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On the cooling energy impacts of combined urban heat mitigation strategies in subtropical urban building environment

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ABSTRACT

Regional climate change leads to more extreme urban heat in desert cities. This affects the building's performance negatively through an increase in cooling energy consumption. To our knowledge, this is the first study investigating the impacts of implementing combined urban heat mitigation strategies of cool materials and increased vegetation on the cooling load demands of 40-various types of buildings in Dubai downtown. Four urban heat mitigation scenarios have been conducted in combination with a base case scenario to examine the effectiveness of the combined strategies in reducing the cooling load demand by using the climatic data from weather research and forecasting model coupled with single layer urban canopy model (WRF/SLUCM) in CitySim. Results revealed that for non-insulated buildings there was an estimated 17.2% to 36.4% reduction in cooling energy demand whereas insulated buildings have an average reduction in energy demand ranging between 15.5% and 29.1%. This reduction in cooling energy consumption is higher when compared with other mitigation techniques like additional urban vegetation and modified cool materials.

1. Introduction

Urban heating and the rapid expansion of cities are two of the major environmental issues being faced by the rapidly growing economies of the world. Urbanization causes an increase in urban density and the increasing number of urban buildings have replaced vegetation [1]. Consequently, urban areas experience a higher ambient temperature than the surrounding areas. This in turn has a detrimental impact on cooling load demands, human thermal comfort, pollution, human health, and electricity consumption in these urban areas [2–5]. However, the most concerning consequence of urban heating and global warming is the increasing rate of morbidity and mortality [2].

Urban energy demand is influenced by industry, buildings, and transportation. Of these, buildings account for 40 % of global energy consumption and 25 % of the net greenhouse gases [6,7]. It is predicted that the energy demand for cooling buildings alone will account for about 34 % and 61 % of the total global energy expenditure by 2050 and 2100 respectively [5]. However, it is estimated that, owing to global warming, by 2100, there will be a 10 % rise in net electricity demand and an 84 % increase in the consumption of cooling load [8]. Hence, the major challenges of the future include reducing the amount of greenhouse gas emitted by air conditioners and tackling urban heat issues [9]. The impact of temperature rises on energy consumption depends upon factors such as the properties of buildings, the intensity of urban heating, the structure of buildings, and the microclimatic conditions of the area [10–13]. Increased urban temperatures create an energy impact of around 70kWh/°C per person and a 0.45 % to 4.6 % increase in electricity consumption for every 1 °C rise in air temperature [14]. Santamouris et al. (2015) found that there has been an increase of between 0.4 °C and 11 °C in the ambient temperature of 100 Australian and Asian cities, with an average increase of 4.1 °C [15]. It has been observed that increase of 1 °C in air temperature would cause an average increase of 4.60 % in electricity consumption [10].

To reduce the adverse impact of urban heat, various urban heat-mitigation techniques have been deployed in numerous large-scale projects [16–18]. Mitigation techniques are the solutions devised to counteract urban heat while considering the root cause of the environmental issue [16]. Studies suggest two primary mitigation technologies to improve the urban climate by reducing urban heating. These techniques involve the use of high albedo materials and the increase of vegetation cover [19–21]. It has been found that a small amount of vegetation and the high absorption of solar radiation by urban surfaces

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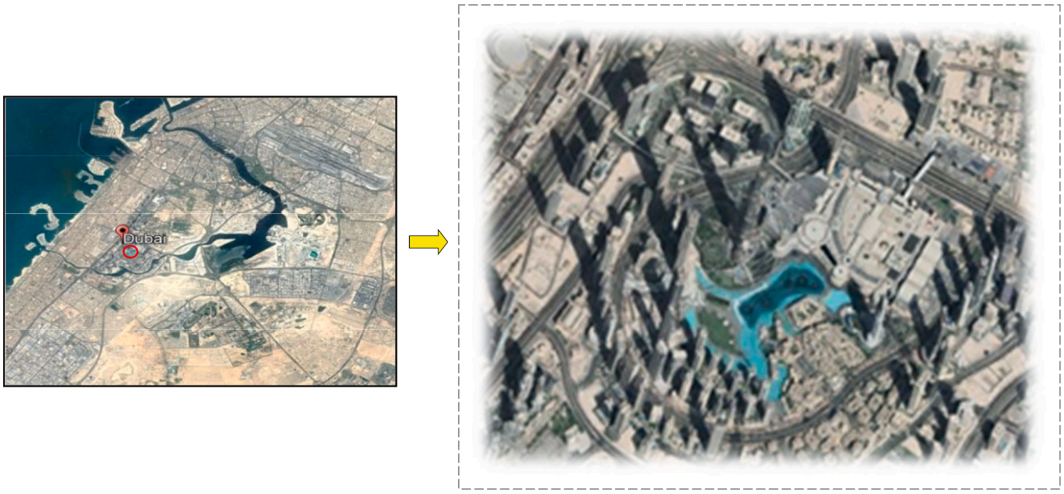


Fig. 1. Location of case study: Downtown Dubai (Google Map).

create an urban heat island which can be reversed by using high albedo materials and increasing the area of urban vegetation [20]. A study conducted in 27 cities worldwide, having diverse metrological conditions, suggested that an albedo rise of 0.65 could cause a reduction between 8 and 48 kWh/m^2 [22]. Santamouris et al. (2018) found that the introduction of high albedo materials in Sydney could significantly improve the urban cooling load requirements. For instance, a cooling demand reduction of 20 % was observed for each 0.7 rise in global albedo fraction and a maximum reduction in cooling energy consumption per 0.1 rise in albedo was observed to be 3.5 % [23]. Algarni selected 13 cities in Saudi Arabia to investigate the performance of a cool roof mitigation technique for cooling load demand. It was found that all cities had a reduction in cooling load in response to an increase of albedo fraction. For instance, in Riyadh, the annual cooling load decreased from 754.3 kWh/m^2 to 572.4 kWh/m^2 for the low-level insulation when the albedo fraction was raised to 0.85 [24]. Similarly, the energy consumption for the cooling of offices, schools and residential buildings could be reduced by 13.4 % to 19.3 % [25]. Parker et al. (2020) studied the impact on the energy demand of buildings after increasing the amount of surrounding vegetation and found that a reduction of 50 % in electricity consumption could be achieved through the evapotranspiration and increase of solar reflectance by plants [26]. Similar findings were observed in Mexico where the planting of trees reduced the annual energy consumption by 76.6 % [27]. Akbari et al. (1986) found that the inclusion of trees in an urban built environment could reduce the residential cooling energy demand by 18 %, 34 % and 44 % according to studies conducted in Phoenix AZ, Sacramento CA, Phoenix and Los Angeles CA [28].

In Dubai, the impact of mitigation strategies was assessed given that this city has been affected by intense overheating and the creation of an urban heat island due to climate change and wind direction [18,29]. weather research and forecasting (WRF) was used in a study that determined the effectiveness of cooling materials in urban areas of Dubai and found that an increase in the amount of albedo could reduce the ambient temperature during summertime [17]. Akbari et al. (1992) investigated the impact of both cooling materials and vegetative cover in various cities of Canada and found that an increase of urban vegetation by 30 % and albedo by 20 % resulted in the reduction of urban cooling load by 40 % [30]. Santamouris et al. (2018) assessed the impact of increasing urban vegetation and albedo in Sydney's urban area and found that cool roofs decreased the cooling load by 2 % to 19 %, while an increase in the amount of urban vegetation decreased the load by 0.48 % to 2.31 % [23]. A study conducted in Florida suggests that an increase in the plant cover could positively affect the efficiency of energy consumption by buildings and cause a reduction of about 50 % in daily energy consumption for cooling purposes. This reduction is achieved by increasing evapotranspiration and reducing solar radiation [31]. Sedaghat et al. (2022) assessed the impact of cool roofs and urban green areas on cooling load reduction in Tehran, Iran. Results from their analysis showed a 21 % reduction in cooling load for the cool roof mitigation scenario, while there was an 11 % reduction for the mitigation scenario where the amount of vegetation was increased [32]. Similarly, in Mexico, plantation of trees could reduce the yearly energy consumption by 76.6 % for residential buildings [27]. On the other hand, in Sydney it was found that the implementation of enhanced albedo materials as a mitigation technique could reduce the amount of cooling demand by 3.5 % per 0.1 rise in albedo of urban areas [23]. Santamouris et al. (2001) evaluated the potential of mitigation techniques for domestic buildings using cool materials and increased urban vegetation and found that by increasing the amount of vegetation, the consumption of cooling energy could be reduced by 50 %, while an increase in urban albedo could save around 55 % of the cooling load demand [12]. There is a lack of literature showing the energy efficiency achieved by combining mitigation techniques using both modified albedo and increased vegetation employing WRF and CitySim for the climatic and energy simulations respectively. Therefore, this paper adopted a novel approach of considering both modified albedo and additional urban vegetation scenarios as ways to reduce the urban heat in Dubai. The combined mitigation scenarios involved various amounts of albedo and vegetation.

United Arab Emirates (UAE) has a hot and extremely humid climate with high levels of solar radiation and heatwaves. These intense weather conditions make it difficult to reduce the consumption of energy for cooling purposes as there is a high demand for heating, ventilation, and air conditioning (HVAC) systems to cool buildings. This has made UAE the world's major per capita energy consumer, where buildings account for 70 % of the net energy consumption. Studies suggest that by 2050, UAE's cooling load demand will increase by 22.2 % and will increase by a further 40 % by the year 2080.

The aim of this study is to evaluate the potential of combining two heat mitigation strategies –modified albedo materials and additional urban vegetation - in terms of improving the energy-efficiency of buildings in Downtown Dubai. The impacts of these strategies for insulated and non-insulated residential and commercial buildings have been determined for the month of July. The cooling load reductions for all combined mitigation techniques have been analyzed to determine their effectiveness in reducing urban heat.

2. Dubai location and climate

Dubai, one of the rapidly emerging global economies, is situated in

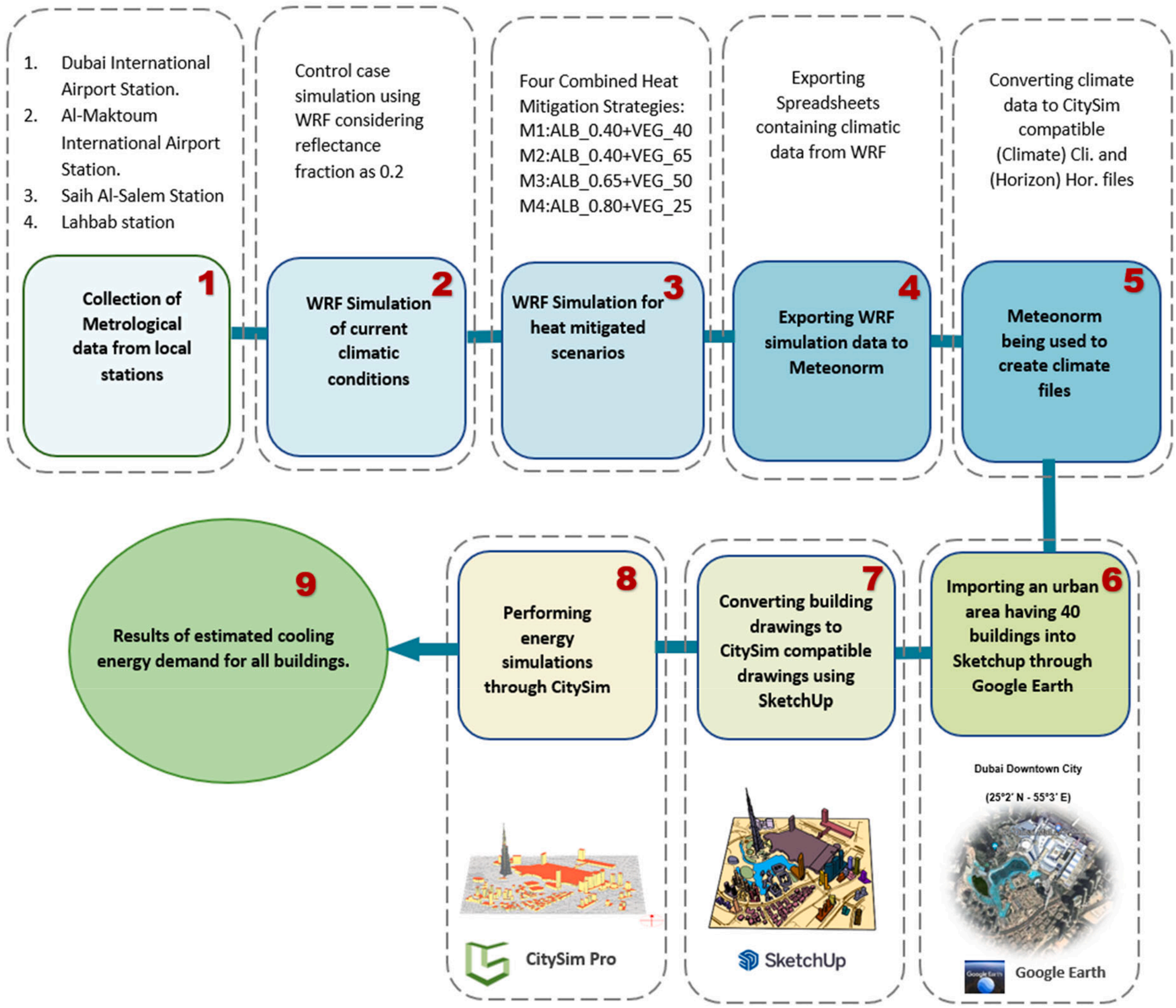


Fig. 2. Flowchart showing the steps for the study.

the tropic of Cancer (25°16′ N and 55°18′ E) as shown in Fig. 1. The city's coastline extends over a length of 72 km [33]. Over the past many years, Dubai has seen huge urbanization, making it the second largest city in UAE, with an area of 4114 km^2, comprising around 5 % of the total area of UAE. According to a report published by the "Statistics Centre of Dubai" the population of Dubai in 2021 was 3.48 million which corresponds to a population growth rate of 1.967 %. Owing to its subtropical location, the city has a hot and humid climate which causes the temperature to rise as high as 48 °C in the summer months, and range between 10 °C and 30 °C during the winter season. Synoptic climatic conditions are the major contributor to urban heating in Dubai. Statistical data suggests that since 1980, there has been a consistent increase in the average temperature of about 0.77 °C which increases people's discomfort during the summer months. Urban areas have a 1.3 °C higher ambient temperature and 3.3 °C greater night-time urban heat island (UHI) intensity than the neighbouring rural zones. Mohammed et al. (2020) found a negative correlation between wind speed and urban heating. However, the extent of urban heating is linked to the local climatic conditions and fluctuations in local convection [29]. UAE has responded by taking measures to avoid the adverse impact of urban climate change through its long-term energy and climate policy. For instance, the government enacted the National Climate Change Plan 2017–2050 in 2017 to regulate greenhouse gas emissions, adaptation to climate change, and the advancements in economic sectors. The government of Dubai has prioritised the development of vegetation coverage in the country, mainly in residential areas and along the roadside. In the 2021, vegetation was planted covering about 2.38 million square metres, totalling in all 43.83 million square metres of vegetation [34].

Moreover, the cultivation of a mangrove forest at Jebel Ali Wildlife Sanctuary proved ecologically valuable as the trees that grow in saltwater can remove three to five times more carbon than other types of shrubs and trees. It has been anticipated in the Dubai urban plan 2040 that natural reserves will constitute about 60 % of the emirate's land.

3. Materials and methods

This study evaluated the impact of using combined mitigation techniques involving both additional urban vegetation and cool materials on the energy efficiency of commercial and residential buildings. The simulation involved four mitigation scenarios with varying amounts of albedo and vegetation against the base case corresponding to an albedo fraction of 0.15 and vegetation value of 0.1. The methodology comprised two phases: a) WRF simulations coupled with single layer urban canopy model (SLUCM) were performed on the meteorological data using the base case and the four mitigation scenarios having variations of albedo and vegetation amounts. b) CitySim was used in the second step to perform building energy simulation on the output files from WRF for each mitigation scenario. The climatic files from WRF/SLUCM were converted to.cli and.hor files using Meteonorm to make it

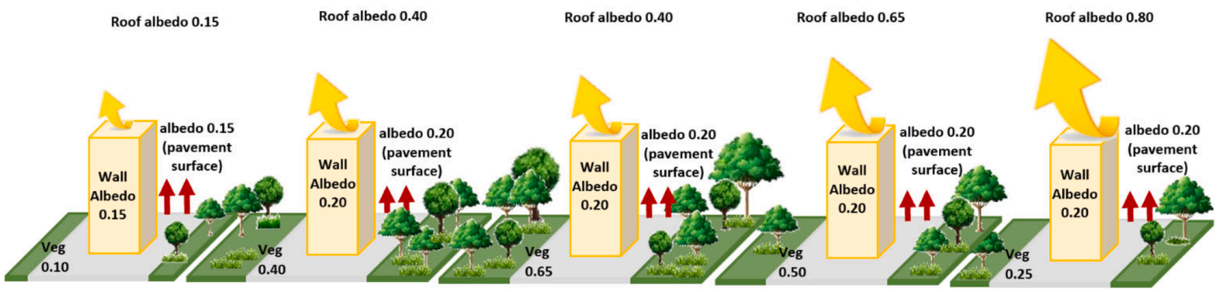


Fig. 3. Heat mitigation scenarios for combined strategies.

Table 1
Building input data for CitySim simulation.

Input parameters	Data			
Surface reflectance (albedo)	0.2			
Temperature [°C]	Res. [19–25] Comm. [19–23,35]			
Infiltration	1 ach			
Glazing U-value [W/m^{2}K]	1.6, 1.9 and 2.1 - (Insulated buildings) 5.8 - (Non-insulated buildings)			
Cut-off irradiance [W/m^2]	100			
Glazing G-value	0.85			
Shading device [λ]	0.2			
Openable fraction	0.5			
Buildings		Occupant density [m^2/P]	Sensible loads [W/P]	Latent loads [W/P]
Commercial	Gym	10	388	315
	Office	9.3	246	55
	Auditorium	1	84	35
	Shopping mall	5	268	55
	Restaurant	1.4	103	80
Residential		18.6	90	45

Note: Calculations for the latent (lighting, people, and appliances) and sensible loads have been evaluated based upon American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) guidelines and Dubai building codes for both residential and commercial buildings.

usable for the CitySim. The steps followed by the current study are depicted in Fig. 2. It is important to mention that the simulation for all mitigation scenarios considered various types of urban greenery amounts using the mosaic technique [18]. This study examined four mitigation scenarios (Fig. 3) which combined varying amounts of vegetation and reflective materials, and one unmitigated scenario:

- Base case: The unmitigated case involves the current climatic conditions. In this case, the albedo fraction is 0.15 for the roof, wall, and pavement; the emissivity is 0.90 for the roof, wall, and pavement; and the vegetation fraction is 0.10 for pavements.
- Scenario M1: Low albedo materials and medium irrigated vegetation: The albedo is 0.40 for the roof, 0.20 for the wall and pavement, while the emissivity remains at 0.90 for all surfaces. The vegetation fraction on the pavement stands at 0.40.
- Scenario M2: Low albedo materials and very high irrigated vegetation: The roof retains an albedo of 0.40, the wall and pavement 0.20 each, with an emissivity of 0.90 across all surfaces. Notably, the pavement hosts a vegetation fraction of 0.65.
- Scenario M3: High albedo materials and high irrigated vegetation: This scenario features a roof with an albedo of 0.65, while the wall and pavement maintain a 0.20 albedo. Emissivity remains constant at 0.90 for all surfaces. A significant vegetation fraction of 0.50 covers the pavement.
- Scenario M4: Very high albedo materials and low irrigated vegetation: In this case, the roof boasts an albedo of 0.80, while the wall and pavement retain a 0.20 albedo. Emissivity remains at 0.90 for all surfaces. On the pavement, the vegetation fraction dwindles to 0.25.

3.1. CitySim model configuration

In order to obtain accurate simulation results from CitySim, a specific procedure must be followed. To simulate the thermal performance of 40 buildings in response to the mitigation strategies, the software must have the required data and settings. The configuration process started with the import of climate data files as.cli and.hor files into the CitySim software. In the second step, the buildings characteristics were described. The infiltration value was taken as 1ach, while the internal and external temperatures for commercial and residential buildings were set at 19 °C and 24 °C, and 20 °C and 26 °C, respectively. The shading device was taken as 0.2, cut-off irradiance as 100 W/m^2, and glazing g-value as 0.85. The openable fraction was set at 0.5, and surface reflectance was varied from 0.15, 0.4, 0.65, and 0.8. The glazing U-value for non-insulation was considered as 5.8 W/m^{2}K, and for insulation, it was set at 1.6 W/m^{2}K, 1.9 W/m^{2}K, and 2.1 W/m^{2}K, respectively as shown in Table 1.

CitySim takes the climatic data from Meteonorm as input while data regarding energy demand for lighting, cooling and heating and building properties are formulated in an extensible markup language (XML) file. Additionally, an XML file containing the information about composite materials and envelope characteristics for roof, wall and floor was also need for the CitySim software. Files for both insulated and non-insulated buildings were considered for the simulation of both types of buildings. The final step was to define the density of occupants and the internal heat gains for the input to CitySim.

To investigate the performance of heat mitigation strategies on cooling load demand, the case study of Dubai Downtown (25.18366°N; 55.26664°E) involved a total of 40 buildings comprising 10 commercial buildings and 30 residential buildings. The selected urban area had a total area of 2 km^2 and is situated on the Sheikh Zayed Road on the northwest side of Dubai. The selected commercial buildings included offices, a gym, an auditorium and shopping malls. Both high-rise and low-rise buildings were considered. Commercial buildings were between 12 m and 89 m in height, while the height of residential buildings ranged from 22 m to 605 m.

3.2. Data input from WRF/SLUCM and SketchUp to CitySim

Weather files for the CitySim input were created by the WRF from the hourly climatic data. The precision of this data directly impacts the simulation results of CitySim. WRF data files consisted of surface temperature, wind speed and direction, ambient temperature, and humidity statistics. Downtown Dubai is the Central Business district (CBD) of the

Table 2
Building parameters for drawing model.

Type	Building height [m]	Area [m^2]	WWR [%]	No. of floors	Building category [High/ Medium/Low]
B01-Res.	56	46,665	50	16	High
B02-Res.	192	61,008	75	48	High
B03-Res.	151	44,650	60	37	High
B04-Res.	190	352,800	65	46	High
B05-Sh. mall	25	1,013,379	35	4	Low
B06-Res.	266	200,087	70	62	High
B07-Res.	158	53,760	60	42	High
B08-Res.	171	35,244	50	41	High
B09-Sh. Mall	25	126,367	50	4	Low
B10-Office	50	36,150	65	13	High
B11-Gym	16	5683	60	4	Low
B12-Res.	67	24,842	50	18	High
B13-Res.	605	259,748	95	162	High
B14-Restaurant	12	1248	25	3	Low
B15-Sh. mall	25	178,594	40	5	Low
B16-Res.	22	236,924	40	6	Low
B17-Res.	184	51,905	65	51	High
B18-Res.	76	36,549	40	20	High
B19-Res.	80	11,856	60	20	High
B20-Office	18	1738	40	5	Low
B21-Res.	115	18,301	60	33	High
B22-Res.	70	42,580	40	17	High
B23-Office	17	5787	40	5	Low
B24-Res.	119	21,280	70	34	High
B25-Res.	115	22,095	70	33	High
B26-Res.	112	22,107	65	34	High
B27-Res.	96	21,588	70	29	High
B28-Res.	115	18,445	70	33	High
B29-Res.	69	15,673	70	19	High
B30-Res.	88	15,237	70	25	High
B31-Res.	142	89,334	60	39	High
B32-Res.	73	43,498	60	19	High
B33-Res.	124	49,011	40	34	High
B34-Office	89	99,106	90	21	High
B35-Office	28	42,182	80	6	Medium
B36-Aud.	44	37,688	95	7	Medium
B37-Res.	119	97,767	60	34	High
B38-Res.	98	38,039	55	28	High
B39-Res.	56	26,771	30	16	High
B40-Res.	76	21,066	30	19	High
B41-Res.	68	26,820	30	17	High

Note: Building category: High = High-rise building, Medium = Medium-rise building, Low = Low-rise building, Res. = Residential, Aud. = Auditorium, Sh. Mall = Shopping mall, WWR = Window-to-wall ratio.

city and the hub of various activities. The chosen area of 2 km^2 containing 40 buildings was integrated into SketchUp from Google Earth and a CitySim-compatible drawing file was created. Building models, as shown in Fig. 2 were drawn in metres and the north was directed towards the top. Finally, the shared building surfaces in the model were excluded so as to use separate layers for a building. This increased the controllability and customizability of each independent building. Finally, the drawing exchange format (DXF) model file created by SketchUp was utilized by CitySim.

The model's properties included building area, window-wall-ratio, number of floors, geometrical dimensions etc. as listed in Table 2. To ensure that the thermal characteristics of the buildings and the conventional standards of the Dubai Municipality are aligned, American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHARE) standards [36,37] (listed in Table 3) and the Dubai Building Code [38] manual were taken into account when selecting the envelope layer and composite materials. The energy requirements of the buildings were analysed using the base case and the combined mitigation scenarios for commercial and residential buildings.

3.3. *Energy simulation at building scale*

Energy simulations were conducted to assess building performance in terms of energy efficiency. The simulations were carried out for various mitigation scenarios to understand the impact of combined mitigation techniques on cooling load. The simulations considered both insulated and non-insulated buildings. Further the buildings were divided into low-rise, medium-rise and high-rise structures depending upon the number of floors i.e., 3–6, 7–12, or more than 12 respectively. Building energy models (BEMs) are widely used to evaluate the thermal performance of buildings. In particular, they are more commonly used for urban areas and are known as urban *building energy models* (UBEMs) [26,39–41]. UBEMs have been utilised in combination with other modelling tools to evaluate the thermal performance of buildings. The UBEM being used in this study is CitySim Pro which was developed by *École Polytechnique Fédérale de Lausanne* (EPFL) [42]. To validate the results of CitySim simulation, a *building energy simulation test* (BESTEST) was performed [43]and the results were compared with those from reference program, *international energy agency* (IEA) BESTEST [44],and minor differences were found when CitySim output was compared with monitored data [29]. Climate files from WRF needed to be converted to climate (.cli) and horizon (.hor) files so as to be used by CitySim. This was carried out by Meteonorm 8.0 software where WRF output in the form of climate data spreadsheets was used to generate.cli and.hor files. Climate file (.cli) contains the hourly meteorological data for a complete

Table 3
Composite material properties for wall, roof and floor.

Buildings	Wall	Roof	Floor
Insulated	External mortar-cement and sand; Cement block; Rockwool board/Slab; Cement board; Internal mortar; plaster (U-Value: 0.32 W/m^2K)	Concrete tiles; Polyurethane (PUR) ; Light weight concrete; Bitumen layer; Concrete (Residential 0.2 m; Commercial 0.3 m); Plaster. U Value-Res: 0.34 W/m^2K; U Value-commercial: 0.33 W/m^2K.	Ceramic tiles; Light weight mortar; Concrete; U Value: 3.27 W/m^2K.
	Glass (U-Value 1.6, 1.9, 2.1 W/m^2K)	Roof metal (Steel sheet; Expanded polystyrene), U Value: 2.11 W/m^2K	
Un-Insulated	External mortar-cement and sand; Cement block; Internal mortar; plaster (U-Value: 2.53 W/m^2K)	Concrete tiles; Light weight concrete; Bitumen layer; Concrete (Residential 0.2 m; Commercial 0.3 m); Plaster. U Value-Res: 2.34 W/m^2K; U Value-commercial: 1.91 W/m^2K	Ceramic tiles; Light weight mortar; Concrete; U Value: 3.27 W/m^2K.
	Glass (U-Value 5.8 W/m^2K)	Roof metal (Steel sheet; Expanded polystyrene), U Value: 2.11 W/m^2K	

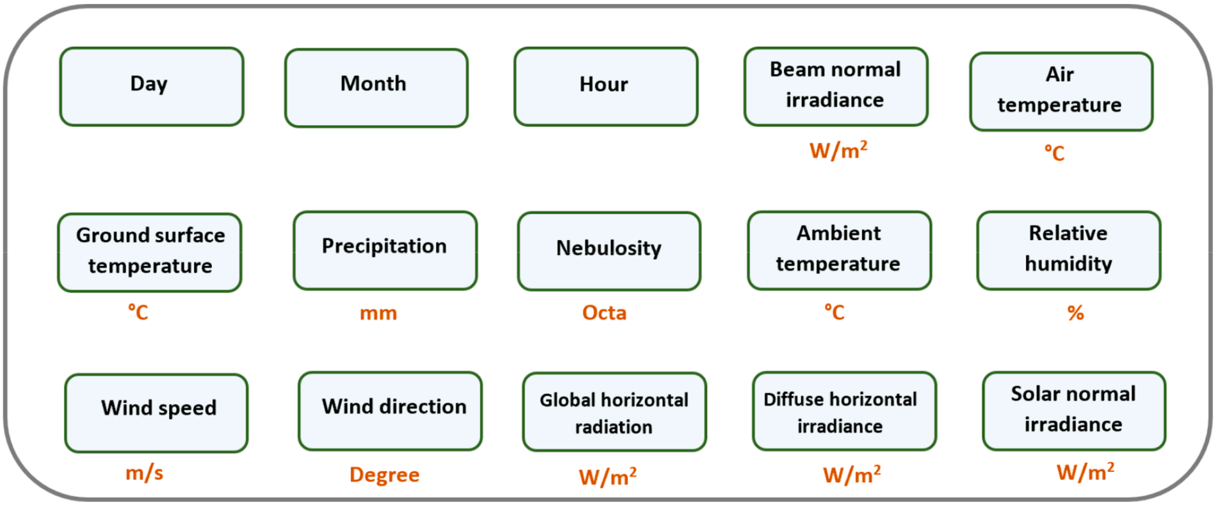


Fig. 4. Climate elements for CitySim simulations.

year (8760 h) as wells as information about various climatic elements as shown in Fig. 4 [45].

When conducting simulations related to energy consumed by buildings, there are several additional of factors to consider: surface temperature (°C), cover fraction (Octas) and precipitation. Meteonorm provided any of the missing parameters. Also, cloud cover data was provided by Meteonorm by taking into account the radiation time series. This hourly climatic parameter was used by CitySim to perform simulations for base case and combined mitigation scenarios, for the month of July. Insulated and non-insulated buildings were considered, and the effects of combined mitigation strategies were evaluated.

4. Results and discussion

This section evaluates the energy performance of mitigation strategies involving combined heat mitigation techniques for Downtown

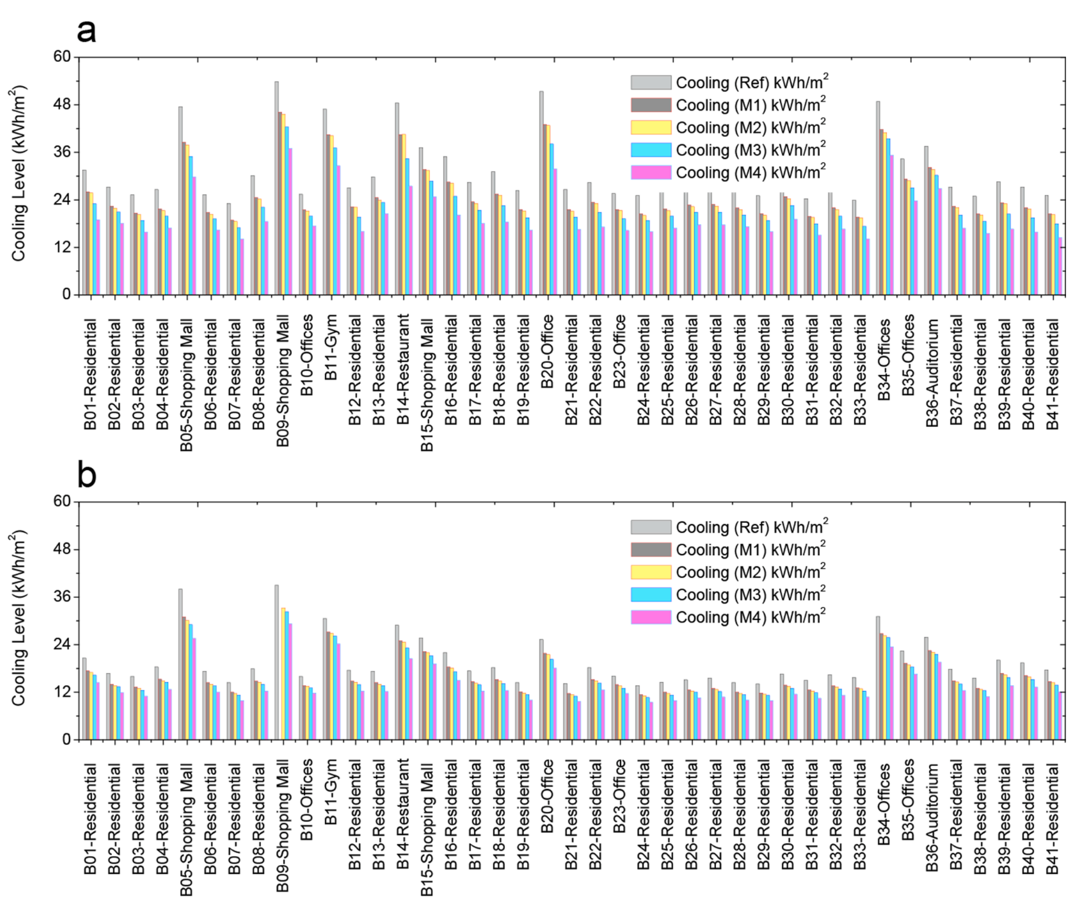


Fig. 5. a) Cooling demand (kWh/m^2) in all non-insulated buildings (commercial and residential) for base case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month, and b) cooling demand (kWh/m^2) in all insulated buildings (commercial and residential) for base case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month.

Table 4
Cooling load for all mitigation scenarios.

Non-insulated buildings						
Building types	Buildings	Cooling load (minimum-maximum) [kWh/m^2]				
		Reference case	(ALB_0.40 + VEG_40)	(ALB_0.40 + VEG_65)	(ALB_0.65 + VEG_50)	(ALB_0.80 + VEG_25)
Residential	Low-rise	34.9	28.5	28.2	24.9	20.2
	High-rise	23.1–31.6	18.9–26	18.6–25.8	17–23.4	14.2–20.5
Commercial	Low-rise	25.6–53.9	21.6–46.2	21.4–45.7	19.3–42.4	16.3–37
	High-rise	25.4–48.8	21.5–41.8	21.2–41	19.9–39.5	17.5–35.3

Insulated buildings						
Building types	Buildings	Cooling load (minimum-maximum) [kWh/m^2]				
		Reference case	(ALB_0.40 + VEG_40)	(ALB_0.40 + VEG_65)	(ALB_0.65 + VEG_50)	(ALB_0.80 + VEG_25)
Residential	Low-rise	22	18.4	18.1	17.2	15
	High-rise	13.7–20.6	11.4–17.4	11.1–17	10.7–16.3	9.5–14.4
Commercial	Low-rise	16.1–39	13.9–33.9	13.6–33.3	13–32.3	11.7–29.3
	High-rise	16–31.1	13.7–26.8	13.5–26.3	13.1–25.8	11.8–23.5

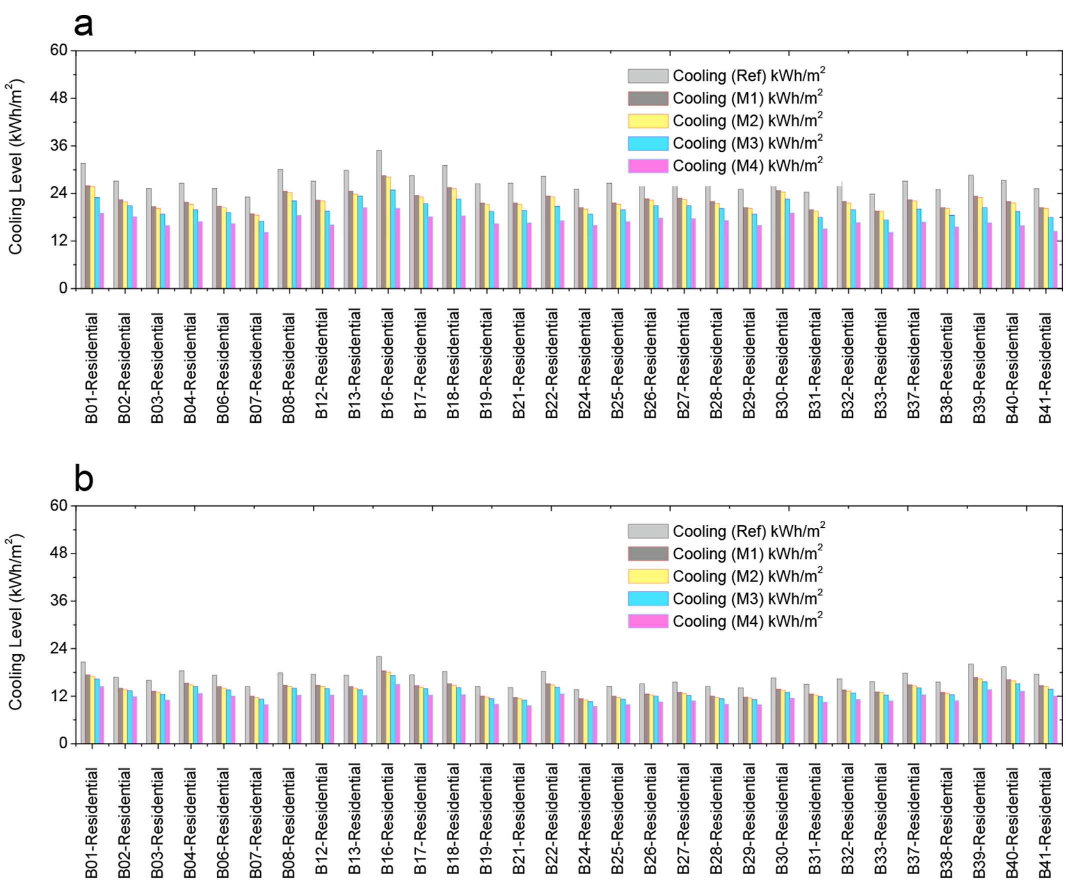


Fig. 6. a) Cooling needs (kWh/m^2) in high-rise (h) and low-rise (l) residential buildings without insulation for base case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month, and b) cooling needs (kWh/m^2) in high-rise (h) and low-rise (l) residential buildings with insulation for base case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month.

Dubai, with a maximum ambient temperature recorded between 10 °C and 30 °C for winter months but it reaches as high as 48 °C for summer months averaging at 41 °C. Combined mitigation techniques also impacted the ambient urban temperatures. For instance, at 14:00 LT combined heat mitigation scenarios M1, M2, M3 and M4 observed a reduction in ambient temperature recorded as1.5 °C, 1.9 °C, 2.3 °C and 2.8 °C respectively while a reduction in surface temperature of 2.7 °C, 3.4 °C, 4.6 °C and 5.3 °C for the combined mitigation scenarios. Similarly, a reduction in sensible heat flux and wind speed while an increase in latent heat flux and relative humidity was also noted when combined heat mitigation techniques were implemented.

4.1. *Base model evaluation and validation*

Building Energy performance for the combined heat mitigation strategies has been evaluated and validated by utilizing four climatic data sets. National Centre of Meteorology (NCM), UAE provided this climatic data from the metrological stations located in Al-Maktoum

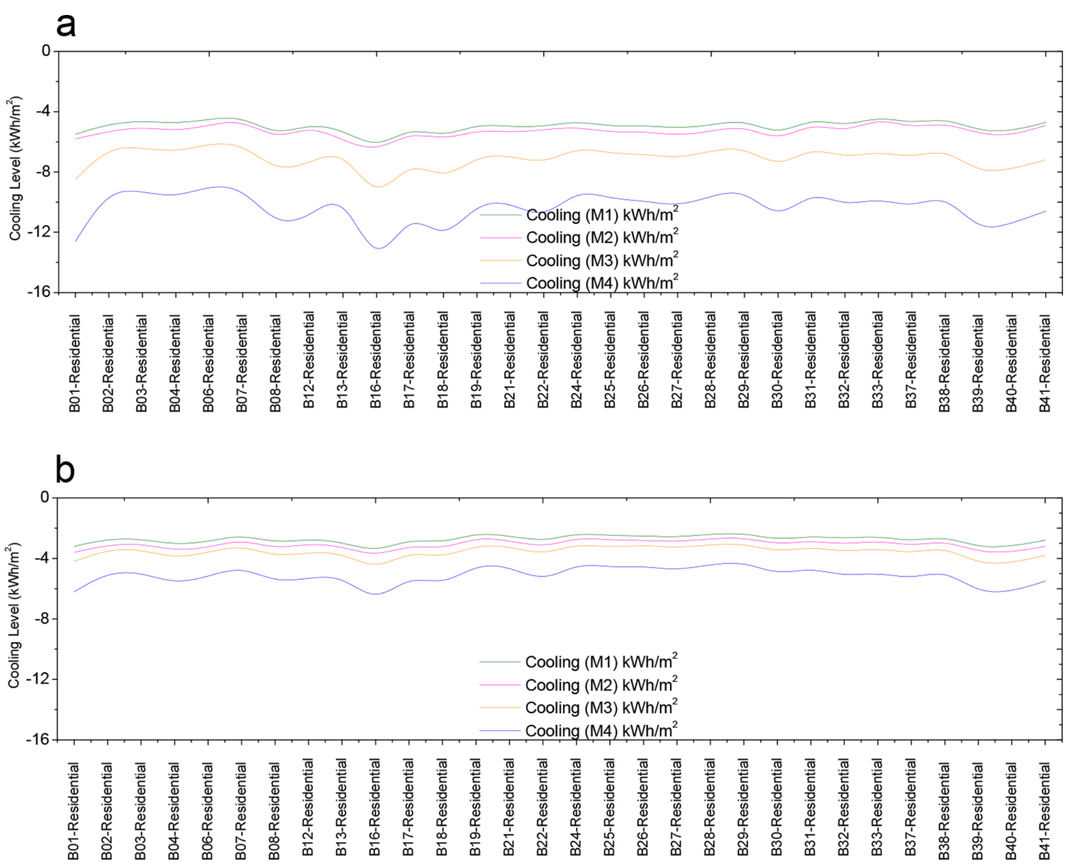


Fig. 7. a) Cooling load reduction against reference case (kWh/m^2) in high-rise (h) and low-rise (l) residential buildings without insulation for control case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month, and b) cooling load reduction against reference case (kWh/m^2) in high-rise (h) and low-rise (l) residential buildings with insulation for control case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month.

International Airport, Dubai International Airport, Lahbab station, and Saih Al-Salem in order to carry out the simulation for Dubai. Various cool materials on the building roof surface were used and green pavements in urban grid cell were installed by implementing mosaic approach through the modification of land use/cover fraction. The WRF model validation and evaluation required a statistical comparison among the mesoscale climatic parameters and the hourly simulation result (considering temperature at 2 m) for the control case scenario.

4.2. *Impact of mitigation technologies on cooling loads*

Citysim was employed to perform building energy simulations for the four combined heat mitigation scenarios with a varying albedo (for urban surfaces including roof, wall, and road) and vegetative fractions and evaluated in comparison with a reference case. The simulations were performed on the climatic data from WRF for July 2019. The results will discuss the cooling load consumption and the reduction for the various combined heat mitigation scenarios for the buildings of Downtown Dubai. Fig. 5 represents the cooling load demand for 40 buildings comprising of commercial and residential buildings having a range of heights and grouped into low-rise and high-rise buildings. The cooling load reduction (as compared to the reference case) for all type of buildings have been listed in Fig. 10 for the four combined mitigation scenarios (M1, M2, M3 and M4) respectively. A detailed cooling load values have been listed in Table 4.

Fig. 6 represents the cooling load demand for all residential buildings for the four mitigation scenarios and one base case. Findings of this study suggested that high-rise non-insulated residential buildings had a cooling load range of 23.1 kWh/m^2 to 31.6 kWh/m^2 for the base case while the mitigation scenarios M1and M4 demonstrated a cooling load

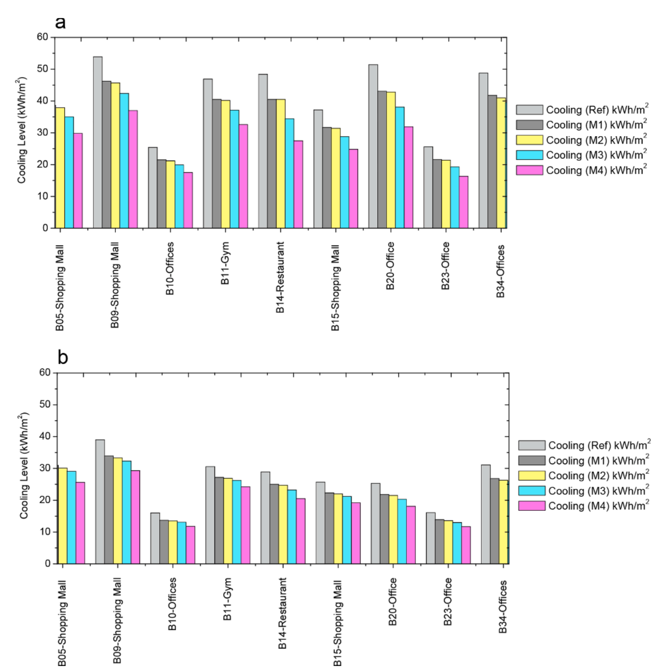


Fig. 8. a) Cooling needs (kWh/m^2) in high-rise (H) and low-rise (L) commercial buildings without insulation for base case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month, and b) cooling needs (kWh/m^2) in high-rise (H) and low-rise (L) commercial buildings with insulation for base case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month.

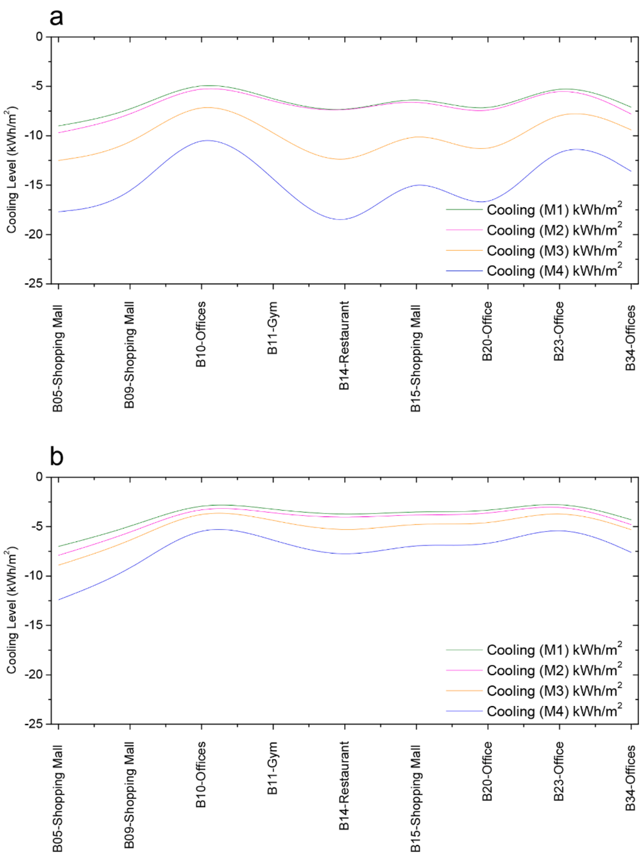


Fig. 9. a) Cooling load reduction against reference case (kWh/m^2) in high-rise (h) and low-rise (l) commercial buildings without insulation for control case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month, and b) cooling load reduction against reference case (kWh/m^2) in high-rise (h) and low-rise (l) commercial buildings with insulation for control case and four heat mitigation scenarios (M1, M2,M3 and M4) in the summer month.

of 18.9–26 kWh/m^2 and 14.2–20.5 kWh/m^2 respectively. Similarly, low-rise buildings have a cooling load demand of 34.9 kWh/m^2 for the base case which reduced to 28.5 kWh/m^2 and 20.2 kWh/m^2 for the maximum and minimum combined heat mitigation scenario respectively. On the other hand, much lesser cooling load demand has been witnessed for the insulated residential buildings where observed cooling load for the high-rise buildings varied between 13.7 kWh/m^2 and 20.6 kWh/m^2 for the base case while it ranged between 11.4 and 17.4 kWh/m^2 and 9.5–14.4 kWh/m^2 respectively for the maximum and minimum combined heat mitigation scenario. Likewise, low-rise residential buildings had a cooling load of 22 kWh/m^2 for the base case which reduced to 18.4 kWh/m^2 and 15 kWh/m^2 for the mitigation scenarios M1 and M4 respectively.

These values of cooling load demand correspond to a significant reduction in cooling load which are depicted in Fig. 7. For instance, low-rise residential non-insulted buildings observed a cooling load reduction of 14.7 kWh/m^2 while high rise buildings experienced a reduction of 8.9 kWh/m^2-12.7 kWh/m^2 for the maximum heat mitigation scenario M4 respectively. Low-rise and high-rise residential buildings with insulation witnessed a reduction of 7 kWh/m^2 and 4.2–6.3 kWh/m^2 respectively for the mitigation scenario M4.

The cooling load demand for the commercial buildings have been illustrated in Fig. 8 where simulation results for the four heat mitigation scenarios have been considered. Results indicate that low-rise non-insulated commercial buildings had a cooling load demand of 25.6–53.9 kWh/m^2 for the base case. This demand reduced to a value of 21.6–46.2 kWh/m^2 and 16.3–37 kWh/m^2 for the maximum and minimum combined heat mitigation scenario respectively. Similarly, high-rise buildings have a base case cooling load of 25.4–48.8 kWh/m^2 while the M1 and M4 scenarios have a cooling load demand of 21.5–41.8 kWh/m^2 and 17.5–35.3 kWh/m^2 respectively. Alternatively, low-rise insulated buildings demonstrated a cooling load demand of 16.1–39 kWh/m^2 for the base case while a cooling load demand of 13.9–33.9 kWh/m^2 and 11.7–29.3 kWh/m^2 for the combined heat mitigation scenario M1and M4 respectively. In the same way, cooling load demand for high-rise buildings was observed between 16 and 31.1 kWh/m^2 for the base case while it reduced to 13.7–26.8 kWh/m^2 and 11.8–23.5 kWh/m^2 for the maximum and minimum combined heat mitigation scenario.

It is noteworthy that many climatic, technological, and environmental parameters affect the building energy performance. It can be interpreted that closely packed buildings have a higher cooling load demand for hot and humid climates like Dubai. Thus, mitigation techniques, especially those involving cool materials and plantation, can significantly contribute to reduce the urban overheating and hence the building cooling energy as well. The reduction in cooling load corresponding to the cooling load demands in various mitigation scenarios for the commercial buildings is depicted in Fig. 9. Mitigation scenario M4 demonstrated a highest reduction ranging between 9.3 kWh/m^2 to 21 kWh/m^2 and 17.5 kWh/m^2 to 35.3 kWh/m^2 for the low-rise and high-rise non-insulated buildings respectively. Likewise, insulated buildings observed a reduction of 4.4–12.4 kWh/m^2 and 4.2–7.6 kWh/m^2 for the low-rise and high-rise buildings respectively.

Overall, a reduction of 17.2 %, 18.3 %, 24.9 % and 36.4 % in cooling load demand was observed for the non-insulated buildings while a corresponding reduction of 15.5 %, 17.3 %, 20.2 % and 29.1 % was noted for the insulated buildings when evaluated for the combined mitigation techniques M1, M2, M3 and M4 respectively.

Analysis of results indicated that combined heat mitigation scenario M4, having albedo fraction as 0.8 and vegetative proportion of 25 %, produced a maximum cooling load demand reduction for all types of buildings whether low-rise, high-rise, insulated or non-insulated. This is owing to the presence of vegetation as well as the high reflectivity of albedo materials being used in combined mitigation scenario M4 as compared to the other scenarios. Building morphology including building insulation and window wall ratio played a vital role in heat mitigation. Building insulation has a positive impact on cooling load reduction. It has also been noted that a higher value of window wall ratio (WWR) elevated the cooling energy demand. Also, the cooling energy demand for the high-rise buildings is lower than the low-rise buildings. This is due to the trapping of heat in the building canyons close to the ground. While high-rise buildings have a high wind speed and infiltration rates close to the upper floors which result in heat loss for such buildings [43].

Apart from this, anthropogenic heat, seasonal variations, various climatic parameters, urban properties, landscapes, and demographic profile also depend upon the rate at which temperature is being reduced by the application of albedo material and urban plantation increase. Combined mitigation strategies adopted a combination of cool materials and greenery increase which elevate the overall albedo hence increasing the solar reflectance and preventing the absorption of thermal energy by the building materials and transferring it to the interior [46,47]. The increased plantation exaggerated the leaf area index (LAI), shading and surface reflectance which led to wind speed changes and effective channelizing of wind to produce cooling effect [48] and evapotranspiration. This reduced the need for mechanical cooling by creating a cool convective zone around the buildings. Hence it can mitigate the occurrence of extreme urban heat events. Utilization of combined heat mitigation techniques across urban area would considerably reduce the overall urban temperature.

4.3. Comparison of combined mitigation techniques with enhanced urban vegetation and cool materials

A comparison of simulation results from this study for the combined

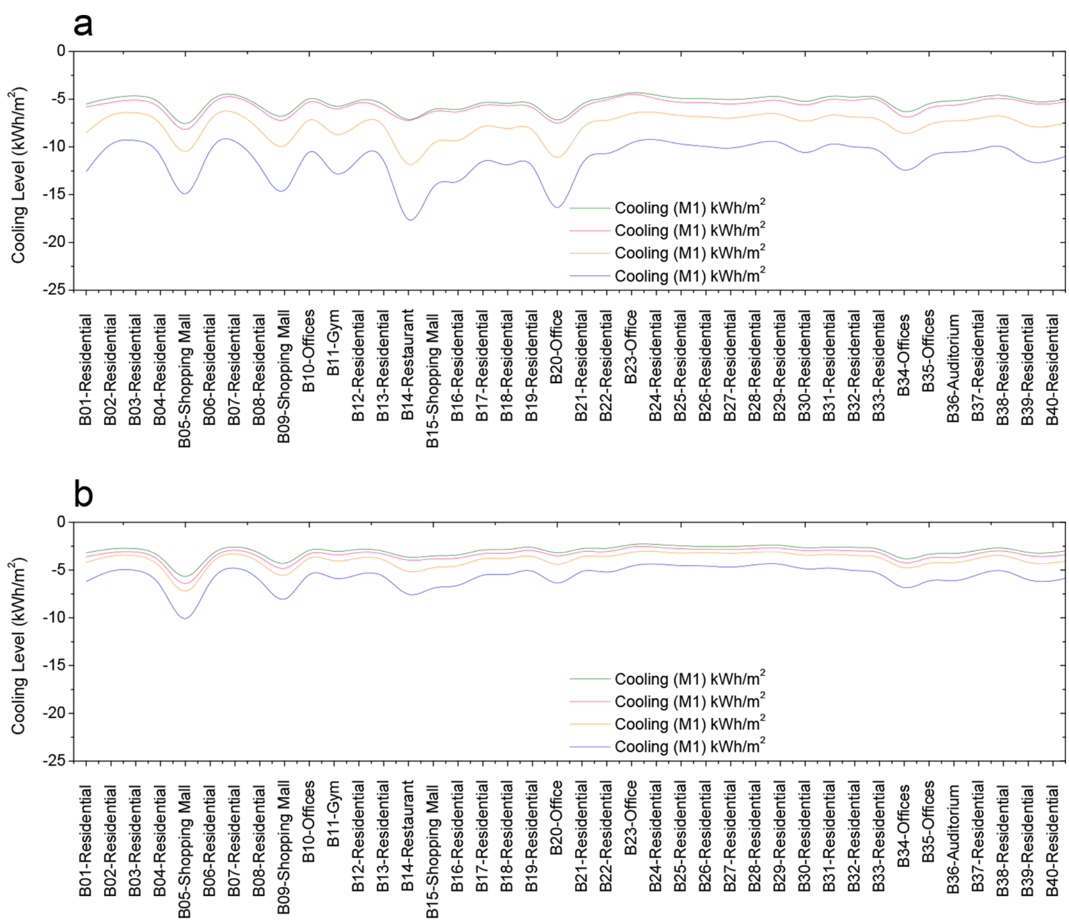


Fig. 10. a) Reduction in cooling load against reference case (kWh/m^2) in all uninsulated buildings (commercial and residential) for base case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month, and b) Reduction in cooling load against reference case (kWh/m^2) in all insulated buildings (commercial and residential) for base case and four heat mitigation scenarios (M1, M2, M3 and M4) in the summer month.

mitigation scenarios having albedo fraction as 0.4 and increased vegetation as 40 % (M1), albedo fraction as 0.4 and enhanced plantation as 65 % (M2), cool material albedo fraction as 0.65 and vegetation cover increase as 50 % (M3) and albedo fraction as 0.8 and increased greenery as 25 % (M4) was made with our previous studies involving the implementation of cool materials having albedo fractions as 0.4 (M1), 0.65 (M2) and 0.8 (M3) and enhanced vegetation fraction by 25 % (M1), 50 % (M2), 75 % (M3) and 100 % (M4). A graphical analysis of these comparisons is presented in Figs. 11–13 and the relation between cooling load demand and these mitigation techniques have been highlighted. The results of cooling energy demand for all building types i.e., residential and commercial with both insulated and non-insulated for low-rise and high-rise buildings were compared for the maximum mitigation scenario in Downtown Dubai.

4.3.1. Comparison of combined mitigation strategies with cool materials

Fig. 14 represented the scatter plot showing the cooling energy reduction for cool materials and combined mitigation scenarios for the 40 buildings in Downtown Dubai. The trend line for combined heat mitigation technologies initially represented a higher cooling energy reduction but the slope of the trend line for cool materials was higher hence the trend lines for both mitigation scenarios crossed each other indicating a higher cooling energy reduction by increased albedo materials for mitigation scenario M3. However, the trend lines for both mitigation techniques showed a positive slope indicating a direct relationship between energy saving and these mitigation scenarios.

Fig. 12 illustrates the comparison between the cooling demand reduction potential of modified albedo materials and combined heat mitigation strategies. It can be observed that the curves of both mitigation scenarios are close to each other. Generally, M1 mitigation scenario in all building types have a lower cooling load demand for combined heat mitigation techniques as compared to the enhanced albedo materials. Similarly, for M2 both mitigation techniques showed a similar magnitude of cooling load consumption. In case of M3 mitigation scenario, cool materials have a higher cooling load reduction rate as compared to the combined mitigation strategies. Finally, combined mitigation scenario M4 (albedo fraction as 0.8 and vegetation as 25 %) demonstrated the highest value of cooling load reduction when compared with the energy performance when modified cool materials were implemented in various buildings. In terms of percentage reduction, non-insulated buildings exhibited a 17.2 %, 18.3 %, 24.9 % and 36.4 % average decrease of cooling demand for combined heat mitigation scenarios M1, M2, M3 and M4 respectively. Additionally, modified albedo materials presented an average percentage reduction of 11.7 %, 17.6 % and 32.2 % for the corresponding mitigation scenarios respectively. Moreover, an average decrease of 15.5 %, 17.3 %, 20.2 % and 29.1 % for insulated buildings were also revealed for the combined mitigation techniques, respectively. The three mitigation scenarios for cool materials demonstrated an average cooling load reduction of 9.3 %, 12.5 % and 24.3 % respectively.

A comprehensive analysis of results indicate that non-insulated low-rise buildings have a cooling load demand of 34.9 kWh/m^2 for base case while the cooling energy need for the three cool materials mitigation scenarios was observed to be around 30.3 kWh/m^2, 27.4 kWh/m^2 and 21.8 kWh/m^2 respectively while the four combined mitigation scenarios produced a cooling energy consumption of 28.5 kWh/m^2, 28.2 kWh/m^2,

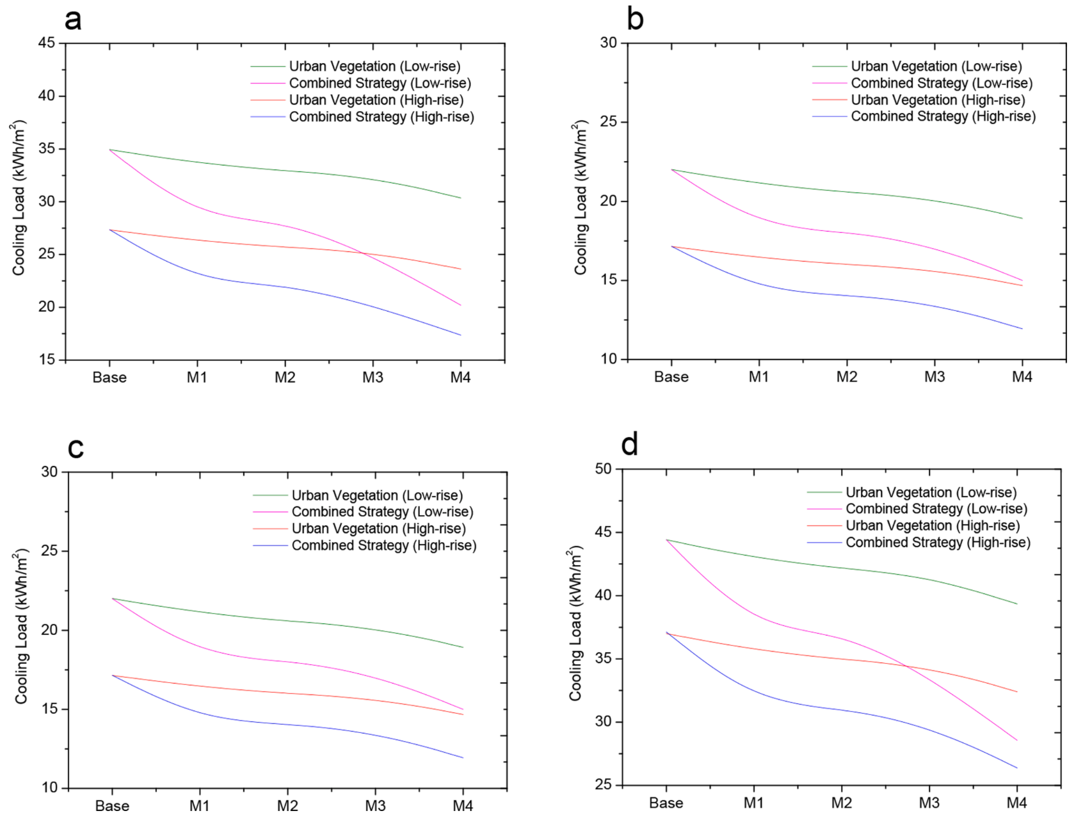


Fig. 11. a) Comparison between cooling load demand in case of greenery infrastructure and combined heat mitigation strategies for non-insulated residential buildings. b) comparison between cooling load demand in case of greenery infrastructure and combined heat mitigation strategies for insulated residential buildings, c) comparison between cooling load demand in case of greenery infrastructure and combined heat mitigation strategies for non-insulated commercial buildings, and d) comparison between cooling load demand in case of greenery infrastructure and combined heat mitigation strategies for insulated commercial buildings.

24.9 kWh/m^2 and 20.2 kWh/m^2 respectively. High-rise buildings, on the other hand, have a cooling energy demand of 23.1–31.6 kWh/m^2 for the base case scenario while the cooling load for combined mitigation scenarios was observed to be between 18.9 and 26 kWh/m^2, 18.6–25.8 kWh/m^2, 17–23.4 kWh/m^2 and 14.2–20.5 kWh/m^2 respectively and the three albedo fractions produced a cooling load varied between 20.2 and 27.5 kWh/m^2, 18.8–25.8 kWh/m^2 and 15.1–21.7 kWh/m^2 respectively.

It has been noted that commercial low-rise buildings have a base case cooling load demand of 25.4–53.9 kWh/m^2 while a cooling load consumption of 22.7–48.4 kWh/m^2, 20.8–45.5 kWh/m^2 and 17.3–38.8 kWh/m^2 was calculated for cool material mitigation scenarios M1, M2 and M3 respectively and 21.6–46.2 kWh/m^2, 21.4–45.7 kWh/m^2, 19.3–42.4 kWh/m^2 and 16.3–37 kWh/m^2 for the four combined heat mitigation scenarios respectively. Similarly, high-rise commercial buildings demonstrated a cooling load demand of 25.4–48.8 kWh/m^2 for base case: 21.5–41.8 kWh/m^2, 21.2–41 kWh/m^2, 19.9–39.5 kWh/m^2 and 17.5–35.3 kWh/m^2 for the four combined heat mitigation scenarios and 22.7– 44.1 kWh/m^{2,} 21.5–42.6 kWh/m^2 and 18.4–37 kWh/m^2 for the three heat mitigation scenarios for cool materials.

Insulated buildings have a lower cooling energy demands as compared to the non-insulated ones. Insulated low-rise residential buildings possessed a cooling energy demand of 22 kWh/m^2 in the base case scenario: 19.6 kWh/m^2 for mitigation scenario M1, 18.7 kWh/m^2 for M2 and 16 kWh/m^2 corresponding to albedo mitigation scenario M3 and 18.4 kWh/m^2, 18.1 kWh/m^2, 17.2 kWh/m^2 and 15 kWh/m^2 for combined mitigation scenarios. Contrarily, high-rise buildings anticipated a cooling load demand ranging between 13.7 and 20.6 kWh/m^2; 11.4–17.4 kWh/m^2, 11.1–17 kWh/m^2, 10.7–16.3 kWh/m^2 and 9.5–14.4 kWh/m^2; 12.2–18.8 kWh/m^2, 11.8–18.2 kWh/m^2 and 10.1 to 15.6 kWh/m^2 for control case; four combined mitigation scenarios and albedo mitigation techniques respectively. A similar trend was observed for commercial low-rise buildings where cooling energy consumption ranging between 16.1 and 39 kWh/m^2 was observed for the base case; cooling load demand varied between 13.7 and 33.9 kWh/m^2, 13.46–33.26 kWh/m^2, 32.33–13.05 kWh/m^2 and 11.7–29.3 kWh/m^2 was observed for the combined heat mitigation scenarios similarly, an expected cooling energy demand of 14.6–35.6 kWh/m^2, 14–34.6 kWh/m^2 and 12.3–30.7 kWh/m^2 for modified albedo scenarios was reported. Finally, high-rise commercial buildings observed a base case cooling energy demand of 16–31.1 kWh/m^2 which reduced to a value of 13.7–26.8 kWh/m^2, 13.5–26.3 kWh/m^2, 13.1–25.8 kWh/m^2 and 11.8–23.5 kWh/m^2 for combined mitigation scenarios and to a cooling energy demand values of 14.5–28.4 kWh/m^2, 14.13–27.8 kWh/m^2 and 12.4–24.6 kWh/m^2 for the three modified albedo scenarios.

4.3.2. Comparison of combined mitigation techniques with enhanced urban vegetation

Fig. 15 depicted the energy saving potential of greenery and combined heat mitigation strategy for all types of residential and commercial buildings. It can be observed that for both insulated and non-insulated buildings, combined mitigation strategies have a higher cooling load reduction as well as higher slope of the linear trend line. Comparative analysis for the results indicated a percentage cooling load demand reduction of 17.2 %, 18.3 %, 24.9 % and 36.4 % in case of non-insulated buildings for combined heat mitigation strategies while a reduction of 3.9 %, 6.1 %, 7.8 % and 13.5 % for the enhanced vegetation mitigation strategies for the M1, M2, M3 and M4 mitigation strategies respectively. Conversely, for insulated buildings a reduction in cooling load corresponding to 15.5 %, 17.3 %, 20.2 % and 29.1 % was observed for the combined heat mitigation scenarios respectively. Enhanced urban vegetation mitigation techniques have a cooling load reduction of 4.1 %, 6.5 %, 8.2 % and 13.9 % respectively for the corresponding urban

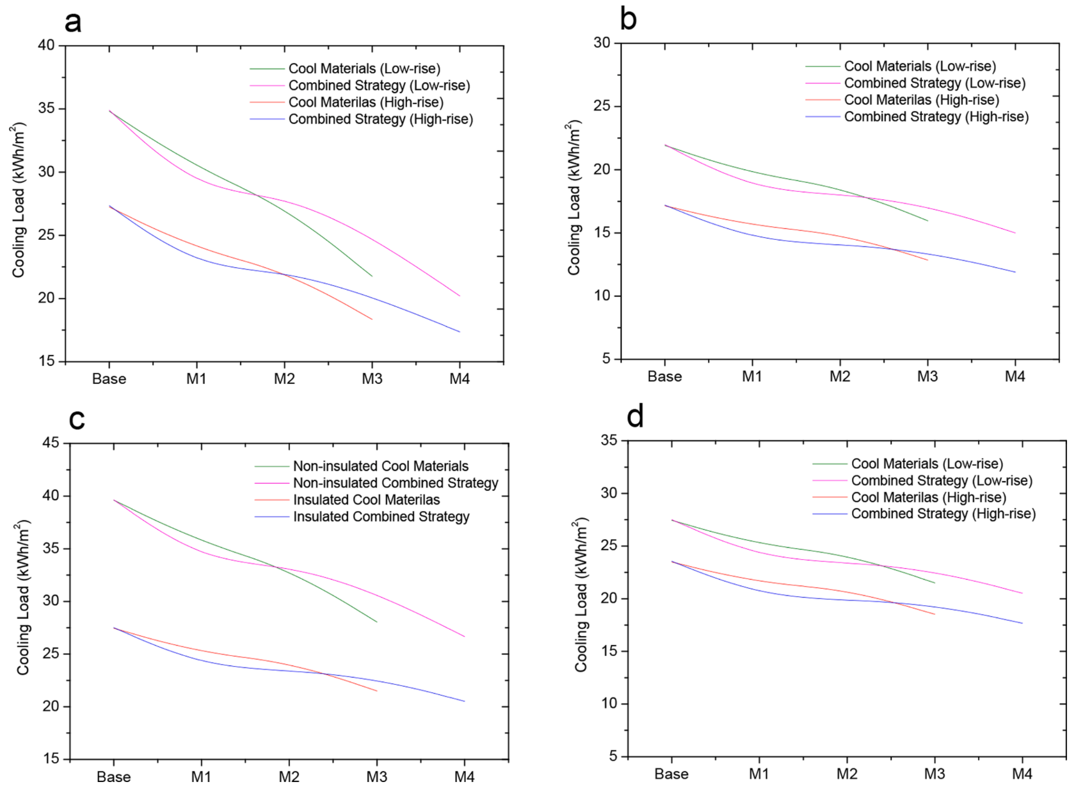


Fig. 12. a) Comparison between cooling load demand forenhanced albedo and combined heat mitigation strategies for non-insulated residential buildings. b) comparison between cooling load demand for enhanced albedo and combined heat mitigation strategies for insulated residential buildings, c) comparison between cooling load demand for enhanced albedo and combined heat mitigation strategies for non-insulated commercial buildings. and d) comparison between cooling load demand for enhanced albedo and combined heat mitigation strategies for insulated commercial buildings.

vegetation scenarios 25 %, 50 %, 75 % and 100 %.

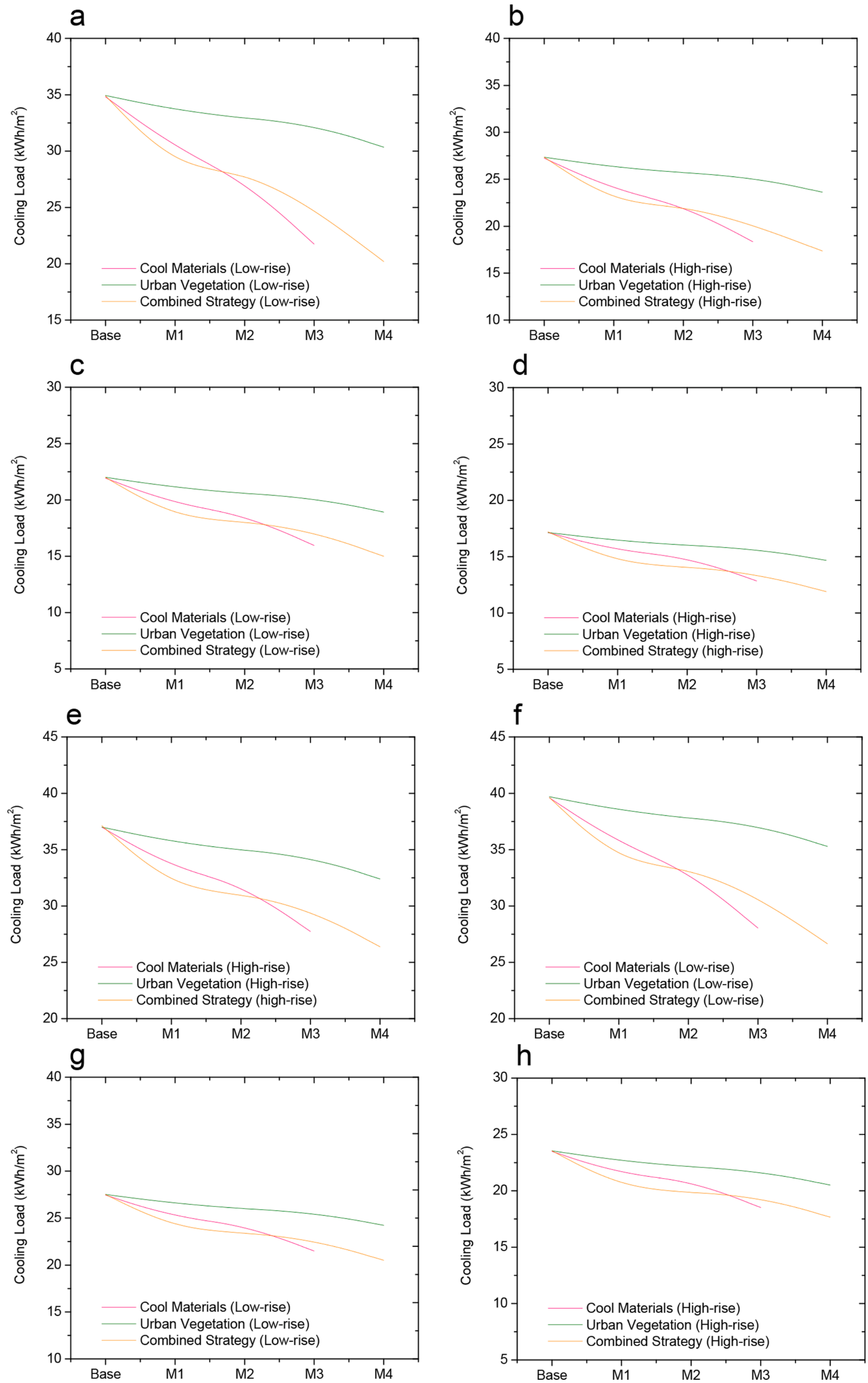
Fig. 11 illustrated the effectiveness of mitigation techniques involving enhanced vegetation and combined technologies. There exists a considerable difference between the cooling energy demand being reduced by the enhanced GI and combined heat mitigation strategies. A lower building cooling load demand has been observed in all mitigation scenarios of combined heat mitigation strategies. Also, the rate of cooling load reduction is almost linear while a much higher reduction rate is observed in case of combined mitigation scenarios. The higher reduction in case of combined mitigation strategies suggests a higher dominance of enhanced albedo materials in combination with enhanced vegetation in reducing cooling energy demands. Detailed investigation of results indicated that base case scenario for non-insulated residential buildings have a cooling load demand of 34.9 kWh/m^2 for the low-rise buildings while the cooling load demand reduced to a maximum value of 30.3 kWh/m^2 and 20.2 kWh/m^2 for the M4 mitigation scenario of enhanced GI and combined mitigation respectively. Enhanced GI mitigation scenario recorded a cooling load demand of 33.65 kWh/m^2, 32.92 kWh/m^2 and 32.33 kWh/m^2 while combined mitigation techniques have seen an estimated cooling energy consumption of 28.5 kWh/m^2, 28.2 kWh/m^2 and 24.9 kWh/m^2 for the mitigation scenarios M1, M2 and M3 respectively. Likewise, in case of high-rise buildings the base case cooling energy demand for both mitigation strategies are observed to be in the range of 23.1–31.6 kWh/m^2 and the four heat mitigation scenarios experienced a reduction in cooling load demand of 18.9–26 kWh/m^2, 18.6–25.8 kWh/m^2, 17–23.4 kWh/m^2 and 14.2–20.5 kWh/m^2 for the combined mitigation techniques respectively and 22.2–30.4 kWh/m^2, 21.6–30 kWh/m^2, 21.2–29.3 kWh/m^2 and 19.8–27.5 kWh/m^2 for the enhanced vegetation fraction respectively. A similar trend is shown in case of non-insulated low-rise commercial buildings where a cooling load consumption of 25.4–53.9 kWh/m^2 for the base case scenario and a reduced cooling energy consumption of 21.6–46.2 kWh/m^2, 21.4–45.7 kWh/m^2, 19.3–42.4 kWh/m^2 and 16.3–37 kWh/m^2 for the combined mitigation scenarios respectively was observed. On the other hand, an estimated cooling energy demand of 24.8–52.2 kWh/m^2, 24.3–51.2 kWh/m^2, 23.92–50.46 kWh/m^2 and 22.7–47.9 kWh/m^2 for the increased vegetation mitigation scenarios was also observed.

Further high-rise buildings have a cooling load demand of 25.4–48.8 kWh/m^2 for base case while a cooling load ranging between 21.5 and 41.8 kWh/m^2, 21.2–41 kWh/m^2, 19.9–39.5 kWh/m^2 and 17.5–35.3 kWh/m^2 for combined mitigation scenarios and a cooling load varying between 24.5 and 47 kWh/m^2, 24–46 kWh/m^2, 23.5–45.2 kWh/m^2 and 22.3–42.6 kWh/m^2 for the M1, M2, M3 and M4 mitigation scenarios of enhanced vegetation techniques respectively.

Analysis of results suggested a much lower cooling load in case of insulated buildings for all mitigation scenarios when compared with un-insulated one. Residential buildings observed a base case cooling load of 22 kWh/m^2 while the cooling load need reduced to 18.4 kWh/m^2, 18.1 kWh/m^2, 17.2 kWh/m^2 and 15 kWh/m^2 for the combined mitigation scenarios M1, M2, M3 and M4. In comparison to this, a cooling load of 21.10 kWh/m^2, 20.57 kWh/m^2, 20.18 kWh/m^2 and 18.9 kWh/m^2 for the mitigation scenarios involving increased vegetation fraction for the low-rise buildings.

Similarly, high-rise buildings have a base case cooling energy demand of 13.7–20.6 kWh/m^2 however, the M1, M2, M3 and M4 mitigation scenarios for combined heat mitigation strategy showed a cooling load of 11.4–17.4 kWh/m^2, 11.1–17 kWh/m^2, 10.7–16.3 kWh/m^2 and 9.5–14.4 kWh/m^2 respectively, conversely, enhanced vegetation presented a cooling energy demand of 13.1–19.7 kWh/m^2, 12.74–19.25 kWh/m^2, 12.5–18.9 kWh/m^2 and 11.6–17.7 kWh/m^2 respectively.

Commercial buildings had a cooling energy demand of 16.1–39 kWh/m^2 for base case in low-rise buildings which reduced to 13.7–33.9 kWh/m2, 13.46–33.26 kWh/m^2, 32.33–13.05 kWh/m^2 and 11.7– 29.3



(caption on next page)

Fig. 13. a) Comparison between cooling load demand for enhanced albedo, increased urban vegetation and combined heat mitigation strategies for non-insulated low-rise residential buildings. b) Comparison between cooling load demand for enhanced albedo, increased urban vegetation and combined heat mitigation strategies for non-insulated high-rise residential buildings, c) Comparison between cooling load demand for enhanced albedo, increased urban vegetation and combined heat mitigation strategies for insulated low-rise residential buildings, d) Comparison between cooling load demand for enhanced albedo, increased urban vegetation and combined heat mitigation strategies for insulated high-rise residential buildings, e) Comparison between cooling load demand for enhanced albedo, increased urban vegetation and combined heat mitigation strategies for non-insulated low-rise commercial buildings, f) Comparison between cooling load demand for enhanced albedo, increased urban vegetation and combined heat mitigation strategies for non-insulated high-rise commercial buildings, g) Comparison between cooling load demand for enhanced albedo, increased urban vegetation and combined heat mitigation strategies for insulated low-rise commercial buildings, and h) Comparison between cooling load demand for enhanced albedo, increased urban vegetation and combined heat mitigation strategies for insulated high-rise commercial buildings.

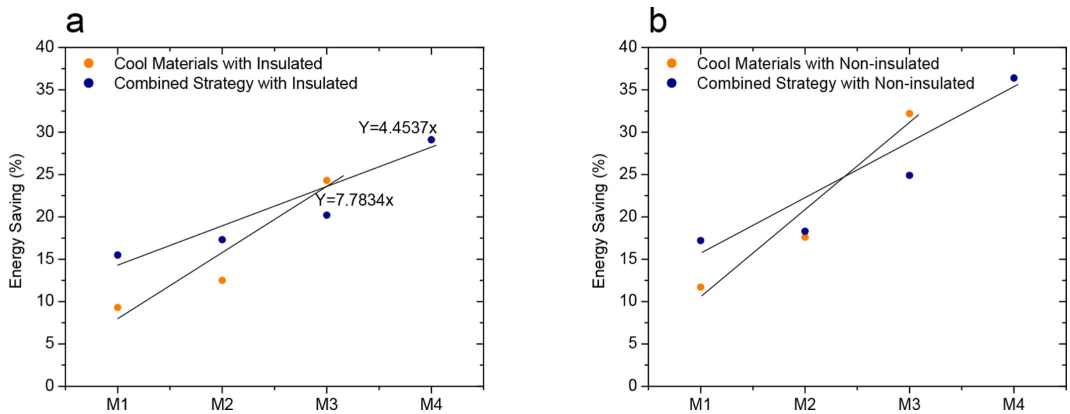


Fig. 14. a) Scatter plot showing the comparison between the percentage cooling load reduction for combined heat mitigation scenarios and cool material scenarios for insulated buildings, and b) scatter plot showing the comparison between the percentage cooling load reduction for combined heat mitigation scenarios and cool material scenarios for non-insulated buildings.

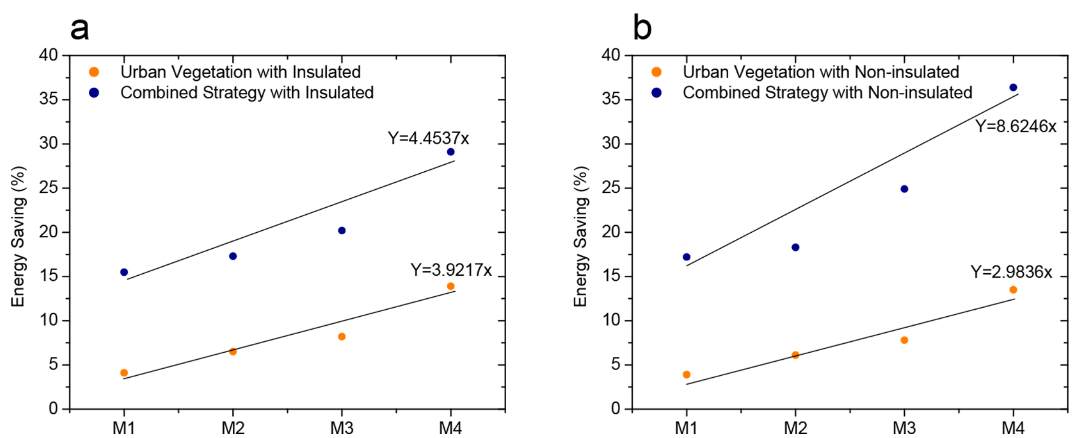


Fig. 15. a) Scatter plot showing the comparison between the percentage cooling load reduction for combined heat mitigation scenarios and increased urban vegetation mitigation scenarios for insulated buildings, and b) scatter plot showing the comparison between the percentage cooling load reduction for combined heat mitigation scenarios and increased urban vegetation mitigation scenarios for non-insulated buildings.

kWh/m^2 for the combined heat mitigation scenarios M1, M2, M3, and M4, on the other hand, enhanced vegetation produced a cooling load of 15.5–37.6 kWh/m^2, 15.16–36.8 kWh/m^2, 14.9–36.2 kWh/m^2 and 14.1–34.3 kWh/m^2 for four mitigation scenarios. Also, high-rise buildings had a cooling load of 16–31.1 kWh/m^2 for the base case while cooling load for the four mitigation scenarios varied between 13.7 and 26.8 kWh/m^2, 13.5–26.3 kWh/m^2,13.1–25.8 kWh/m^2 and 11.8–23.5 kWh/m^2 for combined mitigation techniques and 15.4–29.9 kWh/m^2, 14.8–28.7 kWh/m^2 and 14–27 kWh/m^2 for enhanced vegetation fractions M1, M2, M3 and M4.

4.3.3. Comparison of combined mitigation strategies with enhanced vegetation and cool materials

This section adopted a holistic approach to compare the cooling energy performance of various heat mitigation strategies being studied in this paper with that of our previous studies. So far it has been established that all three mitigation strategies involving enhanced albedo, increased vegetation and simultaneously implementation these two in forms of combined heat mitigation techniques have proved to be effective in reducing cooling load demands. Combined comparisons between these strategies have been presented in Fig. 13. Graphical analysis indicates that, for all type of buildings, increased plantation cover causes a minimum cooling load demand reduction. The other mitigation technologies have a higher reduction in corresponding mitigation scenarios as shown in Fig. 13. However, in case of combined mitigation techniques, some scenarios have a higher reduction value as compared to the other when compared with the corresponding scenario for cool materials mitigation strategy. Even though the reduction in maximum mitigation scenario for combined strategies is higher as compared to that of albedo mitigation strategy.

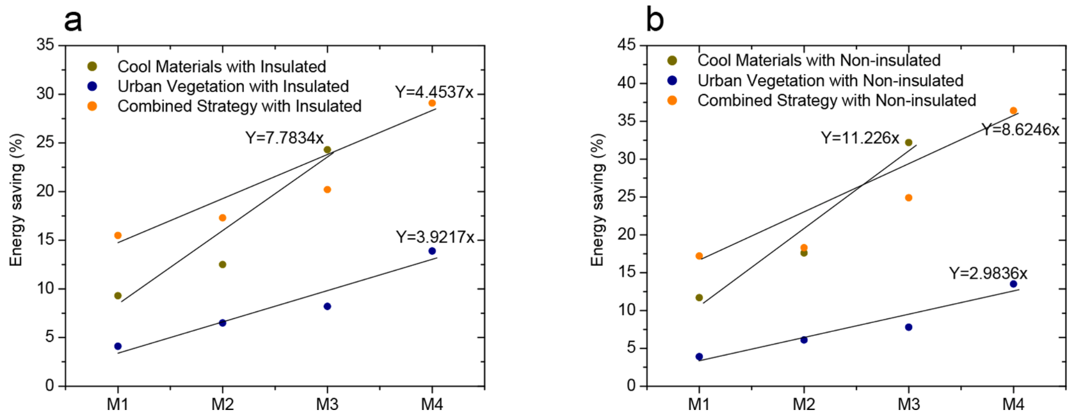


Fig. 16. a) Scatter plot showing the comparison between the percentage cooling load reduction for combined heat mitigation scenarios, cool materials, and increased vegetation mitigation scenarios for insulated buildings, and b) scatter plot showing the comparison between the percentage cooling load reduction for combined heat mitigation scenarios, cool materials, and increased vegetation mitigation scenarios for non-insulated buildings.

A scatter plot representing the cooling load reduction values for all mitigation technologies is presented in Fig. 16. It can be seen that combined mitigation techniques have the maximum cooling load reduction values followed by cool materials and increased vegetation, respectively. This depicted effectiveness of using combined mitigation techniques over the other two. The comparison between all mitigation technologies, as shown in Fig. 17, suggested that the cooling load reduction for the M1 mitigation scenario has been reported as 9.3 %, 4.1 % and 15.5 % for the cool materials, increased vegetation and combined mitigation strategies respectively while the maximum mitigation scenario of these technologies observed a reduction of 24.3 %, 13.9 % and 29.1 % respectively.

Combined analysis of results from section 5.1 and 5.2 have been considered and the maximum mitigation scenarios i.e., M3 (albedo fraction as 0.8) for increased albedo, M4 (100 % increase in vegetation cover) for the enhanced plantation and M4 (albedo fraction as 0.8 and 25 % increase in vegetation cover) for combined mitigation strategies. Un-insulated buildings manifested a cooling load demand of around 34.9 kWh/m^2, 21.7 kWh/m^2, 20.2 kWh/m^2 and 20.2 kWh/m^2 for the base case, enhanced albedo, combined mitigation and increased vegetation fractions respectively for the low-rise residential buildings. While high-rise buildings have an estimated cooling energy consumption in range of 23.1–31.6 kWh/m^2, 14.2–20.5 kWh/m^2, 15.1–21.6 kWh/m^2 and 19.8–27.5 kWh/m^2 for the control case, combined mitigation strategy, increased albedo fraction and improved vegetation, respectively. In the same manner, low-rise commercial buildings have a base case cooling load demand of 25.4–53.9 kWh/m^2 which reduced to 16.3–37 kWh/m^2, 22.7–47.9 kWh/m^2 and 17.3–38.8 kWh/m^2 for the mitigation scenarios involving combined heat strategies, increased plantation and modified cool materials respectively. Likewise, cooling load consumption for high-rise structures was observed to be around 25.4 to 48.8 kWh/m^2 for base case scenario, 22.3 to 42.6 kWh/m^2,17.5 to 35.3 kWh/m^2 and 18.4 to 37 kWh/m^2 for the increased vegetation, combined heat mitigation scenario and modified cool materials.

In all three mitigation techniques, buildings with insulation are found to have a lower cooling load demand. For instance, low-rise residential buildings have a control case cooling energy demand of 22 kWh/m^2, 15 kWh/m^2 for the combined mitigation scenario, 18.9 kWh/m^2 for the increased GI scenario and 16 kWh/m^2 for increased albedo mitigation scenario. On the other hand, a cooling load of 13.7 to 20.6 kWh/m^2, 11.6 to 17.7 kWh/m^2, 9.5 to 14.4 kWh/m^2 and 10.1 to 15.6 kWh/m^2 was calculated for the base case, increased plantation cover, combined heat mitigation scenario and improved albedo mitigation scenario respectively. Commercial insulated building also follows the same trend where low-rise structures had a cooling energy demand ranging from 16.1 to 39 kWh/m2 for the control case, 14.9–36.2 kWh/m^2, 11.7 to 29.3 kWh/m^2 and 12.3 to 30.7 kWh/m^2 for the maximum values of increased urban vegetation, combined mitigation and modified albedo scenarios respectively. Lastly, high-rise structures indicated a base case cooling energy need of 16 to 31.1 kWh/m^2 which decreased to a minimum value of 11.8 to 23.5 kWh/m^2 for combined mitigation scenario M4, 14 to 27 kWh/m^2 for increased urban vegetation fraction M4 and 12.4 to 24.6 kWh/m^2 for modified albedo scenario M3.

Finally, the above analysis and discussion about the comparison of results proved the significance of all mitigation strategies. Factors like building characteristics, local climatic conditions and vegetation type also impacted the simulation results. As mentioned earlier, combined mitigation technologies have the maximum cooling load demand reduction, which is evident from the above analysis, because it aggregated the cooling effect of both vegetation and cool materials together. It employs that the method of this strategy produces cooling from the albedo and evapotranspiration impact of plants as well as by reflecting the solar radiation outside the earth atmosphere. The average percentage reduction for all mitigation scenarios (cool materials, additional plantation and combined strategies) have already been compared above and illustrated in Fig. 14.

4.3.4. Comparison of combined mitigation strategies with existing increased vegetation studies

As per our knowledge a combined analysis for the enhanced vegetation and cool materials has been studied for the first time. Nonetheless, results for the cooling energy saving have been compared with previous studies implementing vegetation increase only as the mitigation technology. The comparison has been presented in Fig. 18. The linear trend line for the combined heat mitigation represented a higher percentage cooling load reduction as compared to that of increased vegetation mitigation scenarios of existing literature. The results for the impact of increased vegetation on building cooling load demand in Thessaloniki, Greece demonstrated a reduction of 9 % and 13 % when vegetation fraction was increased up to 30 % and 60 % respectively [49]. Similarly, In Tel Aviv, Israel a 50 % rise is vegetation fraction potentially reduced the cooling energy demand by 5 % to 6 % for a variety of urban buildings [50]. Santamouris et al. (2018) found a 0.48 %, 1.23 % and 2.31 % reduction in cooling load consumption for the 20 %, 40 % and 60 % increase in plantation respectively [23]. All these results have been compared with the current study and found that combined heat mitigation scenarios have a higher cooling load reduction in all mitigation scenarios of existing studies. For instance, combined heat mitigation scenarios observed a reduction of 17.2 %, 18.3 %, 24.9 % and 36.4 % respectively.

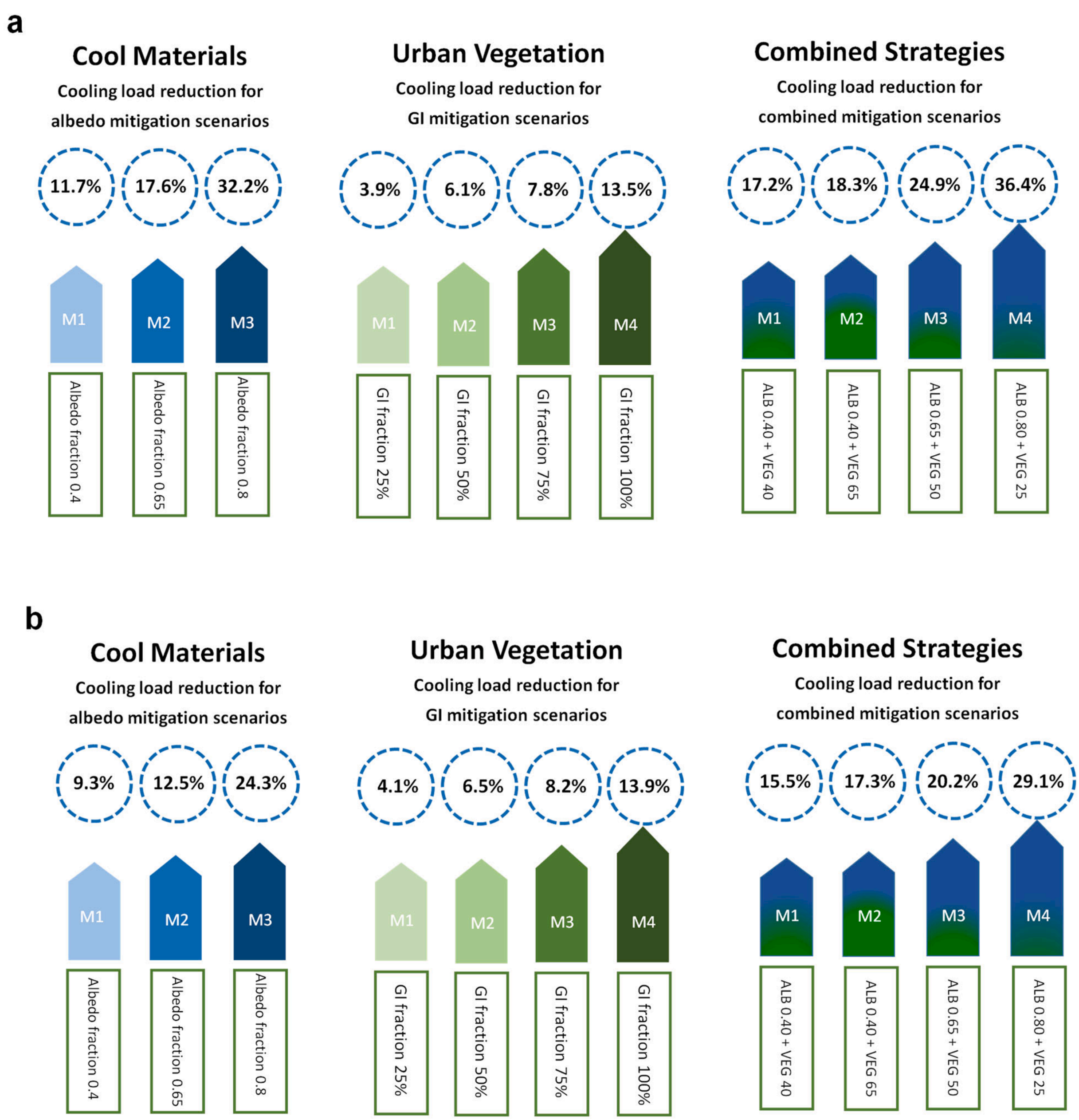


Fig. 17. a) Average percentage reduction in cooling load demand for the mitigation strategies for non-insulated buildings, b) average percentage reduction in cooling load demand for the mitigation strategies for insulated buildings.

4.3.5. *Comparison of combined mitigation strategies with existing cool materials based (albedo modifications) studies*

This section presented the comparison between the cooling load reduction produced by the combined heat mitigation scenarios as discussed in this study and the cool materials as discussed in literature review. Fig. 19 presented the scatter plot showing the trend lines for both mitigation techniques. It is evident that results of cool materials mitigation scenarios from literature showed a lower cooling load demand reduction when compared with our current study. For instance, in case of combined heat mitigation scenarios, a reduction of 15.5 %, 17.3 %, 20.2 % and 29.1 % respectively was observed. It has been reported that cool materials with albedo fraction of 0.41 and 0.31 produced a reduction of 9 % and 8–10 % respectively when implemented in California [51]. Likewise, Rodado et al. (2014) found a reduction value of 26 % corresponding to albedo fraction of 0.51 [52]. Santamouris et al. (2018) selected an urban area consisting of commercial and residential buildings and found that a reduction in cooling load demand from 2.35 kWh/m^2 to 1.89 kWh/m^2 was observed corresponding to the global albedo rise from 0.1 to 0.7 [53]. Similarly, in London, a study by Virk et al. (2015) proposed a 37 % reduction in cooling load when albedo fraction has been raised to 0.7 [48] while Kolokotroni et al. (2013) demonstrated a reduction of 17.4 % when surface reflectance has been increased from 0.1 to 0.6 [54].

5. Conclusion

The immense urbanization, degradation of natural resources mainly vegetation and use of unsustainable building materials have increased the overall temperature of urban areas hence creating urban heat island effect. To mitigate this increased urban heat and to lessen the concentration of pollutants due to the human activities, this study presented a combined heat mitigation technique where increase in vegetative fraction along with increased albedo materials have been implemented to reduce cooling energy demand. This study considered four mitigation

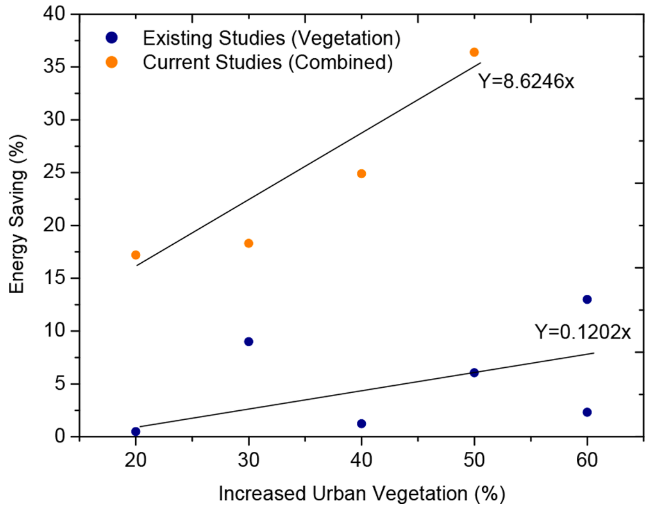


Fig. 18. Average percentage reduction in cooling load demand for the increased vegetation mitigation strategies and previous literature.

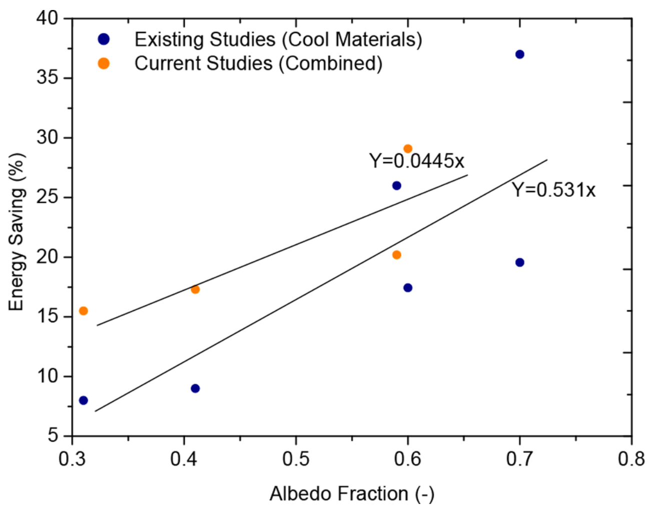


Fig. 19. Average percentage reduction in cooling load demand for the increased albedo mitigation strategies and previous literature.

scenarios with varying albedo fractions and vegetative proportions for the summer month of July 2019 while simulating the behaviour of 40 various residential and commercial buildings, against the base case scenario, having various heights and insulations i.e., insulated, and non-insulated. Dubai downtown (an area characterized by an extreme desert climate) was taken as the study area for this case study. Combining two different mitigation techniques i.e., increased vegetation and cool materials in same scenario has been considered for the first time. A detailed analysis of simulation results has been conducted where it has been discussed that in all cases, non-insulated buildings can have a minimum cooling load reduction of 17.2 % while a maximum reduction of 36.4 % when compared with the base case scenario. Insulated buildings have a cooling demand reduction ranging between 15.5 % – 29.1 %. An extensive comparison among the results have also been drawn with the other mitigation technologies involving cool materials and increased vegetation. It has been noted that the mitigation scenario with albedo fraction as 0.8 and vegetation as 25 % produced the maximum cooling load reduction among all heat mitigation techniques. It has also been observed that factors such as building morphology and local climatic conditions influence the building cooling energy demand. This combined heat mitigation technique can be employed to improve the urban atmosphere as well as the energy consumption owing to the presence of both additional plantation and utilization of cool materials.

CRediT authorship contribution statement

Afifa Mohammed: Data curation, Software, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Ansar Khan:** Conceptualization, Methodology, Software, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hassan Saeed Khan:** . **Mattheos Santamouris:** Project administration, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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