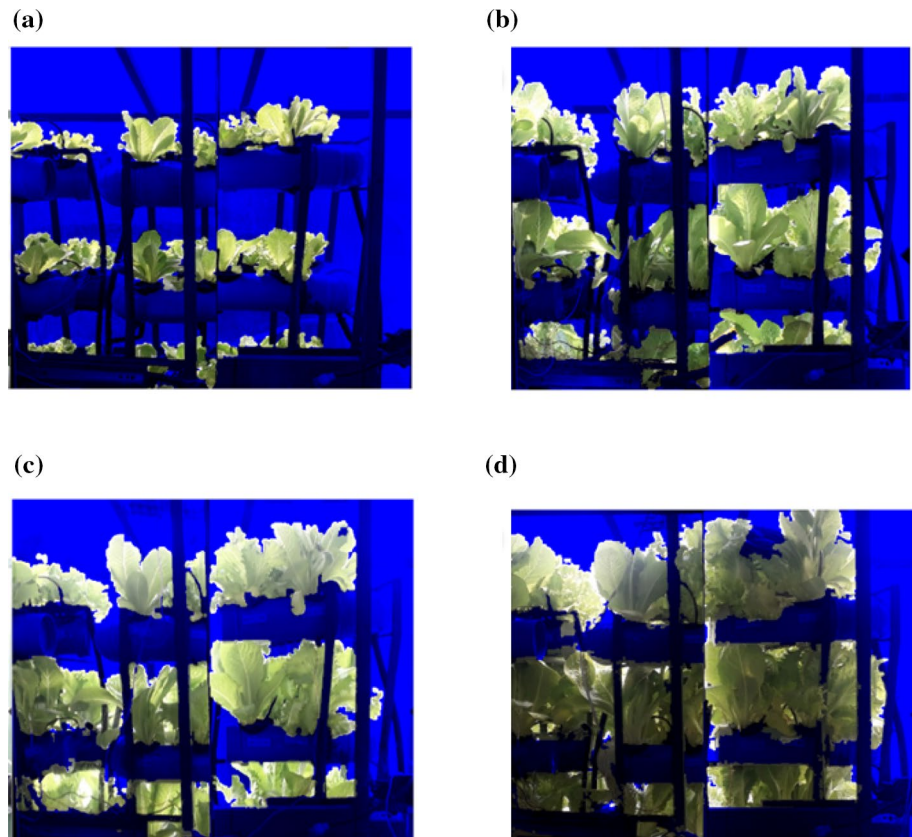
where PAR is the photosynthetically active radiation of plant.

Results and discussion

Indoor air temperature evaluation

In order to study the ability of the plants for passive cooling of the room, the trend of the plants coverage rate (PCR) was investigated. For this purpose, some photos of plant growth stages on different days (Fig. 6) taken, and the coverage rate was determined using a MATLAB code, the PCR, defined as the ratio of the level of pixels detected

Fig. 6 Refined shapes from different stages of the plants growth. **a** day 7; **b** day 14; **c** day 20; **d** day 27



(with bwarea function) as vegetation to the total number of pixels in the image, was calculated. The pictures captured at 7-day intervals. To verify the MATLAB code, the PCR of the first case was measured using a quadrat and the result was compared with the code outcome. The deviation of the results was 0.02.

Figure 7 depicts the variation of the time-averaged indoor air temperature difference between the plant and the control rooms with different PCRs at the daily hot season’s peak electricity demand time (noon—06:00 pm) in Iran [33] and 24-h during the growing period. According to the figure, increasing the coverage rate increases the temperature differences, which indicates the constructive effect of the plant coverage rate on passive cooling of the plant room. Regression analysis was performed on PCR and the ΔT_{ave} . The Pearson Correlation index and p values were 0.98 and 0.0014, respectively. The results revealed that the variables were statistically significant. Therefore, the plant coverage rate and the time-averaged indoor air temperature difference were highly correlated. These results agreed with the results of Kenai et al. [34]. The fitted lines’ intercepts values were almost equal. This result suggests that the plants’ coverage rate increment can increase the passive cooling ability of the system. The fitted line formulas used to automate the plants’ movements. Based on Fig. 7, the variation of ΔT_{ave} with PCR at daily PED is as Eq. (21).

$$\Delta T_{ave} = 2.30PCR + 0.55 \tag{21}$$

Considering the effect of non-vegetal objects coverage rate such as pipes, the equation rewritten as follows.

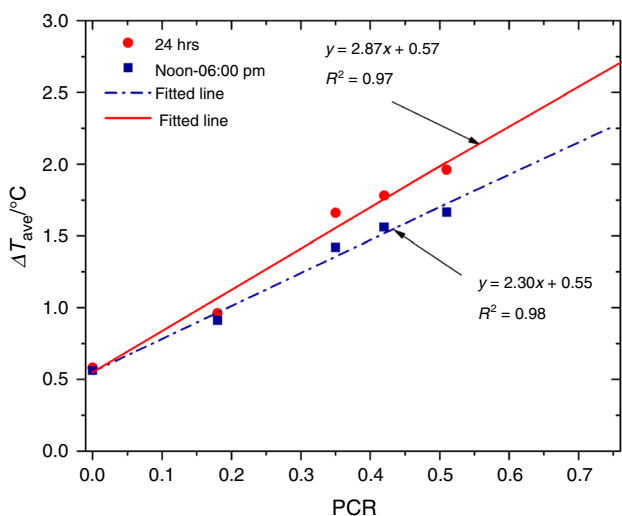


Fig. 7 Variation of the rooms’ time-averaged indoor temperature difference with PCR

$$\Delta T_{ave} = 2.30(TCR - 0.24) + 0.55 = 2.30TCR \tag{22}$$

where TCR and 0.24 represent the total coverage rate and the coverage rate of non-vegetal objects, respectively. As mentioned in the previous section, the system had the ability of horizontal movement when necessary. Assuming an x -meter displacement of the plants and considering the effect of the coverage rate of non-vegetal objects such as pipes, Eq. (4) rewritten as follows.

$$\left. \begin{aligned} TCR &= (PCR + 0.24)\left(1 - \frac{x}{b}\right) & 0 \leq x \leq b \\ PDR &= \frac{x}{b} \end{aligned} \right\} \Delta T_{ave} \tag{23}$$

$$= 2.30(PCR + 0.24)(1 - PDR) \quad 0 \leq PDR \leq 1$$

where PDR (plant displacement ratio) represents the ratio of plant displacement to the windows width.

In hot seasons, the peak electricity demand (PED) occurs in the afternoon due to the buildings’ air conditioning systems [33]. Hence, a solution for reducing the use of air conditioning systems will act as a PED shaver. Previous researchers, for example, Skelhorn et al. [35], declared that 0.7 °C indoor temperature reduction in residential buildings is equivalent to a 20% reduction in the HVAC energy consumption. Therefore, it is necessary to study the rooms’ indoor air temperature in order to evaluate the passive energy performance of the system. Figure 8 shows the rooms’ indoor air temperature and the ambient air temperature in five periods of 48 h. In all of these plots, the indoor air temperature of the plant room was lower than that of the control room throughout the day. During the experiments, the average and maximum-recorded indoor air temperature reductions due to the system were 1.7 °C and 2.9 °C, respectively. The result suggests that the novel system has the potential to act as a passive cooling system and as a result, it acts as a demand peak shaver for the electricity grid.

Thermal investigation

For LAI calculation, the PAR of the plants measured at different points of the system using a PAR meter. The measured values put in Eq. (1) to calculate the LAI of the system indirectly [36]. The average obtained LAI for the system was 5.3 using Eq. (4), which was a reasonable value (in the range of 2.6–7.7) for using as a natural canopy and passive energy cooling demand reducer [24].

In order to study the effect of using the system on the window solar thermal gain, this parameter of the rooms at PCR=0.51 (i.e. maximum investigated PCR) was compared in Fig. 9. According to this figure, the system drastically decreased the window solar thermal gain (about 61% at maximum solar thermal gain time). During the day, especially at the peak of sunshine (here 12:00 pm), the shading plants

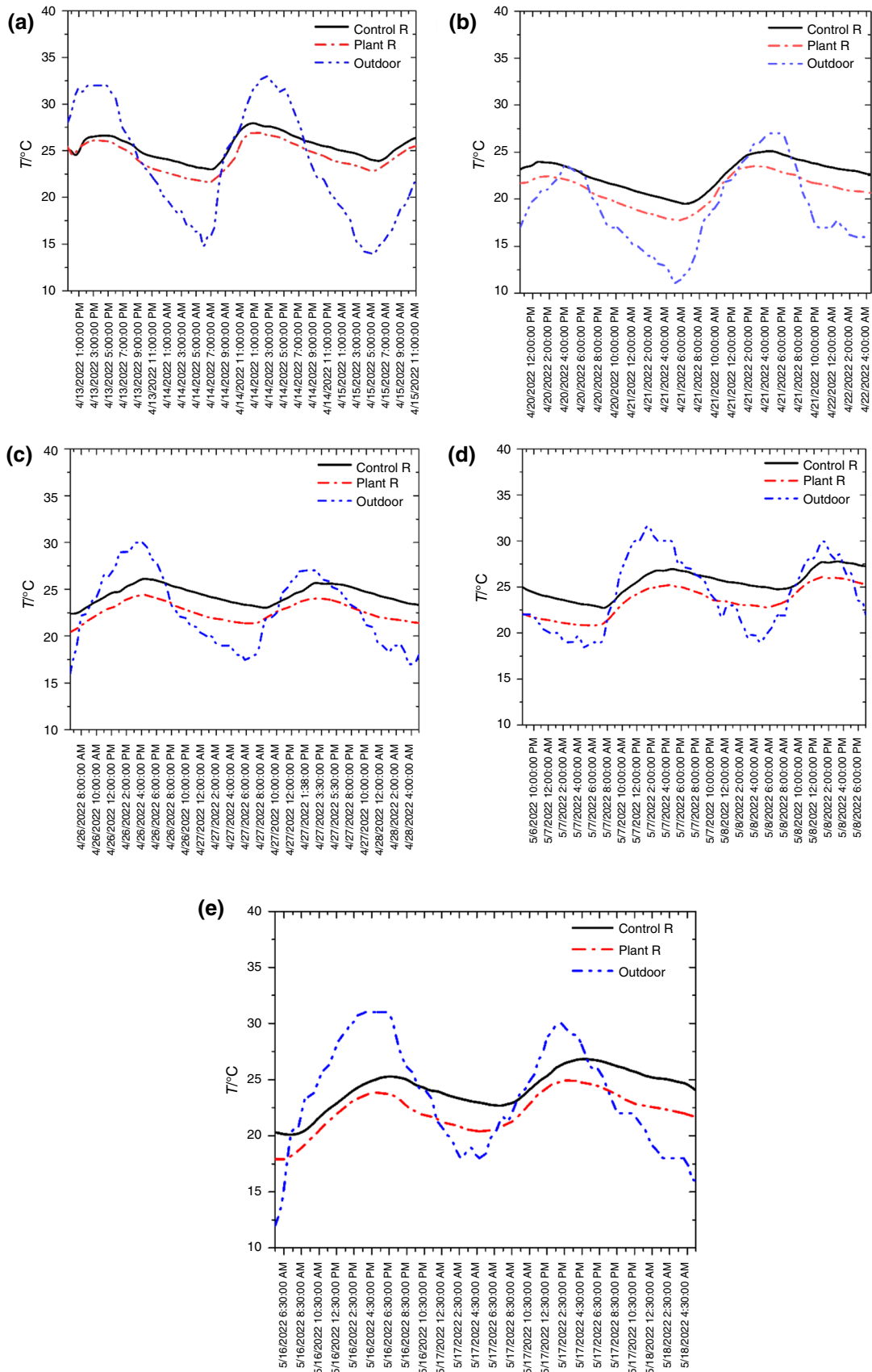


Fig. 8 Hourly variation of the rooms' indoor air temperature and the ambient air temperature in five time periods of 48 h: **a** the 7th day to the 8th day; **b** the 14th day to the 15th day; **c** the 20th day to the 21st day; **d** the 30th day to the 31st day; **e** the 37th day to the 38th day after the plants' cultivation day

reduce the solar thermal gain of the plant room. Refer to the figure, 8:00 am and 16:00 pm are the points that the rate of window solar thermal gain variation altered.

Finally, the indoor thermal images of the windows at 2:00 pm on two different days depicted in Fig. 10. The pictures have captured at the same distance from the windows. According to this figure, the plants had a significant impact on reducing the windows' glass and frame temperature at both days. However, the cooling effect of the plants on the sunny day was averagely 0.7°C higher than that on the cloudy day. Therefore, the plants not only reduced the plant room solar thermal gain but also they acted as natural canopies for window glass and frame as well. Consequently, the body temperature of the plant room window decreased, which resulted in reducing natural convection heat transfer from the window body to indoor air.

Daylight illuminance investigation

Although solar irradiance is effective in building indoor air temperature, visual comfort is greatly influenced by it [37] and therefore both thermal and visual effects were considered in some research works simultaneously [38–43]. In hot seasons, the plants displaced to locate in front of the window to block the solar thermal gain from entering the room. However, one of the side effects of the system was that the system blocks the visible spectrum of sunlight as well [41]. Then before starting to develop the performance flowchart, the impact of the system on the visible spectrum of sunlight transmittance will be discussed. In order to study the impact of TCR on natural daylight transmitted to the plant room via the window, the average useful daylight illuminance (UDI) level in the absence of artificial lighting at the working plane was investigated. UDI here is defined as a measure to quantify the plant growth period occurrence of daylight illuminances in the standard visual comfort range at different sky conditions. The standard illuminance level was considered within the range of 300–2000 lx [42]. Figure 11 illustrated the impact of TCR on the average UDI level. The value of average UDI at minimum TCR ($\text{TCR} = 0$) represented the average UDI of the control room at different sky conditions. This figure revealed that the average UDI decreases with the increment of TCR. Thus, the effect of TCR on the natural daylight illuminance level should be considered in the plants displacement control system. According to the figure, the variation of UDI with TCR is as shown in Eq. (5).

$$\text{UDI} = 30.02(1 - \exp(4.51(\text{TCR} - 0.68))) \quad (5)$$

Based on Eq. (5), the value of UDI would be zero at $\text{TCR} = 0.68$. Then this value of TCR assumed as the maximum limit of this parameter in current experiment, which means the plants would never blind the window completely and 32% of window area would not cover at maximum coverage rate. Assuming an x -meter displacement of the plants and considering the effect of the coverage rate of non-vegetal objects, Eq. (5) rewritten as follows.

$$\text{UDI} = 30.02(1 - \exp(4.51((\text{PCR} + 0.24)(1 - \text{PDR}) - 0.68))) \quad (6)$$

Multi-objective optimization

In current study to obtain the optimal performance of the plant room, the average temperature reduction and UDI were optimized using a multi-objective optimization algorithm [42]. The NSGA-II algorithm employed for optimization purposes [43]. The optimization criteria were as Eqs. (7–8).

$$\text{O.F(1)}: \frac{\Delta T}{\Delta T_{\text{max,av}}} = \frac{2.30(\text{PCR} + 0.24)(1 - \text{PDR})}{0.0156} \quad (7)$$

$$\text{O.F(2)}: \frac{\text{UDI}}{\text{UDI}_{\text{max,av}}} = \frac{30.02(1 - \exp(4.51((\text{PCR} + 0.24)(1 - \text{PDR}) - 0.68)))}{0.28622} \quad (8)$$

$$\text{Minimize} \begin{cases} -\text{O.F(1)} \\ -\text{O.F(2)} \end{cases} \quad (9)$$

The decision variables were PCR and PDR. Usually, the maximum number of iterations and objective functions tolerance are the solver's stopping conditions, which are shown in Table 2. Table 3 provides the upper bound and lower bound for each of the decision variables used in the optimization.

The optimization was conducted. The Pareto-optimal front for the objectives is depicted in Fig. 12. According to the figure, the optimization reduces the UDI but offers suitable average temperature reduction.

The closest point to the ideal point was selected as the desired optimal solution (Table 4). However, the Pareto front is a set of non-dominated solutions, and then choosing the optimal solution could depend on the preferences of the decision-maker and system requirements. PCR level is not controllable and it would increase with plants growth. However, the PDR is fully controllable. Then for optimal performance of the system, the values of optimum PDR at each PCR level were extracted from the Pareto front.

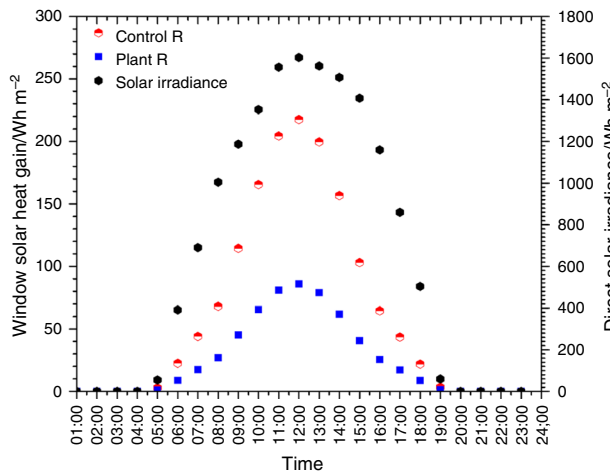


Fig. 9 Hourly local solar irradiance and the rooms’ windows solar thermal gain

Figure 13 shows the values of optimum PDR at each PCR level. The variation of the optimum PDR with PCR is as Eq. (10).

$$PDR_{Opt} = 0.56(1 - \exp(-6.58PCR))^{8.536} \quad (10)$$

The variation of the optimization criteria at each level of the PCR were shown in Fig. 14. Based on this figure,

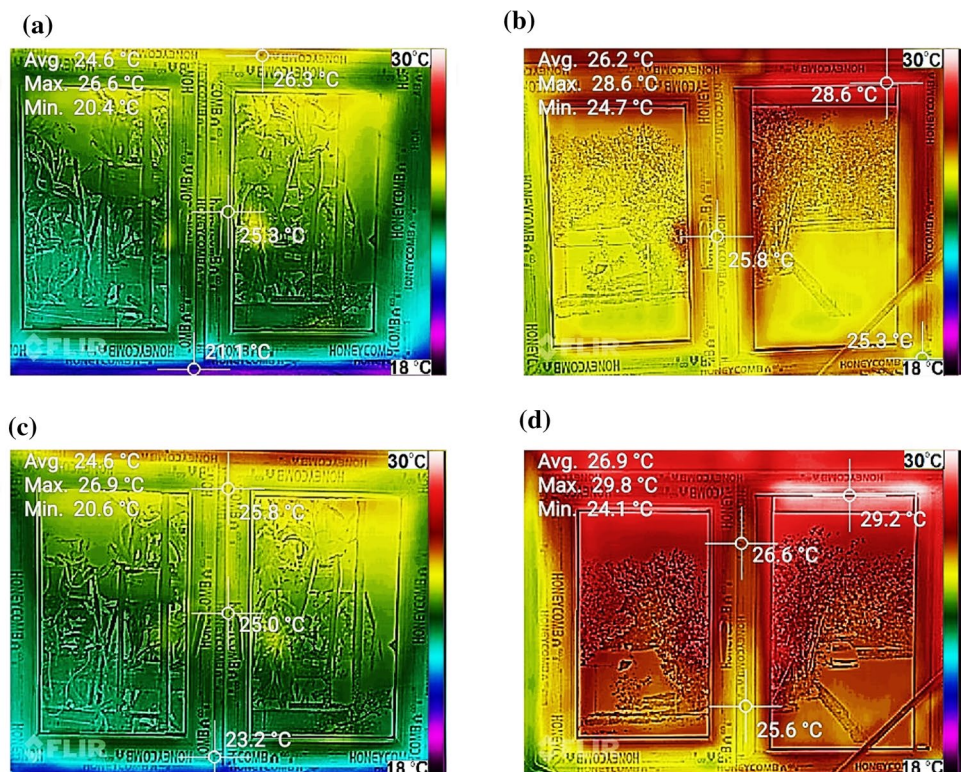
moving plants out of the window according to the Pareto front always keeps the O.F(1) around 66% and the O.F(2) around 68% when the PCR is above 0.25. The fitted curve of the optimal parameters with respect to PCR are as equations below:

$$O.F(1)_{Opt} = \frac{\Delta T_{Opt}}{\Delta T_{max,av}} = 66.12 - \frac{31.07}{1 + \exp\left(\frac{100PCR - 10.36}{4.25}\right)} \quad (R^2 = 0.97) \quad (11)$$

$$O.F(2)_{Opt} = \frac{UDI_{Opt}}{UDI_{max,av}} = 68.00 + \frac{21.19}{1 + \exp\left(\frac{100PCR - 13.09}{3.52}\right)} \quad (R^2 = 0.95) \quad (12)$$

At each PCR, Sensitivity analysis was conducted to study the effect of changing PDR on the performance of the system. Figure 15 presents the results of the sensitivity analysis. As can be seen, the effect of changing PDR, on $UDI_{Opt}/UDI_{max,av}$ is greater than that of the $\Delta T_{Opt}/\Delta T_{max,av}$. Moreover, $UDI_{Opt}/UDI_{max,av}$ is more sensitive to decrement of PDR, rather than increment of it.

Fig. 10 Indoor thermal images of the test rooms’ windows at 2:00 pm on two different days. **a**, and **b** refer to a cloudy day; **c**, and **d** refer to a sunny day



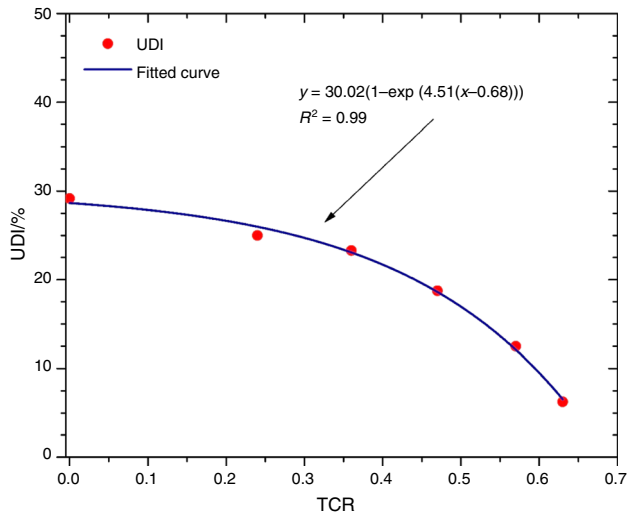


Fig. 11 Variation of the average UDI with the total coverage rate (TCR)

Table 2 Optimization stopping conditions

Converging condition	Value
Number of iterations	4000
tolerance	1e-4

Table 3 Range of decision variables

Parameter	Range
PCR	[0, 0.76]
PDR	[0, 1]

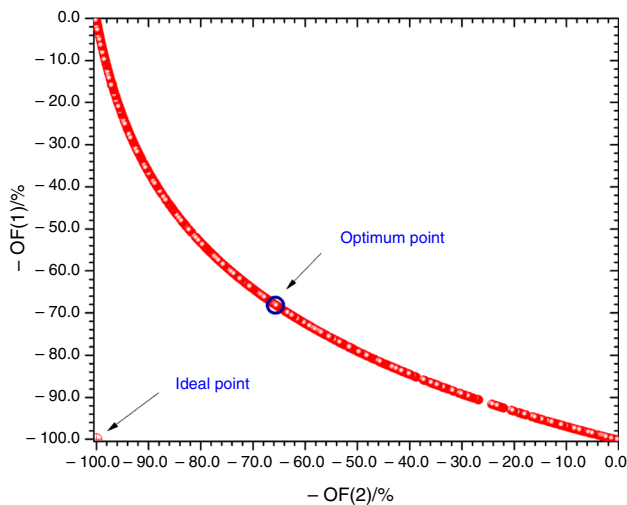


Fig. 12 The Pareto front

Table 4 Optimum point of the Pareto front

PCR	PDR	O.F(1)	O.F(2)
0.51	0.41	69.07%	65.12%

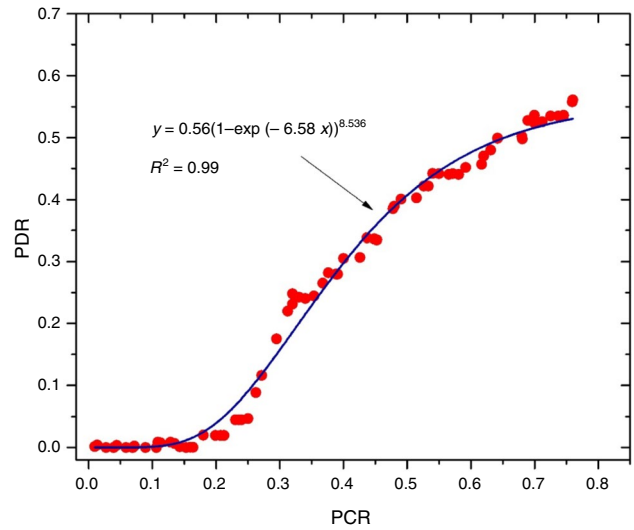


Fig. 13 The variation of the optimum PDR with PCR

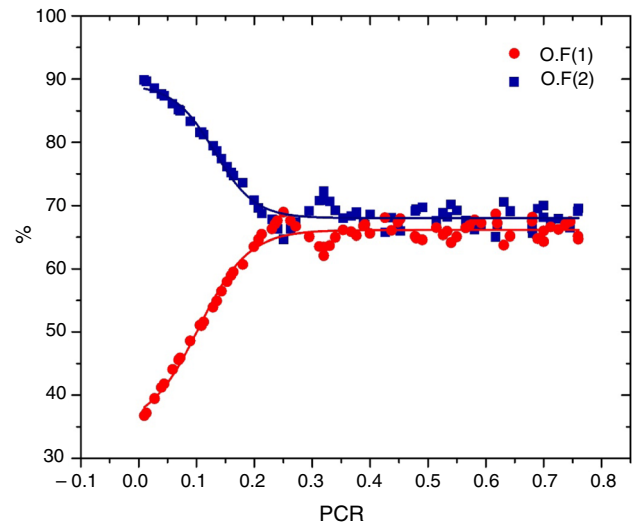


Fig. 14 The variation of the optimization criteria at each level of the PCR

The proposed performance flowchart

In this section, the flowchart of the displacement subsystem for optimal performance of the system is developed. Figure 16 proposed an in detailed flowchart of the automatic performance of the plants displacement subsystem. In summary, the performance of the displacement subsystem in hot seasons would be as follows: At sunrise, to allow maximum

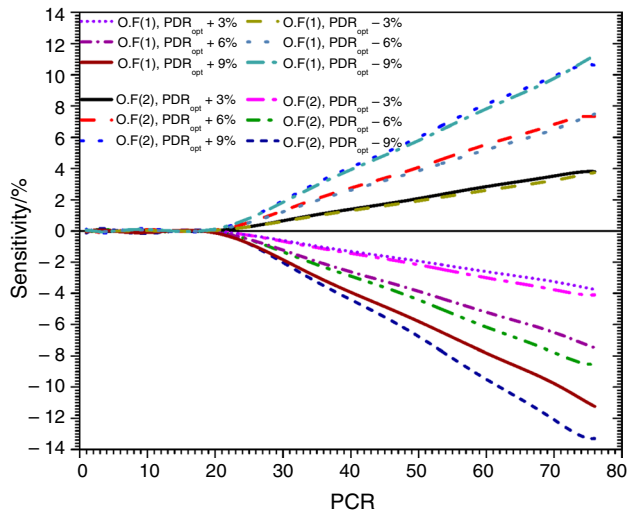


Fig. 15 Sensitivity analysis

natural daylight to enter the room and use the window landscape, the plants displace to pull away from in front of the window. After that, at 8:00 am, when the rate of window solar thermal gain increased (according to Fig. 9), and sunlight directly reaches the window, the plants are displaced partially to locate in front of the window. The amount of the optimum displacement (x) is a function of the window width and is calculated using current day PCR level and Eq. 9. At sunset, the plants displace to place entirely in front of the window. It is important to mention that the horizontal movement of plants is manually available, the residents can

easily move the plants to use the landscape all over day, and it would not effect on plants quality and growing process.

The lettuce seedling were planted in the system and the lettuce production was approximately 8 kg m^{-2} per month. The water used in this hydroponic lettuce farming system was about 0.08 m^3 , which was much lower (about $0.096 \text{ m}^3 \text{ kg}^{-1}$) than in field farming [40]. Moreover, the volume of collected rainwater during the experiment period was 0.04 m^3 .

Limitation and future development

- The proposed novel system was studied in semi-arid climate. However, repeating the process followed in this study for applying the novel system on various climate zones and proposing new performance charts is highly recommended.
- Since the novel system is an enclosed system, it is possible to use it in other climate regions, so it is suggested to investigate the novel system performance in other climate regions as well.
- Based on the results of previous research [22], in the northern hemisphere, south wall receives more sunlight; thus, the novel system performance was only investigated on south window as a case study. However, applying the novel system on other orientations windows is proposed.

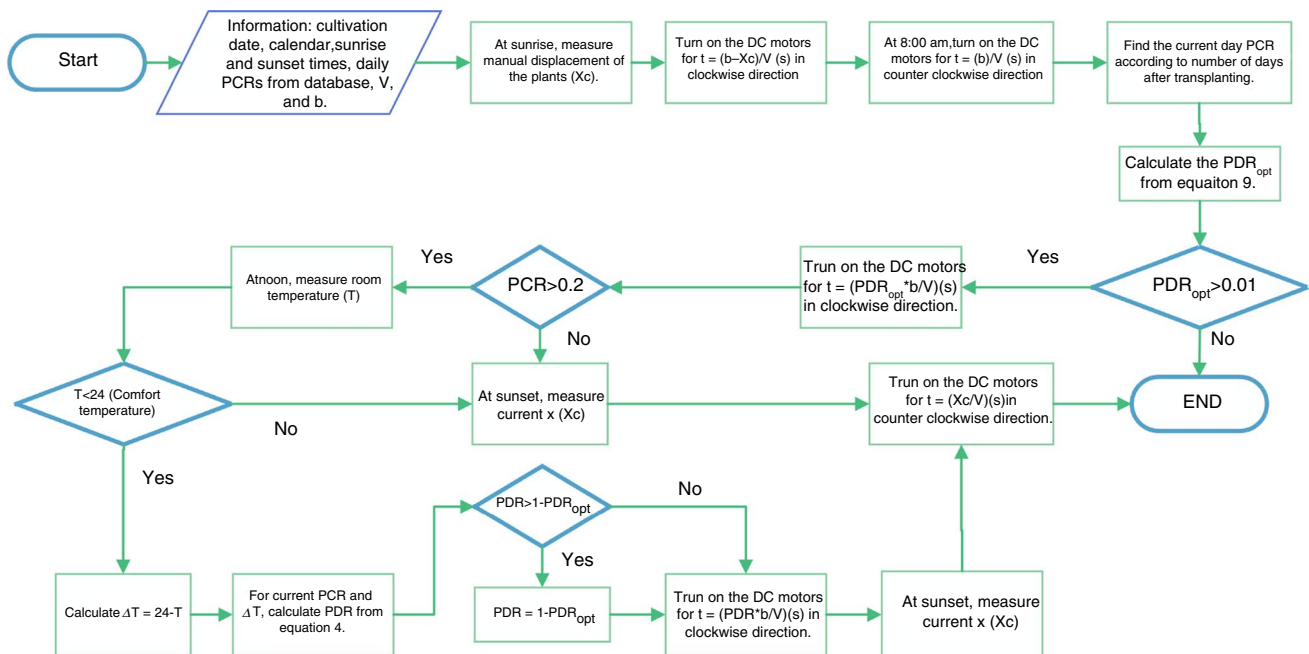


Fig. 16 The proposed flowchart of the displacement subsystem

Conclusions

The aim of this research was relied on the design and development of a novel practical controllable system for solar thermo-visual performance optimization of a building and use the benefits of a small-scale automated vertical farm in a building simultaneously. For this purpose, two rooms in the Ferdowsi University of Mashhad located in a semi-arid climate region were used. One room with the novel system installed outside its window and the second room with typical window installations as the control treatment. The experiments were successfully conducted and the significant conclusions of the research are as follows:

- During the experiments, the average and maximum recorded passive cooling due to the system were 1.7 °C and 2.9 °C, respectively.
- At maximum investigated PCR, the system provided about a 61% reduction in the maximum window solar thermal gain. However it decreased the useful daylight illuminance up to 29.2%
- Increasing the PCR increases the passive building cooling. However, it decreases UDI.
- PCR increased with the plants growth. The values of optimum PDRs at different PCRs level were determined by multi-objective thermo-vision optimization.
- The system performance flowchart was proposed for the smart transient control of the passive cooling and the natural daylight illumination of the room, which reduces drastically the probable side effect of the system and keeps the UDI at the optimum level.
- The water used in this hydroponic lettuce farming system was about 80 L, which was much lower (about 0.096 m³ kg⁻¹) than in field farming.
- The plants do not cover the window during most of the time (especially in cold seasons) and they do not affect the main functions of a window that are the view, landscape and daylighting.
- Some features of the system are as follows:
 - Low-mass soilless farm (hydroponic system).
 - The system provided the passive cooling and the UDI control.
 - Low space occupying system. The system volume was about 1.23 m³.
 - The system included a rainwater collector subsystem. The volume of collected rainwater during the experiment period was 0.040 m³.
 - The system provided indoor available neat organic food production (no pesticide). The produced lettuce was approximately 8 kg m⁻² per month.

- The system was movable (Horizontal movement) and fully mechanized.
- The system was sustainable because of using recycled material in its construction process (i.e., the DC motors and the rain gutter).
- The system was highly reliable, due to the use of three utterly separate irrigation subsystems.

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Author contributions Dr. MMN: Designing, set-up preparation, Writing original draft, Visualization, Methodology, Optimization, Validation, Investigation. Dr. RK: Supervision, Conceptualization, review and editing, funding acquisition. Dr. FK: Contribution in the plants selection, preparation and treatment, review and editing. MJ: Contribution in the plants selection, preparation and treatment.

Declarations

Conflict of 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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