



Review

# A Review and Insights for Eleven Years of Urban Microclimate Research Towards a New Egyptian ERA of Low Carbon, Comfortable and Energy-Efficient Housing Typologies

Mohammad Fahmy <sup>1,\*</sup> , Sherif Mahmoud <sup>1</sup>, Ibrahim Elwy <sup>1</sup> and Hatem Mahmoud <sup>2,3</sup> 

<sup>1</sup> Department of Architecture Engineering, Military Technical College, Kobry El-Kobba, Cairo 11662, Egypt; sherif\_ahmed@mtc.edu.eg (S.M.); ibrahim.elwy@mtc.edu.eg (I.E.)

<sup>2</sup> Department of Architecture Engineering, Engineering Faculty, Aswan University, Aswan 81542, Egypt; hatem.mahmoud@aswu.edu.eg

<sup>3</sup> Environmental Engineering Department, Egypt-Japan University of Science and Technology E-JUST, New Borg El-Arab City, Alexandria 21934, Egypt

\* Correspondence: md.fahmy@mtc.edu.eg

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**Abstract:** Since the mid-1970s, urban development in Egypt has sprawled far from the distinguished compact arid built environment, as the court-yarded housing typologies that completed the vernacular picture of desert architecture have been discarded in the early 20th century. This has motivated urban microclimate research in Egypt. The main objective was initially to improve outdoor thermal comfort. Therefore, Egyptian research started with assessing different existing patterns for the sake of climate responsive and sustainable urban design practice characterized with low carbon, thermal comfort and energy efficiency in such a hot arid conditions. That is why the review workflow of this article has followed a design progress workflow that led to solving design complexities with regard to generating housing urban forms on a microclimate basis rather than an article regular review workflow in order to extract the research gaps and conclude insights. After discussing a general framework for generating housing sustainable design identified from the concluded gaps, the main conclusion is a vision and a call to integrate the Urban microclimate-Building passiveness-Renewables design dimensions, UBR, towards the evolution of a new era of energy efficient housing typologies and a 5th generation of Egyptian sustainable cities where the 1<sup>st</sup> generation of new Egyptian cities started 1970s.

**Keywords:** urban microclimate; clustered urban form; GreenSect; housing typologies; Egyptian cities

## 1. Introduction

Like most developing countries, Egypt witness a rapidly increasing urbanization. The population growth and urban development have caused city-induced climate changes [1]. While Egypt has a minor impact on the global greenhouse gas (GHG) emissions (0.6% of global emissions), GHG is one of the main parameters affecting climate change in Egypt [2–4]. Egypt is considered as one of the countries highly vulnerable to climate change [5]. By 2060, as a result of global warming, the average temperature in Cairo, capital of Egypt, is expected to increase by 4 °C, and for the rest of Egypt, by 3.1 to 4.7 °C [6]. Under an extreme emissions scenario, the increase in temperature is expected to be 5.6 °C during the period 1990 to 2100. If emissions decreased dramatically, the increase in temperature would be under 1.6 °C [5]. The increasing global research attention to the thermal conditions of the built environment is due to the high level of health-related risks due to the climate change. For instance,

the European heat waves in 2003 resulted in between 25,000 to 70,000 deaths throughout Europe [1]. This problem has stimulated Egyptian researchers to investigate the adverse effects of urbanization on outdoor thermal conditions of existing cities and new cities which are mostly located in desert regions.

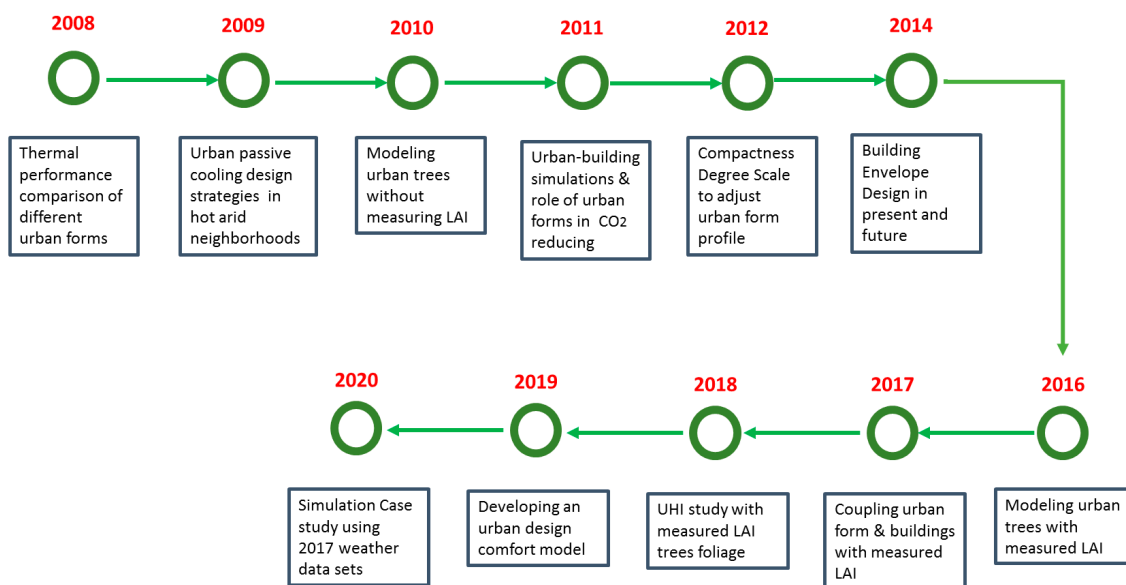
The American society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has defined the thermal comfort as the state of mind which expresses satisfaction with the thermal environment [7]. The outdoor thermal performance is influenced by various parameters, such as the arrangements of buildings, shaded areas, materials albedo, water bodies, orientation and space aspect ratio. It is important to investigate the impact of manipulating those variables in the early stages of urban and architecture design process. In this regard, this review article started to collect, and analyze the studies published in the Egyptian urban microclimate research field since 2008 when the first study on Egyptian urban forms was published to numerically investigate the mutual effects between different existing patterns (dot—clustered—compact) and the microclimatic conditions. The lack in the urban microclimate studies in the Egyptian context dedicated to physically designing urban forms especially concerning half of the land use budget, residential buildings, directed the authors of the aforementioned reference towards defining the corresponding thermal performance and in turn estimating the pedestrian thermal comfort, energy efficiency and the negative effects of those different patterns in later studies [8]. Since then, many other investigations have been dedicated to design residential neighborhoods on a climate responsive basis [9]. In this concern, achieving thermal comfort as a cumulative parameter that represent a good design of urban form, is very difficult to be conducted passively, especially during summer when it is very warm [10] despite that, an enhancement in thermal comfort is possible through interventions in the design of urban buildings. Moreover, the outdoor thermal performance in shape of air temperature and solar radiation significantly influence the indoor thermal performance through windows and building envelop, thus improving the outdoor will improve the indoor climate and reduce the cooling and heating loads.

From this stance, this study aims to present a review of studies published over the last eleven years on the behavioral and energy efficiency aspects of the outdoor environment in Egypt. It seeks to contribute towards a more in-depth understanding and assessing the present situation of the related researches in Egypt to identify the knowledge and applied practice gaps and steps towards a new Egyptian era of housing environment. In Egypt, buildings contribute to 67% of electricity consumption [11], and 42% of energy consumption [12], whereas housing that represents about 50% of the Egyptian built environment, contributed to 51.3% of electricity production [11], 19% of energy consumption and 9.7% of carbon emissions, [2,13]. That is why much of the Egyptian microclimate research described in this review focused on the urban form design of housing built environment. Further, that is why the review workflow of this article has followed a design progress workflow which concluded a research line that pulled many researchers in Egypt (Figure 1). In this review article, the survey of this research line was designed to filling the knowledge gaps and solving the complexities with regard to the connection between microclimate and the housing urban forms rather than an article regular review workflow.

## 2. Methodology

The workflow of this review article is not a regular classification, but rather it is built along research line that followed the idea of how to design, select, model, simulate and/or assess the effect of different alternatives of each element of the residential built environment, fabric-network-vegetation, on the most common sustainability measures; comfort, energy and carbon emissions in such a hot arid country like Egypt. This study did the review not in the regular traditional way of a review article; it focuses on the last eleven years of Egyptian studies that have addressed the impacts of urban form (fabric and network), mitigation, and adaptation strategies on the outdoor thermal performance which had implications on the evolution and design of residential buildings and their carbon emissions, thermal comfort and energy efficiency.

The study is divided into four main parts. The first (Section 3) reports the studies on the impact of urban patterns (geometry) on outdoor thermal conditions (fabric effects) through the publications that involved Egyptian case studies. Urban geometry aspects were categorized into aspect ratio H/W, sky view factor (SVF), street orientation, and neighborhood configuration. Moreover, this part will address the studies that incorporated energy aspects. The second (Section 4) presents the research on the adaptation and mitigation strategies through the publications that had also Egyptian case studies. The surface material albedo and vegetation species are examples worth mention among the mitigation and adaptation strategies. The third part (Section 5) presents the methods that have been applied to investigate urban microclimate research case studies in Egypt. Finally, the fourth part (Section 6) will present the urban microclimate research gaps and what can be proposed in Egypt for the sake of developing a new ERA of housing typologies on a climate responsive basis.



**Figure 1.** A brief for the design complexities and milestones that have been solved by the research line reviewed in this article, (2008–2020).

### 3. Research for urban fabric geometrical adjustments

#### 3.1. Urban Patterns Thermal Comfort Assessment

Built environment elements—fabric, network and vegetation—have a swinging and mutual effect with the micro and local climate scales that reveal different sites’ conditions. The effect appears in the main sustainability measures, either inside or outside the building such as thermal comfort, energy consumption and carbon emissions, as well as urban heat island (UHI) generation which in turn affect the energy consumption and carbon emission cycle again [14–18]. Specifically, in hot arid regions where both fabric and network receive a huge amount of solar radiation, there is still a lack in the application of climate knowledge to the urban development projects [19–21]. This is due to the increased population that needs vast actions to be accommodated. In a country like Egypt, the housing policies depend on the multifamily multistory dot pattern developments. However, such an overwhelming point cannot justify the lack of urban fabric geometry adjustments to alleviate arid conditions. As housing land use budget reaches 50% of neighborhoods, urban fabric geometry controls the solar radiation coming to surfaces through aspect ratio, sky view factor, orientation and compactness as urban passive cooling applications for the shading and ventilation strategies [22–25]. Urban canyons’ microclimates and related thermal comfort studies are defined in literature by their aspect ratio H/W, and by their SVF [19,26–28]. For a whole pattern, a study in Cairo mentioned that urban geometry can be adjusted through defining the built-up volume of a neighborhood—the compactness degree. This is because

there is no sole solution for excessive heat stresses [29,30] in hot dry climates, to the extent that using some sensitive, intelligent and responsive design elements such as the traditional courtyard [31–33] is not sufficient [34], and the solution has to be comprehensive.

Nevertheless, it is essential to understand the interaction between the prevailing climate and the urban form prior to assessing the outdoor thermal comfort achieved by the diverse of urban forms [35,36]. Fahmy and Sharples assessed and analyzed three cases of urban designs using ENVI-met CFD numerical simulations [8]. The first form is compact and possesses high thermal performance during the daytime only, yet it hasn't enough wind access besides its high population density that affects the inhabitants' health. The second form is a medium density fabric that allows both enough wind speed and solar access for passive cooling- and health-related aspects. Nevertheless, its canyon aspect ratio does not provide enough shelter at higher solar altitudes, which can be enhanced by applying vegetation and urban trees. The third urban form is the dot single and multi-family urban form that provides enough wind flow, but more surfaces are subjected to direct radiation, but it involves more land consumption and urban sprawl that need more vegetation and green coverage when compared with the previous cases. Furthermore, Mahmoud [35] concluded that the appropriate urban form with its SVF and the intensity of direct vertical solar radiation are of a drastic influence on the thermal comfort of the outdoor spaces. Fahmy and Sharples, [8] concluded that the thermal comfort can be achieved by using spatial networks with precise orientation selection and by using fabric unit with urban spaces to provide an adequate compactness degree for specific housing and population while allowing wind flow through the urban spaces for passive cooling. From these viewpoints many other researchers have contributed to the analysis of urban patterns in order to suggest design instructions based on the mutual effects of built environment on microclimate and vice versa. Fahmy [37] reviewed the patterns of urban formation applied to Greater Cairo based on the vehicular network and the shape of the fabric. Vehicular network is divided into; (a) Grid type includes (normal grid and the branched grid), (b) hierarchical type (radial and longitudinal routes with long routes), (c) organic type, (d) mixed type. Same author referred to the shape of the fabric as a method of classification: it refers to the buildings, which is divided into: (a) point or dot shape patterns, (b) linear shape patterns, (c) compact shape patterns. It has been realized that different urban forms act thermally in different ways. Therefore, Shalaby and Shafey [38] optimized street canyon orientations with the aspect ratio in a hot eastern site in Egypt to increase daytime thermal comfort levels while mitigating nocturnal UHI. They found that north-south oriented streets are better in daytime provided that aspect ratio proportion is 1:3, which in addition permit an acceptable amount of heat release starting from evening. In the east-west oriented streets, a limited impact of increasing aspect ratio daytime is noticed and therefore a 1:1 proportion is recommended. The paper also finds that the diagonal urban form with 1:2 and 1:3 aspect ratios given to its NE and NW streets, respectively, is thermally the best along the day on average.

### 3.2. The Compactness Degree Scale

As the aspect ratio of an urban form, canopy asymmetries, vertical properties, shading effects and irradiated surfaces control urban canyon thermal behavior which means a specific degree of compactness of in a certain city zone can control the total heat exchange process [26]. Fahmy and Sharples [34] introduced the compactness degree terminology to define the overall degree of compactness of urban site as the aspect ratio represents only a single canyon in the site. The Compactness Degree Scale (CDS), defines the built-up volume from 0.1 to 10 calculated by multiplying the general floor area ratio of an urban site by the average floor number in this site. The 0.1 unit less value represents a site with only 10% of general floor area ratio multiplied by only one single floor whereas the 10 value is approximated after a site with 12 floors having 80% of general floor area ratio.

It is the product of the total local urban construction percentage times the average number of floors of the local canopy layer. Moreover, Fahmy [39] calculated empirically the compactness degree scale (Dc) to adapt forms to its corresponding climate change scenario. This scale is classified into five

categories on the transect of a city (Table 1), to help comparing the overall thermal performance of a neighborhood to another on a built-up volume basis not on a single street canyon geometry basis.

**Table 1.** Categories and ranges of the compactness degree scale [34,39–41].

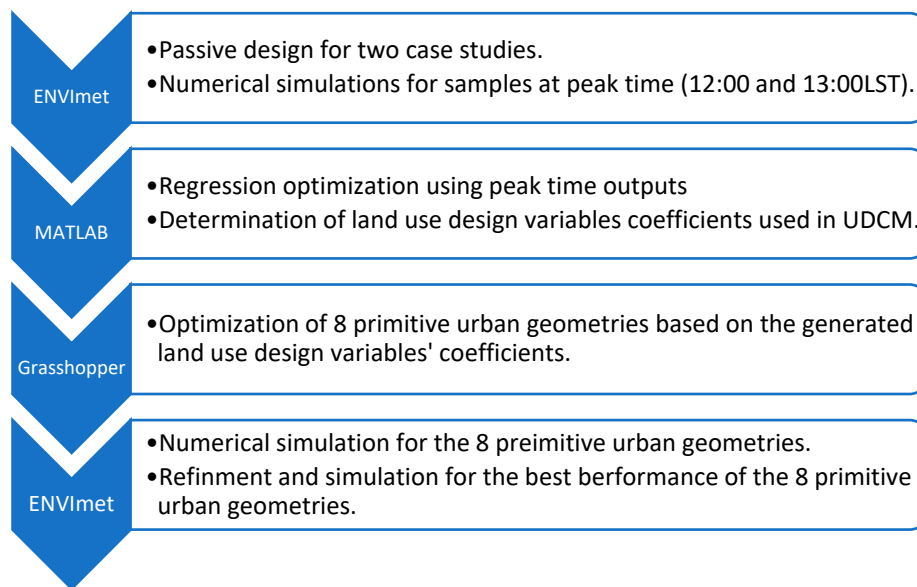
No.	City Sector	Corresponding Compactness Category	Compactness Degree
1	City center	Very compact	5–8
2	Central urban	Compact	2.8–5
3	General urban	Medium	1.6–3
4	Suburban	Open	0.4–1.8
5	Rural urban	Very open	0.3–0.5

### 3.3. Development of an Urban Passive Thermal Comfort System

Thermal comfort depends on the radiant exchanges represented by the mean radiant temperature which is affected by the fabric compactness. The thermal comfort assessment and measurement cannot be dependent on the theoretical heat balance when studying the inhabitants' thermal behavior in reality. Fahmy and Sharples [34] introduced an urban passive thermal comfort system, to utilize two elements: (1) the urban fabric form with its green structure; and (2) thermal comfort adaptation by introducing urban green scene stimulation. Moreover, the study proves that the parallel avenues clustered form act climatically well, if the Dc is to be studied considering the local land use and housing that needs design, taking into consideration the thresholds of population. Also, the study demonstrates an approach towards green structuring and urban patterns geometrical adjustments on a climate basis, as well as, it illustrates that the outdoor thermal comfort levels are dependent on: (1) the form design details; (2) its vegetation; (3) orientation of both the canyon axes; and (4) linear trees arrangement. Furthermore, Hassan and Mahmoud [42] studied the urban surface structure in an urban park, in which these variations in the urban surfaces affect surrounding microclimate and in turn affect the human's thermal comfort through measuring of the PET. Also, these differences in microclimates owing to different solar radiation and wind speed, in which these two factors resulted in variation in the mean radiant temperature and PET that impacts human's thermal perception. Moreover, Limona et al. [43] had examined three layouts in the coast of Baltim in Egypt to stand for the best urban form that enhance the outdoor microclimate and improve human thermal comfort. The results had proved that the outdoor comfort in the three different urban layouts differ depending on the air temperature, wind speed, relative humidity, and the predicted mean vote (PMV), emphasizing that urban geometry parameters have impacted the human thermal comfort based on the orientations, volume of buildings, width of the streets.

### 3.4. Development of an Urban Thermal Comfort Design Model

There are two main aspects that play a crucial role in modifying arid microclimates in city planning, which are the neighborhood fabric and vegetation. Yet, Fahmy et al. [44] discussed other parameters affecting the arid microclimates, which are compactness degree, grass coverage, leaf area density, trees ground coverage, and asphalt and building areas. There are numerous mutual effects between built environment elements, fabric, network and vegetation that affect the microclimate change, in which these parameters should be taken into consideration when developing the urban design comfort model (UDCM) (Figure 2).



**Figure 2.** UDCM research methodology workflow.

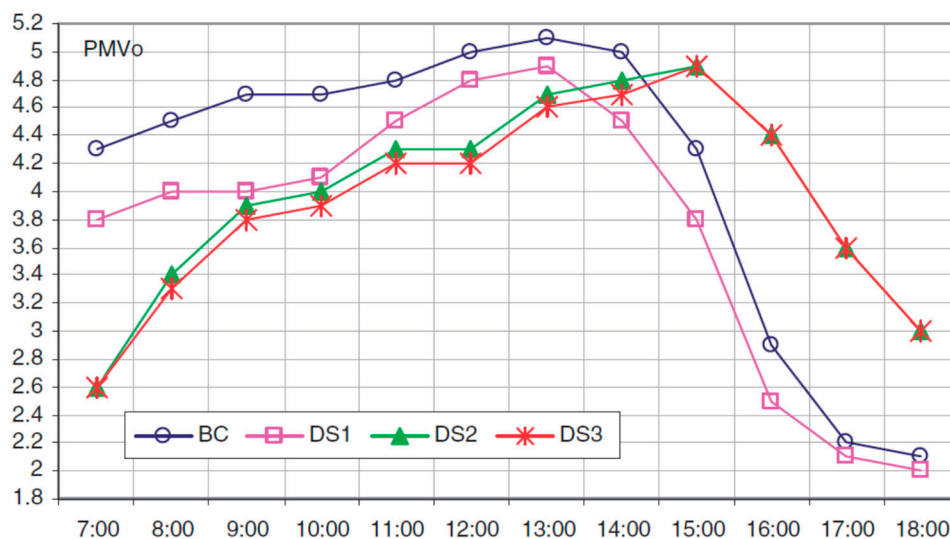
### 3.5. The Clustered Urban Form: from Cairo to Aswan

This section will discuss the different urban cluster forms and how they affect the mean comfort level. Fahmy and Sharples [45] suggested three urban forms for a case study of a dot pattern of a single family villas, in New Cairo settlement (Egypt), which are: (1) clustered urban form planned over the base case zoning to examine the effects of clusters regardless the orientation; (2) using the same land uses percentage but allocated in different zones; (3) using the same master plan of the previous case but applying different albedo for walls and roofs. The study used PMV as a scale for pedestrian thermal comfort. It has been developed originally for the assessment indoor conditions and doesn't represent adaptation effects; however, PMV scale in ENVI-met calculations is not the regular PMV scale of Fanger. PMV was used when ENVI-met as an assessment tool that models all outdoor environment element, didn't have the PET yet. In the previous versions of ENVI-met it used an improved PMV for outdoor conditions after the work of Jendritzky and Nübler to account for the outdoor wind speed and all net wave radiation [46], however, much discussion can be found in the work of d'Ambrosio et al., for the calculation issues of the original Fanger PMV [47]. Considering that the three design suggestions have 8 cm grass and 15 m height *Ficus elastica* trees, the results of this study showed that the first design suggestion reduced the external thermal comfort with range 0.1–0.7 than the base case. The other two design suggestions have the same thermal behaviors due to the similarities in the zoning, however they are different from the base case and the design suggestion as the former's comfort peak is displaced forward due to the increased compactness degree that provides more direct shelter. Contrarily, in the evening the behavior of the second and third suggestions differs also from the base case and the first design suggestion in which the  $PMV = 0$  increased by 0.6–1.4 from early evening until sunset. This may be attributed to the increased number of dense trees which increase the amount of long-wave radiation from the ground near the walls that is trapped by the tree's canopies. Therefore, the local scale clustered form with dense tree arrangement delayed heat gain during the day and reduced cooling overnight. Hence, the usage of high albedo roof in the third design suggestion prevent majority of short-wave radiations to be absorbed by the building fabric resulted in lower level of  $PMV_0$  when compared with the second case. Further, Mahmoud [35] investigated the effect of the urban form on the outdoor thermal comfort in New Aswan (Egypt) that aimed to identify the suitable model for the urban geometry concerning the environmental point of view. The study found that there was a wide range of Physiological Equivalent Temperature (PET) values between the

examined cases due to the shape of the SVF and orientation in which these variations led to relatively comfort spaces and discomfort spaces with extreme heat stress.

### 3.6. Connecting Outdoor—Indoor Environments

There is a strong relation between the outdoor urban thermal performance and the indoor environmental quality (IEQ), such that IEQ is the result of indoor thermal comfort, indoor air quality (IAQ) acoustic and visual comfort, [48,49]. In a study that took place in the Egyptian environment, urban trees' effects on the occupant thermal comfort has been studied in a residential building [50]. Another study investigated the effect of baseline and two urban cluster form alternatives on the outdoor predicted mean vote (PMV) that was used to quantify thermal comfort, as well as, their effect on a building occupant thermal comfort and its CO<sub>2</sub> emissions [45]. The study found that urban passive designs strategies and their applications in terms of orientation towards prevailing wind and clustering the housing are much efficient and shifts the PMV peak output two hours later from the noon time and improves buildings IEQ in comparison to the baseline and reduced the annual carbon emissions. Such shift is owed to the clustered urban form which has been called hybrid urban form when associated with a green infrastructure and revealed an urban thermal mass and urban time lag, (Figure 3).



**Figure 3.** The figure illustrates that an urban form with comprehensive passive design applications concluded a shift in heat gain, loss and an urban time lag of about 2 h; Bas case (BC), design suggestion no.1 (DS1) is a clustered housing over the same vehicular network, design suggestion no. 2 (DS2) is a newly designed clustered housing with adjusted aspect ratios and green infra over a new vehicular network, whereas DS3 is the same as DS2 but with higher albedo for building surfaces and asphalt roads. It has to be noted that curves in Figure 2 report modified PMV values according to Jendritzki and Nubler [46].

Moreover, Abdallah [51] investigated the influence of outer courtyards between buildings using two types of courtyards: (1) shallow canyons with H/W ratio 0.24–0.6 that is located in the urban pattern of youth housing sector in New Assuit city; and (2) deep canyons with H/W ratio of 4 in one of the new residential houses in El-Abrahimia and El-Moalemeen complexes in the center of Assuit city. According to a comparison that was conducted between the two cases based on; the indoor thermal comfort, energy consumption, and IEQ, the study revealed that there was a reduction of the indoor temperature of the spaces that overlooked the deep canyons with a difference of 11 °C from the outdoor temperature, and the indoor temperature reaches the upper limit of 90% acceptable range of ASHRAE.

#### 4. Urban Adaptation and Mitigation Strategies Research

Vegetation is widely recognized as a major player in enhancing microclimatic conditions for the many benefits it supports: sound comfort, pollution reduction, aesthetic values, social habitat in addition to the energy savings in buildings owing to the lesser cooling or heating loads [52]. Urban vegetation acts through three main characteristics, which to a large extent, affect the climate; basically shading, evapotranspiration and wind blockage [53,54]. In this concern, within urban street canyon, the influence of vegetation is found to be dependent on the green-to-built-up area ratio, i.e.; size, density, shape, age, species, site case of the plant [55] along with grouping and orientation as well [56–58].

Urban trees represent an important element of site vegetation, which it can improve the microclimatic performance of built environment, adapt patterns to climate change and reduce energy consumption [59,60]. Tree microclimate arises based on radiation intercepted and evapotranspiration. The canopy parameters Leaf Area Index (LAI), and Leaf Area Density (LAD), contribute to canopy shading and to the circulation of water through tree roots-trunk-foliage system [54,61–63] which leads to lowering air temperatures [64] and bettering comfort levels in and out buildings if accompanied with urban fabric geometrical adjustments [26,65,66]. Radiation interception occurs due to canopy blocking of short and long-wave radiation from the upper hemisphere, whereas evapotranspiration occurs relying on the water content carrying capacity of the soil-tree-air. Evaporation happens from the surface of leaves to air, and transpiration happens from soil to stem and leaves according to the photosynthesis process. These processes resulted in increasing is latent heat and decreasing of sensible heat within the tree leading to lower air temperature, less heat gain for surrounding air, and in turn achieve better outdoor and indoor thermal comfort. Based on the previous discussion, selection of urban trees can be based on thermal performance that depends on: (1) foliage characteristics; (2) total height and canopy geometry; (3) botanical aspects such as (type of soil, tree deciduousness, depth and radius of roots, and capability of bearing the hazards and harsh conditions. Studying urban trees should thus be based on two environmental canopy modeling parameters, which are LAI and LAD, as will be illustrated in the following subsections.

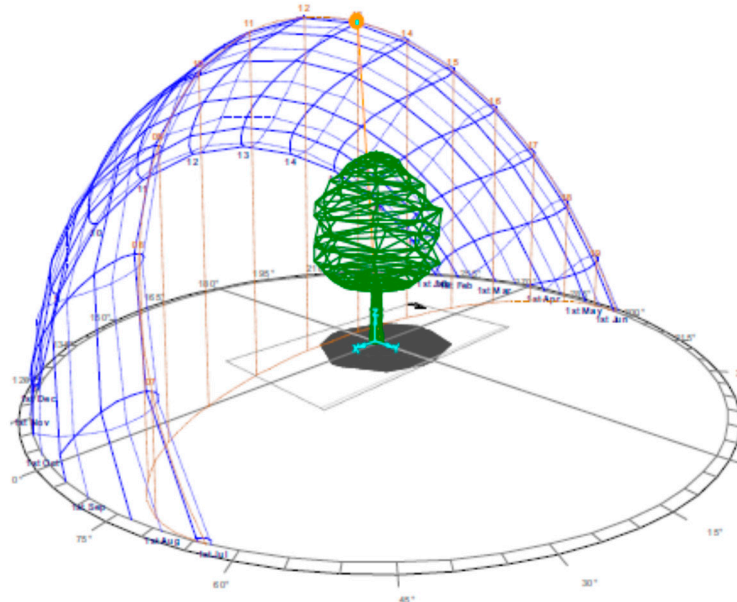
##### 4.1. Assessing Urban Trees Numerical Parameters Without Measurements

LAI and LAD are the main foliage parameters needed to model radiation through a tree a canopy and between a tree and its environment. It can be estimated utilizing field measurement or using instruments and empirical models. There is lack of research concerning LAI and trees modeling in hot regions, as well as, the urban trees modeling to access their thermal effect in contact with buildings in hot arid regions. Hence, there is an urge need to model trees even without LAI or LAD sources for specific species, and it is essential to know the preferred LAI of tree to produce maximum shadow at peak hour of a mid-latitude site. following Lalic et al. [67], Fahmy et al. [59] developed an empirical method to model LAD values of a mid-latitude urban tree and its effects at peak time without the need to measure LAI which is an essential parameter to introduce trees LAD foliage values to the vegetation database of ENVI-met microclimate CFD model [68].

LAI definition of flat leaves reveals its calculation. It is equal to the upper leaves area divided by the tree ground planting area, at peak time if the shadow is solid, and then the ground planting area is equal to the projected ground shadow of the tree. Moreover, the maximum projected ground shadow of the tree is at the maximum solar altitude; therefore, the least value of LAI to produce a solid ground shadow at peak time is when the leaves area equal to projected shadow area and the LAI value is equal to 1. Hence, LAI = 1 can be used as a reference value for urban trees of semi-arid Mid Latitude region in which Egypt lies (Figure 4). Using this empirical methodology, Fahmy, et al. [50] had investigated the influence of using two types of trees (15 m high *Ficus elastica*, and 20 m *Yellow poinciana*) on the indoor thermal comfort represented in PMV. The study concluded that 15 m high *Ficus elastica* achieved better thermal comfort, which came to conclusion that urban developments in Cairo, Egypt should consider not only trees planting, but also the type of trees during the planting stage. Continuing the research



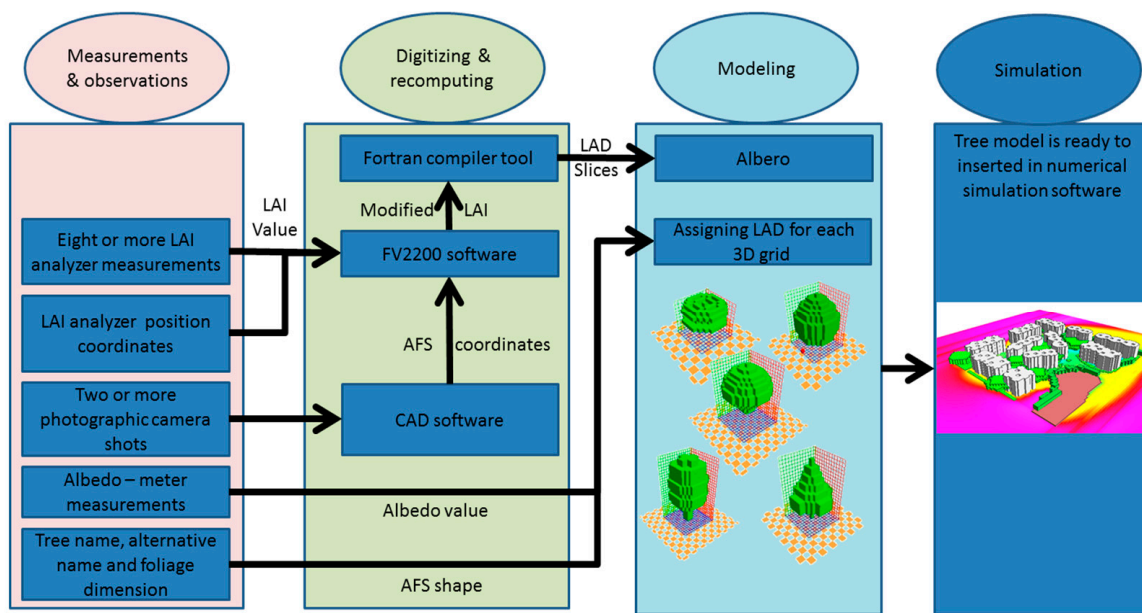
streamline, the coupled outdoor-indoor (urban-building) simulations, Fahmy, et al. [60] discussed the benefits of applying urban green cover and its effect on domestic energy efficiency in present and future. Two different urban cases were examined using green cover and the results showed the effect of the different urban microclimates on the energy consumptions and energy savings even the same domestic residential buildings were used in the two cases. Figure 4 indicates the empirical idea of solving the modeling calculations to add Egyptian environment trees to ENVI-met database.



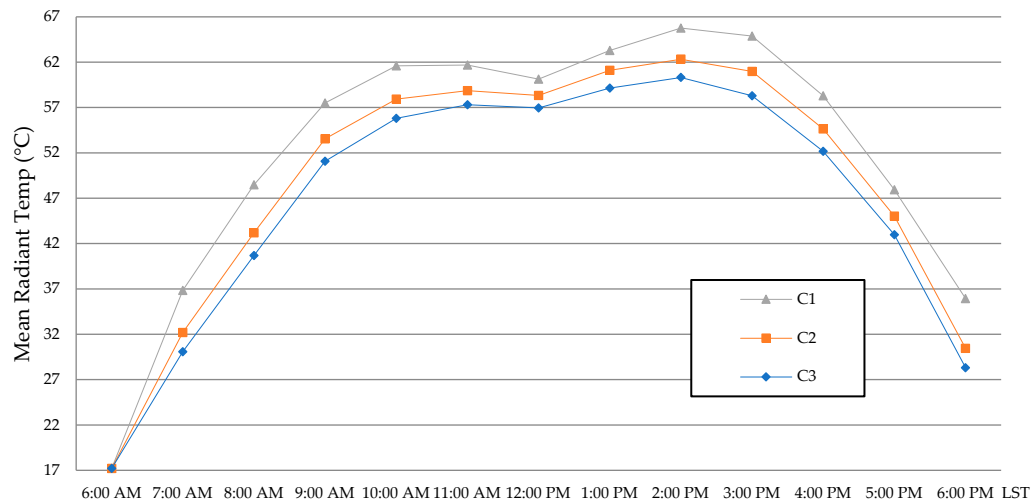
**Figure 4.** A 3D modeling for the solar path diagram of Cairo at 13:00LST (Local Solar Time) indicates an altitude angle of  $82^{\circ}40'$  which is empirically generated an LAI of at least 1 to conclude a ground solid shade of flat leaves urban trees.

#### 4.2. Assessing Urban Trees with Measured LAI and Albedo

In order to assess the complete built environment elements, urban trees real foliage has to be modeled on real LAI basis rather than an empirical one to assess trees role in modifying their urban environments' thermal performance [69]. Therefore, a four stages methodology has been applied in case study in Borg El-Arab (Alexandria, Egypt) to compare the thermal performance of urban spaces that applied urban trees, once modeled empirically and another modeled on a measured LAI and Albedo basis [69]. The measurement experiment applied a LAI2200c plant canopy analyzer [70] and the use of two back to back CMP21 second class high temperature pyranometers as albedometers, [71]. Those four steps can be summarized as following; (1) field measurements of albedo and LAI and observations of the trees geometry; (2) digitizing and recomputing the tree initial measurements; (3) modeling the selected local trees numerically to be added to the simulation tool; and (4) and finally modeling and simulation of the urban site selected to assess trees within its built environment. It is found that the modeled trees on a measurement basis for LAI and Albedo are thermally performing better than those empirically modeled and that a database for urban trees on LAI measurement basis is needed (Figure 5).



(a)



(b)

**Figure 5.** (a) Methodology of generating LAD values to simulate a single (isolated) tree in meteorology numerical simulation software, [60,69]. (b)  $T_{mrt}$  comparisons between different cases of a site in Alexandria, Egypt; C1 is without trees, C2 is with trees of LAI = 1, and C3 is the site with measured LAI.

### 4.3. UHI Mitigation

Urban heat islands have been investigated in Cairo from a thermal effect point of view in the work of Hamid et al. [72] and it was found that Land Surface Temperature (LST) which is the Surface Urban Heat Island (SUHI) in new towns is 2 K warmer than in Cairo due to the non-uniform distribution of urbanization. Moreover, the study indicates that the selection of suitable rural references in SUHI

studies is an important in a desert city with significant landscape and surface difference with their most surrounding areas such as Cairo. However, as intelligent, innovative, and aesthetic urban environment element, trees patterns and lines mitigate urban heat island.

In the study of Fahmy et al. [73], the mitigation of UHI took place in Cairo in present and future by the application of tree lines, green roofs, high albedo pavements and shading structures mentioned in the green rating system LEED-ND, and the microclimatic numerical model ENVI-met was the assessment method. The study proved the efficiency of using selected Egyptian trees lines in UHI mitigation in present and under climate change scenarios until the end of century (2020, 2050 and 2080) in terms of air and radiant temperature reductions.

In the research of Yasser [74], tree ground coverage percentages improved pedestrian thermal comfort by maximum of 6 °C on the PET scale, and with a minimum of 2 °C but with a wind speed reduction ranging from 0.2–1.0 m/s in two street canyons; one of them is NE-SW axe and the other is NW-SE axe. The trees coverage percentages were best for the NE-SW axe canyon with 50% whereas for the NW-SE axe canyon, it was 22%.

A recent work of Abolelata and Sodoudi [75] aimed to reducing energy consumption by mitigating UHI in Cairo through different urban tree coverage scenarios. Comparing the baseline scenario and alternative scenarios (30% trees, 50% trees and 30% trees + 70% grass) revealed 3 K cooler thermal comfort for the 50% trees scenario, but none of the scenarios fulfilled reductions in buildings energy consumption, as the geometrical adjustments didn't took place; the street orientation, the aspect ratio and other geometry parameters play an crucial role and have to be considered.

In another study by the same authors [76], two case studies in Cairo were simulated using ENVI-met; Imbaba—65% urban density, and officers residences in the Elsalam district—23% urban density. A percent of 30% trees, 50% trees and 70% grass scenarios were applied to investigate their energy consumption implication. The study revealed a reduction of 0.2–0.4 K to the daily air temperature in very high density Imbaba site, while increasing air temperature by 3 K in low density site owed to the increased humidity.

#### 4.4. The Green and Blue Infra

The *GreenSect*, *Green* cooling cover over a city tran*Sect*, is a passive urban planning strategy that considers a bio-meteorological green structure along the urban transect [77] from the rural reserve to urban core [78]. Pedestrian walking speed of about 4 km/h is used to calculate the distances between each *GreenSect* cooling node using the 5–15 min maximum walking distance between neighborhood sides. Within a city *GreenSect*, Urban trees lines play an essential element modifying urban microclimate conditions of both new and existing developments especially in arid environments. Furthermore, urban trees possess visual, aesthetical, and psychological adaptation [79], as well as, noise reduction, and air filtering effects [80–82]. Moreover, the main thermal performance advantages of trees are attributed to the radiation interception and evapotranspiration effects that modifies the heat budget of surrounding air and surfaces [26,44,63,83,84]. However, that is why adaptation to climate change considers vegetation as major applications to reducing heat stresses, energy consumption and in turn carbon emissions [18,52,85]. In completion to the green infrastructure, Ayad et al. [86] used a coupled simulations workflow for three combined simulation models; microclimate, building energy and climate change. The author investigated the effect of both green and blue infrastructure (GBI) in present and future climates through the climate change projections of the Fifth Assessment Report (AR5) published by IPCC around Al-Mahmoudya channel in Alexandria, Egypt. ENVI-met, Design Builder and Weather Shift were the methods of the later study which revealed that using BI alone increased energy use efficiency by (8.12%) followed by GBI (6.73%) and GI (4.78%). Increasing the canopy green coverage percentage has a negligible impact on the energy savings. There is a potential of increased energy efficiency of 2.87% appear by using water cover. The usage of GBI, increase the energy efficiency by about 5.14%.

## 5. Methods of Microclimate Research in the Egyptian Context

### 5.1. ENVI-Met and Field Measurements

Evaluation of urban design environmental effects is crucial at the early design stages of urban environment. This approach has been presented by Bruse [68,87], who developed and used ENVI-met for assessing thermal effects in many cases. It should be noted that bigger urban sites necessitate more details when using the numerical methods to differentiate between master plans. In this concern, ENVI-met as a 3D prognostic model is the only tool that assesses human thermal comfort in terms of PMV, the Physiological Equivalent Temperature (PET) [88] and Universal Thermal Climate Index (UTCI), and predict all meteorological and soil-building-plant-air physical properties [26–28,59]. The meteorological and physical data entry of the design day (simulated day) can be derived for ENVI-met from the weather analysis tool of ECOTECT [89], field measurements and from calculations. In completion to the application of ENVI-met, either Energy Plus or Design Builder can be used to couple the outputs with the indoor environment, energy and carbon emission simulations [3,60,90].

ENVI-met is validated by many research studies and proven reliability for many meteorological parameters, [3,91,92]. It has been validated for solar radiation in the work of Toudert [93], and for the RH [59]. In addition, ENVI-met has been combined with field measurements to represent Egyptian urban trees in the vegetation database through the measurements of LAI and Albedo using LAI2200c plant canopy analyzer [70] and the use of two back to back CMP21 high temperature pyranometer manufactured by Kipp & Zonnen [71] as albedometer. In the study of Fahmy et al., to develop UDCM [44], ENVI-met has been validated against both air temperature and the mean radiant temperature. This took place by comparing field measurements and ENVI-met receptor point output at the same field grid, using the Onset HOBO-U30 portable weather station [94] to measure  $T_a$ , RH, and V, while the Heat Stress WBGT globe thermometer measurements [95–98] were used to measure the radiant temperature at the same grid of the receptor placed in ENVI-met Spaces modeling tool. The comparisons indicate statistical confidence both in the ENVI-met meteorological results as well as in the Ladybug tools workflow that can be also applied to calculate PET [99]. In a further improvement for urban simulations, Grasshopper has been developed in association with Ladybug Tools to generate the INX model area file of ENVI-met simulations after reading all model and sub-models data bases including the vegetation but such a valuable connection hasn't been applied in the Egyptian context yet. As a programming environment, Grasshopper is capable of running integrated and compact graphical algorithmic editor for the 3D tool [100], Rhinoceros generates complex 3D models from simple shapes and curves [101] hence is considered a forward step towards sophisticated urban simulations [102].

### 5.2. Assessing Energy Efficiency through Coupling ENVI-Met and Design-Builder

Since the early landmark contributions of Olgyay [103,104], Fanger [105] and Givoni [106,107], the assessment of either the single building scale or the urban environment scale has emerged rapidly due to the fast urbanization and complex interactions between the atmospheric environment and the built environment. However, both scales of fabric; building and urban have been mostly dealt with separately from each other owed to the complexities of field measurements and the incapability of simulation packages to do both jobs in one tool.

Consequently, coupling outdoor-indoor simulation methodology using ENVI-met and the CAD interface, Design Builder of the EnergyPlus tool [108], has been used in the Egyptian context starting from the work of Fahmy et al., [50]. The latter study investigated the effect of urban trees on both pedestrian and occupant thermal comfort in Cairo and concluded a positive effect of trees in terms of PMV reductions. The methodology has been applied again [60,109] to study the influence of greenery (trees, green roofs and walls) in two different climatic zones of Egypt on the energy efficiency in present and under climate change scenarios (2020, 2050 and 2080) using the tool that applied the 4th assessment report morphing methodology of IPCC representative climate pathways, CCWorldWeatherGen [110]. The study revealed that, "in comparison to their un-adapted cases, the least energy efficiency result for

whole site was 10.0% corresponding to 23.8% cost saving at 2080 in case two whereas the maximum was 21.3% corresponding to 35.7% cost savings at present day. Summing energy savings until the end of century, case one payback period was 20 years (in 2037) and case two was 15 years (in 2032)".

A further step using the same methodology is applied in the work of Ayad et al. [111] to study the green and blue infrastructure effects on the energy efficiency in Alexandria in present and under climate change scenarios of the 5<sup>th</sup> assessment report of IPCC [112] using the weather shift tool [113]. Eventually, Abolelata and Sodoudi [75,76] used the same methodology to mitigate UHI in Cairo using trees.

The methodology depends on transferring the meteorological output of ENVI-met urban simulations to modify the weather files used in Design Builder to account for urban details that indoor simulations do not consider such as the evapotranspiration of trees as an example not to mention. The methodology proved reliable outputs and therefore can be considered the second movement of using simulation assessment tools in the process of sustainable design of built environments. Another further step investigates the differences between using the 2003 ETMY data sets in comparison to 2017 data sets but still needs to be related to urban scale rather than only for buildings to consider the urban context effects, [114].

## 6. Urban Microclimate Research Gaps in Egypt

### 6.1. The Need for an Urban Microclimate Design Model

In order to mitigate the lack of connection between climate knowledge and real practice, the UDCM model has been developed after a numerical and optimization workflow to predict land use budget at the early urban design stages while sketching design alternatives on a pedestrian thermal comfort basis as holistic parameter that summarizes built environment and meteorological effects. However, there still a need to enhance such design model approaches through the increased cases that build the sample regression and optimization upon. Furthermore, UDCM has been designed for specific sections within transect of Cairo as mid-latitude site of Egypt not for all the eight climatic regions of the country. On the other hand, despite such models facilitates, speeds the urban form design process and gives passive basis for the urban form which will be a useful tool for urban designers; it needs more insights on the limitations of such models towards a promising code for sustainable neighborhood design.

### 6.2. Neighborhood as a Sustainable Town Planning Unit in Egypt

Neighborhood represents a significant interest to the built environment stakeholders as a crucial planning unit. However, Egyptian governorates are very crowded, overpopulated, and possess a great amount of GHG emissions and heat island effects. Therefore, the government has taken into responsibility to plan new communities. Hence, it is important to construct these communities on a sustainable strategies basis to mitigate the aforementioned impacts. There are three main milestones that can improve the sustainability in the neighborhood scale, which are: (1) heat island mitigation, (2) vegetation and thermal performance, and (3) pavements and microclimates. Vegetation can play a major role in improving the microclimate in several aspects such as acoustics, pollution alleviation, aesthetic values, social issues, and energy saving in buildings achieved by less cooling or heating loads. Moreover, in typical city, pavements cover about 20%–40% of the urban fabric that consist of asphalt and concrete surfaces that possesses high surface temperatures during summer and contribute to the development of urban heat island. Utilizing cool pavements are favored for their increased solar reflectivity, thermal emissivity, and their ability to promote water evaporation. However, reflective pavements are more advantageous because of their ability to reduce the surface and ambient temperatures, decrease CO<sub>2</sub> emissions, reduce smog, increase the illumination and increase durability.

### 6.3. Present Housing Typologies; with or against the Climate Responsive Neighborhood Design?

Due to increase in population that are expected to live in urban areas, as well as, the increase in air temperature because of the changing climate [115], it is crucial to establish an adaptive and responsive thermally efficient built environment by means of implementing passive design strategies at both building and urban scales. At the urban scale, reducing energy consumption in buildings and alleviating the urban canyon temperature is an integration of several passive design strategies such as trees [3,59,60,116], green roofs [69,73,117,118], green walls, and the fabric of local micro-climate scale [44,119–121]. Based on these studies, the energy consumption of the whole examined urban forms and the housing typologies is proposed to be passively reduced through design, and the remaining energy demand can be met by renewable energy systems.

Egypt, as a hot arid zone country, has a unique climate that is favored by high solar energy potential. Therefore, planning and designing urban communities to be compatible with this climatic condition is crucial. There are 2.2 million residential units constructed in the new cities in Egypt. The typologies and character of these housing projects replicated in spite of the variation in geographical locations and corresponding climate. At the urban planning level, most of these constructed communities formed from repetitive freestanding models of apartment blocks. The drawbacks of these urban arrangements are the lack of consideration to the energy efficiency and the mitigating of the microclimate conditions, especially during the hot summer, which can be alleviated by considering; the orientation of the buildings, the outdoor space proportions, the streets and path ways aspect ratio should be logically related to shading and wind speed characteristics, Albedo of the ground-level materials, configuration of greenery. On the other hand, at the building scale or housing typology, energy efficiency was not considered in these constructed buildings which rely on the thickness of the building envelope, the window to wall ratio, roof materials. Therefore, the indoor and outdoor climate are negatively affected in these new communities, making the residents rely on the using air conditioning to achieve their thermal comfort, and making them not prefer to walk when they are outdoor. In which these activity profile of residents increases the energy consumption, depletion of resources, increasing CO<sub>2</sub> emissions and GHG. Hence, well considering the housing typologies and the urban microclimate became substantial aspect, not any more a matter of achieving prosperity and welfare in living conditions.

### 6.4. Limitations of Urban Microclimate Research Methods

#### 6.4.1. Limitations of Simulation Tools

While ENVI-met is regarded as a reliable and validated microclimate simulation tool at early urban design stages, it doesn't support bigger climate scales' simulations with regard to the city and regional scales which can be generated through field measurements in order to either project them in future with consideration to climate change scenarios, downscale them in order to generate recent weather files or couple different climate scales models' generated by them, the work of Li, H., et al., is just an example not to mention [122,123]. On the other hand, microclimate simulation tools have limitations with regard to computational optimization of urban form designs according to environmental conditions. Even after implementing most of its new options in the Grasshopper canvas through Dragonfly plugin [124] to generate required model and simulation files. This connection has two main advantages: (1) significantly reduces time required for modelling and simulation setup processes, especially when investigating several microclimate models. (2) facilitates the ability to import complex and non-traditional building 3D shapes into ENVI-met spaces. However, retrieving simulated readings and generating microclimate maps are executed manually after finishing the simulations. Hence, parametric microclimate and outdoor comfort simulation tools are regarded as the most suitable alternative for urban form optimization process. Yet these tools have their own shortcomings regarding computational power, user experience and the credibility of the simulation outputs.

Regardless the persistent advancements of Ladybug Tools [125], for instance, a single integrated parametric workflow that generates outdoor thermal comfort and microclimate maps from basic inputs - such as meteorological data and model's geometry and materials - has yet come to existence. The workflow introduced by Mackey et al. [126] was validated against ENVI-met results and in-situ measurements for a tree-less actual site in Cairo, Egypt by Elwy et al. [99], incorporates different effectual factors on outdoor thermal comfort that were calculated separately. Location specific wind speed, radiant temperature, and accounting for Urban Heat island (UHI) effect using Urban Weather Generator (UWG) [127] are all separate applications for different tools, which are combined into a simulation workflow by a manual and sequential technique [128].

Another limitation for using such tools is that they do not account for the interaction between vegetation and microclimate, in terms of their evapotranspiration effect on air temperature ( $T_a$ ) and air relative humidity (RH). Trees' canopies could nevertheless be modeled using these tools as shading objects, with a transparency factor according to the percentage of reduction of solar radiation that corresponds to each type of tree. UWG, and its connection tool with Grasshopper, Dragonfly, can estimate vegetation effect on UHI while morphing a rural weather file into an urban one. But this is inconvenient on an urban micro-scale, since it does not provide location specific  $T_a$  and RH variations depending on the effect zones of vegetation or water bodies. On the contrary, this approach produces a single value throughout the whole site to investigate, which are obtained from the resultant weather file. Moreover, taking into account that most of new towns nationwide are deficient in meteorological data. Hereafter, UHI morphing an interpolated weather file using Meteororm software [129] while providing the proposed location as a city would give a deceptive weather data file.

Refraining from the shadow impact of trees on the ground and adjacent buildings' facades, and their wind blockage capability using CFD analyses, some recent software innovations account for vegetation and water bodies much effectively. For example, to demonstrate the significance of evapotranspiration in microclimate simulations, and under the condition of no air movement (wind speed ( $U$ ) = 0 m/s), Nielsen [130] realized an average reduction in UTCI values of about 3.7 °C by comparing the same case study in Abu Dhabi, UAE, with and without including evapotranspiration effect from trees and water. The study was mostly centered on developing an alternative simulation method to be utilized along with Ladybug Tools to create UTCI thermal comfort maps, yet, still lacks to validate its results. On the other hand, Manickathan et al. [131] used OpenFOAM [132] CFD model to investigate the cooling effect of trees, in which the influence of air movement on evapotranspiration-based cooling is highlighted. According to the study, the cooling effect reached its maximum at low wind speeds ( $U < 1$  m/s), and it almost diminished as  $U$  reach high values. The case study was implemented in the city of Zurich, Switzerland, which climate is classified according to Köppen-Geiger [133] as Warm-Fully Humid. Therefore, this approach needs to be calibrated at Egypt's Hot-Arid climate.

Furthermore, another recently developed CFD tool of OpenFOAM that predicts outdoor thermal comfort is the uhiSolver [134]. Developers of this tool introduced it as a set of adjustments that were applied to the existing CFD solver to comprise different physical features for outdoor thermal comfort prediction. Radiative heat fluxes, sun and shadow tracking, evaporative cooling and humidity effect from vegetation, green structures and water bodies are some of the added capabilities of the CFD solver [135]. Being run under the platform of OpenFOAM might give it the potential to be connected via Grasshopper canvas. Additionally, these tools are desirable to come into practice during the early environmental urban form design stages in Egypt, in order to identify its suitability for Egyptian context and figure out their application benefits and shortcomings.

#### 6.4.2. Limitations of Field Measurement Methods

Despite that some few studies took place in the urban climate research in the Egyptian context using field measurements [10], there still a lack in the remote sensing and airborne methods which can be dedicated to thermography, laser scanning and meteorological measurements. It can be argued that funding such methods is an obstacle in spite of the increased knowledge and availability of

importing drones and surveying planes (airborne methods) to Egypt. In future investigations, such approaches can be applied in the UHI research [136], scanning and retrofitting already existing urban forms towards concluding implications for the new urban developments in Egypt.

#### *6.5. Vegetation in the Energy Codes and Green Rating Systems*

Trees Canopies ground Shade coverage (TCS) hasn't been considered as a vital element in the Egyptian building energy code [137] nor in green pyramid rating system [138], the GPRS, or any green rating system. Except for the Singapore Green Mark Rating System, trees are considered but only empirically through a greenery provision term considering the 3D volume of trees in an urban space. To consider such, and to calculate green rating system's credit points and determine the weights of urban trees' ground coverage effects on microclimates which in turn affect indoor environments, a database for the modeling parameters of famous Egyptian urban trees' species have to be established. Such database in terms of LAI and Albedo measurements has to be followed by numerical modeling and simulation for the thermal effects of each tree for the sake of weighing the accreditation of TCS points according to the expected microclimatic amelioration that a tree shading and evapotranspiration can do rather than empirical. The same concept applies to introduce a new chapter in the Egyptian buildings energy code. However, such improvements to the codes and rating systems needs a rigorous research fund dedicated towards supporting the required field measurements devices by urban environmental measurements' labs.

#### *6.6. The Need to Customize a Hot Arid Thermal Comfort Index*

The Egyptian studies used the global thermal indices to assess the thermal performance whether for indoor or outdoor performance such as PET and PMV. Despite, these indices are well documented and include thermo-physiological and meteorological parameters; they limit values thought for special climatic conditions and might not express human comfort for other climatic regions especially with respect to hot arid region as Egypt. Therefore, it should be investigated in term of its applicability in the Egyptian climate context. Such investigations are important to identify regional particularities, and it can be considered an approach to have an adaptive thermal comfort index based on human sensation vote using questionnaire even for the eight climatic zones of the Egyptian map. The later approach has been investigated similarly in the project RUROS [139], where the psychological adaptation played an important role in the formulation of a thermal comfort index in some European cities and new concepts such as stimulating pedestrian to accept higher rates of thermal stresses has been introduced.

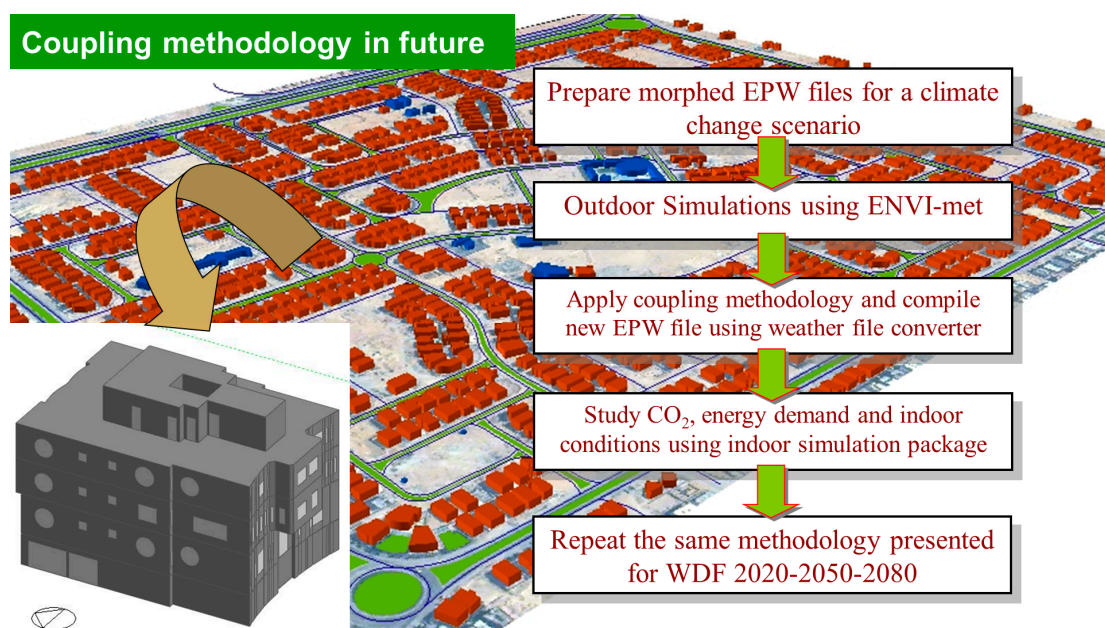
#### *6.7. Integrating Multidisciplinary Sustainable Design Experts Towards the 5th Generation of Egyptian Cities*

Gathering the research line that has been presented through Sections 3–5 of this article for the urban built environment elements in the Egyptian context; fabric, network and vegetation, this section presents a vision for a new ERA of Egyptian housing through the integration of both passive architecture and passive urban design scales that conserves energy, and the triple core mission of ERA can be completed by proposing a renewable system that might be applied both on building envelope and on-site land use. It worth mentioning that ERA is a two parts proposed research project collaboration between multidisciplinary experts and it has been designed in three steps for the sake of a new generation of Egyptian energy efficient housing and resilient cities; (1) It starts in the urban form were a geo-informatics drone assisted surveys and auditing will take place for thermal imagery and meteorological measurements to be used for energy retrofitting of existing housing. (2) It suggest the clustered urban form for medium population (medium and social class housing) which is built on prior findings illustrated in the previous sections of this article; it identified the neighborhood clustered urban form as an appropriate residential archetype. However, a parametric optimization should be used to generate the most suitable building-courtyard relation of cluster geometry according to each climatic zone configuration on the Egyptian map which is the core of the new ERA housing typologies of the project. (3) It focuses on the residential building and its passive cooling techniques according the



Egyptian code for energy efficiency. A whole-building energy simulation will be conducted depending on the urban simulations' outcomes from the first step using coupled simulation methodology. (4) The fourth step incorporates the possible solutions for introducing PV systems into the building envelope as an integrated building active-passive design. ERA has a tripling evaluation methodology (TEM) that explores the impact of neighborhood configurations have on urban microclimate conditions, and in turn on urban housing energy efficiency, considering also the improvements of urban form that may affect the PV/envelope system. ERA suggests considering the climate change scenarios to adapt its generated housing for future. ERA project proposal is still under development and didn't have results yet.

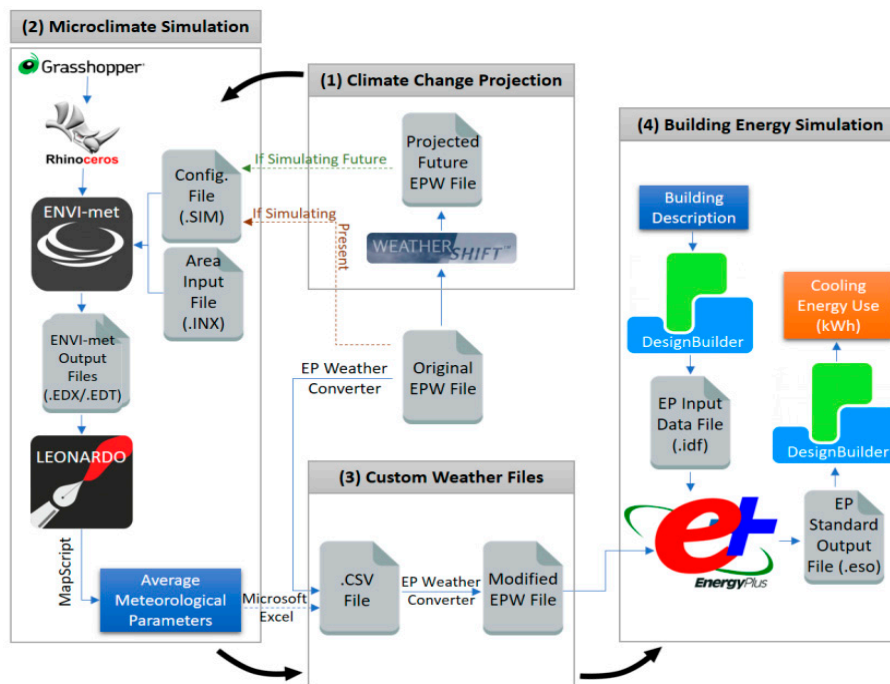
Figures 6–9 summarize and show the connection between the methods reviewed in this article and how ERA can introduce what can be called the 5th generation of Egyptian sustainable cities knowing that the 1st generation of new cities developments started with the 15th of May and 10th of October cities five decades ago [140].



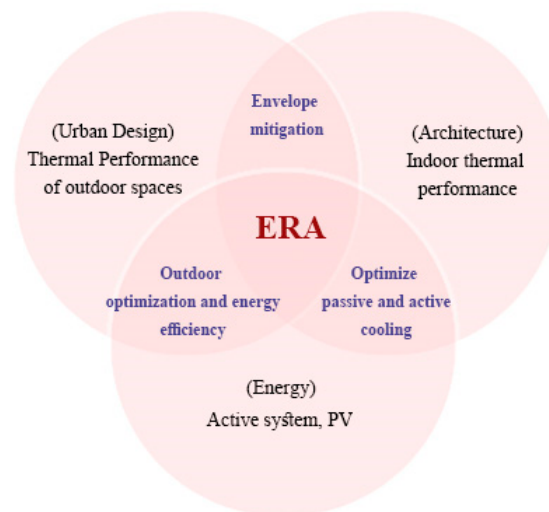
**Figure 6.** The coupled simulation methodology in present and future as a baseline for ERA Tripling Evaluation Methodology, TEM, modified after [37].

The connection between the aforementioned methods and the 5th generation can be explained as the original coupling urban-building simulation methodology (Figure 6) has been modified by adding grasshopper optimization of the clustered urban form for different climate zones (Figure 7), then the urban-building dimensions has been extended to include the third pillar of ERA project, energy, (Figure 8). Finally, the dominant concerns of ERA pillars have to be evaluated through the tripling methodology (Figure 9).

It worth mentioning that in the 1970s, Cairo plans were drawn up with satellite cities around it. The construction of 10th of Ramadan city, an industrial city, was the first generation experimental new city to take place. 2nd generation examples include Sheikh Zayed City, whereas New Cairo represents the 3rd generation which moved away from the working-class cities to form new communities for the privileged high income class, [140]. The new cities housing strategy remained vehicular oriented urban development that applies typical repetitive designs in different Egyptian regions discarding the different climate conditions. Today the New Urban Communities Authority (NUCA) has promising plans for the 4<sup>th</sup> generation but kept new cities such as New Mansoura and New Alamain without in-depth responsive design to climate despite the different climate zones on the map, Figure 10.

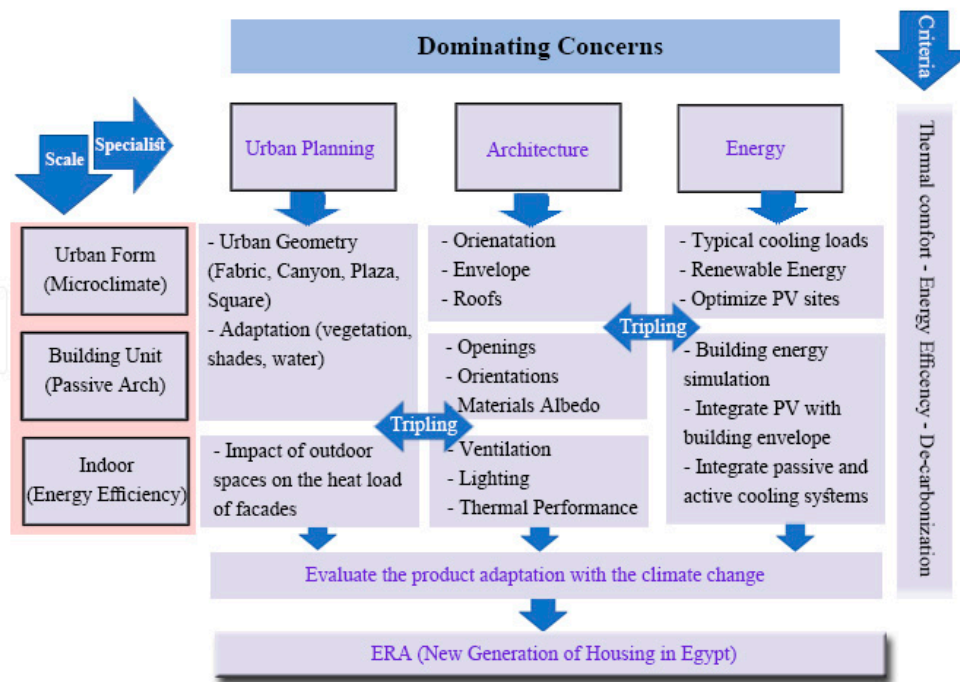


**Figure 7.** Software cycling of ERA core starts with modifying the original coupled urban-building simulation with grasshopper parametric optimizations of the urban cluster baseline for the different climatic zones on the Egyptian map, modified after [60,86].



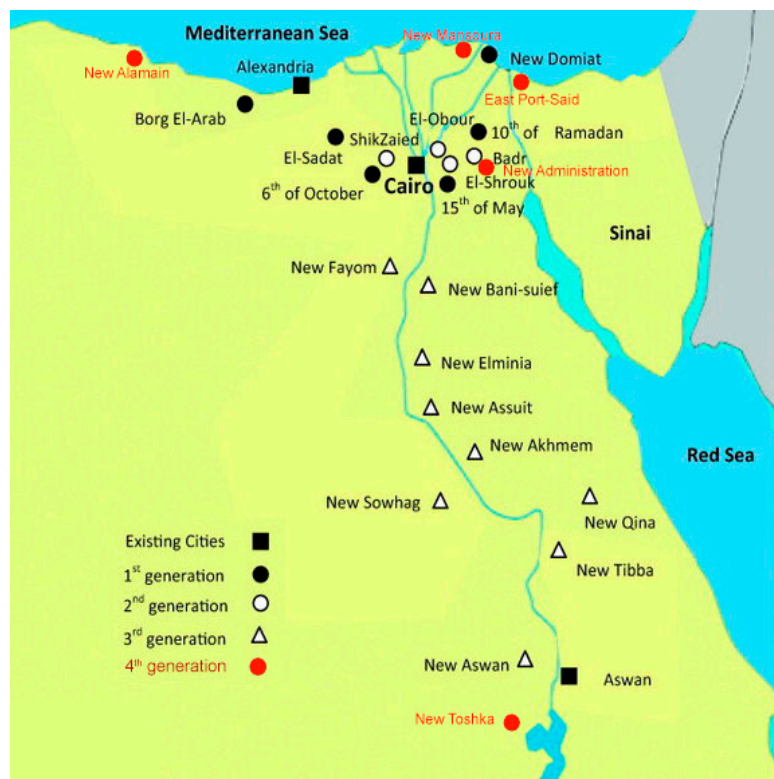
**Figure 8.** ERA Tripling Evaluation Methodology, TEM.

Furthermore, the point is not only a physical design of the urban form, the application of such fabric that generates the linear/clustered semi-attached housing typologies has to be accompanied with a development in the construction legislations that necessitates the urban designer to stop at the step of planning a residential zones within neighborhoods rather than designing the housing linear/clustered housing itself. The fixed concepts of executive plans that oblige setbacks for a residential building from the four sides of lots which generates the dot housing patterns have to be improved to an urban microclimate-passive housing linear/clustered oriented concept. In addition, this facilitates Building Integrated PV system, BIPV in which the PV panels are adapted and integrated with building envelope architecture form, [141].

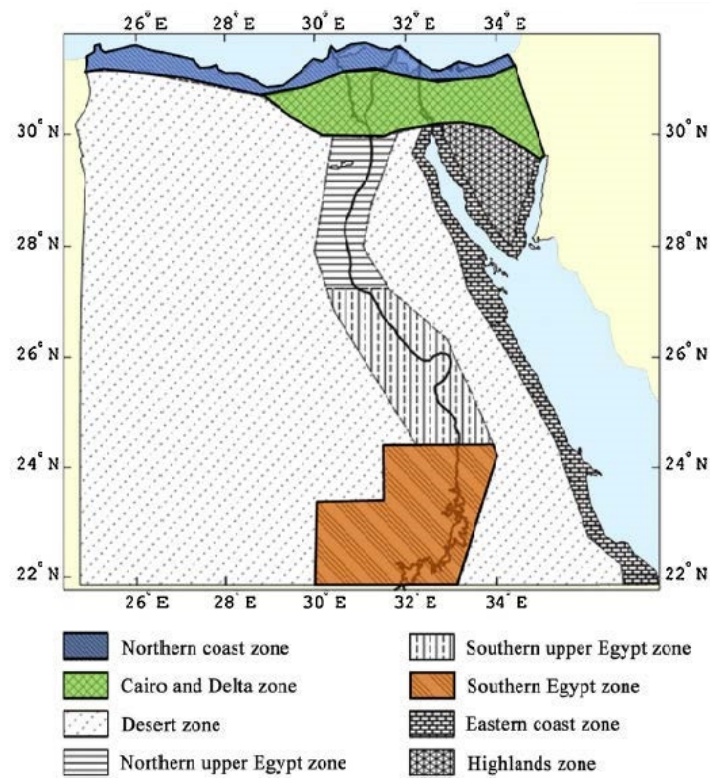


**Figure 9.** ERA dominating concerns that have to be evaluated by the Tripling Evaluation Methodology, TEM, to integrate the Urban-Building-Renewables dimensions, UBR.

Therefore, a call for the 5th generation of Egyptian cities can be raised from this review article based on the integration of an Urban microclimate basis to generate linear/clustered fabric, Building passive design that generate envelope, along with Renewables, such integration can be abbreviated as UBR., Furthermore, despite the fact the two examples presented in Figure 11a,b are from different climate regions and conditions, they still represent a successful example for 2 dimensions of UBR, housing environmental and BIPV design, which is not part of the housing typologies design process in Egypt. Moreover, it gives a positive indication for how UBR can be disseminated over the different eight climate zones of Egypt. On the other hand; Figure 12a,b represent examples of the newly constructed housing in New Asyut and 10th of Ramadan cities as part of the efforts of the national mega project of social class that ERA target to improve. It is proposed that UBR considers the microclimatic basis to guide optimizing the geometrical adjustments of urban form design practice and generating specific clustered housing typology for each climate zone rather than the common typical multi story apartment buildings. In this concern, the majority of the inhabited locations in Egypt has climate that is either hot and humid or hot and arid. Moreover, most of the regions in Egypt are favored by high solar energy potential. Therefore, as the population has grown beyond the 100 million; planning and designing urban communities to be compatible with these climatic conditions become crucial. The legislation has to comply with the requirements of the 21st century and its major environmental challenge, climate change, not only to construct to accommodate, in another word; a city sustainable design code has to emerge having UBR and TEM as a core. From this standing point, improvements of energy efficiency and de-carbonization of housing environment will contribute to the submission of the second National Determinant Contribution, NDC of Egypt commitments to the United Nations Framework Convention on Climate Change, UNFCCC, and Paris Agreement and facilitate Egypt sustainable development vision 2030. The UNFCCC and Paris agreement are a mankind contributions to the global environmental safety of human future on earth through which, both developed countries (Annex I countries of UNFCCC) and developing countries (Annex II countries of UNFCCC) can fulfill this safety by their de-carbonization projects either in terms of mitigation or adaptation plans [142,143].



(a)



(b)

**Figure 10.** (a) Generations of New Cities in Egypt since 1970s, modified after (Hegazy and Moustafa 2013) [140]. (b) different climatic zones in Egypt, [137], (North is up and scale is to fit).



(a)



(b)

**Figure 11.** (a) The energy plus solar housing settlement at Freiburg by ROLF DISCH, Germany, [144].  
(b) Beddington Zero Energy Development (BedZED), London, UK, [145].



(a)

**Figure 12.** *Cont.*



(b)

**Figure 12.** (a) Social housing in New Asyut, the same typology as in 12b [146]. (b) Social housing in 10th of Ramadan city [146].

The above mentioned vision needs an integrated multidisciplinary specialists' team formation in order to undergo such ambitious project, there is a lack of an Egyptian platform or a hub that initiates research collaboration and uses the resources of the academia and industry rigorously in this area of research.

## 7. Conclusions

Due to the climate change and the rapidly growing population density in Egypt, it is necessary to pay more attention to the urban microclimate and its related housing strategies, typologies and research studies. Egyptian studies that addressed the urban microclimate and the thermal performance of outdoor spaces emerged early in the 21st century for the sake of filling the urban form design gap towards sustainable and resilient built environment; in this concern; a research line can be noticed out of those studies, but we need to ask what did they achieve? and what are the weaknesses? For that, this study highlighted and reviewed the Egyptian studies on the impact of urban pattern and adaptation strategies on outdoor thermal performance and on the indoor energy efficiency.

In last eleven years, despite the number of researches which specifically concentrate on assessing outdoor spaces are few, the Egyptian studies could achieve distinguished results in term of adjusting fabric, green infra and coupling the evaluation with introducing valuable recommendations. However, it is crucial to develop a comprehensive vision using this knowledge, focus on more details, locations and different climate zones of Egypt, and develop a framework stepping forward towards a national future vision and a new era of housing projects in Egypt to cope with the sustainability vision of Egypt 2030. Design implications can be summarized in terms of an optimized clustered urban fabric on a specific climate conditions basis along with selected vegetation species and adjusted trees ground coverage and spacing.

Furthermore, the study suggested the Tripling Evaluation Methodology (TEM) which represents an upgrade for the coupling simulation methodology that has been introduced in an Egyptian study. TEM methodology facilitates a comprehensive vision for the future studies and applications of Urban-Building-Renewables (UBR), dimensions towards a new era of energy efficient Egyptian housing typologies as part of a 5th generation of Egyptian sustainable cities. Such housing environment vision can contribute to both mitigation and adaptation plans through de-carbonization which in turn contribute to the submission of the second Egyptian NDC to UNFCCC. Moreover, a code for sustainable cities design having UBR and TEM as a core has to emerge. Nevertheless, no doubt that fund limits

the usage of advanced field measurements such as remote sensing and airborne methods in urban climate research in compliance with simulation to validate and integrate the Egyptian multidisciplinary fields to contribute to sustainable urban development practices, a design code for it to adapt future communities for the adverse impacts of climate change.

**Author Contributions:** M.F.: Article’s initiator, corresponding author, urban-building research line designer, contributor and initiator of the 5th generation of Egyptian sustainable cities idea and expression, PI of the two parts research project proposal ERA, gathering literature, defining methodology, contributing to several sections, writing and formatting of the manuscript, responses to and discussions with reviewers. S.M.: data gathering, contributing to several sections, writing and formatting of the article. I.E.: data gathering, contributing to several sections, writing and formatting of the article. H.M.: data gathering, defining methodology, contributing to several sections, writing and formatting of the article. All authors have read and agreed to the published version of the manuscript.

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