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ORIGINAL STUDY

Investigation of Greening Façade and Retrofitting Strategies on Outdoor Thermal Comfort and Indoor Energy Consumption in New Assiut City, Egypt

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Abstract

This study aims to investigate the effect of greening façades and roofs on the outdoor thermal comfort of residences and indoor energy consumption within the context of different retrofitting strategies. The proposed methodology consists of two main stages, first Envi-met will be used to model the base case and study the effect of green walls and roofs on outdoor thermal comfort, then DesignBuilder will be used to estimate the annual energy consumption of the base case and six retrofitting strategies. An investigation was performed for a new residential complex Youth housing sector in New Assiut City as a model of public low-income housing in many Egyptian desert cities. The results concluded that a significant reduction in Physiological Equivalent Temperature (PET) is achieved in the canyon between buildings using green walls, a reduction that ranged between 4.20 °C and 11.20 °C. Furthermore, the integration of green walls with different retrofitting strategies (wall and roof insulation and replacing lamps with light emitting diode (LED) units) achieved a further reduction in energy consumption that reached 32.67% in the weather file of 2020. Additionally, the usage of green walls and roofs in the case study is considered an appropriate strategy for the residential existing buildings, besides its durability, low economic required compared with other strategies such as adding concrete shading, its role in preserving the environment, ease of implementation by the residents, and applicability in different Egyptian desert cities. Finally, the findings generate wider benefits for a residential community of low-income people.

Keywords: Coupled simulation, DesignBuilder, Energy consumption, ENVI-met, Outdoor thermal comfort

1. Introduction

Recently, a rapid increase in energy consumption has occurred inside residential buildings in Egypt due to the raising in living standards and comfort requirements. It is known that buildings' façades have a significant influence on indoor thermal comfort and, consequently, buildings' energy consumption. Recently, various studies have illustrated how buildings' façades and green roofs and façades can affect outdoor temperature ranges and their role in improving outdoor thermal comfort. For example, Envi-met was used to investigate the influence of vertical vegetation; trees, grass, and shrubs on the residential building Liao and colleagues (Liao et al., 2021). The results indicated that trees have the highest effect by 0.49 °C and 17.7 °C for air temperature (Ta) and mean radiant temperature (MRT), respectively, and that trees could reduce the heat load of the adjacent façades. Abdallah and Mahmoud (2022) have used Envi-met in studying the effect of six scenarios on improving outdoor thermal comfort in a hot climate zone in Egypt. Consequently, the reduction of PET reached 19.1 °C in the deep by applying a hybrid scenario of grass, trees, and semi-shading at 50%. Also, four mitigation techniques(cool pavements, cool coating façades, and roofs, green walls with ivy and green roofs, and a combination of those) have been assessed by using Envi-met by Zhu and colleagues (Zhu et al., 2021). It was revealed that the reduction of the surface temperature (Ts) of walls

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and canopy's Ta have occurred based on green walls and roofs and the cool pavement, respectively. Additionally, Knaus and Haase (2020) have conducted a simulation process to study the effect of greening on the rooftop on improving outdoor thermal comfort in a residential building in Berlin, Germany. Consequently, the Physiological Equivalent Temperature (PET) has declined by 9 K. Furthermore, Li and colleagues (Li et al., 2021) have used Envi-met to analyze diverse greening patterns. It was found that the modular green wall pattern has the highest proportion of livable (68.22%), then the liner green wall pattern and the green wall by 60.06% and 56.83%, respectively. Therefore, the patterns of liner green walls and modular green walls are suitable for a hot climate in contrast to green walls Li and colleagues (Li et al., 2021).

Finally, the *T*mrt has been observed in front of two buildings; the first façade was half-greened, whereas the second façade with part is bare by using ENVI-met, RayMan, and SOLWEIG Janicke and colleagues (Jänicke et al., 2015). It was found that *T*mrt was reduced by 2 K and short-wave radiation was reduced by 14.39 W/m^2.

1.1. Effect of green walls on indoor energy consumption and thermal comfort

Furthermore, various studies have discussed different types of green walls as being one of the most promising technologies for reducing the cooling demand in hot climate zones. Yang and colleagues (Yang et al., 2018) investigated the cooling performance of a double-skin green wall in four directions of the administrative building on the Shanghai University campus. The reductions in indoor Ta were 5.5 °C and 3.3 °C for the southern and northern façades, respectively. Further, the indoor thermal improvement reached 2.7 °C and 1.9 °C on the southern façade northern façade, respectively. Djedjig and colleagues (Djedjig et al., 2016) have studied the influence of green walls and mass flow on buildings' energy loads and simulated them by TRNSYS program. The results showed that green walls can reduce 37% of the cooling load and mitigate the thermal conditions within street canyons.

A comparison between traditional roofs and green roofs has been conducted by using EnergyPlus software in eight cities in Mexico by Ávila-Hernández and colleagues (Ávila-Hernández et al., 2020). The results indicated that green roofs could reduce the indoor temperature by 4.7 °C, CO_2 by 45.7%, and cooling energy demand by 99%. Furthermore, Hoffmann and colleagues (Hoffmann et al., 2021) have measured the energy-saving potential of one-layered façade greenings by proposing a model of numerical heat–mass transfer. Thus, the model calculates temperature and energy, and outflows for nine walls. Green Façade could reduce the exterior and interior wall temperature by 17 K and 2.9 K, respectively, in addition to energy savings ranging from 2 to 16 kWh m−2. Bano and Dervishi (2021) have analyzed the effect of three green and glazing façade scenarios on energy consumption reduction by using DesignBuilder software. It was found that the reduction of energy has ranged from 9% to 11% by applying 50% windows-to-wall on the façade. In addition, the energy-saving of a scenario of a fully glazed building was 34%, in addition to 4.7 °C and 9 °C reductions in indoor temperature and radiant temperature, respectively. Moreover, the heating and cooling load reductions of three buildings with green walls at the Korea Advanced Institute of Science and Technology campus have been investigated by Poddar and colleagues (Poddar et al., 2017) by using DesignBuilder software. It was found that the energy-saving value of green walls is 31%, whereas the demand for heating and cooling could reduce by 60% and 10%, respectively, in residential buildings.

1.2. Effect of retrofitting strategies on energy consumption reduction

Several studies have illustrated diverse retrofitting strategies to reduce energy consumption inside residential buildings. Al Saadi and colleagues (Al Saadi et al., 2017) have used simulation programs such as DesignBuilder to investigate the effect of retrofitting strategies on improving the rationalization of energy consumption for a residential building in Oman. It was found that there is a considerable impact from insulating the external walls and roof, in addition to usinglight emitting diode (LED) lights, on minimizing energy consumption. Finally, combining the best strategy from each category could reduce building energy consumption by as much as 42.5%. On the other hand, an optimization algorithm NSGA-II and DesignBuilder were used to evaluate the performance of shading devices and to determine the optimal one Zhao and Du (2020). Additionally, Hema and colleagues (Hema et al., 2021) have tested triple-layer wall materials as insulation material to improve indoor thermal comfort. The results revealed that the highest reduction in indoor temperature was obtained when the triple-layer wall material was placed inside to prevent overheating. Additionally, Prakash (2015) has studied the influence of insulation layer-wood wool in walls and roofs by using the computational fluid dynamics technique. It was obtained that the Predicted Mean Voted (PMV) by the indoor thermal comfort index has been improved by 3%. Moreover, Golasi and colleagues (Golasi et al., 2019) have examined the effect of LED lighting on indoor Ta and thermal comfort. It was revealed that the Ta increased by to 1.02 °C after using a LED cold light instead of a warm LED light. Finally, O'Donovan and colleagues (O' Donovan et al., 2021) have used the TRNSYS 17 model to simulate the combination of 10 passive cooling strategies in Dublin. It was revealed that passive cooling strategies assisted in improving indoor thermal comfort by a range between 57% and 95%.

1.3. Coupled simulation for indoor and outdoor environments under climate change

A set of studies has illustrated the influence of vertical vegetation and green walls on outdoor and indoor thermal comfort to achieve high performance of thermal comfort in exterior and interior spaces addressed together to adapt to future climate changes. For instance, Fahmy and colleagues (Fahmy et al., 2020) have proposed a coupled simulation process integrated between Envi-met and DesignBuilder to study the influence of climate changes in the future on outdoor and indoor thermal comfort. Hence, the effect of strategies; trees, green walls, and roofs have been studied on residential buildings' façade, and their results have been compared in the present time and in 2050, and 2080. It was found that passive mitigation procedures, such as green walls, could reduce Ta by 1.40 °C and 2.04 °C and energy consumption by approximately 6% and 7% for the two buildings by 2050. Similarly, the influence of urban morphology and geometry scenarios on indoor energy consumption has been investigated by Mahmoud and Ragab (2020) at present time and in the future in 2035. Thus, the results of outdoor thermal comfort and energy consumption have been obtained by Envi-met and DesignBuilder, respectively in 2020 and 2035. Consequently, a reduction in energy consumption has occurred by a range from 6% to 9% within applying the scenario of deep canyon (H/W = 1.5) by 2035. This set of studies has illustrated the importance of evaluating the energy consumption of residential buildings, whereas many designers seek to balance improving indoor thermal comfort and reducing the energy demand Bano and Dervishi, Poddar and colleagues, Fahmy and colleagues, Zhao and colleagues (Bano and Dervishi, 2021; Poddar et al., 2017; Fahmy et al., 2020; Mahmoud and Ragab, 2020; Andric and Al-Ghamdi, 2020; Andric et al., 2020; Zhao et al., 2017). Additionally, various strategies play the main role in saving energy consumption and can be either implemented inside the building, such as LED lighting or integrated with the building's envelope, such as a green wall Widiastuti and colleagues (Widiastuti et al., 2020); Avila-Hernández et al., 2020; Hoffmann and colleagues (Hoffmann et al., 2021). Moreover, the combination of these passive strategies, such as using insulation walls with LED lighting, may have a more positive effect Zhu and colleagues (Zhu et al., 2021). Furthermore, there is a need to assess the efficiency of these strategies not only in the present time but also in the future to guarantee indoor thermal comfort throughout the coming years Fahmy and colleagues, Mahmoud and Ragab, Ismail and colleagues, Sanchez-Garcia and colleagues (Fahmy et al., 2020; Mahmoud and Ragab, 2020; Ismail et al., 2021; Sabunas and Kanapickas, 2017; Sánchez-García et al., 2019) because climate change could have both negative and positive effects on energy consumption Flores-Larsen and colleagues (Flores-Larsen et al., 2019). Few researchers have studied the usage and impact of a set of retrofitting strategies for reducing the energy consumption of residential buildings in new Egyptian desert cities by integrating coupled simulation of the outdoor environment. Therefore, the novelty of this study is represented in proposing a coupled-aim methodology to study the influence of integration of retrofitting strategies such as green walls and roofs to reduce the heat transfer to indoor spaces and reduce solar radiation in outdoor spaces. Hence, the outputs of this methodology are improving outdoor thermal comfort and so for reducing energy consumption, consequently encouraging outdoor social activities among the residents. The main aim of this present study is to improve the outdoor thermal comfort of residential outdoor spaces, indoor thermal comfort, and energy consumption rationalization in the current time by integrating different retrofitting strategies. Besides, predicting the efficiency of these strategies with the expected height of Ta and climate changes in the future and its performance on indoor energy consumption and thermal comfort. Residential complex Youth housing in New Assiut city was selected as a model of public low-income housing in many Egyptian desert cities. As a result of that, improving the thermal comfort and energy consumption for low-income Egyptian people will reflect on the general improvement of thermal comfort and rationalization of energy consumption in the country. Accordingly, this improvement lightens the load on the public energy grid and on the government, so that is considered the significance of this paper. Additionally, the usage of green walls and roofs in the case study is considered an appropriate strategy for the residential existing buildings, besides its durability, ease of implementation by the residents, and applicability in different Egyptian desert cities.

2. Methodology

First, the investigation was conducted for the indoor environment inside one of the youth housing buildings in New Assiut city, and four data logger measurement devices were inserted inside different orientations facing the outer courtyard. The third floor (middle) was chosen for monitoring so that no effect of high solar radiation on the top floor. The Ta, relative humidity (RH), were measured using data loggers- Thermos Recorder model TR72Ui with measuring accuracy: ±1%RH, ±0.1 °C during the one of the hot months; August 2014 and the devices were calibrated with the reference device. Based on applying an efficient hybrid scenario of grass, trees, and semi-shading 50% Abdallah and colleagues (Abdallah and Mahmoud, 2022), this study will investigate the influence of other retrofitting strategies and green walls and roofs on outdoor thermal comfort and indoor energy consumption as described in the first step.

Second, an investigation of the effect of a green wall integrated with building façades was studied on outdoor thermal comfort and building surface temperature to decrease heat transfer for the indoor environment and decrease discomfort hours using ENVI-met 4.4.5 numerical software. Third, an investigation for energy consumption reduction was conducted due to the integration of a green wall using DesignBuilder software and coupled simulation ENVI-met. In addition, an investigation of applying different retrofitting strategies to a building with respect to its impact on annual energy consumption was conducted. Two models were validated. First, outdoor measurements conducted in August 2014 were compared with the results of the Envi-met software to validate the model. Second, the actual measured temperature in an apartment of youth housing on the third floor in August 2014 were compared with the numerical model of DesignBuilder to validate the model (Abdallah, 2015). The simulation period to evaluate outdoor thermal comfort was selected between 8:00 a.m. and 8:00 pm due to the effect of solar radiation on the outdoor and residents conducting different activities in an outdoor environment. Fig. 1 shows the steps of the methodology adopted. The two strategies adopted to investigate their performance on outdoor thermal comfort are green walls and green roofs

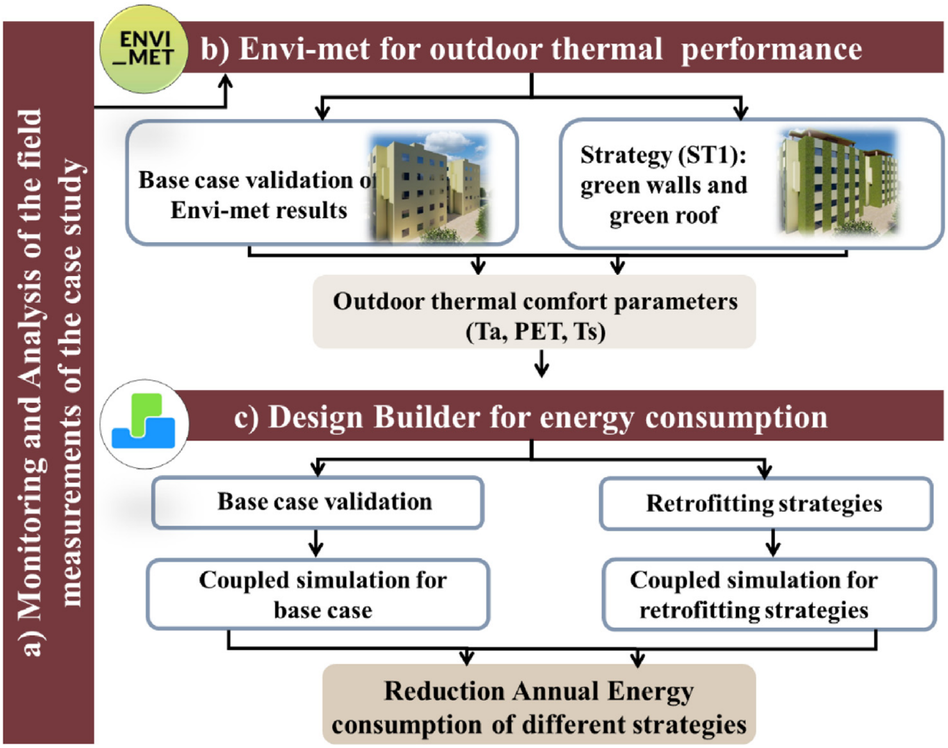


Fig. 1. The methodology adopted for this research.

using ENVI-met. The studies that have addressed applying vertical vegetation in Egypt have elaborated the importance of the role played by green walls in mitigating the outdoor effect on the indoor thermal quality and energy consumption in hot dry zones like Egypt such as (Fahmy et al., 2020). From the merits of green walls and roof are; a) mitigation of urban heat island, b) improving outdoor thermal comfort by reducing Ta, c) reducing the area of solar radiation of building, d) reducing heat gain for indoor spaces, e) improving indoor energy consumption by reducing cooling energy demand, f) adaptation method to climate changes in future and g) ease of applicability in existing buildings Fahmy and colleagues, Momtaz (Fahmy et al., 2020; Momtaz, 2018). Accordingly, the impact of green walls and roofs reflects on both outdoor and indoor thermal comfort which makes it more efficient than other passive strategies such as the reflective cooling strategy which affects indoor thermal comfort only. In addition, the new drip irrigation method contributed to reducing the required amount of water in such desert cities Fahmy and colleagues (Fahmy et al., 2020). Therefore, Fig. 2 shows the proposed scenarios for green walls and roofs using ENVI-met simulation software. The parameters of green walls and roofs for the simulation process are shown in Fig. 2c. A green wall has been hung using steel frames as the main structure and inner layer and steel net to hold plants. In addition, there is an air gap of the distance of 10 cm between the vertical plants and the actual building façade to prevent transferring of heat gain, besides distributing the irrigation system on each floor. The outdoor layer consists of the loam soil and plants, Ivy is selected as being climber plant and native in Egypt Fahmy and colleagues, Momtaz (Fahmy et al., 2020; Momtaz, 2018). Thus, the layer thickness is about 30 cm to reduce solar radiation and prevent high heat from reaching indoor spaces. Also, the green roof is a height of 3 m than the concrete roof for easy usage by residents, and its layers are layer consists of loam soil and Ivy plants with a thickness of 30 cm.

Six retrofitting strategies have been proposed to investigate their performance on annual energy consumption in DesignBuilder software based on their feasibility and the literature review. These scenarios are replacing existing lighting units with more efficient LED units; adding wall insulation; roof insulation; adding wall insulation with increasing roof insulation; horizontal louvers for windows; and combining wall and roof insulation with replacing LED lighting units. Table 1 provides the description of the six strategies simulated in DesignBuilder. Three cases were studied using the DesignBuilder software. In the first case, energy consumption and indoor thermal comfort were improved for the existing building (base case) using

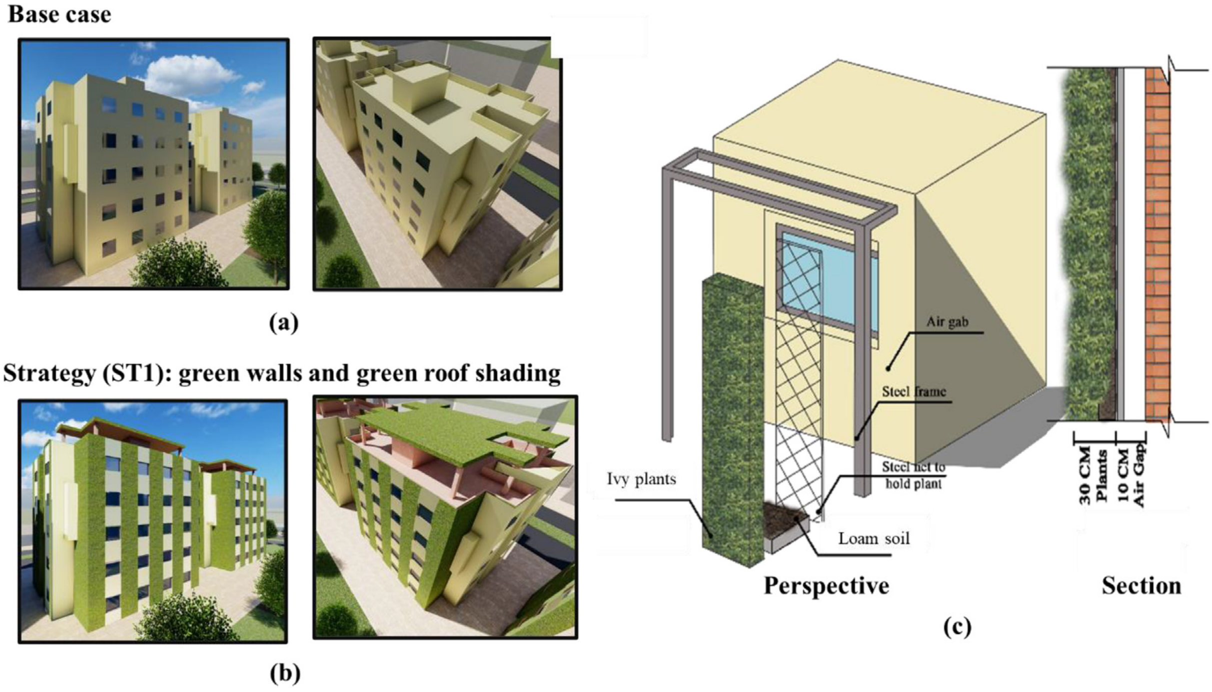


Fig. 2. The proposed scenarios for the youth housing sector using ENVI-met software; (a) the base case, (b) the strategy ST1 of green walls and green roof shading, and c) green wall components on building walls.

Table 1. Description of six strategies used in Envi-met and DesignBuilder.

Strategy:	ST1	ST2	ST3	ST4	ST5	ST6
	Green walls and green roof shading	Wall insulation	Roof insulation	LED lighting system	Wall and roof insulation	Wall and roof insulation and LED lighting system
Wall Material:	[01AGDS] Green wall with greater leaves 90% Ivy tree thickness = 30 cm Soil is Loam thickness 5 cm Air gab = 10 cm	Passive wall by thermal tiles for good insulation by rigid foam boards	Brick wall (12 cm) with no insulation	Brick wall (12 cm) with no insulation	Passive wall by thermal tiles for good insulation	Passive wall by thermal tiles for good insulation
Roof Material:	[01NADS] Green roof on the top of roof shading on height 2.7 m Ivy tree thickness = 30 cm Mixed substrate thickness = 5 cm Soil is Loam thickness 5 cm	Squirrel tiles	Thermal insulating tiles is made from Extruded foam with white cement layer reinforced with fiber mesh	Squirrel tiles	Thermal insulating tiles is made from Extruded foam with white cement layer reinforced with fiber mesh	Thermal insulating tiles is made from Extruded foam with white cement layer reinforced with fiber mesh
Lighting system:	Fluorescent bulbs	Fluorescent bulbs	Fluorescent bulbs	LED lighting system	Fluorescent bulbs	LED lighting system
HVAC system:	One AC	One AC	One AC	One AC	One AC	One AC
Windows shading:	Non	Non	Non	Non	Non	Non
Simulation Program:	Envi-met	Design- Builder	Design- Builder	Design- Builder	Design- Builder	Design- Builder

different retrofitting strategies. The second case was an investigation of the effect of a green wall on annual energy consumption without any other retrofitting strategies using the weather file output from ENVI-met of the green wall. A third case was an investigation of retrofitting strategies of the first case with the integration of the effect of the green wall in the second case.

The methodology includes two main stages. First, ENVI-met 4.4.5 was used for modeling the base case, validation, and strategy of green walls and roofs to determine their impact on outdoor climate variables, such as Ta, RH, and wind speed. As a result, the weather data files for the two cases could be obtained to modify them in element software and EnergyPlus converter. Secondly, energy modeling processes for the base case, validation, and the six retrofitting strategies could be conducted by using DesignBuilder software to estimate the annual energy consumption. PET was used as an index for evaluating the performance of outdoor thermal comfort. PET was calculated based on RayMan software, developed by Andreas Matzarakis, University of Freiburg, Germany Farhadi and colleagues (Farhadi et al., 2019) based on the climate outputs (Ta, RH, Wind speed, and *T*mrt) from ENVI-met.

2.1. Case study location and description

Assiut City is located in Egypt at a latitude of 27°3′N and a longitude of 31°15′E. In the summer months, the maximum temperature is between 41 °C and 45 °C, in contrast to the minimum temperature, which is between 16 °C and 22 °C.

(Fig. 3) shows field monitoring for outdoor temperature and humidity in New Assiut City. The Youth housing government sector was selected as a case study whereas the sector consists of 12 residential buildings. Additionally, the urban canyon ratios (H/W) of the Youth housing sector range between 0.6−0.24. The street pattern outside the housing sector is regular with a few trees providing shade as shown in Fig. 4.

Each residential building in the Youth housing sector model consists of five floors and four flats per floor with an area of 280 m^2. Each flat has two orientations. Fig. 4 shows the plan, elevation, outside view, and housing layout. Table 2 shows the building material description used in building this model based on physical properties specification Asan and Sancakter (1998). The location of a selected residential building is in a narrow canyon, although the shade of the surrounding buildings is not efficient due to the small building height which reached 15 m

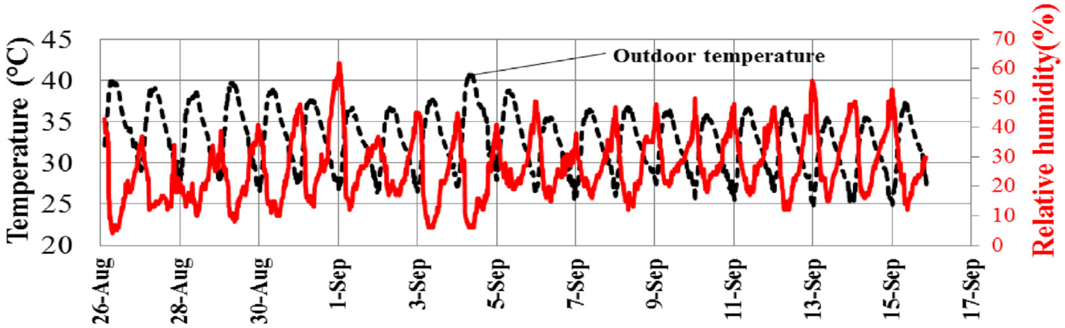


Fig. 3. Temperature patterns during hot periods of 2014 in New Assiut City.

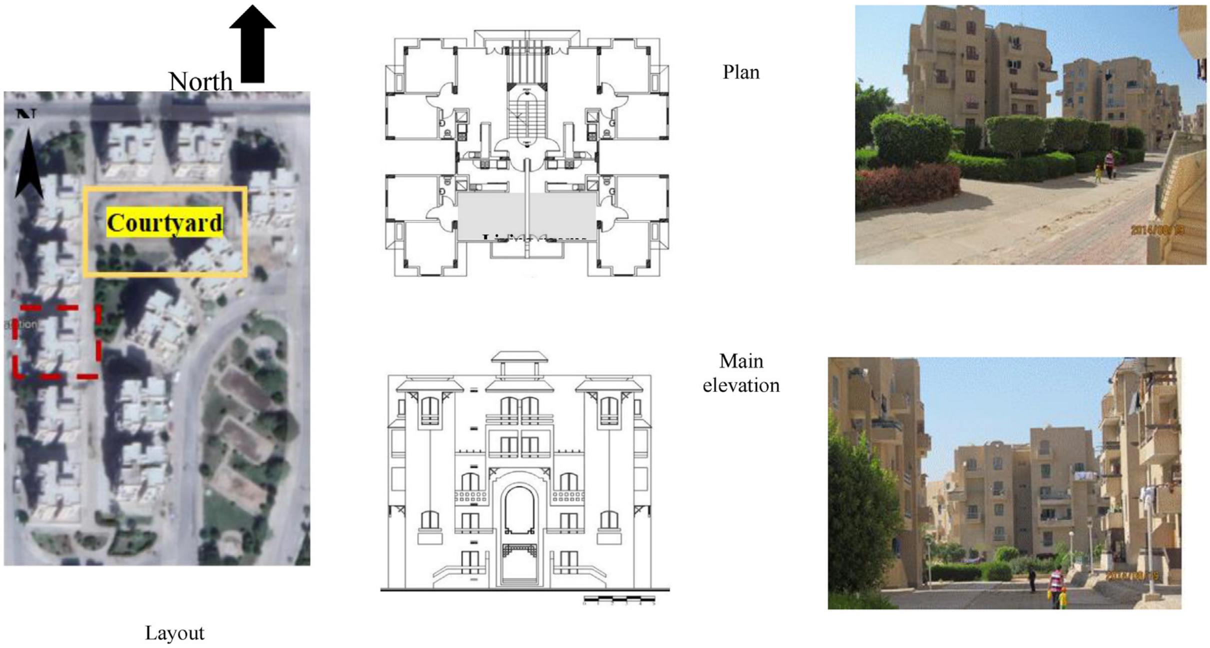


Fig. 4. The overview of the Youth housing sector (Layout, plan, elevation, and outside view).

Table 2. Description of building material (Asan and Sancakter, 1998).

Building part	Material	U-Value (W/m^{2}K)	Thickness (m)
Glass windows	Single glass	5.7	0.006
External walls	Red brick (with 2 cm cement plaster on every side) with a thickness of 12 cm without thermal insulation	2.86	0.16
Roof	Clay tile (roofing) with slope Insulation Concrete slab Cement plaster (coating)	2.93	0.60

only. In addition, the lack of vegetation and shading leads to the high indoor temperature inside residential flats in the four different building orientations. The outer façade was affected by high solar radiation without any shading from buildings or trees which causes a rise in indoor temperature with high cooling demand as noted in the extant literature Abdallaha (2015). Thus, the improvement of the indoor and outdoor temperature is needed to achieve comfort with energy consumption reduction. Particularly, this sector represents the approved model by the Egyptian government for low-income housing in many new Egyptian cities, hence its improvement is considered an improvement of many models at the level of hot desert new cities inside Egypt.

Table 3. The case study parameters as inputs for the simulation process in ENVI-met (Abdallah and Mahmoud, 2022).

Building properties		Landscape properties	
Area of existing case	17250 m^2	Street width	10 m and 18 m
Building width	20 m	Street material	Asphalt
Building length	15 m	Sidewalk width	4 m: 8 m
Building Height	15 m	Sidewalk material	Yellow brick
Courtyard width	62 m	Soil material	Loamy soil
Aspect ratio (H/W)	0.24−0.6	Green area	2400 m^2
Façade material	Yellow painted	Tree type	Ficus Nitida trees

2.2. Outdoor and building numerical simulation and validation

To calibrate the ENVI-met model, the base case study was modeled via ENVI-met based on the parameters of the case study in Table 3. The outputs were compared with the field measurements conducted on 22nd August 2014 as a sample of hot days of summer that are considered critical days of high outdoor thermal radiation and accordingly indoor thermal effect.

As well as, in the last years, hot days represented many of summer days in Egypt based on the statistics of the Ministry of Energy in Egypt (Ministry of Energy in Egypt, 2021). Accordingly increasing of the ratio of energy consumption in residential buildings by 45%. As shown in Fig. 5, the coefficient of determination (R^2) has been calculated. Thus, the values of R^2 were 0.998, 0.9477, and 0.928 for Ta, RH, and wind speed, respectively. Hence, model validation was obtained to check the accuracy of the results that will be obtained from the simulation and to compare them to the actual measurement Andelkovic and colleagues, Reddy and colleagues (Andelkovic et al., 2016; Reddy et al., 2006).

For simulation, a model of the youth housing was created using DesignBuilder software in its fifth version (V.5.0.3.007). The building was built and simulated based on the material properties in Table 2. Fig. 6 shows the exterior view of the youth housing building in DesignBuilder.

A fixed schedule was used for HVAC operation with a fixed activity based on the common lifestyle for the residents in the residential community of New Assiut City from the field study survey during the previous research Abdallaha (2015). The numerical model using DesignBuilder was validated

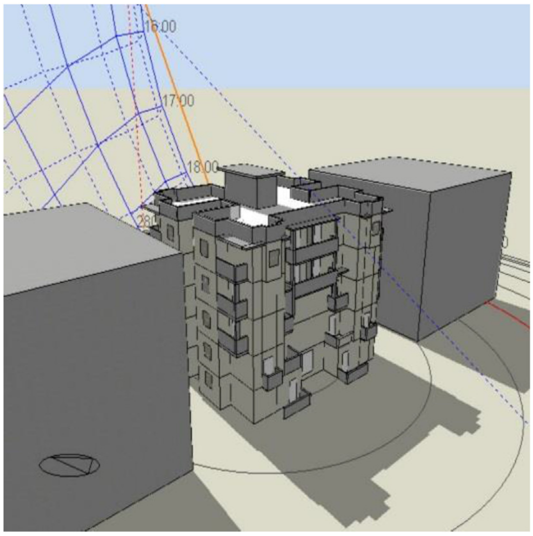
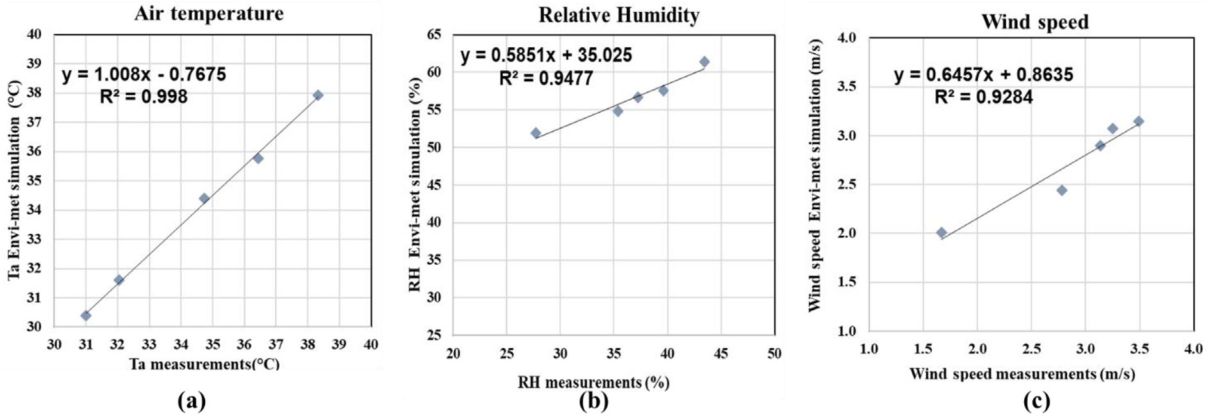


Fig. 6. The exterior view of the youth housing building inside DesignBuilder.



(a) (b) (c)

Fig. 5. The Linear regression of; a) Ta, b) RH and c) wind speed inside the courtyard.

using the actual measured temperature in an apartment of youth housing on the third floor with a north- and west-facing orientation in the summer of 2014 Abdallaha (2015). The calibrated model showed variation between 2.7% and 5.5% of the actual measured temperature during the measured period. Therefore, the variation is within the acceptable variation according to the extant literature Rahman and colleagues (Rahman et al., 2008) and produces an actual environment of the residential building.

2.3. Abilities and limitations

The abilities of the proposed methodology and the optimization model are detailed below.

(1) Relying on coupled simulation between ENVI-met and DesignBuilder to improve outdoor thermal comfort and indoor energy consumption.
(2) The flexibility of applying the methodology to other residential buildings in the new desert Egyptian cities.
(3) Studying the effect of green walls and roofs on both outdoor thermal comfort and indoor energy consumption.
(4) Relying on retrofitting strategies to improve indoor energy consumption.
(5) Assisting in solving environmental problems such as global warming and confronting climate changes by studying the thermal performance of retrofitting strategies, green walls, and roofs in the early design stages.
(6) Expansion potential of the methodology to include several developed retrofitting strategies.

On the other hand, the limitation and shortcomings are detailed below.

(1) Ignoring other strategies for improving outdoor thermal comfort such as the Albedo effect and shading ratio and height.
(2) The study focused on residential buildings with a fixed height of 15 m and not on the varied height between buildings.
(3) Focusing on the energy consumption of residential buildings without taking into account the accurate analysis of indoor thermal comfort.

3. Results and discussion

3.1. Evaluation of indoor thermal comfort inside the residential flat

(Fig. 8) shows the temperature and absolute humidity patterns for one of the hot days in August. High temperature was observed in the living room with different orientations and most of the measurement time is far from the 90% acceptability limits of the Adaptive Comfort Standard (ACS) of ASHRAE except in the northwest flat due to using the cross-ventilation strategy Abdallah and colleagues (Abdallah et al., 2014). The urban canopy ratio (H/W) of 0.6–0.24 without any shading or strategies for the outer façade causes high heat gain and solar radiation that affects strongly indoor thermal comfort. The outer façades are exposed to high solar radiation most of the time without any shading or trees. Whereas adding shading or louvers devices or double skin façade significantly achieves reducing solar radiation and improving indoor thermal comfort accordingly. Also, the absolute humidity fluctuates strongly due to using natural ventilation only and no cooling strategies. Thus, the main reason for the high temperature is due to the lack of shading for the outer wall. Based on data monitoring of the indoor environment, it is recognized the importance of outer wall shading using double skin façade like green wall to decrease heat gain through walls and its reflection for outer environment and discomfort for residents. Therefore, numerical simulation using ENVI-met simulation tools for integration of green wall to investigate and evaluate its effect on outdoor/indoor thermal comfort.

3.2. Evaluation of outdoor thermal performance simulation using green walls and green roof

Fig. 9 shows the influence of using green walls and roof shading on the outdoor Ta and PET. A reduction in the outdoor temperature is achieved that ranged from 3.78 °C to 5.08 °C based on the simulation process from 8:00 a.m. to 8:00 pm on August 22, 2020. Accordingly, the PET index was calculated using RayMan software, and the reduction of PET ranged between 4.40 °C and 11.20 °C in 2020, 4.20 °C and 10.70 °C in 2050, in addition to 4.60 °C and 10.50 °C in 2080, which compatible with the previous literature Kanaus and Haase, 2020 (Li et al., 2021; Chen et al., 2021). Fig. 10 shows the Ts of the outer façade with the integration of a green wall with a comparison of the real thermal image taken at 3:00 pm. It is concluded that a reduction of façade Ts for the three directions of the green walls (east, south, and west) could be obtained by ENVI-met compared with the base case based on the previous research Zhu and colleagues (Zhu et al., 2021). The thermal images by the thermal camera (Flir-C2) were taken for the outer façade of the residential building with different orientations. Based on thermal image monitoring, it is clear that a higher

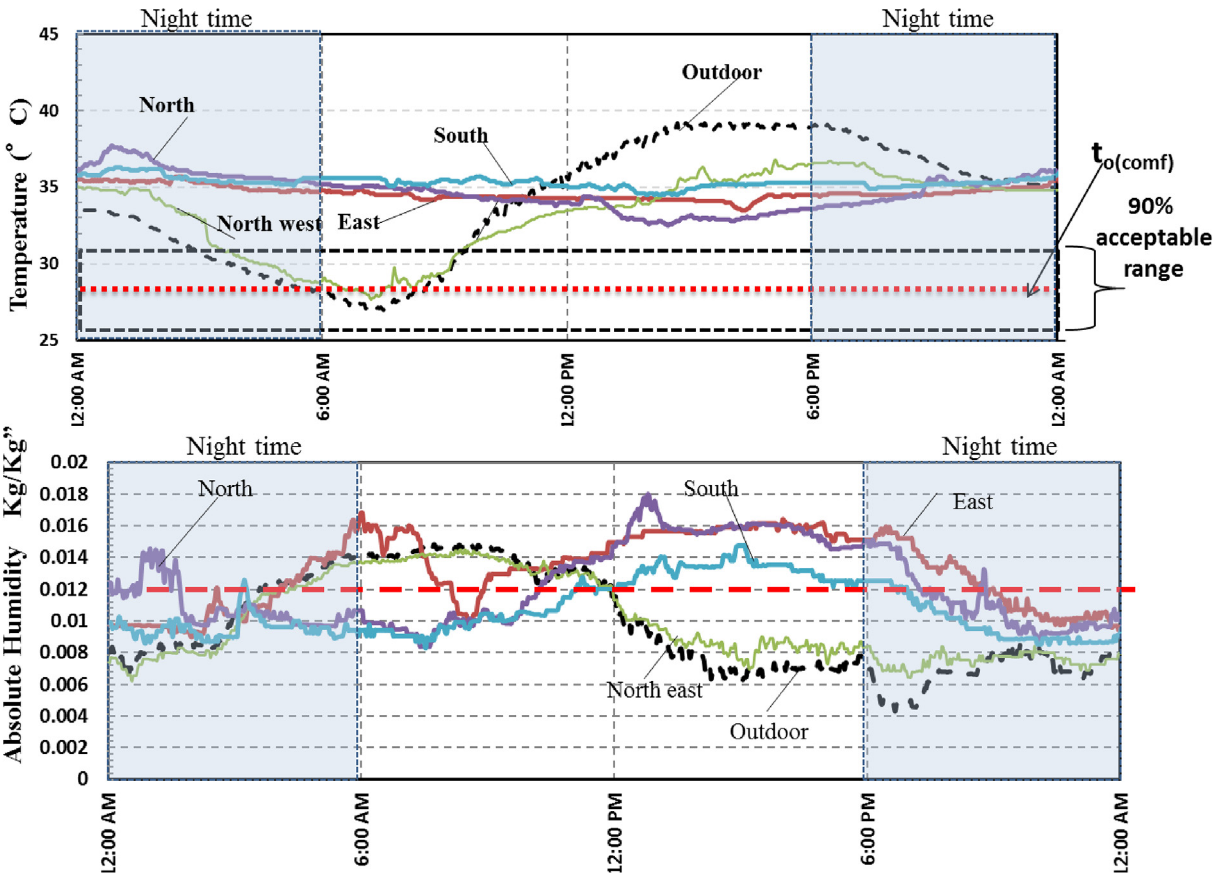
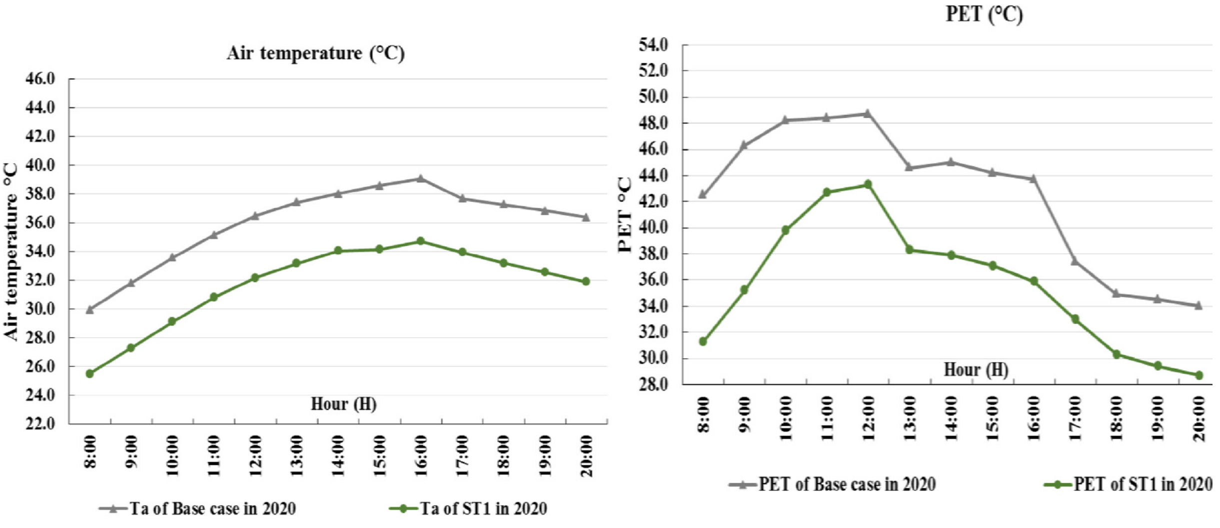


Fig. 7. Temperature and absolute humidity pattern inside the residential flat with different orientation.

temperature for outer Ts for building façade was found for the west and southwest orientations, ranging between 45 °C and 50 °C when the outer temperature reached 41 °C. This causes high heat transfer through the outer wall during the daytime with a U-value of 3.02 (W/m^2 K).



a

b

Fig. 8. Comparison between the base case and ST1 influence on outdoor thermal comfort on 22 August; a) Ta and b) PET.

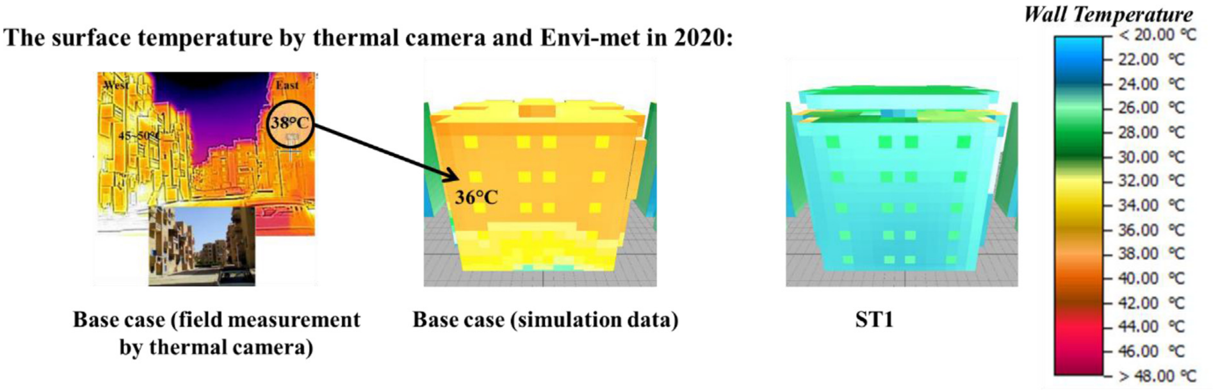


Fig. 9. The surface temperature of the base case and ST1 of green walls and green roof shading at 3:00 pm.

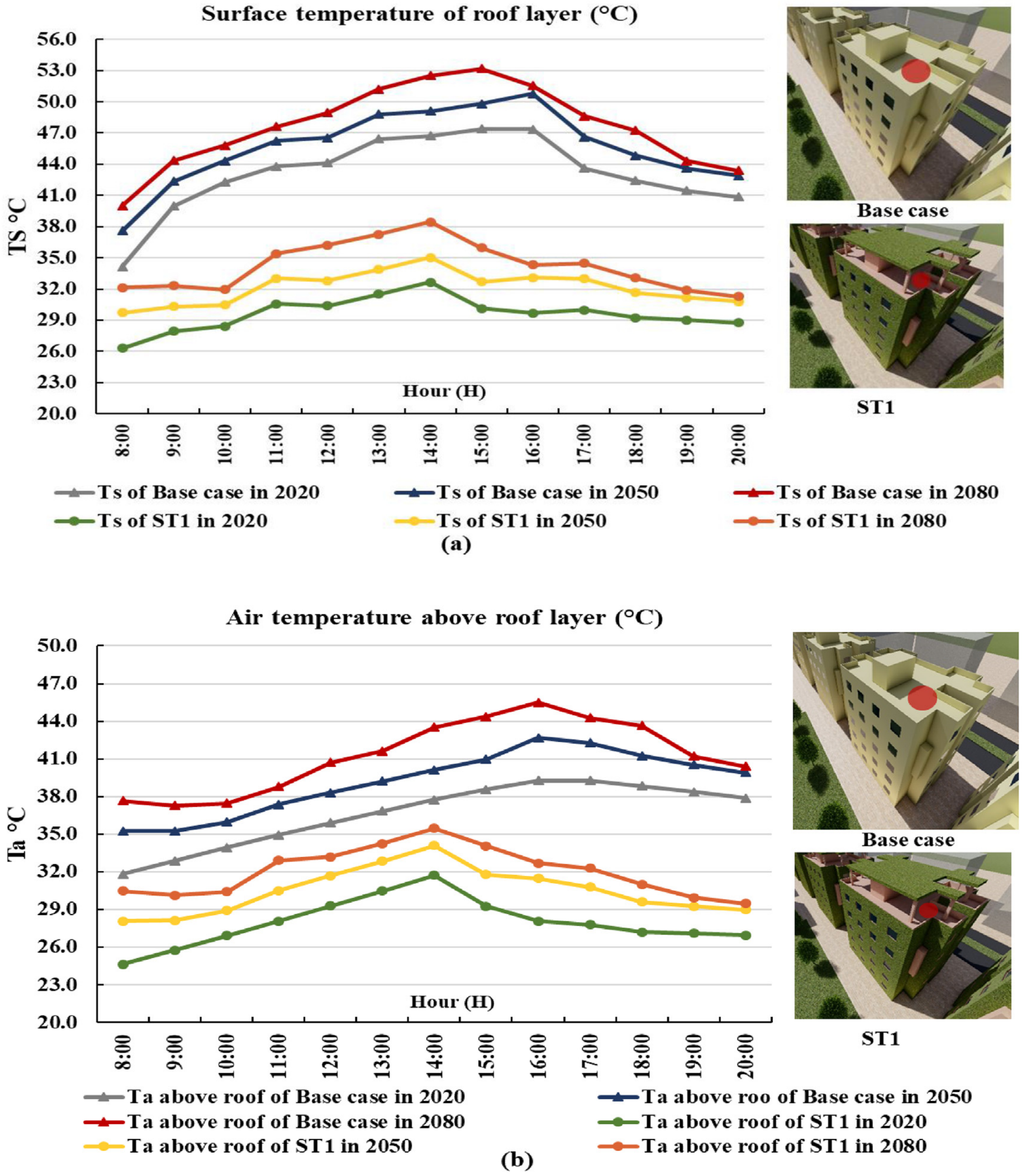


Fig. 10. The temperature of the roof layer of base case and ST1; a) the surface temperature of the roof layer and b) Ta above the roof layer.

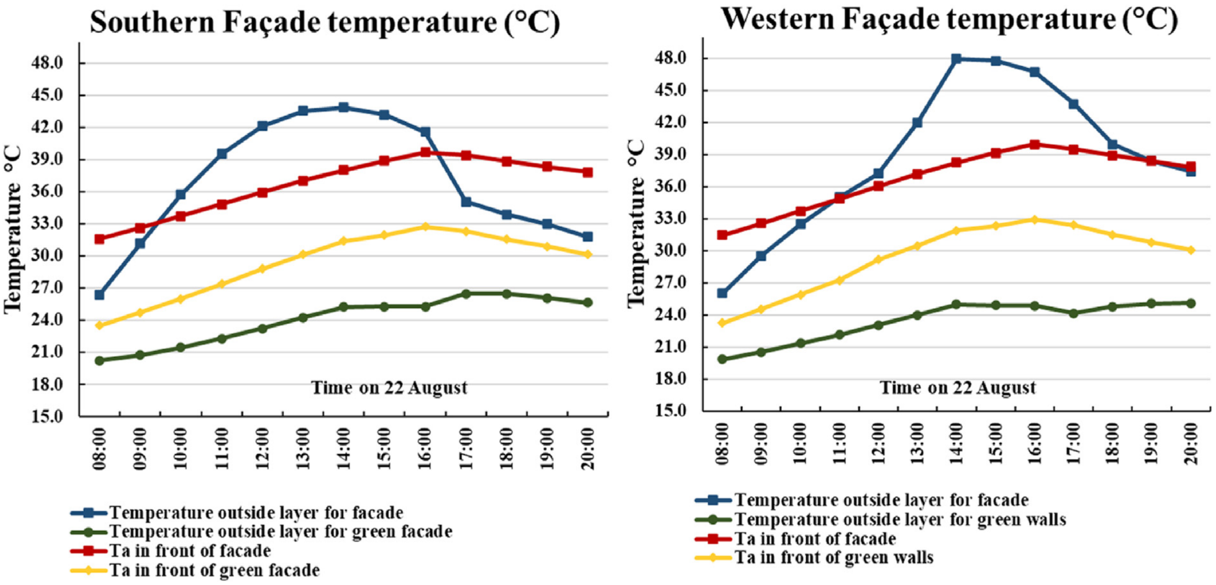


Fig. 11. Temperature pattern for Ta in front of the south and east façades with/without a green wall.

After the implementation of the green wall strategy, the reduction of Ts for the eastern façade was approximately 9 °C for the year 2020 Fig. 11 (see Fig. 12).

Ta patterns for the south and west façade with/without green walls and in front and outside façades. A significant reduction of Ta is achieved due to the integration of a green wall with an average temperature difference equal to 6 °C compared with the Ta in front of the outer façade for the year 2020.

3.3. Adapted retrofitting strategies to improve total energy consumption

In the second phase of this study, the effect of integration of different retrofitting strategies in the building was evaluated to improve annual energy consumption, and in the third stage, all-weather data files, which have been extracted by ENVI-met, were modified by Element software and EnergyPlus converter. Hence, all-weather files were used as

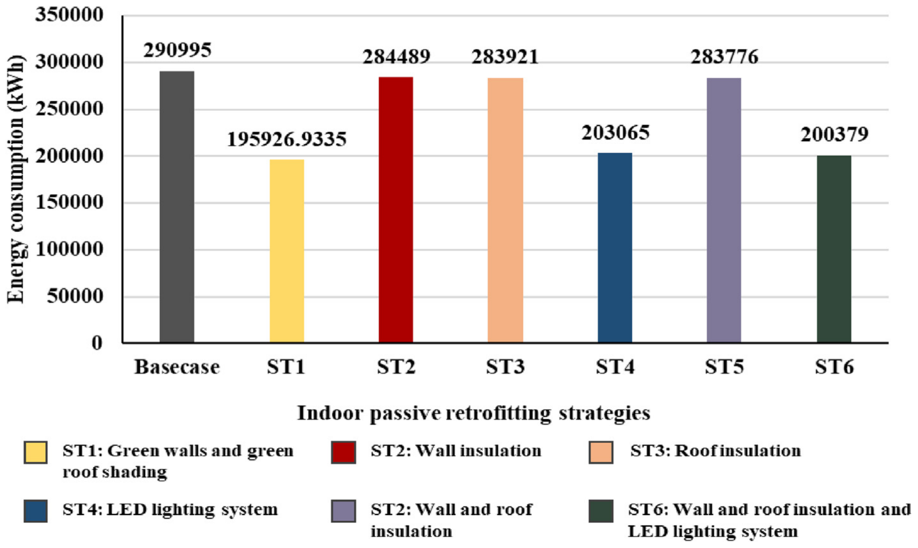


Fig. 12. The annual electricity consumption for integration of different retrofitting strategies.

input for the DesignBuilder software to calculate the annual energy consumption of the base case and the six different retrofitting strategies.

Annual energy consumption for different retrofitting strategies. Using wall and roof insulation could save 2.5% of the total annual energy consumption and reduce the cooling load with a natural ventilation strategy without a significant reduction in indoor temperature and indoor thermal comfort. This helps decrease heat transfer through the outer wall and roof when U-values decrease to 0.56 (W/m^2 K) and 0.25 (W/m^2 K), respectively. A reduction of total energy consumption was achieved when using wall and roof insulation by replacing old lamps with LED units. This reduction could save 31.1% of the annual total energy consumption based on the DesignBuilder model.

Based on coupled simulation between ENVI-met and DesignBuilder and using the results of outdoor temperature from ENVI-met based on using the green wall in the outer façade, it is concluded that using the green wall only on the outer façade of the base case without integration of retrofitting strategies achieved a reduction of annual total energy consumption for one building in the first case. Integration of a green wall and using retrofitting strategies (wall and roof insulation and replacing lamps with LED units) achieved more reduction in energy consumption that reached 32.67% in the current weather file. This indicates that using the green wall with the building envelope achieved a reduction of total energy consumption compared with using insulation in the building walls and the roof only. Installation of a green wall with building wall and roof insulation weakens insulation material's effect on the indoor environment and total energy consumption. As a result of the position of the insulation material behind the green wall and the air gap reduced the performance of the insulation material due to the fact that it was not directly exposed to the external microclimate parameters, so it does not work in its full thermal performance such as it is alone. It was found that using the green wall for the building façade could reduce the indoor Ta by 2.16 °C compared with using wall insulation for the building envelope which concurs with the previous research Fahmy and colleagues (Fahmy et al., 2020). Also, significant reduction of indoor temperature equal 1.38 °C using integration of green roof in the top floor. Furthermore, a reduction in annual energy consumption was achieved with the same percentage of current data and a different range between 2% and 3% for one residential building.

4. Conclusion

The present study helps to improve the outdoor thermal comfort of residential outdoor spaces, indoor thermal comfort, and energy consumption rationalization in the current time by integrating different retrofitting strategies inside a residential building in New Assiut City, Egypt. The results from the simulation of outdoor thermal comfort analysis using ENVI-met and DesignBuilder simulation models and the combination of the two can be summarized as follows.

A significant reduction in wall surface temperature due to integration of green wall for west and south façade with a temperature difference reached 6 °C. Also, sharp drop in Ta under the green roof shading with an average of 8.84 °C. This affects strongly heat transfer to the indoor environment through walls or roofs with indoor temperature reduction equal to 2.16 °C and 1.38 °C for the wall and roof respectively with a reduction for the cooling demands and total annual energy consumption. While more reduction is achieved for total energy consumption due to the integration of different retrofitting strategies (wall and roof insulation with replacing lamps with LED units) that reached 32.67%.

Also, the integration of a green wall affects strongly the reflection of heat and radiation through outer spaces between buildings (near the building) and improves residents' thermal comfort with a value ranging between 4.20 °C and 11.20 °C, especially for the deep canyon.

It is recommended to integrate green walls and roofs with different retrofitting strategies for Egyptian residential buildings in the hot arid climate of the southern climatic zone to help low-income Egyptian people, that represent 50% of total Egyptian families to improve thermal comfort and rationalization energy consumption in all the country Fig. 7.

Conflicts of interest

No potential conflict of interest was reported by the authors.

Acknowledgments

Statement: This paper has not been previously published and is not currently under consideration by another journal and that all authors have approved of and have agreed to submit the manuscript to this journal.

Credit authorship contribution statement

A. Abdallah conceived the idea, conduct the measurement and performed data analysis. Both authors wrote and developed, improve the paper, and read and agreed to the published version of the manuscript. R. Mahmoud built and validated the simulation model, performed data analysis.

References

Abdallah, A.S.H., Mahmoud, R.M.A., 2022. Urban morphology as an adaptation strategy to improve outdoor thermal comfort in the urban residential community of new Assiut city, Egypt. Sustain. Cities Soc. 78, 103648.

Abdallah, A., Goto, Y.H., Enteria, T., Abdelsamei, N., Eid, M., Radwan, M.M., 2014. Analysis of thermal comfort for indoor environment of the new Assiut housing in Egypt. World Acad Sci Eng Tech 77, 845–851.

Abdallah, A., 2015. The influence of urban geometry on thermal comfort and energy consumption in residential building of hot arid climate, Assiut, Egypt. Procedia Eng. 121, 158–166.

Al Saadi, S.N.J., Al-Jajri, J., Sayari, M.A., 2017. Energy-efficient retrofitting strategies for residential buildings in hot climate of Oman. Energy Proc. 142, 2009–2014.

Andelkovic, S., Mujan, I., Daki, S., 2016. Experimental validation of a energyplus model: application of a multi-story naturally ventilated double skin facade. Energy Build. v118, 27–36.

Andric, I., Al-Ghamdi, S.G., 2020. Climate change implications for environmental performance of residential building energy use: the case of Qatar. 6th International Conference on Energy and Environment Research, ICEER 2019, 22–25 July, University of Aveiro, Portugal. Energy Rep. 6, 587–592.

Andric, I., Kamal, A., Al-Ghamdi, S.G., 2020. Efficiency of green roofs and green walls as climate change mitigation measures in extremely hot and dry climate: case study of Qatar. Energy Rep. 6, 2476–2489.

Asan, H., Sancakter, Y.S., 1998. Effects of Wall's thermophysical properties on time lag and decrement factor. Energy Build. 28, 159–166.

Ávila-Hernández, A., Simá, E., Xamán, J., Hernández-Pérez, I., Téllez-Velázquez, E., Chagolla-Aranda, M.A., 2020. Test box experiment and simulations of a green-roof: thermal and energy performance of a residential building standard for Mexico. Energy Build. 209, 109709.

Bano, P., Dervishi, S., 2021. The impact of vertical vegetation on thermal performance of high-rise office building façades in Mediterranean climate. Energy Build. 236, 110761.

Chen, C., Zhang, Y., Han, J., Li, X., 2021. An investigation of the influence of ground surface properties and shading on outdoor thermal comfort in a high-altitude residential area. Front Architect Res. 16 Available online 24 January 2021.

Djedjig, R., Bozonnet, E., Belarbi, R., 2016. Modeling green wall interactions with street canyons for building energy simulation in urban context. Urban Clim. 16, 75–85.

Fahmy, M., Mahdy, M., Mahmoud, S., Abdelalim, M., Ezzeldin, S., Attia, S., 2020. Influence of urban canopy green coverage and future climate change scenarios on energy consumption of new sub-urban residential developments using coupled simulation techniques: a case study in Alexandria, Egypt. 6th International Conference on Energy and Environment Research, iceer 2019, 22–25 July, University of Aveiro, Portugal. Energy Rep. 6, 638–645.

Farhadi, H., Faizi, M., Sanaieian, H., 2019. Mitigating the urban heat island in a residential area in Tehran: investigating the role of vegetation, materials, and orientation of buildings. Sustain. Cities Soc. 46, 101448.

Flores-Larsen, S., Filippín, C., Barea, G., 2019. Impact of climate change on energy use and bioclimatic design of residential buildings in the 21st century in Argentina. Energy Build. 184, 216–229.

Golasi, I., Fsalata, F., Vollaro, E.L., Peña-García, A., 2019. Influence of lighting colour temperature on indoor thermal perception: a strategy to save energy from the HVAC installations. Energy Build. 185, 112–122.

Hema, C., Messan, A., Lawane, A., Soro, D., Nshimiyimana, P., Moeseke, G., 2021. Improving the thermal comfort in hot region through the design of walls made of compressed earth blocks: an experimental investigation. J. Build. Eng. 38, 102148.

Hoffmann, K.A., Šuklje, T., Kozamernik, J., Nehls, T., 2021. Modelling the cooling energy saving potential of façade greening in summer for a set of building typologies in midlatitudes. Energy Build. 238, 110816.

Ismail, F.H., Shahrestani, M., Vahdati, V., Boyd, P., Donyavi, S., 2021. Climate change and the energy performance of buildings in the future – a case study for prefabricated buildings in the UK. J. Build. Eng. 39, 102285.

Jänicke, B., Meier, F., Hoelscher, M., Scherer, D., 2015. Evaluating the effects of façade greening on human bio climate in a complex urban environment. Adv. Meteorol. 2015, 747259.

Knaus, M., Haase, D., 2020. Green roof effects on daytime heat in a prefabricated residential neighbourhood in Berlin, Germany. Urban For. Urban Green. 53, 126738.

Li, J., Zheng, B., Chen, X., Qi, Z., Bedra, K.B., Zheng, J., Li, Z., Liu, L., 2021. Study on a full-year improvement of indoor thermal comfort by different vertical greening patterns. J. Build. Eng. 35, 101969.

Liao, J., Tan, X., Li, J., 2021. Evaluating the vertical cooling performances of urban vegetation scenarios in a residential environment. J. Build. Eng. 39, 102313.

Mahmoud, H., Ragab, A., 2020. Urban geometry optimization to mitigate climate change: towards energy-efficient buildings. Sustainability 13, 27.

Ministry of Energy in Egypt, 2021. Report of Egyptian Ministry of Energy.

Momtaz, R.I., 2018. Vertical garden as a sustainble urban prespective in Cairo. J. Eng. Sci., Assiut University, Faculty of Engineering 46, 246–262.

O' Donovan, A., Murphy, M.D., O'Sullivan, P.D., 2021. Passive control strategies for cooling a non-residential nearly zero energy office: simulated comfort resilience now and in the future. Energy Build. 231, 110607.

Poddar, S., Park, D.Y., Chang, S., 2017. Simulation-based analysis on the energy conservation effect of green wall installation for different building types in a campus. Energy Procedia 111, 226–234.

Prakash, D., 2015. Transient analysis and improvement of indoor thermal comfort for an air-conditioned room with thermal insulations. Ain Shams Eng. J. 6, 947–956.

Rahman, M., Rasul, M.G., Khan, M.M.K., 2008. Energy Conservation Measures in an Institutional Building by Dynamic Simulation Using DesignBuilder. 192-197. University of Cambridge, UK: Conf. on Energy & Environment.

Reddy, T.A., Maor, I., Panjapornpon, C., 2006. Calibrating detailed building energy simulation programs with measured data Part I: general methodology. HVAC& Research v13, 221–241.

Sabunas, A., Kanapickas, A., 2017. Estimation of climate change impact on energy consumption in a residential building in kaunas, Lithuania, using HEED software. International scientific conference 'environmental and climate technologies', CONECT 2017, 10–12 May 2017, Riga, Latvia. Energy Proc. 128, 92–99.

Sánchez-García, D., Rubio-Bellido, C., Martín del Río, J.J., Pérez-Fargallo, A., 2019. Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change. Energy Build. 187, 173—185.

Widiastuti, R., Zaini, J., Caesarendra, W., 2020. Field measurement on the model of green façade systems and its effect to building indoor thermal comfort. Measurement 166, 108212.

Yang, F., Yuan, F., Qiana, F., Zhuang, Z., Jyao, J., 2018. Summertime thermal and energy performance of a double-skin green façade: a case study in Shanghai. Sustain. Cities Soc. 39, 43—51.

Zhao, J., Du, Y., 2020. Multi-objective optimization design for windows and shading configuration considering energy consumption and thermal comfort: a case study for office building in different climatic regions of China. Sol. Energy 206997—211017.

Zhao, D., Fan, H., Pan, L., Xu, Q., Zhang, X., 2017. Energy consumption performance considering climate change in office building. 10th international symposium on heating, ventilation and air conditioning, ISHVAC2017, 19- 22 october 2017, Jinan, China. Procedia Eng. 205, 3448—3455.

Zhu, Z., Zhou, D., Wang, Y., Ma, D., Meng, X., 2021. Assessment of urban surface and canopy cooling strategies in high rise residential communities. J. Clean. Prod. 288, 125599.