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Article

Designing for comfort: The application of landscape elements in microclimate regulation and staff productivity

Jiadai Tang[1,2], Nafisa Binti Hosni[3], Wan Yusryzal Bin Wan Ibrahim[1,*]

[1] Department of Landscape Architecture, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
[2] Infrastructure Department & Office of New Campus Construction, Jiangsu University of Technology, Changzhou 213001, China
[3] Department of Landscape Architecture, Faculty Built Environment and Surveying, UTM 81310, Malaysia
*** Corresponding author:** Wan Yusryzal Bin Wan Ibrahim, wyusryzal@utm.my

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Abstract: The paper presents a quantitative study analyzing how Classical Chinese Gardens (CCGs) have the capacity to regulate the microclimate and the potential effects on the productivity of staff through the Humble Administrator Garden at Suzhou. The study uses a combination of field measurements and Ordinary Least Squares (OLS) regression analysis to determine the effect of important landscape features, such as vegetation, water bodies, architecture, pathways, and corridors, on vital microclimate attributes, such as the air temperature, surface temperature, wind speed, and relative humidity. The study results show that vegetation has a strong cooling effect (β =0.875), humidity control effect (β = 0.250) and all water bodies have a strong cooling effect (β = 0.875) but a weak warming effect (β = 0.125) and Buildings and hard surfaces have a strong cooling effect (β = 0.875) and a weak effect (β = −0.008) of reducing the wind speeds and surface temperatures in corridors, respectively. Among them, trees would offer the best cooling (score 5), grasslands would do the best at controlling the humidity and wind speed (score 5), and water bodies would also contribute to the humidity regulation (score 4) significantly. Combining these results with an existing scheme of thermal sensation and work efficiency, the paper demonstrates the capacity of the microclimate changes to be applied to cognitive functioning and productivity. The study reveals practical recommendations in implementing the traditional Chinese garden design framework to the modern urban space and workspace setting, and presents approaches to enhancing the environmental sustainability, the thermal comfort and finally, the well-being of the staff and their productivity.

Keywords: employee productivity; microclimate; office environment design; classical garden wisdom; human resource management; workplace well-being

1. Introduction

As an architectural and ecological tradition, Classical Chinese Gardens (CCGs) are deeply founded on the ideological human nature of the balance and harmony principle. These gardens have originated in the Ming and Qing dynasties and are additionally created to enrich aesthetics and spiritual experience and as microclimate refuges that are able to amplify thermal comfort due to the spatial strategic planning [1,2]. The combination of water, vegetation, architecture, and topography proves the implicit knowledge of the modulation of the environment long before the appearance of modern climatology. The arrangement of CCGs follows the concept of "nature and man in one," which entails the compatibility between man and his environment.

The current research has highlighted the importance of studying how the traditional landscape compositions can be used to guide present-day climate-resistant urban designs [3,4] Controlling microclimates has become one of the most crucial functions of an urban green cover, and both vegetation and water features have been mentioned as important in the reduction of heat stress and a positive change in the quality of the environment [5–7]. Furthermore, anthropogenic structures make a difference in the way wind moves and heats, which is crucial to define local climates [8].

For a long time, while striving for high work efficiency, people have often overlooked the importance of indoor environmental quality. Building codes and standards that define indoor environmental quality parameters based on minimum requirements have been used to design and operate buildings, with the aim of creating healthy, comfortable, and efficient work environments. It is noteworthy that many of these standards are designed to protect personnel from substantial physical harm. Compared to physiological responses, the human central nervous system is more sensitive to external stimuli, making work efficiency more susceptible to environmental factors [9,10]. Prolonged exposure to conditions that push workers to the brink of physiological limits is detrimental to both health and productivity. Therefore, ensuring accurate and efficient work performance should be the primary standard for contemporary workplace design and operation [11,12].

The design practices that can be identified in the traditional East Asian gardens are being considered in the modern ecological discourse of the urban context as they entailed an in-depth understanding of the passive control of climatic conditions through space organization and choice of materials of composition [13]. Scholarly articles on the history of CCGs lack empirical studies that quantitatively identify the microclimatic performance and staff productivity using a spatially explicit model. The present paper closes this gap by applying OLS regression to assess the effects of features of the landscape on the microclimate conditions in a high-profile garden; And by using the quantitative relation of thermal sensation and work effectiveness presented by Seppänen et al. [14], the influence of green landscape-modified microclimates on employee productivity could be identified. Combining field measurements with spatial modelling allowed closing the gap between the classical design theory and the current quantitative analysis.

2. Materials and methods

2.1. Study site

As shown in **Figure 1**, the study site is the Humble Administrator's Garden, which is situated in the northern part of Suzhou's ancient city, adjacent to residential areas and historic waterways. The garden has a strong association to the ancient canal channel of Suzhou, which was a greater canal infrastructure of the Grand Canal. These waterways are part and parcel of the city and it is very important in water management and beauty of the garden. **Figure 2** illustrates the layout plan of the Humble Administrator’s Garden, which spans approximately 52,000 square meters. Its spatial design integrates water features, plantings, architecture, and open spaces.

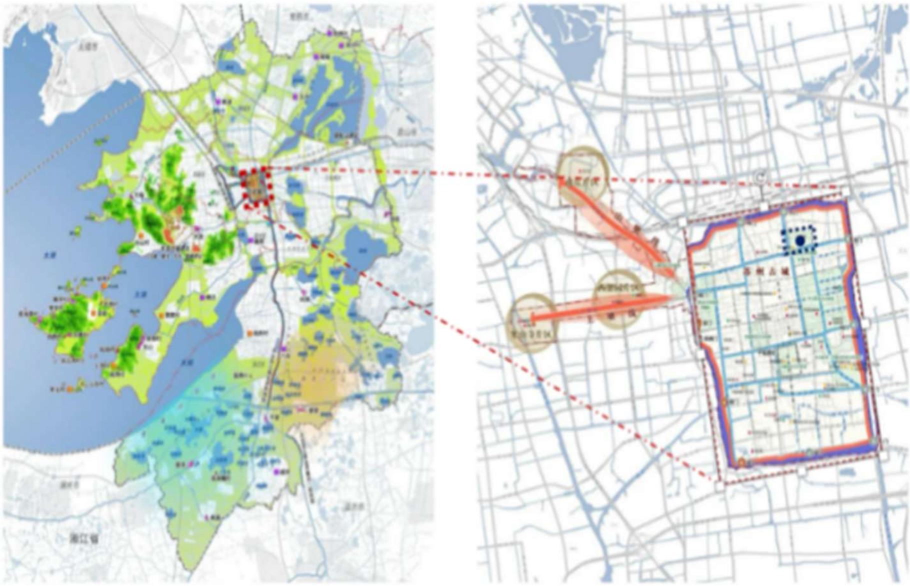


Figure 1. Location of the Humble Administrator's Garden.

Figure 2. Plan of the Humble Administrator's Garden.

2.2. Data collection and processing

Microclimate or climatic scales, including air temperature, surface temperature, wind speed and the relative humidity were sampled by a mix of field data and OLS interpolation over a square grid of 10m × 10m (**Figure 3**). On the 22 July 2024 to 10 August 2024, the average climate data were measured in the microclimate stations throughout the garden. The ArcGIS was used to digitize the features of the landscape and classify them into seven categories of features including plant cover, grass, architecture, pathways, corridors, rocks, and water bodies.

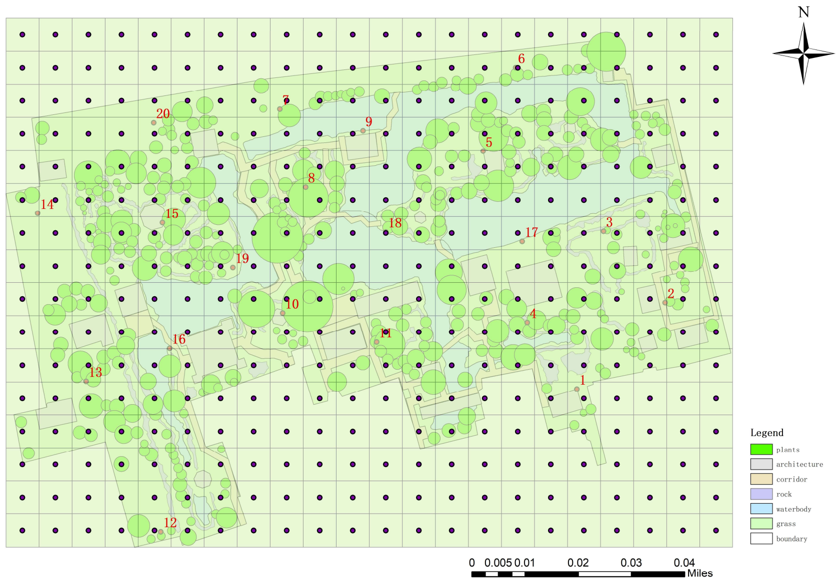


Figure 3. Grid and stations in the humble administrator's garden.

2.3. A unified model indicating the mechanisms of indoor environmental effects on human productivity

Figure 4 illustrates the proposed mechanism model for the impact of indoor environmental quality on personnel work efficiency. This model promotes the theoretical foundation of the systematic and logical assessment of efficiency of personnel work. Subjective perceptual responses refer to the perceptions concerning the quality of the environment, enthusiasm in the workplace and symptoms of sick building syndrome. Physiological measurements involve neurophysiological features that exemplify the presence of thermoregulation, brain activity, and health condition in a human being. Ultimately, the performance revealed in the results of information processing is reflected in the working performance. The following sections provide detailed explanations of these three factors.

Under the intricate interaction between individuals and indoor environment, one of the long-standing research interests has been the perceptions or subjective ratings of the work places by individuals. This is because people subconsciously and continuously assess their surroundings, which influences their mood, work attitude, and ultimately impacts their job performance and overall efficiency. As a psychological state, Work motivation refers to the internal and external forces that stimulate behaviors related to work performance, determining their form, direction, intensity, and duration, such as psychological incentives and enthusiasm for work. Without enthusiasm, even highly capable individuals will not achieve high efficiency. Emotions also warrant examination. Emotions alert the cognitive system to the friendliness of the external environment, and intense or negative emotions can reduce work efficiency through the following pathways [15]: (1) Disrupting state regulation, causing cognitive overreaction that hinders performance improvement; (2) Directly interfering with task information processing; (3) Generating psychological complaints that divert attention from work. In stressful environments, people's emotions can be affected. The performance of tasks is determined by the extent of put in effort and this measure encompasses the magnitude of the exertion and the tactical adaptations coupled with additional concerns relating to whether the overdependence on environmental discomfort is disruptive of the information processing process. Health and comfort refer to personnel's psychological and physiological well-being, physical comfort, and subjective satisfaction with the environment. Illnesses caused by indoor environmental quality, commonly known as Sick Building Syndrome (SBS), include: (1) Respiratory disorders, which include throat discomfort, dry mouth, hoarseness, and wheezing; (2) Skin conditions, such as dry skin, rashes, and itching; (3) Neurological, which include headaches and dizziness, drowsiness, reduced cognitive ability, lack of concentration, fatigue, and forgetfulness; (4) Nasal disorders, including nasal congestion, runny nose, eye irritation, and asthma symptoms; and (5) Complaints regarding unpleasant odors in the air. The pathways through which indoor environments affect occupants' perceptions have not yet been comprehensively examined. Nonetheless, the major part of the research literature has a similar vision, as the occupants usually report such symptoms in the working hours, and it should be associated with the quality of the work environment to which workers are regularly exposed on the long-term basis. There is significant evidence that it might be one of the leading factors contributing to symptoms of sick building syndrome attracting quantifiable physiological reactions, which are caused by poor indoor environmental quality.

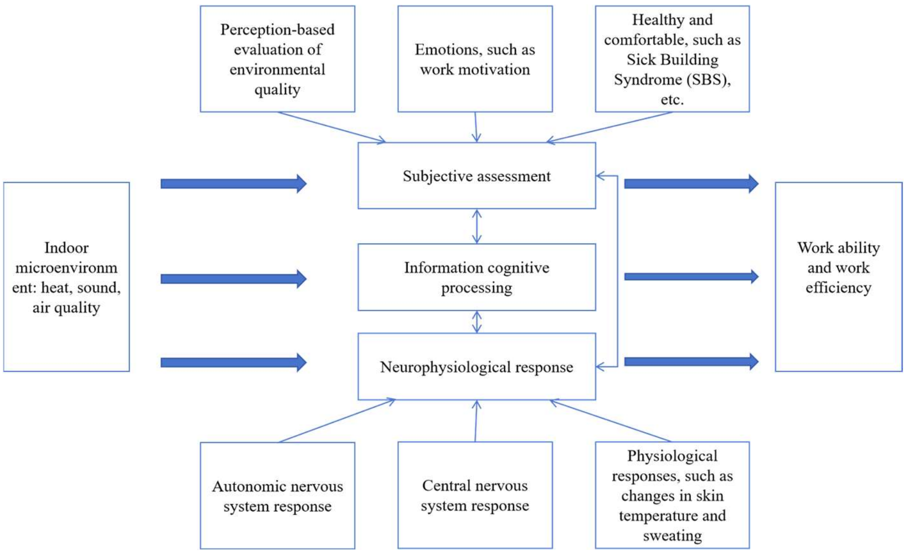


Figure 4. A unified model indicating the mechanisms of indoor environmental effects on human productivity.

2.4. Statistical analysis

To complete the analysis, Ordinary Least Square (OLS) is used to estimate the parameters of a linear regression model. The dependent variables are microclimate variables, while the independent variables are potential influencing factors. The analysis can help in understanding how different factors contribute to the microclimate and in predicting microclimate conditions in unsampled areas of the park. To specify the OLS model, the model temperature as a function of vegetation cover, elevation, and proximity to water:

Temperature = $\beta0 + \beta1$·Vegetation + $\beta2$·Elevation + $\beta3$·roximity to Water + ϵ.

Diagnostic tests confirmed the assumptions of linearity, independence, homoscedasticity, and normality. To perform the regression, use GIS software and input the data then fit the OLS regression model. The program will approximate the coefficients (β) and give the measures of the statistical significance of these coefficients in the form of the R-squared value and the *p*-values. The fitted model can predict microclimate conditions at unsampled locations in the park. Test the predictions of the model by comparing their predictions with more observed data. It is possible to validate the model by comparing its predictions to extra considered data and produce a GIS map to illustrate the predicted microclimate throughout the park.

3. Results

Based on the OLS results in the Humble Administrator's Garden, each landscape feature has a distinct impact on the garden's microclimate (**Table 1**). The coefficient of the corridors is −0.250, which means that the existence of the corridors in the garden is relatively associated with the slight decline in optimal air temperature, which can be attributed to the amplified airflow and exposure to wind in the corridors. Corridors result in a reduction of average air temperature (β = −1.250). This result will support the idea that open and unsaturated spaces like hallways tend to be cooler because it has natural ventilation and is naturally exposed to the wind, capturing heat inside surfaces to a certain extent (the coefficient of maximum surface temperature = 0.375; the coefficient of mean surface temperature = 0.000). The coefficient (β = 0.375) of maximum surface temperature is positive, indicating that corridors have a minor effect on the upper limit of surface temperature. The coefficient for mean surface temperature is 0.000 (neutral), signifying that corridors exert no substantial influence on the average surface temperature of the garden. The impact of the wind can be used against solar heating. The research has shown that the factors of maximum wind speed (β = −0.006) and the average wind speed (β = −0.008) have negative relationships with corridor areas and thus indicate that corridors can slightly slow down wind speeds. This loss can be explained by the fact that boundary structures are an impediment to airflow even though such spaces are fairly open. And maximum relative humidity (β = −1.000) and average relative humidity (β = −0.500) show the negative correlation with the areas of the corridors meaning that the corridors help to decrease the air humidity. This can be connected with the increased airflow, the movement of which prevents the formation of moisture in air.

Table 1. OLS result of Humble Administrator's Garden.

Landscape features	Corridor	Grass	Pathway	Architecture	Rocks	Tree	Water
Maximum air temp	−0.250 (Negative)	−0.250 (Negative)	0.125 (Positive)	0.125 (Positive)	0.125 (Positive)	0.000 (Neutral)	0.125 (Positive)
Mean air temp	−1.250 (Negative)	−1.250 (Negative)	−0.750 (Negative)	−0.875 (Negative)	−1.000 (Negative)	−0.875 (Negative)	−0.875 (Negative)
Maximum surface temp	0.375 (Positive)	0.375 (Positive)	0.750 (Positive)	0.875 (Positive)	0.750 (Positive)	0.625 (Positive)	0.625 (Positive)

Table 1. *(Continued*).

Landscape features	Corridor	Grass	Pathway	Architecture	Rocks	Tree	Water
Mean surface temp	0.000000 (Neutral)	0.125 (Positive)	0.375 (Positive)	0.375 (Positive)	0.250 (Positive)	0.250 (Positive)	0.375 (Positive)
Maximum wind velocity	−0.006 (Negative)	−0.007 (Negative)	−0.003 (Negative)	−0.004 (Negative)	−0.006 (Negative)	−0.003 (Negative)	−0.003 (Negative)
Mean wind velocity	−0.008 (Negative)	−0.006 (Negative)	0.000000 (Neutral)	−0.002 (Negative)	−0.002 (Negative)	−0.004 (Negative)	−0.002 (Negative)
Maximum relative humidity	−1.000 (Negative)	−1.000 (Negative)	−0.500 (Negative)	−0.750 (Negative)	−0.750 (Negative)	−0.500 (Negative)	−0.500 (Negative)
Mean relative humidity	−0.500 (Negative)	−0.250 (Negative)	0.500 (Positive)	0.250 (Positive)	0.250 (Positive)	0.250 (Positive)	0.250 (Positive)

There is a small decrease in the maximum air temperature (β = −0.250) in the connection of grass areas, which demonstrates that grass also regulates the temperature a little, providing some form of shade and moisture preservation. Grass also contributes to a cooling effect on the mean air temperature (β = −1.250). This has been can attributed to cooling impacts of transpiration and evaporation of grassy surfaces which reduce the average temperature of air over time. The coefficient for maximum surface temperature is 0.375 (positive), demonstrating that grass areas are associated to a modest rise in surface temperature. Nonetheless, this effect might be more significant under drier climatic conditions when grass areas have less moisture to be evaporated (β = 0.125), presumably because of solar gain and insulation properties of grass in direct sunlight despite its cooling effects of water evaporation. There is a negative effect of grass area effect on the maximum wind velocity (β = −0.007) and mean wind velocity (β = −0.006), suggesting that grass plays a significant role in down-playing the velocity of the wind, causing it to move slowly across the surface, and blocking the way of the wind. On the other hand, the humidity mean over the surface (β = −0.250) reflects an increase, which is comparatively less; resistant to the surface velocity.

Pathways are positively related to the rise of the maximum air temperature (β = 0.125), which might be owed to the heating capability of hard surfaces that absorb and release heat into the surrounding air particularly in open grounds. Pathways thus increase the average air temperature (β = −0.750), because of the heat storage capacity of materials of rigid surfaces which store and lose heat over period of time, increasing the average temperature. Pathways contribute to a minor rise in maximum surface temperature (β = 0.750) and this is probably because the stiff construction materials, stone or concrete, absorb and release heat directly to the earth through solar heat. The pathways show a slight increase in mean surface value of temperature (β = 0.375) since the amount of heat trapped by the pavings will cumulatively increase the overall surface temperature in the garden. The pathways have a negative impact on the velocity of the wind (β = −0.003) implying that walkways do not extremely obstruct wind velocity, but could still cause a slight decrease in wind speed in open spaces due to no vegetation or impediments. The path directions cause a negative change in the maximum humidity (β = −0.750) and a small positive change in the mean humidity (β = 0.250) and maybe due to the evaporation of nearby surfaces which partly increase the total atmospheric moisture.

Architecture positively influences both maximum and mean air temperature (β = 0.125 for each). The walls, structures, or pavilions used in architecture absorb the heat and after that they emit it back to the atmosphere leading to an increase in the air temperatures in the vicinity of the structures. This is enabled by the heat storage capacity of materials of building materials such as stone or brick which absorb heat during the day and turn out at night. Architecture has a strong impact on the temperature of surfaces (β = 0.875) with the surfaces on the buildings (rigid) and the covered area (paved) absorbing and emitting heat. Naked surfaces like walls and ceilings enhance surface heating, which increases the temperature around the building. Some shade can be achieved through the use of architectural features and, as a result, this problem is relieved, but in most cases, building will increase the surface temperature in open spaces. Architecture has a negative effect on wind speed (β = −0.004), meaning that pavilion, building, and walls are used to shield the garden against wind to make closed areas with a reduced influx of air. The elements of architecture that are used as windbreaks create calm and comfortable conditions in the garden. Humidity is usually reduced by architecture since rigid surfaces and built structures do not aid through an important effect the moisture release. There are negative effects of architectural elements, such as discouraging evaporation of nearby vegetation; however, they also reduce the total humidity levels, by blocking airflow and evapotranspiration.

The correlation between rocks and a rise in maximum air temperature is positive (β = 0.125), and it indicates that rocks absorb the heat during the day and then release it into the air. The negative dependency on mean air temperature (β = −1.000) tends to indicate that there is a possibility that rocks are slightly increasing average air temperatures, particularly during the nighttime when rocks can radiate all the heat accumulated. Rocks share thermodynamic characteristics with the other surfaces since the rocks contain heat and reflect radiation during the day, which traps heat. The presence of rocks causes a minimal rise in average surface temperature (β = 0.250), because the thermal bulk of the rocks causes massive variations on the surface temperature. Rocks have a negative effect on the speed of wind, (β = −0.003) maybe because the velocity of the wind is affected in some way by rocks and is diverted around these rocks. The effects of rocks on maximum humidity (β = −0.500) and mean humidity (β = 0.250) are negative and positive respectively, which implies that rocks can conserve the humidity through evaporation of moisture trapped within rock structures.

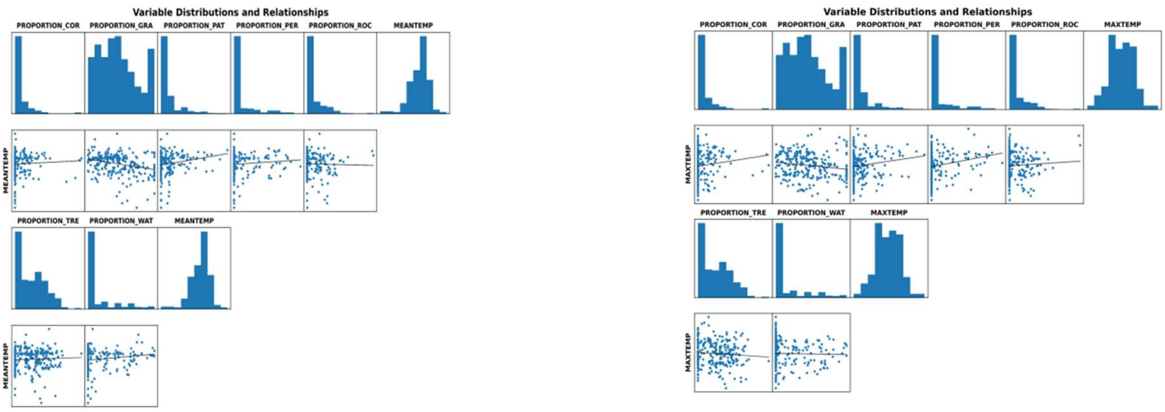
There is insignificant neutral effect association of trees on peak air temperature (β = 0.000). Although tree covers the garden, the effect of this is not much to cause any significant changes in the maximum air temperature in the garden. Trees reduce the mean air temperature (β= −0.875), probably because through transpiration and shadow, trees cool and therefore reduce the average temperatures. Trees lower the surface temperatures (β = 0.625) through the therapy of shades and reduction of direct sunlight access on garden lands. Similarly, the trees have mid-range cooling impact on average surface temperature (β = 0.250) by decreasing variation in temperature owing to uniform shadowing. Trees are associated with a negative correlation on the velocity of the wind (β = −0.004) as they serve as a windbreak at the expense of wind flow in the shadowed regions, and a neutral correlation with the increase in the mean humidity (β = 0.250) owing to transpiration; however, the tree cover gives a minimal link to the augmentation of the maximum humidity (β = −0.500) since trees modulate the temperature and humidity in the atmosphere.

The coefficient on waterbody is 0.125 (positive), indicates moderate increase in the maximum temperature of air in the regions that have high water features. This shows that water bodies, which would be expected to reduce the ambient air temperature, in this case have the ability to cause a slight warming effect. This could be due to the amount of exposure to the sun on the water surface or the size of the water and its location compared to the other features in the garden. The waterbody is also associated with a slight increase in the mean air temperature (β = −0.875). Even though the rule of thumb is that a body of water cools the air through evaporation, the relative insignificance in terms of the coefficient suggests that the cooling effect of water could be limited possibly with other components within the garden. The effect of water bodies on air temperature can be more complex, which depends on such factors as the size of the water body, and the surrounding vegetation. The maximum surface temperature coefficient is positive (β = 0.625) meaning that water bodies are a contributory factor to slightly high surface temperature. Even though it could be expected that water cools down surfaces, this positive association could explain the thermodynamic processes of water as evaporation cools the surrounding air but warms up the surrounding surfaces especially in smaller or less-shaded sources of water.

The waterbody positively influences the mean surface temperature (β = 0.375). This fact confirms the idea that water is able to cool the surface temperatures because it can be seen as a heat sink that cleanses the heat in the daytime and releases the heat slowly. This effect can be particularly apparent in water features that are in the direct sunlight, in which case the temperature of the water and its immediate surround could be elevated over long periods. Both mean and maximum wind velocity are affected marginally by the presence of water bodies with coefficients of −0.002 and −0.003 respectively with a showing of marginally negative impact on the wind speed. The occurrence of a waterbody is associated with a decreased maximum relative humidity (β = −0.500), and slight increase in mean relative humidity (β = 0.250). The negative effect on the peak humidity can be attributed to the process of evaporation, where water bodies could be used in evaporating moisture; however, this could not have a significant effect on the peak humidity in the garden. The positive effect on means humidity points out that the evaporation of water bodies helps to increase the average humidity of the surrounding area and increase the level of humidity in the area near water.

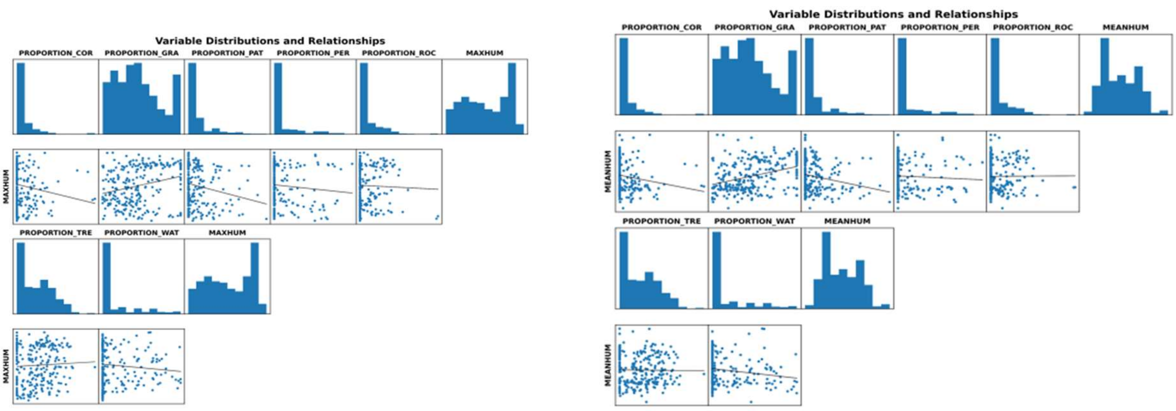
The comparison of the features of landscape and correlation between landscape features and the micro climate variables in the Garden at Humble Administrator provides substantial information about the impacts of landscape design on the environmental conditions of the garden (**Figures 5–8**).

The regression analysis demonstrated that water bodies play a crucial role in moderating temperature by lowering air temperature and increasing humidity while reducing wind velocity. This cooling effect is in line with the convention of water effects in Chinese gardens whereby water is visually attractive and helps in controlling the microclimate to bring comfort towards the environment. The presence of plant cover was observed to play a dual role whereby the cover brings down the highest air temperatures. It enhances humidity especially by way of shade and transpiration although it may result in the higher surface temperatures through heat trapping within dense plants. Conversely, open spaces also tend to increase surface temperatures although it is likely to cool a mean air temperature because of the enhanced air movement. The existence of architectural structures, including walls, pavilions and walkways, greatly decrease the wind speed resulting in shielded micro climatic settings that promote thermal relaxation. In general, the paper illuminates the significance of combining water bodies, plant cover, open spaces, and architectural spaces in the design of gardens to maximize microclimate conditions and equal aesthetic beauty, comforting and green designs. Such results characterize the prospects of landscape design as the approach to the increase of the environmental quality and orchestration of the visitor experience in the traditional and contemporary garden areas.



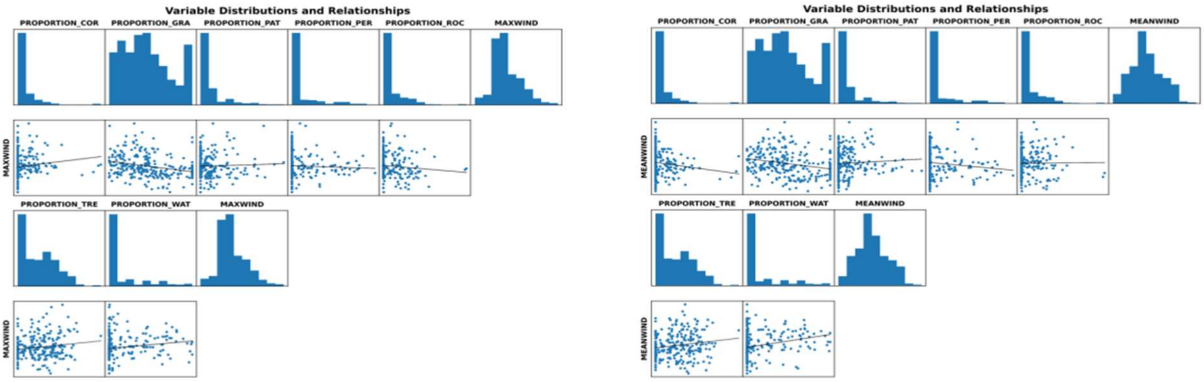
(a) **(b)**

Figure 5. Relationships between landscape features and air temperature. **(a)** Mean air temperature response to landscape features, **(b)** Maximum air temperature response to landscape features.



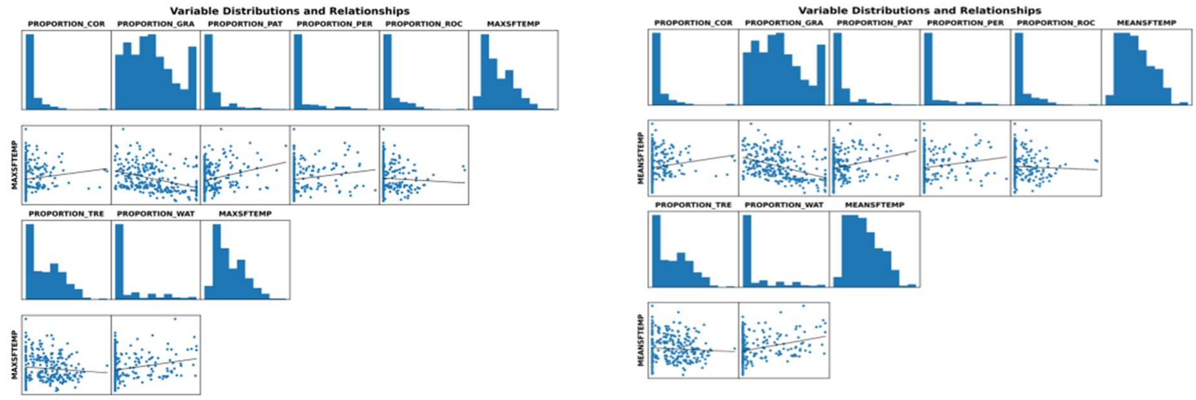
(a) **(b)**

Figure 6. Relationships between landscape features and relative humidity. **(a)** Maximum relative humidity response to landscape features, **(b)** Mean relative humidity response to landscape features.



(a)   **(b**)

Figure 7. Relationships between landscape features and wind velocity. **(a)**Maximum wind velocity response to landscape features, **(b)**Mean wind velocity response to landscape features.



(a)   **(b)**

Figure 8. Relationships between landscape features and surface temperature. **(a)**Maximum surface temperature response to landscape features, **(b)**Mean surface temperature response to landscape features.

Based on the data in **Table 1**, we synthesized the influence of each landscape element on four microclimate variables (air temperature, surface temperature, wind speed, relative humidity) to derive a thermal usability score and work efficiency score. Here we primarily focus on aspects that positively influence comfort. The cooling capacity is quantified through the depreciating effect on the air temperature (that is depicted by negative coefficient), the bigger the depreciating effect, the more the cooling capacity. The relative humidity was positively affected (positive coefficient), which is an indication of increased humidity control. As additions of humidity in arid conditions are positive, remember that it can be negative when it is humid. However, classical gardens in this context typically require increased humidity for cooling purposes, hence it is considered positive. Wind speed adjustment represents a negative impact on wind speed (with a negative coefficient), indicating reduced wind speed. While this can decrease hot airflow during hot summers, it may also hinder ventilation. Therefore, we consider it a positive effect when wind protection is needed. Surface temperature control is also a type of negative effect on a surface temperature (negative coefficient), meaning that a surface temperature will be lower and will thus reduce heat radiation. Nevertheless, **Table 1** contains both negative and positive coefficients, and the units of various variables are not equal, which is why simple summation cannot take place. As such we standardize each variable and then we give it a weight of its positive contribution to the thermal comfort. A total rating of the stars is given on the basis of the performance of every landscape element in all the four dimensions and efficiency of working. The overall thermal utility scores are presented in the table above.

In **Table 2**, the values were computed by taking the OLS regression coefficients as in **Table 1**. In order to make the variables which belong to different units comparable, all coefficients were standardized by the Min-Max standardization method:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}}$$

Table 2. Quantitative table of landscape factors on work efficiency, cooling capacity, humidity regulation, wind speed regulation and surface temperature control.

Landscape Features	Corridor	Grass	Pathway	Architecture	Rocks	Tree	Water
Cooling capacity	4	4	2	1	2	5	3
Humidity control	1	5	2	2	2	3	4
Wind speed adjustment	3	5	1	3	1	2	1
Surface temperature control	3	4	1	1	1	2	1
Work efficiency	3	1	3	2	1	3	3

4. Discussion

4.1. Performance comparison of landscape feature

The relative study of the three gardens indicates that there is a distinct stratification of the thermal energy of landscape features. Vegetation especially a blend of grass and trees proved to be the best element in the reduction of the air and surface temperatures. This outcome is consistent with the process of evapotranspiration and the shading effects provided by dense canopy structures [16,17]. Although water was assumed to cool the environment, it showed a context-dependent behavior of heating the surrounding air temperatures in the regions with a high concentration of solar radiation and the lack of shade covering the ground area as water has a capacity to store the heat.

The water-cooling effect was felt more in shaded region where the water bodies had trees or were bordered by vegetation growing around them. The shade minimized direct solar gain which enabled the evaporation to be more effective and decreased the air temperature in the surroundings besides slightly raising humidity. However, water surfaces located in the open where all the sun reached acted quite differently in small bodies. These water bodies heated up during the day without shade to cushion the absorption of heat and then later in the day they emitted the heat back to the atmosphere, producing minor temperature changes in the immediate environment around them in the afternoon. It is this contrast that indicates the cooling behavior of water is not predetermined and this is highly based on shading conditions, size, and space context.

The hardscape features were also linked with high temperatures so it is clear that architectural structures and paved pathways are heat sinks. These reflect and re-emit solar energy, so coming to enhance local thermal stresses [18]. Although it offers the means of needed spatial enclosure and aesthetic structure, architecture that is overly covered may have a detrimental effect, unless balanced with proper (sizeable) vegetation or some other means of ventilation.

Corridors exhibited a micro-climate dichotomous behavior. Although their darker and semi-enclosed features may lower the surface temperatures and direct the air movement, their effects on air temperature were neutral or slightly positive, probably owing to poor air circulation of thicker areas. This highlights how their design setting, orientation and openness in influencing microclimatic results and should be incorporated.

4.2. Spatial and climatic context sensitivity

The contribution of spatial heterogeneity proved to be one of the determinants crucial to landscape features behavior [19]. Water, vegetation, are all elements that do not act without reaching out to other materials and spatial arrangements. As an example, cooling efficiency of water bodies was greatly improved in the vegetation-enclosed regions implying some kind of synergistic effect that presence of trees will decrease the amount of radiation reaching water bodies, hence restricting unnecessary heat retention. On the other hand, the presence of water in arid areas facing the sun was used as thermal and heat amplifier [20].

Also, there was a variation in wind modulation depending not only on the layout of each corridor but also the relative isolation of every garden. Canglang Pavilion had perimeter wallways or thick clusters of structures and this minimized general air circulation even as corridor networks existed within the structures. This underscores the necessity of multiscale spatial analysis - the connection between internal spatial features to the larger garden enclosing and urban form.

To further prove the generalizability of the findings of this study to other climatic regions, scholars extended their research to a typical classical garden in southern Chinese-GuangZhou-Yuyin Garden to compare them. They tested the difference between the Humble Administrator Gardens (humid subtropical climate to the Yuyin Gardens in Guangzhou (South subtropical monsoon climate). Studies in Yuyin Mountain Villa showed that water bodies lower daytime temperatures as well as humidity level in the air [21]. Nevertheless, to reduce the uncomfortable effects of high humidity in hot and humid climates, garden design should eliminate too much evaporative cooling in the form of high shading coverage (e.g. dense tree shade, building eaves) or discomfort will be reduced by excessive humidity [22]. This is consistent with our discoveries of shaded conditions (β = −0.875) having a higher contribution towards cooling compared to the sunny conditions (β = 0.125). Even though, there are showcasing effects of cooling in water bodies in the southern parts of the world because such bodies are characterized by transpiration, the research shows that optimization in shade design, including changing the shaded areas and covers, is key in ensuring thermal comfort [23].

4.3. The influence of hot environment on personnel work efficiency

Factors influencing the indoor thermal environment include temperature, relative humidity, air velocity, and radiant temperature. All these factors affect human work efficiency, with temperature being the primary determinant. Both ISO 7730 [24] and ASHRAE [25] standards establish indoor air temperatures based on creating a physiologically comfortable thermal environment, taking into account the combined effects of air velocity, relative humidity, and other variables. For light (primarily seated) physical activity, the recommended operating temperature range is 20 °C–24 °C in winter and 23 °C–26 °C in summer. These standard ranges rely on the Fanger indicators of thermal comfort including the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfaction (PPD) [26]. Predicted Mean Vote (PMV) index is a combination of parameters in a thermal environment and human behavior response to predict thermal sensation, which is related to Predicted Percentage of Dissatisfaction (PPD) in thermal environments. According to ISO 7730, a PPD value of less than 10 percent refers to a thermal environment, so a thermal environment in which more than 90 percent of occupants are satisfied is said to be comfortable with PMV values between −0.5 and +0.5. In practical applications, the upper limit for PPD in thermally comfortable environments may be relaxed to 20% [27]. Clearly, both excessive heat and excessive cold adversely affect work performance [28]. Room temperature can indirectly affect work efficiency by exacerbating sick building syndrome and reducing air quality. Additionally, room temperature directly impacts personnel productivity.

Since 1960s, scholars have carried out a lot of research on work performance-thermal environment relationship. A number of studies show that working performance reduces in hot workplaces. Niemelä et al.’s [29] research demonstrated that call center workers’ efficiency decreased when room temperatures exceeded 25 °C. According to a study carried out by Sundstrom, the longer one works in a hot workplace, the higher the rate of error in mental tasks and those which involve a visual and manual coordination of the body parts- activities that are popular in offices [30]. Pang et al. [31] found that there was an inverted U-shaped relation between temperature and task reaction time and that the maximum of the response times were noticed in temperatures of 26.7°C although the errors made were the lowest at this temperature.

In Peng’s experimental study, 18 male and 18 female participants wearing summer attire performed a series of tasks at different effective temperatures (24, 27, and 30 °C). Except for measuring task utilization and attention in sensorimotor tasks, most performance declines as temperature rises. Performance in perceptual tasks follows an inverted U-curve with temperature, peaking at 27 °C. Dong summarized his early experimental research, also finding that temperature’s impact on work performance is highly dependent on task characteristics [32]: For mental tasks, at a neutral temperature of 21 °C, work rate decreased by 30% at 27 °C. Beyond 27 °C, the decrease leveled to 70%. In typing duties, it was found that the performance decreased by 70 percent when the temperature was past the neutral temperature of 4 °C and the rate of reduction was the same thereafter. The hypothesis that Li made is that when there is thermal discomfort due to skin sensors and sweating, in warm environments, accuracy in work reduces but when the core body temperature has started to vary, work speed is altered [33]. Under mild heat stress conditions, Chu et al. [34] provided a detailed account of the impact of ambient temperature on human performance and its potential mechanisms. Individuals become more likely to experience the sick building syndrome under the influence of moderate heat stress. Simultaneously, to minimize sweating, they tend to reduce metabolic rate and arousal levels. Both factors impair work performance. Those who had the symptoms of sick building syndrome displayed slowed time in carrying out computer-based tasks and lower accuracy in other tasks. The theory firstly proposed by Provins that moderate heat stress depresses arousal and that additional heat stress up to the sweating threshold increases arousal was based on the hypothesis that heat stress causes a baseline level of stress to moderate the arousal levels. Low levels of mental arousal diminish attention levels and work performance. These findings indicate that even moderate heat stress reduces work performance. Additionally, job satisfaction and effort investment correlate with the work environment. In thermally uncomfortable settings, workers take more breaks, ultimately leading to decreased productivity.

4.4. Functional trade-offs and landscape optimization

The results shed light on essential functional trade-offs of landscape design. Vegetation is not perfect with regard to thermal regulation, though when spread too thickly or becoming thickly spaced the vegetation may block the flow of air. On the same note, structures also offer much needed shade and enclosure and can trap heat in limited areas. The only way to maximize microclimate is to maximize favorable characteristics but also balance them meticulously so as to prevent the appearance of unintended consequences.

A landscape strategy that is effective should then combine a multifunctional concept which incorporates vertical shading with the use of trees, cooling on the ground with the use of grass, humidity control with the use of water, and spaces rhythm with the help of architecture [35]. These features have to be spatially spread so as to encourage wind paths, spread solar radiation and mitigate thermal extremes. The design structures to be used in the future must focus on flexible buildings that are dynamic in terms of seasonal and diurnal changes.

Trees can form the main component of an efficient microclimate zone of cooling and humidification since they received the highest score of cooling and have a high shading ability. Grass may be placed under or around the tree canopy, which offers more cooling and moderating the wind velocity at the pedestrian level. The presence of a medium-sized water body near vegetation also intensifies additional evaporation cooling together with the increase of humidity particularly when partly covered. In the meantime, rather than concentrating on paving it should be dispersed to allow circulation without the formation of areas of heat accumulation.

4.5. Theoretical integration and design implications

The evidence-based information based on this research is the support of ancient philosophical and aesthetic beliefs concerning Classical Chinese Gardens. The idea of Daoism of the unity of opposites is expressed in climate-control interplay of solid (architecture) and open space, light and shadow, moistness and aridity. The Confucian order which is present in the structured pathways and spatial hierarchy strengthens predictability of the environment and psychological comfort.

Practically, the work supports the modern usefulness of the CCG-based design in the context of sustainable cities. The landscape architectures and planners ought to salvage the spatial logic and materials palettes of the historical garden structures and duplicate them into climate-qualified designs of municipal parks, residential gardens, and institutional campuses. The empirical research shows that the ratio of 25%–35% (trees + lawn) vegetation coverage is effective in terms of cooling and air circulation and corresponds to the best levels of thresholds of green infrastructures efficacy in urban areas [6]. The water bodies are to be placed at a distance of 5-10 meters beneath tree covers to maximize evaporative cooling through synergistic cooling and moisture exchange [36]. Pathway design proposes the basic width to be 1.8 meters so that ventilation can be provided without compromising the windbreak functionality which is also a learning of the studies of the pedestrian comfort in small urban environment [37]. These parameters give practical guidelines of how to translate the principles of classical gardens to the present-day workspace design. By so doing, cities might not only become more resilient in the environmental parts of their landscapes, but also exhibit cultural viability and introduce past insights into the city of tomorrow.

4.6. Limitations and future research directions

This study has achieved some results in exploring the microclimate regulation capacity of classical Chinese gardens, but there are some limitations. To begin with the study concerned only Humble Administrator Garden in the Suzhou region, and its sample was limited and was also restricted to one climatic zone. This may limit the generalizability of the study results and cannot fully reflect the microclimate regulation characteristics of classical gardens under different geographical and climatic conditions. Second, the constrained duration of the study, as the data on the effects of seasonal variations on microclimate were measured during only a period between July and August 2024, is not enough to encompass the impacts of seasonal variations on microclimate. In addition, although OLS regression analysis was used in this study, the interactions between landscape elements, such as the synergistic effects of vegetation and water bodies, and the complex effects of building structures on wind fields and temperature distributions were not adequately considered in the model.

Future studies can improve and expand the model to address the above limitations. First, future research can expand the scope of the study by selecting classical gardens in different geographic and climatic regions for comparative analysis in order to verify and enrich the conclusions of this study. For example, the variations between microclimate regulation of the royal gardens at the north and the domestic garden of the south might be explored, and the mechanisms by which they adjust to the climatology of their areas. Second, a wider time frame including data during various seasons should be addressed in the study to have a fully developed picture of the microclimate control resources of classical gardens over the year. Such researches will play a role in uncovering the fruitful consequences of the seasonal variation on the microclimates in gardens and offer more holistic recommendations to garden designs.

In addition, future research could further explore the interaction mechanisms between landscape elements. For example, the interrelationships between elements such as vegetation, water bodies, buildings, etc. and their combined effects on microclimate can be more precisely quantified through the establishment of more complex statistical models or the use of spatial analysis methods such as geographically weighted regression (GWR). Meanwhile, the combination of field observation and numerical simulation techniques, such as Computational Fluid Dynamics (CFD) simulation, can provide a more in-depth understanding of the distribution characteristics of the wind, temperature and humidity fields within the garden space, and provide a scientific basis for optimizing the layout of the garden.

Finally, future research can also focus on the impact of human activities on garden microclimate. For example, the flow of tourists and the type of activities in the garden may have certain disturbances on the microclimate. Through the combination of behavior mapping and microclimate monitoring, the dynamic impact of human activities on the microclimate can be assessed, and then reasonable visitor management and garden operation strategies can be proposed to achieve the sustainable regulation of the garden microclimate.

5. Conclusion

In summary, this study reveals the effects of landscape elements (e.g., vegetation, water bodies, buildings, paths, etc.) on microclimate variables (air temperature, surface temperature, wind speed, and relative humidity) by investigating the microclimate regulation ability of CCGs. Taking Suzhou Humble Administrator’s Garden as an example and using OLS regression analysis, the findings show that vegetation and water bodies have significant effects in reducing temperature and increasing humidity, while buildings and hardscape elements regulate the microclimate by increasing heat capacity and blocking wind speed. The results offer a good logic of applying the traditional ideas of garden design in the modern urban landscape planning that can be used to enhance the environmental sustainability and thermal comfort.

Through detailed analysis of the Humble Administrator’s Garden, it was found that vegetation and water bodies play a key role in regulating microclimate. Vegetation reduces air temperature through shading and transpiration, while increasing relative humidity. Water bodies, on the other hand, reduced air temperature through evapotranspiration while increasing humidity. However, the blocking of the wind speeds by buildings and hardscape features (paths, corridors, etc.) imply that the design of the classical Chinese gardens is not limited to insisting on aesthetic and cultural connotations, but also has a strong ecological wisdom.

This study further emphasizes the application value of classical garden design in modern urban planning. With the acceleration of urbanization, the urban heat island effect and microclimate problems are becoming more and more prominent. Among the concepts that are incorporated in the designs of the classical gardens are Heaven and Man Are United as One and Combination of the Actual and Visual Conditions that give significant information to the contemporary urban landscape design. By rationally arranging vegetation, water bodies and buildings, the microclimate conditions of cities can be effectively improved, and the quality of life of residents can be enhanced.

In addition, this study also points out that although the design concept of classical gardens has important scientific value, its limitations still need to be considered in modern applications. For example, the design of classical gardens is mostly based on specific climatic conditions and cultural backgrounds, and its applicability in different geographical regions needs to be further verified. In addition, complex factors in modern urban environments (e.g., high-density buildings, traffic flow, etc.) may also have an impact on the microclimate regulation ability of classical gardens.

Overall, this research not only confirms the effectiveness of classical Chinese gardens in regulating the microclimate, but also the theoretical value of research on the ability to provide more comfortable and sustainable living conditions to the inhabitants of a particular city. In addition to its environmental effects, the cultural wisdom of classical gardens has much deeper socio-psychological significance; it can create cultural identity and relieve the psychological stress of the urban environment [38]. Classical gardens also have positive effects on the wellbeing of the workplace as their experiential aesthetics and narrative spaces form healing environments, which may be especially effective in relieving mental fatigue akin to wellbeing research [39]. By blending the philosophy of the ancient gardens and modern urban landscape planning, one can not only develop the cities as much more comfortable and sustainable places to live in but also develop spaces that echo cultural importance and contribute to increased well-being of populations. Future research should further explore the potential of applying classical garden design concepts in different climatic regions and modern urban environments in order to promote the sustainable development of urban landscape design.

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