Heliyon 10 (2024) e23160

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Spatial and temporal variations of microclimate and outdoor thermal comfort in informal settlements of warm humid Dar es Salaam, Tanzania

Modest Maurus Baruti [a,b,*], Moohammed Wasim Yahia [a,c], Erik Johansson [a]

[a] Housing Development & Management, Dept. of Architecture and Built Environment, Lund University, P.O. Box 118, SE-22100 Lund, Sweden
[b] School of Architecture, Construction Economics and Management, Ardhi University, P.O Box 35176, Dar es Salaam, Tanzania
[c] University of Sharjah, Department of Architectural Engineering, University City, 27272, Sharjah, Sharjah, United Arab Emirates

ARTICLE INFO

Keywords:
Outdoor thermal comfort
Spatial variability
Microclimate
Simulations
Informal settlements
Dar es salaam
ENVI-met

ABSTRACT

In developing countries, urbanization is dominated by the growth of informal settlements which represents 40–80% of major cities. The challenges brought up by the growth of informal settlements spans from social-economic to environmental. Previously, upgrading of the informal settlements focused on social-economic aspects such as provision of necessary services for the residents, whereas the quality of the outdoor thermal environment has not received much attention. This paper entails to investigate the potential of upgrading the outdoor thermal environment in informal settlements in the warm humid city of Dar es Salaam, Tanzania through examining the influence of addition of trees with different Leaf Area Index (LAI) and incremental increase of buildings heights. The study uses simulation as a method for analysis of the warm season and calculates the Physiological Equivalent Temperature (PET) as a thermal index. Results show substantial improvement of both microclimate and outdoor thermal comfort. Incremental increase of buildings heights in a street canyon to 12, 18, and 24 m leads to the reduction of PET by 2.5, 2.8, and 3.8 °C respectively at 2:00 p.m. Similarly, applying LAI's of 2, 4, and 6 m^2/m^2 leads to reduction of the mean radiant temperature by 7.9, 10.1, and 12.2 °C; while PET was reduced by 3.9, 4.7, and 5.6 °C respectively at 2:00 p.m. Nonetheless, upgrading of informal settlements shows marginal influence on the reduction of air temperature. Despite the noted thermal improvement in the studied area, the thermal comfort limits of the warm season were difficult to reach. The findings suggest that addition of vegetation is the economically most effective way for upgrading thermal conditions in informal urban fabric areas.

1. Introduction

Urban microclimate encompasses complex processes influenced by the interaction of microclimate variables and the urban fabric. Microclimates within urban centres differ substantially from those in the surrounding natural environment as each urban fabric element - buildings, roads, parking areas, factories, etc. - interact with climatic variables to create a modified microclimate [1]. The climatic variables such as air temperature, humidity, wind speed, solar radiation, and soil temperature are very sensitive to any

* Corresponding author. Housing Development & Management, Dept. of Architecture and Built Environment, Lund University, P.O. Box 118, SE-22100 Lund, Sweden.

E-mail addresses: modest.maurus_baruti@hdm.lth.se, mmbaruti@gmail.com (M.M. Baruti).

https://doi.org/10.1016/j.heliyon.2023.e23160
Received 6 August 2023; Received in revised form 6 October 2023; Accepted 28 November 2023
Available online 7 December 2023

3-dimensional changes in the urban areas [2], as built up areas directly influence the microclimate in an urban environment [3]. Each urban area creates its own microclimate and leads to spatial variability of microclimate and consequently outdoor thermal comfort [4,5]. Several studies have reported microclimate and outdoor thermal comfort differences between low-rise and high-rise building areas [6–10]. Similarly, each urban setting faces its own climate related challenges. Climate-related environmental challenges in tropical regions include poor dispersion of air pollutants (generally low wind speeds and lack of ventilation); high incidences of human discomfort and heat stress, which decreases productivity and increases mortality due to heat related illness; and, space cooling needs which increases energy usage, which, in turn may exacerbate climate change [11,12]. A notable example is Dar es Salaam, where low-rise, dense, informal settlements areas are more stressful urban spaces than formal urban areas, posing thermal discomfort challenges in the informal areas [10]. It is argued that improved urban designs that maximize thermal comfort can raise the quality of life in general, as well as helping urban dwellers cope with the episodes of hot weather and allowing year-long outdoor activities [13–15].

Several studies [6,8,16–19] have investigated spatial variability of microclimate and outdoor thermal comfort in the formal urban fabric settings in warm humid climates. Conversely, only a few studies [9,10,20] have explored these issues in the informal settlements in warm humid climates. Informal settlements are defined as urban areas where the residents often have no security of tenure of the land or dwellings they occupy. Moreover, these neighbourhoods are usually lacking essential services and infrastructure, and housing does not comply with planning and building regulations [21]. Globally, it is established that 1 billion people are residing in informal settlements with the majority located in the countries in the Global South [22]. A study [23] shows that informal settlement residents are projected to increase to 2 billion by 2030 and 3 billion by 2050. It is worth noting that, the informal settlement condition is more pronounced in the developing economies, as 90 % of the areas in the developing countries are home to informal settlements [24]. In Dar es Salaam, informal settlements have grown exponentially since 1960 [25]. Baruti et al. [26] noted that social, economic, and environmental challenges presented by informal settlements have been subject of research for decades. Similarly, measures for upgrading of informal settlements have been explored in several studies [27–35] with the main focus being on policy issues, methods, physical and socio-economic characteristics, as well as financial aspects. However, little has been investigated on upgrading of informal settlements in terms of microclimate and outdoor thermal comfort [26]. With the current trends of urbanisation and the challenges of climate change, it is necessary to consider aspects of thermal comfort and heat stress when upgrading the informal settlements.

In this study, simulation modelling is used to investigate spatial variability of microclimate and thermal comfort in the informal urban fabric in the warm humid climate of Dar es Salaam. Both micrometeorological measurements [6,17,20,36] and numerical modelling [7,16,37,38] have been employed to study the influence of climatic variables within the urban fabric. However, the constraints associated with field measurements make numerical modelling more convenient for researchers especially in terms of investigating the effect of different design parameters [2]. Numerical modelling also makes it easier to study spatial variations of the microclimate, whereas measurements are normally limited to a few spots. It is worth pointing out that numerical modelling is limited to the informal settlement of Tandale, Dar es Salaam. Also, vegetation used was limited to a 10 m high deciduous tree. The main aim of the study is twofold: (1) examine the thermal conditions in the existing informal settlement (Tandale) and (2) investigate the effect of different measures for possible improvements of the thermal environment. The following measures were simulated.

(i) Addition of trees of different leaf densities in the street canyon
(ii) Incremental increase of building heights

2. Methods

2.1. Climate of Dar es Salaam

Dar es Salaam city, situated at 6 °51 'S and 39 °18 'E, is categorised by a warm humid climate (tropical savanna-Aw) according to the Köppen classification [39]. The annual mean maximum temperature varies between 29 °C and 32 °C, while the annual mean minimum temperature varies between 19 °C and 25 °C. The city experiences the highest temperatures from December to March, while the cool period with relief in thermal stress is between June and September. Relative humidity always remains high; it is about 75 % most of the time, but it may vary from 55 % by day to almost 100 % at night. In this study, simulations were conducted for the Tandale area. Tandale is 7.2 km from the coast of Indian Ocean. Field surveys were carried out in the main street, which acts as the main access to the inner part of the neighbourhood. Tandale represent a category of informal settlements known as consolidated high density, low rise which represent a larger part of the residential settlements where residents reside in Dar es Salaam city [40]. The typical character of this settlement is narrow and winding streets due to compactness of the building structures. Large sections of the housing areas of the settlement are only accessible by footpaths.

2.2. Microclimate simulations using ENVI-met 4

This study employed the numerical simulation software ENVI-met 4.4.3 [41] for analysing microclimate and outdoor thermal comfort in the studied informal settlement. ENVI-met is a simulation tool that recreates the microclimate of the outdoor environment by taking into account the interaction between climatic parameters, vegetation, surfaces, the soil and the built environment [42]. It involves a sequence of mathematical calculations established by the laws of fluid dynamics and thermodynamics, which govern the atmospheric motions [2]. The ENVI-met model has a horizontal resolution from 0.5 to 10 m, and a time-step of 1–10 s. This high resolution is crucial for analysing pedestrian comfort and interactions between individual buildings, surfaces, and plants [43,44].

One of the improvements with of ENVI-met version 4 compared to the previous version 3.1, is the possibility to include the simple forcing of air temperature and humidity. This feature requires maximum and minimum values of air temperature and relative humidity at 2 m height over a 24 h cycle [2]. The forcing also has the option to input values on an hourly basis that are collected either from weather stations or directly from on-site measurements. This new feature enables the software to account for atmospheric temporal variations and consequently represent the evolution of meteorological variables along the day [45]. Apart from the previous vegetation model where plants were modelled as vegetation columns, version 4 implements a new 3D vegetation module to describe varied shapes of plants and spatial distribution of the leaves. Version 4 also accounts for the thermal inertia of walls and roofs [41].

This study has used ENVI-met Monde in modelling the study area Tandale as shown in Fig. 1. ENVI-met Monde is a vector-based editing system designed to bridge the gap between vector based tools such as GIS and Open Street Maps and the raster based ENVI-met [46]. Through its option of importing Open Street Maps Geo-data and the possibility of editing building geometry using an integrated editor, it was possible to create the ENVI-met model of the complex informal urban fabric. Nevertheless, in this study, vegetation was not modelled by ENVI-met Monde but were added manually based on Google maps.

Furthermore, this study has used ENVI-met Biomet 1.5 [46] to calculate different thermal comfort indices. Despite the fact that Biomet 1.5 is capable of estimating outdoor thermal comfort using several indices such as the Physiological Equivalent Temperature (PET) [47], the Standard Effective Temperature for outdoors (SET*) [48] and the Universal Thermal Climate Index (UTCI) [49], the study opted to present results for PET only. Moreover, PET has been widely used, including in tropical climates, thus allowing comparison with other studies globally.

2.3. Model calibration

A series of calibration tests were conducted comparing the simulated results with measured values of air temperature from Ref. [50]. Air temperature has been used in several studies to validate the performance of the model [17]. Calibration was conducted where the observed (measured) air temperature was compared to the predicted (simulated) air temperature for the Tandale area. The root mean square error (RMSE), which was the statistical parameter used to evaluate the performance of the model, was 0.84 °C.

Several studies [51–54] pointed out the reliability of the ENVI-met software for simulating the outdoor thermal environment. To achieve an agreement between measured and simulated variables, adjustments were made to some of the values of the input data such as wind speed at 10 m, relative humidity, and initial temperature of the atmosphere. Since the solar radiation was not measured, data from Meteonorm V.7 [55] was used. In order to adjust the solar radiation generated by ENVI-met to the Meteonorm data, the solar adjustment factor was used. Table 1 shows input data used for the model for the selected month of March, which represents the warm season.

It should be pointed out that at the beginning of the calibration process, the study area was imported by the ENVI-met Monde with its topography. After several test simulations, the following was noted: first, simulations take longer time with the topography, and second, reading of results from the receptors required identifying the exact height of the location of the receptors and the difference in terms of height across the model was not big. In view of that, further calibration tests were conducted without topography, i.e., flat terrain.

2.4. Simulation scenarios

The main focus area of the study is part of the main street-oriented NW-SE as indicated in Fig. 1. Simulations of Tandale were

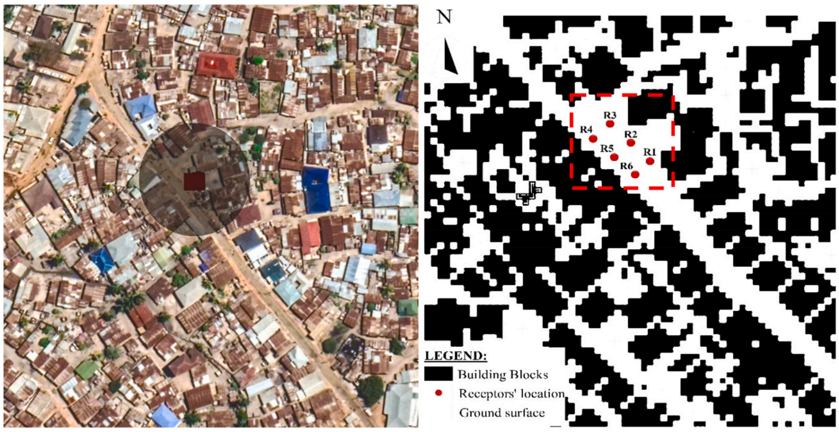

Fig. 1. Study area, Tandale (a) Google Earth photo with the location of measurement (round dot) and (b) simulated area as exported to ENVI-met modelling layer by the use of Open Street Map and ENVI-met Monde, R1–R6 represent receptors where R1 is the receptor at the location of micrometeorological measurements.

Table 1
Input data for ENVI-met models for Tandale area.

Category	Input data
Model geometry measurements	
Model area	150 m × 150 m
Grid size in metres	
Dx = size of X grid	dx = 2
Dy = size of Y grid	dy = 2
Dz = size of Z grid	dz = 2
Nr of nesting grids	10
Construction materials	
Wall material	Concrete wall (filled block)
Roof material	Iron sheets
Soil	Loamy soil
Geo reference	
Latitude	6° 47' 36"S
Longitude	39° 14' 39" E
Start and duration of the simulation	
Date of simulation	March 20, 2017
Start time	05:00
Total simulation time (h)	15
Initial meteorological conditions	
Roughness length of the measurements site	0.3
Simple forcing: Air temperature (°C)	Min 28 at 06:00; Max 35 at 12:00
Simple forcing: Relative humidity (%)	Min 60 at 06:00; Max 96 at 12:00
Wind speed at 10 m height (m/s)	4
Wind direction (deg) (0° = from North, 180° = from south)	165
Solar adjustment factor[a]	0.95
Initial temperature of the atmosphere (K)	301
Cover of low clouds (octas)[a]	2
Cover of medium clouds (octas)[a]	2
Cover of high clouds (octas)[a]	2
Soil data, for all the models	**Soil humidity (%)**
Upper layer (0–20 cm)	92
Middle layer (20–50 cm)	96
Deep layer (50–200 cm)	96

[a] For the cases with vegetation the adjustment factor was 0.63 and cloud cover 0. The global solar radiation was maintained.

conducted based on three scenarios: addition of trees with varying leaf area index (LAI), incremental increase of building heights in both sides of the street canyon, and combination of trees and an incremental increase of building heights of the street canyon. LAI is a dimensionless variable and is defined as one-half the total green leaf area per unit of ground surface area [56].In this study, the base case presents the existing model of the main street in Tandale in which no upgrading measures were employed (Fig. 2a). The variables analysed were air temperature (T_a), mean radiant temperature (T_{mrt}) and thermal comfort expressed as PET. The area of investigation had the following characteristics.

(i) Single storey buildings of typical walls of sand/cement blocks and roofs of corrugated galvanized steel sheets with maximum 4 m height
(ii) Irregular pattern of buildings dominated by narrow footpaths (1–2 m) between buildings and limited number of roads with car access
(iii) Limited amount of vegetation that is located in few places.

Receptors were used to analyse both the existing condition and the influence of various design parameters on outdoor microclimate and thermal comfort. The six receptors were located in similar positions for the different simulation scenarios. Table 2 presents the simulation scenarios regarding increased building height. Mean values of data for both microclimate and thermal comfort were analysed. In all three scenarios, the street width was increased from the base case of 5 m–8 m with exception of the area where receptors were located which was having an open space (refer Fig. 3a).

Hourly microclimate data required for the calculation of PET were obtained at six points (receptors) situated as indicated in Fig. 2 with the width of the street as indicated in Fig. 3. The location of the points was not changed in the simulation scenarios; however, the street canyon facades were straightened and some building footprints modified, as part of the upgrading of the informal urban fabric, followed by gradually increasing building heights (Fig. 3). The locations of the receptors represent areas where pedestrians spend most of their time. PET for each point was calculated with Rayman [57] based on the simulated microclimatic variables. The mean value of PET from the six points was reported as a single PET value for each specific time and simulation scenario.

To investigate the influence of vegetation on both microclimate and outdoor thermal comfort, trees were introduced in the canyon. The types used were 10 m high deciduous trees with Leaf Area Index values of two, four and six considered as low, medium and high

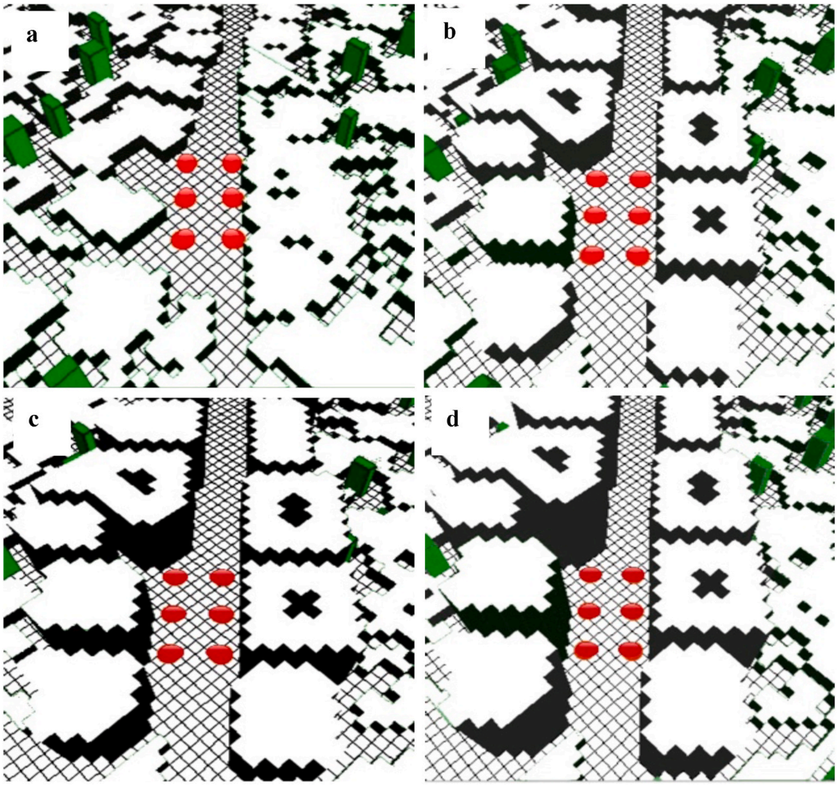

Fig. 2. A 3d representation of (a) existing 4 m height model (b) 12 m height model (c) 18 m height model, and (d) 24 m height model for Tandale informal urban fabric area. The red dots show the positions of the receptors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Variation of aspect ratio and SVF for the receptors of the existing case and the different heights of the street canyon in Tandale.

Receptor	Existing/Base case		Height 12 m		Height 18 m		Height 24 m	
	H/W ratio	SVF	H/W ratio	SVF	H/W ratio	SVF	H/W ratio	SVF
R1	0.4	0.62	1.2	0.31	1.8	0.21	2.4	0.15
R2	0,33	0.72	1.2	0.35	1.8	0.24	2.4	0.18
R3	0.33	0.68	1.2	0.35	1.8	0.25	2.4	0.2
R4	0.33	0.58	1.2	0.36	1.8	0.27	2.4	0.24
R5	0.33	0.58	1.2	0.36	1.8	0.26	2.4	0.2
R6	0.4	0.59	1.2	0.34	1.8	0.25	2.4	0.19

density respectively. It is worth noting that ENVI-met simulates vegetation based on Leaf Area Density (LAD), thus, equation (1) [42, 58] which shows the relationship between LAI and LAD was used to estimate the respective LAD for the respective horizontal layer of the tree:

$$LAI = \int_0^h LAD.\Delta z \tag{1}$$

Where:

h is the height of the tree (m), Δz is the vertical grid size (m), LAI is the leaf area index (m^2/m^2), and LAD is the leaf area density (m^2/m^3).

LAD is a parameter defined as the total one-sided leaf area (m2) per unit layer volume (m3) in each horizontal layer of the tree crown [59]. The influence of vegetation was analysed in two steps: introduction of vegetation in the existing model/condition for LAI of 2, 4, 6 and introduction of vegetation with an LAI of 6 while increasing the height of the buildings from 4 m gradually to 12 m, 18 m and 24 m. The detailed information of the simulations and their objectives are presented in Table 3.

It was noted that the diffuse part of the solar radiation was not blocked by the trees. Therefore, the portion between the direct and diffuse parts of the radiation was changed to maximize the direct part. This was done by removing the clouds and at the same time

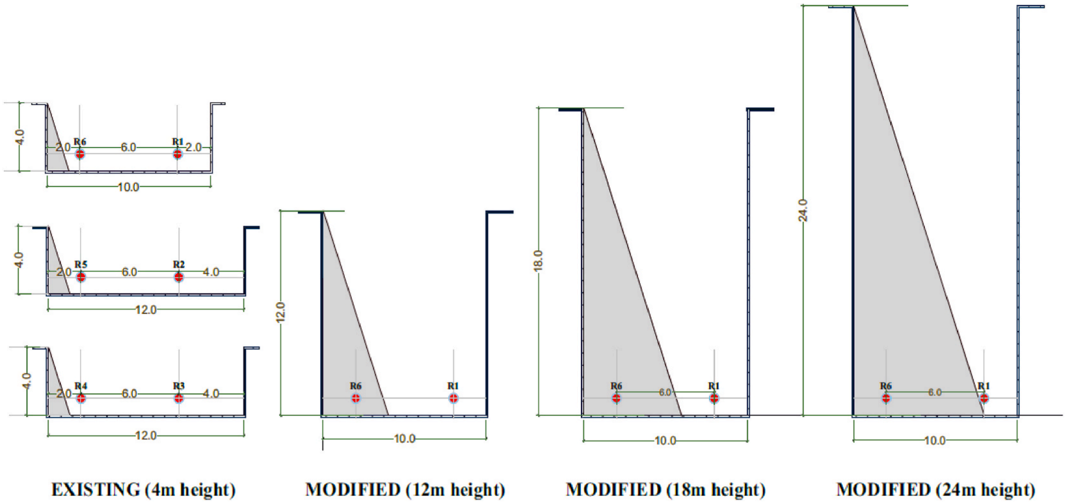

Fig. 3. Schematic cross-sections of urban canyon scenarios which involves changes of height from existing low-rise (4 m) to 12 m, 18 m, and 24 m. Red dots indicate position of receptors where microclimate variables were analysed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

adjusting the solar adjustment factor to maintain the same global radiation as in the real case (see Table 1). Although this does not completely correspond to the reality, it was considered the best way to take the shading effect of the trees into account.

3. Results

3.1. Influence of trees of different LAI values

Addition of trees to the existing main street of the area was applied as an in-situ upgrading measure to improve microclimate and thermal comfort.

3.1.1. Temporal and spatial variations of the microclimate

Fig. 4 shows the influence of addition of trees on both air temperature and T_{mrt}. The study found that addition of trees with Leaf Area Index (LAI) of 2, 4 and 6 did not contribute to a considerable change in T_a (which was taken as mean of T_a for all receptors) as shown in Fig. 4a. A marginal decrease (less than 0.2 °C) is observed from 12:00–15:00 p.m. On the other hand, addition of vegetation showed noteworthy reduction of $T_{mrt.}$ Application of trees with LAI 2, 4 and 6 leads to the decrease of T_{mrt} by 7.9, 11 and 13 °C respectively at 2:00 p.m. (Fig. 4b). Fig. 5 shows spatial variation of T_{mrt} at the height of 1 m for the Tandale area at 2:00 p.m. for the base case and LAI of 2, 4, and 6. T_{mrt} decreases proportionally with an increase of LAI. The difference in T_{mrt} between different LAI values and the base case varies with time being more pronounced around noon (11:00 a.m.–15:00 p.m.).

On the other hand, addition of vegetation showed noteworthy reduction of T_{mrt} (Fig. 4b). Application of trees with LAI 2, 4 and 6 leads to the decrease of T_{mrt} by 7.9, 11 and 13 °C respectively at 2:00 p.m. (Fig. 4b). Fig. 5 shows spatial variation of T_{mrt} at the height of 1 m for the Tandale area at 2:00 p.m. for the base case and LAI of 2, 4, and 6. T_{mrt} decreases proportionally with an increase of LAI. The difference in T_{mrt} between different LAI values and the base case varies with time being more pronounced around noon (11:00am–15:00pm).

Table 3
Simulation scenarios, codes, upgrading measures and their objective for different study cases.

Simulation scenarios	Scenario code	Measures employed within the informal urban fabric	Simulation objective for analysis
	Base case	None (4 m height buildings)	Analyse existing condition
1	LAI 2	Addition of trees (LAI 2) to the existing model	Analyse the influence of use of vegetation in the existing condition
	LAI 4	Addition of trees (LAI 4) to the existing model	
	LAI 6	Addition of trees (LAI 6) to the existing model	
2	H12 M	Increase of height to 12 m (4 storeys)	Analyse the influence of different building heights
	H18 M	Increase of height to 18 m (6 storeys)	
	H24 M	Increase of height to 24 m (8 storeys)-maximum allowable by the building regulations	
3	H12M-LAI 6	Increase of height to 12 m and trees of LAI 6	Analyse the influence of combining different building heights and vegetation with LAI 6
	H18M-LAI 6	Increase of height to 18 m and trees of LAI 6	
	H24M-LAI 6	Increase of height to 24 m and trees of LAI 6	

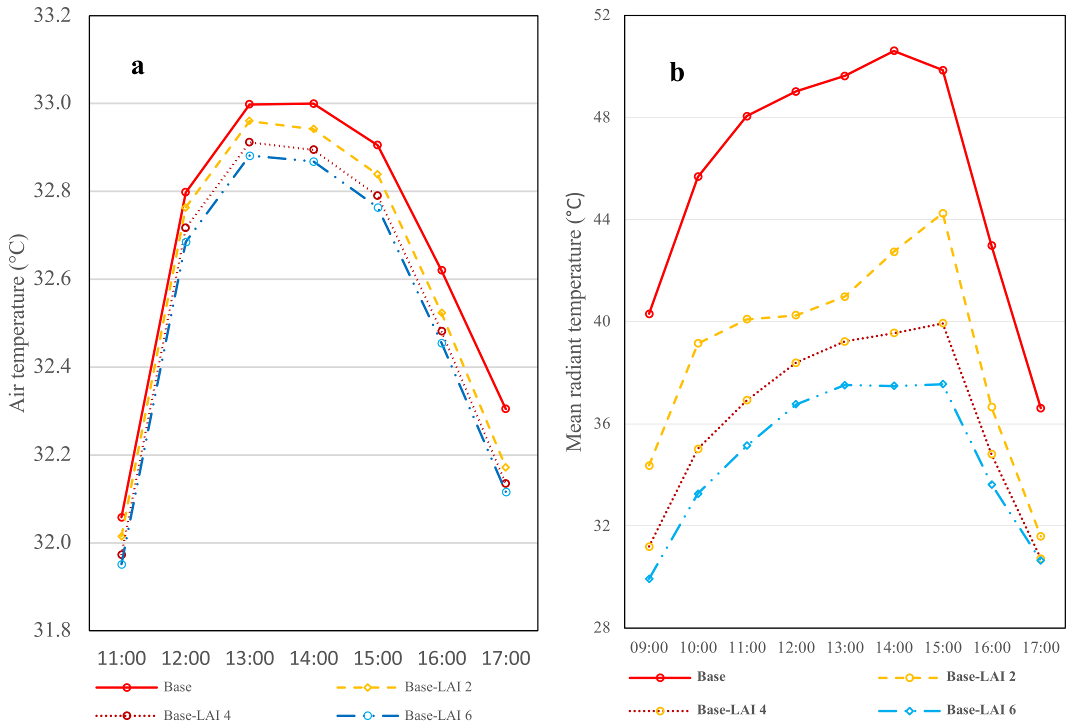

Fig. 4. The influence of addition of trees with different LAI on (a) air temperature and (b) mean radiant temperature in the informal urban fabric at pedestrian height (1 m).

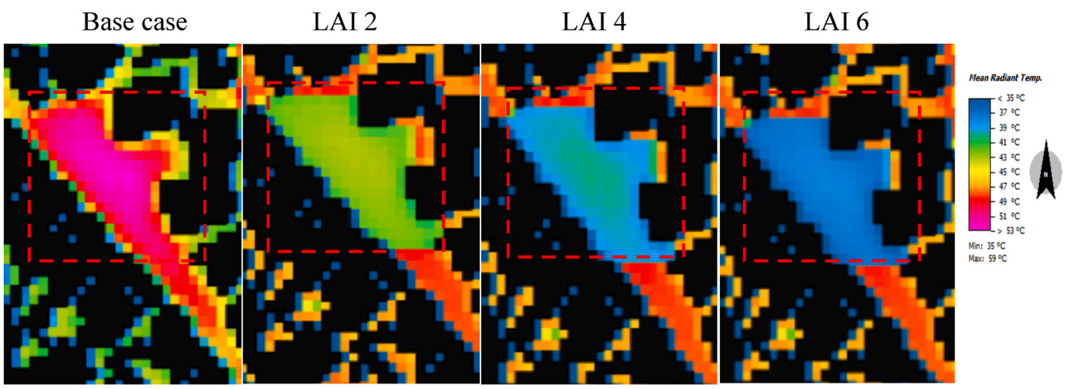

Fig. 5. The influence of addition of trees with different LAI values on mean radiant temperature in the informal urban fabric at pedestrian height (1 m) at 2:00pm.

3.1.2. Outdoor thermal comfort

Fig. 6 shows the influence of addition of vegetation on the outdoor thermal comfort. Analysis shows substantial influence of vegetation on the reduction of PET in the informal urban fabric. It was noted that addition of vegetation with LAI of 2, 4 and 6 in the existing informal urban fabric reduces the maximum PET by 3.7, 4.7 and 5.6 °C respectively at 2:00 p.m. (Fig. 6a). For LAI of 2, 4, and 6, a reduction of PET ranging from 2.3 to 3.9 °C, 3.8–4.7 °C, and 4.5–5.6 °C respectively was observed from 10:00 a.m.-4:00 p.m. (Fig. 6b). It was shown that addition of vegetation had maximum influence on PET reduction from 11:00 a.m.-3:00 p.m., see Fig. 6b. Fig. 7 shows spatial distribution of PET at 2:00 p.m. for the base case and LAI of 2, 4, and 6.

3.2. Influence of increased building heights

One of the possible upgrading measures to improve microclimate and thermal comfort within informal urban fabric areas is increase of building heights. It is referred to as intensification [60], and it is one of the common expansion ways in informal settlements [61]. In this study building heights were increased incrementally on both sides of the main street canyon.

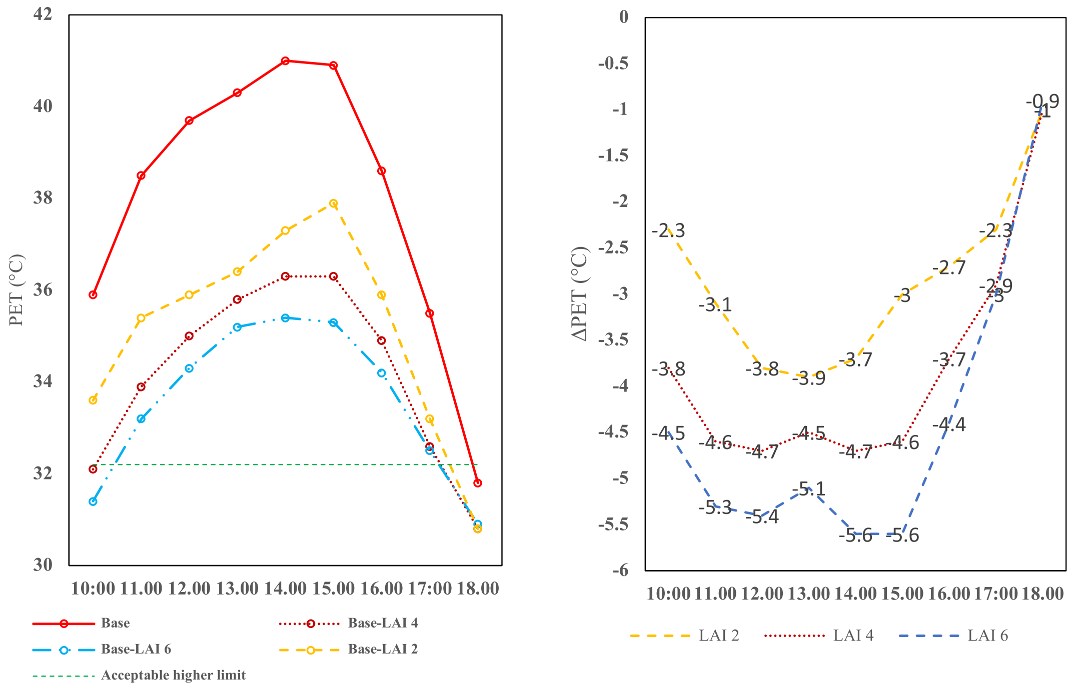

Fig. 6. The influence of addition of vegetation on the outdoor thermal comfort at pedestrian height (1 m) (a) and reduction of PET for different LAI values (b).

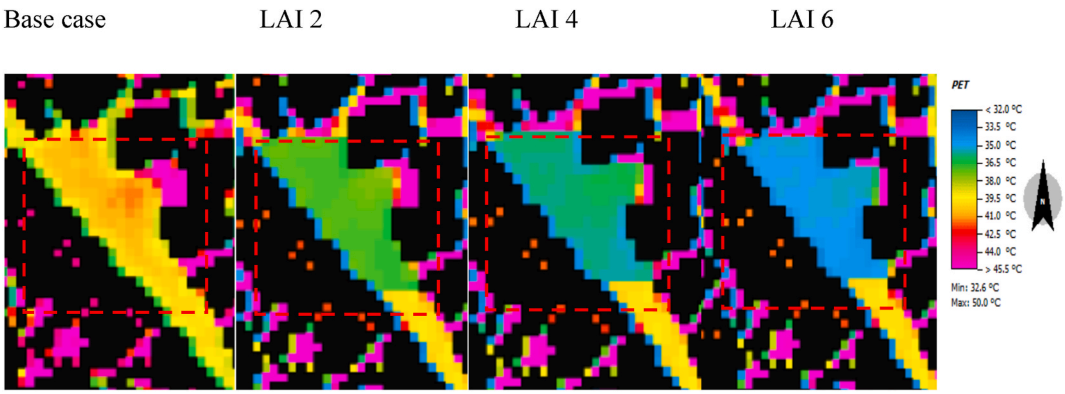

Fig. 7. The influence of addition of trees on the outdoor thermal comfort at pedestrian height (1 m) showing reduction of PET for different LAI.

3.2.1. Temporal and spatial variation of the microclimate

Fig. 8a shows the influence of increase of building height on air temperature. An increase of building height shows marginal reduction of T_a; a decrease of T_a by maximum 0.15 °C was noted. This might be due to the fact that the changes have been applied in a limited area of the existing urban canyon while the large portion of the informal settlement remains the same. On the other hand, an increase in building height shows a substantial decrease in wind speed from an mean of 1.4 m/s to 0.4 m/s.

Fig. 8b shows and influence of increase of building height on T_{mrt}. The study found a substantial decrease of the mean $T_{mrt\ with}$ an increase in building height; for example, an increase of building heights from existing single story (4 m) to 12 m high leads to a 7.2 °C decrease at 2:00 p.m. during peak hours of the warm season. Further increase of building height to 18 m and 24 m shows a reduction at 2:00 p.m. of T_{mrt} with 9.4 and 11.2 °C respectively (Fig. 8b). The reduced T_{mrt} due to the increase of building heights leads to a reduction of PET in spite of the decrease of wind speed.

3.2.2. Outdoor thermal comfort

Fig. 8b shows an influence of increase of building heights on outdoor thermal comfort. An increase of building height from single storey (4 m) to 12 m reduces maximum PET at 2:00 p.m. from 41 °C to 38.5 °C (Fig. 9). Further increase of the height to 18 m and 24 m leads to reduction of PET at 2:00 p.m. by 2.8 °C and 3.8 °C respectively. For building heights of 12 m, 18 m, and 24 m, a reduction of

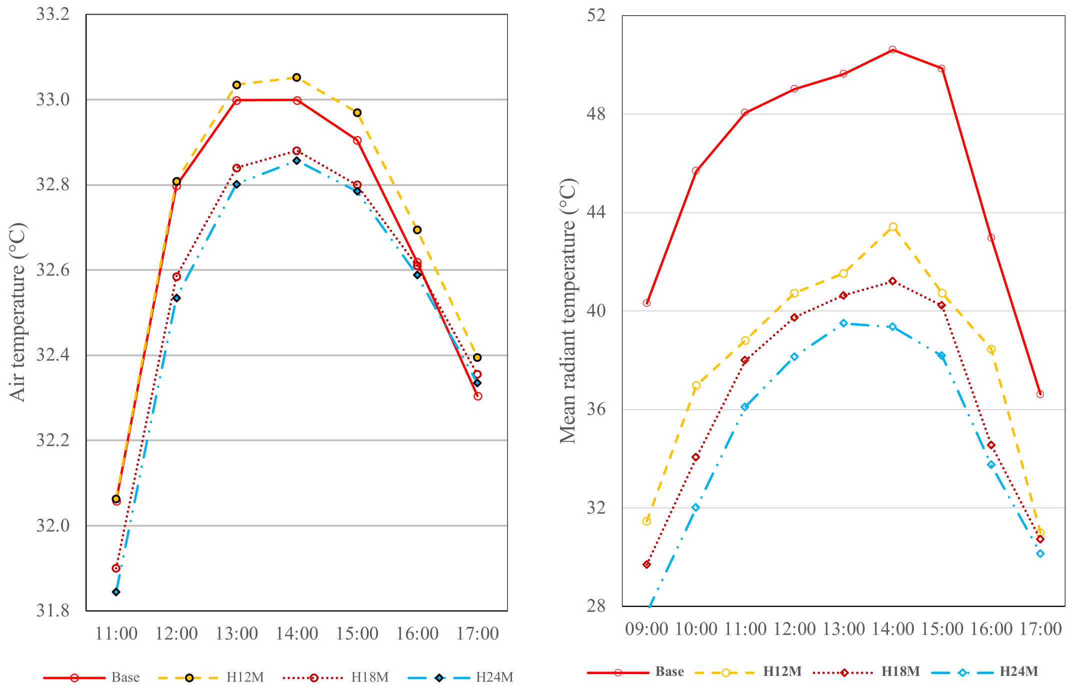

Fig. 8. The influence of an increase in building height on air temperature (a) and mean radiant temperature (b) within the informal urban fabric.

PET ranging from 2.0 to 3.0 °C, 2.7–4.0 °C, and 4.1–4.6 °C respectively was observed from 10:00 a.m.-4:00 p.m. (Fig. 9b). Increasing building heights had maximum influence on PET reduction from 10:00 a.m.-3:00 p.m. as shown in Fig. 8b. However, the highest reduction is noted in the morning hours around 10:00 a.m. and in the late afternoon (4:00 p.m.) where different building heights show a similar trend (Fig. 9b).

3.3. Influence of combining vegetation and increased building heights

3.3.1. Temporal and spatial variations of the microclimate

Upgrading of the informal urban fabric through a combination of increased building heights and addition of vegetation led to a slight improvement of T_a. The maximum decrease of T_a was found to be 0.25 °C at 2:00 p.m. for a building height of 24 m and a LAI of 6 (Fig. 10a). Conversely, tremendous improvement in T_{mrt} was noted. A combination of increased building heights of 12 m, 18 m, and 24 m with a LAI of 6 leads to a decrease of T_{mrt} by 12.3 °C, 14.4 °C and 15.1 °C respectively (Fig. 11b). In fact, it was possible to reach the neutral T_{mrt} of 32 °C through these improvement measures of combined height and vegetation.

3.3.2. Outdoor thermal comfort

The study found that a combination of increased building heights and added vegetation brings about the maximum influence on outdoor thermal comfort. Though it is not possible to reach thermally acceptable limits during the warmest month as indicated in Fig. 11a, the improvement is significant. It is worth mentioning that the studied day was warmer than normal; thus, during a typical day, thermal comfort conditions will be better. Furthermore, the results show marginal differences between 12 m and 18 m building heights. For building heights 12 m and 24 m, a reduction of PET ranging from 5.0 to 6.2 °C, and 5.2–6.4 °C respectively was observed from 10:00 a.m.-4:00 p.m. (Fig. 11b). Combining an increase of building height and adding trees had maximum reduction of PET from 10:00 a.m.-4:00 p.m. as shown in Fig. 11b. The maximum reduction of PET of 6.4 °C is found at 3:00 p.m. The effect can also be seen in the spatial distribution of PET at 2:00 p.m. (Fig. 7). A comparison of Figs. 6 and 10 shows that when combining an increase of building height and addition of vegetation, it is the vegetation which has the highest end effect on the reduction of PET. Addition of vegetation can be considered the most cost-effective way of reducing heat stress though the notable challenge is high compactness of building blocks.

4. Discussion

4.1. Influence of addition of trees on microclimate

4.1.1. Temporal and spatial variations of the microclimate

Addition of trees with different LAI as shown ins section 3.1.1 had marginal influence on T_a.A similar trend was observed by

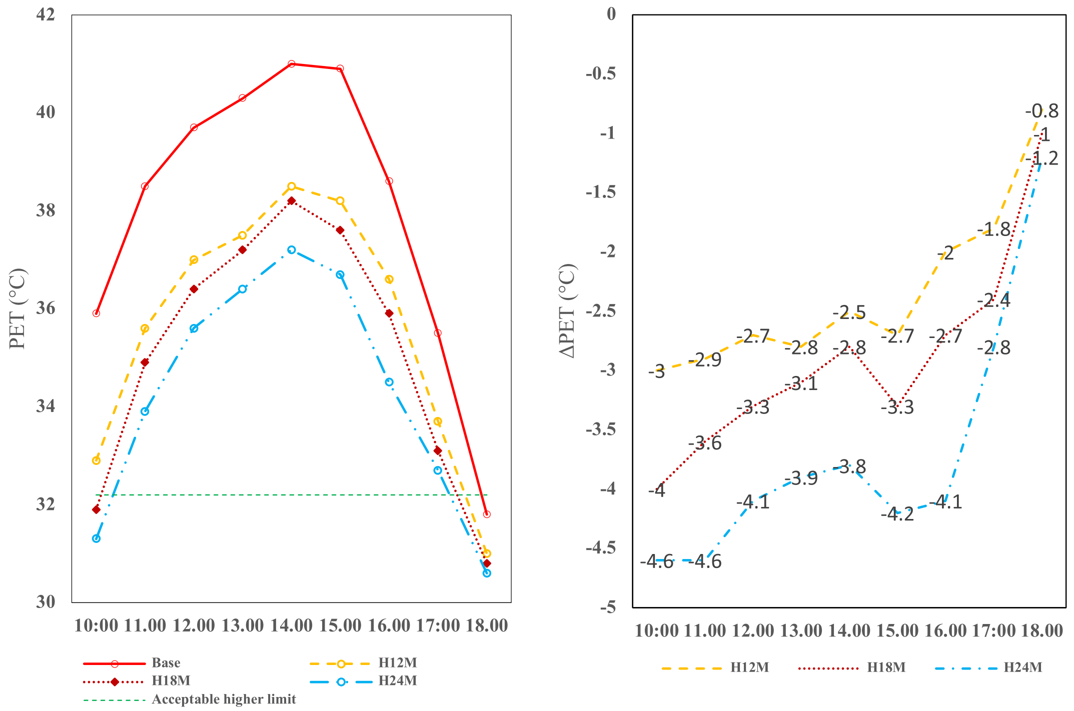

Fig. 9. The influence of increase in building height on outdoor thermal comfort at pedestrian height (1 m) in the informal settlement. The green and dashed horizontal line (Fig. 11a) represents upper comfort limit. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

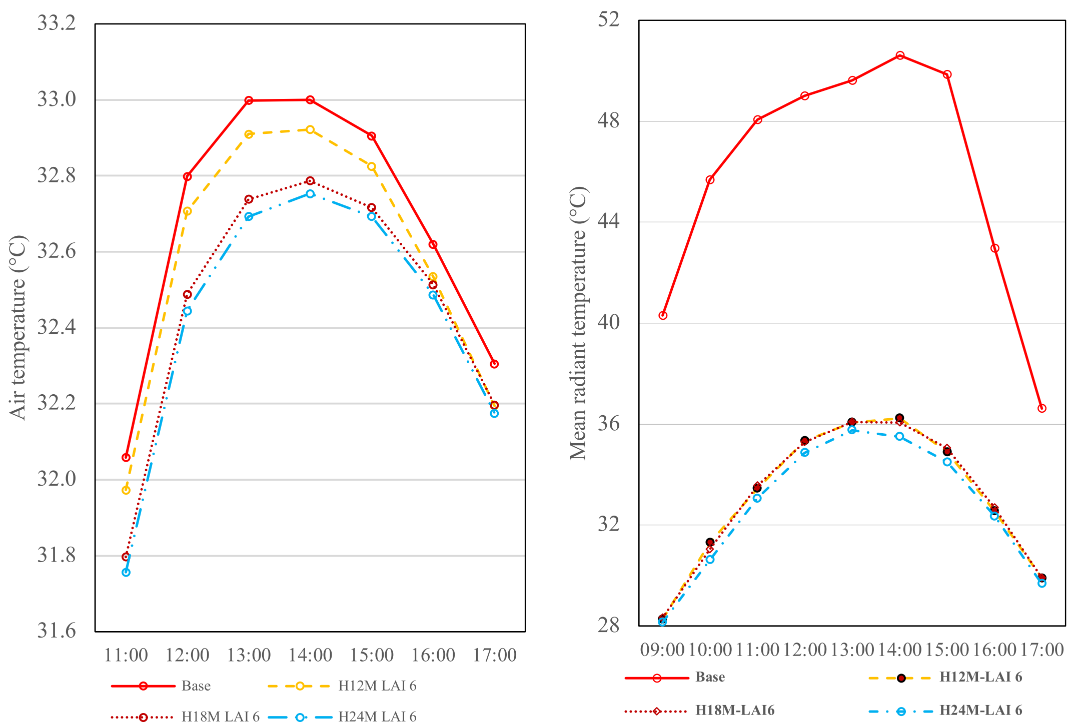

Fig. 10. The influence of combination of building height and vegetation on (a) air temperature and (b) mean radiant temperature at pedestrian height (1 m) in the studied informal urban fabric.

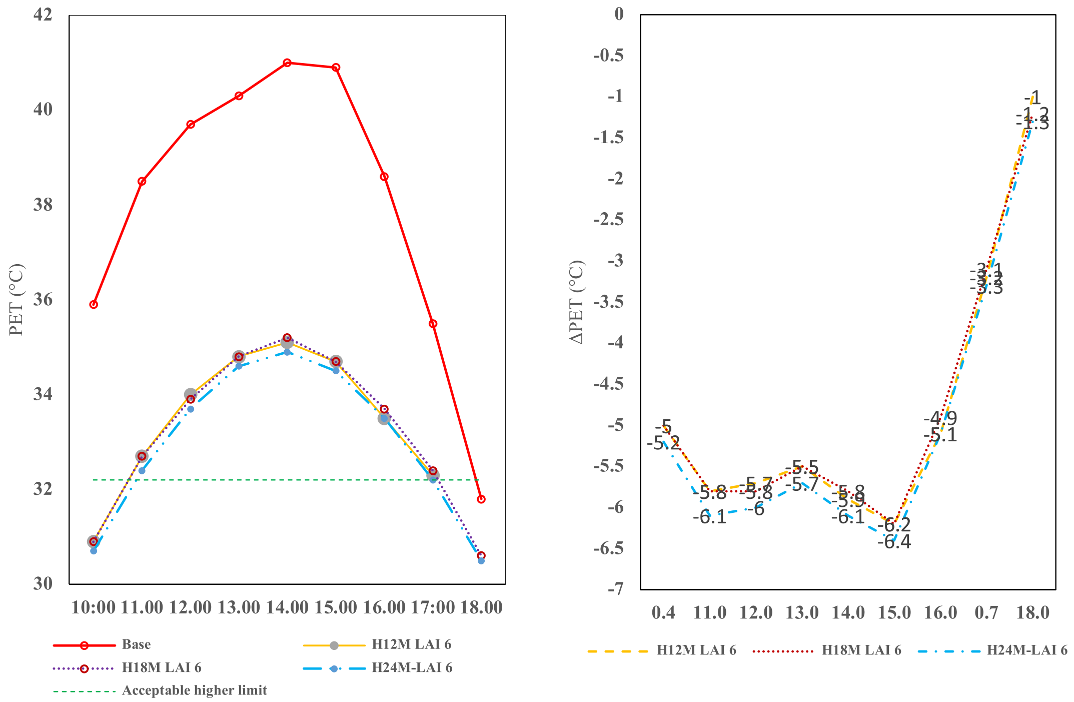

Fig. 11. The influence of combination of building height and vegetation on outdoor thermal comfort in informal settlement. The dotted green line (Fig. 11a indicates upper comfort limit. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Ref. [62], though in their study the reduction of T_a was much higher (0.63–1.46 °C). The major factors which contribute to a decreased T_a are shading and evapotranspiration [63]. Studies [64–66] have shown that the cooling effect of vegetation is larger on surface temperatures than on T_a. It is obvious that under a tree the reduction of radiative fluxes by canopy shading is large [67]; nevertheless, T_a around the location may not show much difference due to air turbulence within short distances [68]. On the contrary, addition of vegetation showed significant reduction of T_{mrt} at 2:00 p.m. and more pronounced on the midday. A similar trend was observed by Ref. [62]. Trees with LAI of 6 have a potential of reaching the neutral T_{mrt} for Dar es Salaam which is 32 °C at 2:00 p.m. as observed in Ref. [50]. This is a significant reduction considering the fact that low-rise informal settlements with no vegetation have been noticed to have spaces between buildings with the most stressful spots (PET varies from 40 to 47 °C) when compared to those with less vegetation [10].

4.1.2. Outdoor thermal comfort

Informal settlements are dominated with areas with high heat stresses [10] associated with a substantial loss of vegetation [69]. An addition of vegetation in informal settlement shows substantial improvement on thermal comfort by significant decrease of PET. This concurs with other studies, which have investigated the influence of vegetation in warm-humid climates [5,7,10,70,71]. The influence of vegetation on the reduction of PET is more pronounced on the midday from 11:00 a.m.-3:00 p.m. The period concurs with empirical findings by Ref. [72]. The trend is due to the effectiveness of vegetation on blocking overhead solar radiation at the midday hours as explained above for T_{mrt}. Fig. 7 shows spatial distribution of PET at 2:00 p.m. for the base case and LAI of 2, 4, and 6.

4.2. Influence of increased building heights

4.2.1. Temporal and spatial variation of the microclimate

Incremental increase of building height shows marginal changes in T_a. This might be due to the fact that the changes have been applied in a limited area of the existing urban canyon while the large portion of the informal settlement remains the same. Another study [73] also notes a weak relationship between T_a and a changing urban geometry. This can be explained by the fact that air temperature distribution is not only affected by urban geometry but also by the combined effect of surface characteristics and air mixing rate, etc. [74]. Other studies in warm humid climates such as [50,75] noted the sensitivity of respondents to a small decrease in T_a; however, it is not easy to ascertain the impact of the decrease of 0.15 °C on the residents.

On the contrary, substantial decrease of T_{mrt} was noted as a result of incremental increase of building heights. It worth noting that studies have shown that areas with low-rise buildings have more thermally stressful urban spaces than areas with high-rise buildings [7,10]. In such an environment, the low building heights make the dark coloured streets and facades exposed to the sun which increases the absorption of solar radiation and consequently increases the surface temperatures. Similarly, other studies [4,20,36] in warm humid climates have shown that an increase in building height, and consequently an increase in the H/W ratio, significantly reduces $T_{mrt.}$ Although the increase in building height shows significant reduction in T_{mrt}, it is difficult to reach neutral T_{mrt} which was found to be 32 °C [50]. This is due to the fact that an increase in building height alone cannot provide effective shade in areas close to the Equator due to high solar elevation around solar noon [10].

4.2.2. Outdoor thermal comfort

Incremental increase of building heights leads to improvement on outdoor thermal comfort through reduction of PET. The noticeable feature is the highest reduction of PET in the morning hours around 10:00 a.m. and in the late afternoon (4:00 p.m.) where different building heights show a similar trend (Fig. 9b). The fact that the highest reduction of PET occurs in the morning and afternoon can be explained by the low solar angle at that time. Despite the fact that there is a noticeable reduction of PET, it is not possible to reach the comfort limits during hot days of the warm season as indicated in Fig. 9a where the dashed horizontal line indicates thermal acceptable limits during the warm season. An increase of building height to 24 m in these informal settlements is 5 °C PET short of the acceptable thermal comfort limits of 32.2 °C PET as shown in a previous study [50]. The response of different building heights which marks the changing deepness/shallowness of the canyon is proportional to the improvement of thermal comfort by shadow-cast as noted by Ref. [58].

4.3. Influence of combining vegetation and increased building heights

4.3.1. Temporal and spatial variations of the microclimate and outdoor thermal comfort

A combination of increased building heights and addition of vegetation has a marginal influence on reduction of Ta as noted in previous discussion section 4.2.1. However, significant changes in reduction of T_{mrt} was noted. It is worth noting that in these intensified informal settlements; upgrading measure which entails to increase the building heights can allow spaces for planting trees contrary to the current condition where vegetation is lost [69]and occupied with multiplied low-rise buildings with high heat stress [10]. Significant improvement of outdoor thermal comfort is noted through combining incremental increase of building height and vegetation. Addition of vegetation can be considered the most cost-effective way of reducing heat stress though the notable challenge is high compactness of building blocks.

5. Conclusions

The main objective of this paper was to investigate the influence of upgrading measures on the microclimate and outdoor thermal comfort of the urbanites in informal areas. Normally informal settlements upgrading measures do not consider upgrading of the outdoor thermal environment but rather upgrading of services. An in-situ upgrading approach was considered in this study and three major upgrading measures were applied. The following notable conclusions can be highlighted.

i) the influence of increasing building heights on microclimate is significant in terms of reduction of T_{mrt} especially in the morning and afternoon,
ii) the influence of adding trees is more pronounced around midday as its capacity for solar radiation attenuation outweighs the shadows cast by the buildings at high solar elevation angles;
iii) uniform increase of building height on both sides of the canyon tends to decrease the wind speed in the urban canyon;
iv) the combination of increase of building heights and addition of trees brings about the maximum reduction of PET up to 14.9 %.

Although increasing building height (H/W) has positive effect on thermal environment by reducing heat stress in informal settlements, buildings fail to provide shade during the hottest parts of the day, therefore addition of shading trees is crucial. Adding shading trees is considered as a cost-effective means of reducing heat stress in informal settlements. Further research to investigate different tree species existing in Tanzania, their speed of growth and LAI which was beyond the scope of this study need to be conducted. Also, the need to explore how the urban landscape can contribute to informal settlements is crucial.

CRediT authorship contribution statement

Modest Maurus Baruti: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Moohammed Wasim Yahia:** Software, Supervision, Writing – review & editing. **Erik Johansson:** Methodology, Software, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Dr. Modest Maurus Baruti reports financial support was provided by Swedish International Development Cooperation Agency.

5.0 Acknowledgement

Swedish International Development Cooperation Agency (Sida) supported this study financially under a bilateral agreement

between Ardhi University, Dar es Salaam, Tanzania and Lund University, Sweden.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e23160.

References

[1] B. Givoni, Climate Considerations in Building and Urban Design, Thomson, New Yirk, NY, 1998.
[2] T. Sharmin, K. Steemers, A. Matzarakis, Microclimatic modelling in assessing the impact of urban geometry on urban thermal environment, Sustain. Cities Soc. 34 (2017) 293–308.
[3] I. Eliasson, M.K. Svensson, Diurnal air temperatures in built-up areas in relation to urban planning, Landsc. Urban Plann. 61 (2002) 37–54.
[4] R. Emmanuel, E. Johansson, Influence of urban morphology and sea breeze on hot humid microclimate; the case of Colombo, Sri Lanka, Clim. Res. 30 (2006) 189–200.
[5] R. Emmanuel, H. Rosenlund, E. Johansson, Urban shading—a design option for the tropics? A study in Colombo, Sri Lanka, Int. J. Climatol. 27 (14) (2007) 1995–2004.
[6] E. Johansson, R. Emmanuel, The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka, Int. J. Biometeorol. 51 (2) (2006) 119–133.
[7] E. Johansson, et al., Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of São Paulo, Brazil, Urban Clim. 6 (2013) 24–43.
[8] J.A. Rodríguez Algeciras, L. Gómez Consuegra, A. Matzarakis, Spatial-temporal study on the effects of urban street configurations on human thermal comfort in the world heritage city of Camagüey-Cuba, Build. Environ. 101 (2016) 85–101.
[9] T. Sharmin, K. Steemers, A. Matzarakis, Analysis of microclimatic diversity and outdoor thermal comfort perceptions in the tropical megacity Dhaka, Bangladesh, Build. Environ. 94 (2015) 734–750.
[10] M.W. Yahia, et al., Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania, Int. J. Biometeorol. 62 (3) (2018) 373–385.
[11] M. Roth, Review of urban climate research in (sub)tropical regions, Int. J. Climatol. 27 (14) (2007) 1859–1873.
[12] E. Johansson, Urban design and outdoor thermal comfort in warm humid climates: studies in Fez and Colombo. PhD Thesis, in: Housing Development and Management, Lund University, Sweden, 2006, p. 237.
[13] L. Kalkstein, K. Valimont, An evaluation of summer discomfort in the United States using a relative climatological index, Am Meteorol Soc 67 (1986) 842–848.
[14] L. Chen, E. Ng, Outdoor thermal comfort and outdoor activities: a review of research in the past decade, Cities 29 (2) (2012) 118–125.
[15] M. Nikolopoulou, K. Steemers, Thermal comfort and psychological adaptation as a guide for designing urban spaces, Energy Build. 35 (2003) 95–101.
[16] E.L. Ndetto, A. Matzarakis, Effects of urban configuration on human thermal conditions in a typical tropical african coastal city, Adv. Meteorol. 2013 (2013) 1–12.
[17] A. Qaid, D.R. Ossen, Effect of asymmetrical street aspect ratios on microclimates in hot, humid regions, Int. J. Biometeorol. 59 (6) (2015) 657–677.
[18] Y. Zhang, D. Xiaohan, S. Yurong, Effects of street canyon design on pedestrian thermal comfort in the hot-humid area of China, Int. J. Biometeorol. 61 (2017) 1421–1432.
[19] S.-R. Yang, T.-P. Lin, An integrated outdoor spaces design procedure to relieve heat stress in hot and humid regions, Build. Environ. 99 (2016) 149–160.
[20] A.N. Kakon, N. Mishima, S. Kojima, Simulation of the urban thermal comfort in a high density tropical city: analysis of the proposed urban construction rules for Dhaka, Bangladesh, Build. Simulat. 2 (4) (2009) 291–305.
[21] UN-Habitat, International Guidelines on Urban and Territorial Planning, UN-Habitat, 2015.
[22] UN-Habitat, Habitat III Issue Papers vol. 22, UN-Habitat, New York, 2015.
[23] R. Mahabir, et al., The study of slums as social and physical constructs: challenges and emerging research opportunities, Regional Studies,Regional Science 3 (1) (2016) 399–419.
[24] UN-Habitat, Implementing the New Urban Agenda by Strengthening Urban-Rural Linkages: Leave No One and No Space behind, UN-Habitat, 2017.
[25] S. Bhanjee, C.H. Zhang, Mapping latest patterns of urban sprawl in dar es Salaam, Tanzania, Papers in Applied Geography 4 (3) (2018) 292–304.
[26] M.M. Baruti, E. Johansson, J. Astrand, Review of studies on outdoor thermal comfort in warm humid climates: challenges of informal urban fabric, Int. J. Biometeorol. 63 (10) (2019) 1449–1462.
[27] B.W. Wekesa, G.S. Steyn, F.A.O. Otieno, A review of physical and socio-economic characteristics and intervention approaches of informal settlements, Habitat Int. 35 (2) (2011) 238–245.
[28] L. Marais, J. Ntema, The upgrading of an informal settlement in South Africa: two decades onwards, Habitat Int. 39 (2013) 85–95.
[29] M. Huchzermeyer, Pounding at the tip of the iceberg: the dominant politics of informal settlement eradication in South Africa, Politik 37 (1) (2010) 129–148.
[30] M. Huchzermeyer, The struggle for in-situ upgrading of informal settlements: a reflection on cases in Gauteng, Dev. South Afr. 26 (1) (2009) 59–73.
[31] R.J. Skinner, M.J. Rodell, *People, Poverty and Shelter: Problems of Self-Help Housing in the Third World*, Methuen, London, 1983.
[32] R. Del Mistro, D.A. Hensher, Upgrading informal settlements in South Africa: policy, rhetoric and what residents really value, Hous. Stud. 24 (3) (2009) 333–354.
[33] A.E. Menshawy, S. Shafik, F. khedr, Affordable housing as a method for informal settlements sustainable upgrading, Procedia - Social and Behavioral Sciences 223 (2016) 126–133.
[34] J. Corburn, A. Sverdlik, Slum upgrading and health equity, Int J Environ Res Public Health 14 (4) (2017).
[35] J. Abbott, An analysis of informal settlement upgrading and critique of existing methodological approaches, Habitat Int. 26 (2002) 303–315.
[36] A.N. Kakon, et al., Assessment of thermal comfort in respect to buildings height in high-density city in the tropics, American J. of Engineering and Applied Sciences 3 (3) (2010) 545–551.
[37] E. Johansson, et al., Outdoor thermal comfort in public space in warm-humid Guayaquil, Ecuador, Int. J. Biometeorol. 62 (3) (2018) 387–399.
[38] B. De, M. Mukherjee, "*Optimisation of canyon orientation and aspect ratio in warm-humid climate: Case of Rajarhat Newtown, India*", Urban Clim. 24 (2018) 887–920.
[39] M. Kottek, et al., World Map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (3) (2006) 259–263.
[40] J.M. Lupala, Urban Types in Rapidly Urbanising Cities: Analysis of Formal and Informal Settlements in Dar Es Salaam, Tanzania. PhD Thesis, in *Department of Infrastructure and Planning*, Kungl Tekniska Högskolan, Stockholm, 2002, p. 253.
[41] M. Bruse, ENVI-Met 4, 2014 [cited 2019; Available from: http://www.envi-met.info.
[42] M. Bruse, H. Fleer, Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model, Environ. Model. Software 13 (3–4) (1998) 373–384.
[43] F. Ali-Toudert, H. Mayer, Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyons, Sol. Energy 81 (6) (2007) 742–754.
[44] M. Bruse, Modelling and Strategies for Improved Urban Climates, Biometeorology and urban climatology at the turn of the millenium, 1999, p. 6.

[45] J.A. Acero, J. Arrizabalaga, Evaluating the performance of ENVI-met model in diurnal cycles for different meteorological conditions, Theor. Appl. Climatol. 131 (1–2) (2016) 455–469.
[46] M. Bruse, ENVI-Met 4: A Microscale Urban Climate Model, 2015. https://www.envi-met.com/. (Accessed 13 February 2020).
[47] P. Höppe, The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment, Int. J. Biometeorol. 43 (1999) 71–75.
[48] J. Pickup, R.J. de Dear, An outdoor thermal comfort index (OUT_SET*) part 1-the model and its assumptions, in: Selected Papers from the ICB-ICUC99 Conference, World Meteorological Organization, Geneva, 2000. Sydney, WCASP-50, WMO/TD No. 1026.
[49] D. Fiala, et al., UTCI-Fiala multi-node model of human heat transfer and temperature regulation, Int. J. Biometeorol. 56 (3) (2012) 429–441.
[50] M.M. Baruti, E. Johansson, M.W. Yahia, Urbanites's outdoor thermal comfort in the informal urban fabric of warm humid Dar es Salaam, Tanzania, Sustain. Cities Soc. 62 (2020), 102380.
[51] M. Taleghani, et al., Thermal assessment of heat mitigation strategies: the case of Portland State University, Oregon, USA, Build. Environ. 73 (2014) 138–150.
[52] M.W. Yahia, E. Johansson, Landscape interventions in improving thermal comfort in the hot dry city of Damascus, Syria—the example of residential spaces with detached buildings, Landsc. Urban Plann. 125 (2014) 1–16.
[53] A. Qaid, D.R. Ossen, Effect of asymmetrical street aspect ratios on microclimates in hot, humid regions, Int. J. Biometeorol. 59 (2015) 657–677.
[54] E.L. Krüger, F.O. Minella, F. Rasia, Impact of urban geometry on outdoor thermal comfort and air quality from field measurements in Curitiba, Brazil, Build. Environ. 46 (3) (2011) 621–634.
[55] Meteotest, Meteonorm 7.0, in: Meteotest, Meteotest: Bern, Switzerland, 2014.
[56] D.H.S. Duarte, et al., The impact of vegetation on urban microclimate to counterbalance built density in a subtropical changing climate, Urban Clim. 14 (2015) 224–239.
[57] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple andcomplex environments - application of the RayMan model, Int. J. Biometeorol. 51 (2007) 323–334.
[58] T.E. Morakinyo, et al., A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort, Build. Environ. 115 (2017) 1–17.
[59] B. Lalic, D.T. Mihailovic, An empirical relation describing leaf-area density inside the forest for environmental modeling, J. Appl. Meteorol. 43 (4) (2004) 641–645.
[60] H. Timoth, Unplanned Urban Development: Spatial Growth and Typology of Unplanned Settlements, Dar Es Salaam, Tanzania. Unpublished Master's Thesis for Urban Survey and Human Settlement Analysis, ITC: Enschede, 1995.
[61] F.K. Abebe, Modelling informal settlement growth in dar es Salaam, Tanzania. Master's thesis, in: Instute of Geo-Information Science and Earth Observations, University of Twente, Twente, 2011.
[62] S. Zheng, et al., Influence of trees on the outdoor thermal environment in subtropical areas: an experimental study in Guangzhou, China, Sustain. Cities Soc. 42 (2018) 482–497.
[63] M.F. Shahidan, et al., An evaluation of outdoor and building environment cooling achieved through combination modification of trees with ground materials, Build. Environ. 58 (2012) 245–257.
[64] D.E. Bowler, et al., Urban greening to cool towns and cities: a systematic review of the empirical evidence, Landsc. Urban Plan 97 (3) (2010) 147–155.
[65] P. Cohen, O. Potchter, A. Matzarakis, Daily and seasonal climatic conditions of green urban open spaces in the Mediterranean climate and their impact on human comfort, Build. Environ. 51 (2012) 285–295.
[66] G. Papadakis, P. Tsamis, S. Kyritsis, An experimental investigation of the effect of shading with plants for solar control of buildings, Energy Build. 33 (2001) 831–836.
[67] A.H.A. Mahmoud, Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions, Build. Environ. 46 (12) (2011) 2641–2656.
[68] P. Lin, et al., The impact of urban design descriptors on outdoor thermal environment: a literature review, Energies 12 (10) (2017).
[69] M. Roy, et al., Climate change and declining levels of green structures: life in informal settlements of Dar es Salaam, Tanzania, Landsc. Urban Plann. 180 (2018) 282–293.
[70] F. Yang, S.S.Y. Lau, F. Qian, Thermal comfort effects of urban design strategies in high-rise urban environments in a sub-tropical climate, Architect. Sci. Rev. 54 (4) (2011) 285–304.
[71] Z. Tan, K.K.-L. Lau, E. Ng, Planning strategies for roadside tree planting and outdoor comfort enhancement in subtropical high-density urban areas, Build. Environ. 120 (2017) 93–109.
[72] L.V. de Abreu-Harbich, L.C. Labaki, A. Matzarakis, Effect of tree planting design and tree species on human thermal comfort in the tropics, Landsc. Urban Plann. 138 (2015) 99–109.
[73] E. Andreou, K. Axarli, Investigation of urban canyon microclimate in traditional and contemporary environment. Experimental investigation and parametric analysis, Renew. Energy 43 (2012) 354–363.
[74] M. Santamouris, Energy and Climate in the Urban Built Environment, James & James, London, UK, 2001.
[75] K. Villadiego, M.A. Velay-Dabat, Outdoor thermal comfort in a hot and humid climate of Colombia: a field study in Barranquilla, Build. Environ. 75 (2014) 142–152.