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Integrating Health and Well-being into Urban Design: Microclimate, Walkability, and Walking Behaviour in Buraydah City, Saudi Arabia

Fahad Alharbi[1, 2], Shibu Raman[3], Simon Lannon[4]

[1]*PhD research student at the Welsh School of Architecture, Cardiff University, UK*

[2]*Lecturer, Department of Architecture, College of Architecture and Planning, Qassim University, Qassim, 52571, Saudi Arabia*

[3]*Senior Lecturer in Architecture and Urbanism, Director of International at the Welsh School of Architecture, Cardiff University, UK*

[4]*Senior Research Fellow at the Welsh School of Architecture, Cardiff University, UK*

Abstract

Amid global concerns about physical inactivity and its relationship to health, this study aims to understand the relationships between walking behaviour, neighbourhood walkability, and outdoor thermal comfort. A detailed investigation of three high-to-low walkable and comfortable neighbourhoods in Buraydah City, Saudi Arabia, forms the basis of this study. The fieldwork included a questionnaire to survey thermal sensations and preferences, walking activities, and perceptions of walkability. Site-specific climatic data were collected for each participant from this hot-arid climatic zone during the hot summer of 2023. Data collected were collated in a GIS platform and tabulated for statistical correlation analysis. Findings reveal significant relationships between 1) high-to-low walkable and comfortable neighbourhoods and 2) perceived (land-use mix and intensity, street connectivity, and retail density) walkability and pedestrian behaviour, specifically regarding 1) frequency and duration of walking and 2) pedestrians estimated Physiological Equivalent Temperature (PET). By optimising microclimatic conditions through strategies such as shading, green spaces, and improved neighbourhood characteristics—like increased street connectivity and compact, mixed-use development—cities can enhance outdoor thermal comfort and promote walking. The study highlights a positive association between high walkability, thermal comfort, and increased walking, offering guidance for urban planners to create healthier, more active communities, especially in extreme climates.

Keywords

Outdoor Thermal Comfort; Urban Density; Urban Microclimate; Walkability; Walking Behaviour

1. Introduction

Walking, as a form of physical activity, provides substantial health benefits, such as reducing the risk of non-communicable diseases like heart disease and type 2 diabetes and combating obesity (Adlakha & Sallis, 2020; X. Li et al., 2021). Walking also plays a critical role in sustainable urban development by reducing the impacts of urbanisation, including air pollution and urban heat islands (Tainio et al., 2021). However, despite these advantages, nearly 30% of adults globally do not meet the World Health Organization's (WHO) recommended 30 minutes of moderate physical activity daily (WHO, 2019). This issue is particularly pronounced in countries like Saudi Arabia and Kuwait, where inactivity rates exceed 50% (Guthold et al., 2018). Consequently, promoting walking through supportive urban environments has become a priority in public health, urban planning, and design (Barton, 2005).

The built environment is crucial for integrating walking into daily routines (Zuniga-Teran et al., 2017). The extent to which a neighbourhood-built environment supports walking—known as walkability (Southworth, 2005)—is determined by characteristics like residential density, street connectivity, and land-use mix. Enhancing these through urban policy and design is a proven strategy to promote walking (Frank et al. 2019). Over the past two decades, walkability has garnered significant attention due to its potential to improve health, environmental sustainability, and quality of life (Barker, 2012; Gadais et al., 2018). Recognising the importance of walkability has led to integrating these principles into urban planning and design practices worldwide (Berghauser Pont et al., 2019).

To better understand walkability, key built environment characteristics have been identified as critical to supporting pedestrian activity. These characteristics include population density, diversity of destinations, and pedestrian-friendly design—often collectively known as the "3 Ds" (Cervero & Kockelman, 1997). In practice, a fourth factor, "distance," also plays a crucial role (Townshend, 2022). Researchers have expanded on these categories by subdividing them into macro-scale and micro-scale characteristics (Sallis et al., 2011; Ledraa, 2015). Macro-scale characteristics include (i.e. residential density, land-use mix and intensity, street connectivity, and retail density) (Leslie et al., 2007; Sallis et al., 2016; Zandieh et al., 2019). In contrast, micro-scale characteristics, such as safety, pedestrian infrastructure, and aesthetics, affect specific route features within a neighbourhood. Despite these reclassifications, the core argument remains consistent.

This distinction between macro-scale and micro-scale characteristics is critical for understanding how the built environment influences different aspects of walking. Macro-scale characteristics have a long-term impact and are often resistant to change after urban development (Shafieiyoun & Zamani, 2021), shaping neighbourhood design and influencing micro-scale characteristics, thus affecting pedestrians' decisions to walk for various purposes, such as commuting and recreation. This reflects Jane Gehl’s public space and public life theory (Fonseca et al., 2021; Saelens & Handy, 2008), which classifies activities into necessary (i.e. commute walking), social and optional (i.e. recreation walking). Different types of walking are linked to various built environment characteristics: both commuting and recreational walking are related to macro-scale characteristics (Hirsch et al., 2014; Saghapour et al., 2019), while micro-scale characteristics are found to influence only recreational walking (Fonseca et al., 2021; Saelens & Handy, 2008). These connections underscore the importance of macro-scale characteristics in shaping walking behaviours and activities within neighbourhoods.

Research has shown that populations in neighbourhoods with high walkability report nearly twice the total weekly walking compared to those in low-walkable neighbourhoods (e.g. Kärmeniemi et al., 2018). These findings suggest that variations in neighbourhood macro-scale characteristics are associated with differences in walking behaviour. High-walkable neighbourhoods, by offering proximity to destinations and activities (Gao et al., 2020), are likely to encourage more walking (Wang et al., 2016). However, the role of microclimate—particularly its effect on outdoor thermal comfort—has received less attention in walkability studies despite its significant influence, especially in hot-arid climates. This oversight raises important questions: Do residents in low-walkable neighbourhoods face greater challenges in terms of thermal comfort compared to those in high-walkable areas? How do different levels of walkability impact thermal comfort? What urban planning and design strategies can simultaneously enhance walkability and thermal comfort in hot-arid environments? Addressing these questions is crucial for urban planners to identify and mitigate the factors contributing to walkability deficiencies in less walkable neighbourhoods.

Microclimate characteristics significantly affect walking activities and comfort. Environmental characteristics such as air temperature, mean radiant temperature, wind, and humidity influence outdoor thermal comfort. In regions like Buraydah, extreme temperatures can impact the feasibility and desirability of walking (Chen et al., 2023; Cleugh & Grimmond, 2012). Air temperature and mean radiant temperature directly affect thermal sensation, while wind and humidity modify these sensations by influencing the body's heat exchange processes (Azegami et al., 2023; J. Li et al., 2018; Sangkertadi & Syafriny, 2016; Yin et al., 2019). Personal characteristics (i.e. clothing levels and metabolic rate) also determine an individual's tolerance to varying thermal conditions (Colom et al., 2019; Mitra & Faulkner, 2012). Studies on the relationship between microclimate and walking have yielded mixed results, depending on climate: in cold regions, walking activity increases in summer, while in hot regions, it often declines (Hino et al., 2021; Shaaban et al., 2018). Understanding thermal comfort in relation to walkability is thus crucial for encouraging walking across diverse climates.

This study applies specific criteria to identify walkable and thermally comfortable neighbourhoods in Buraydah City, Saudi Arabia, to address these questions. Objective characteristics such as urban growth patterns, population density, and land surface temperature (LST) will be used as proxies for walkability and thermal comfort. Urban growth patterns influence the quality of walking routes (Mouada et al., 2019), and well-planned urban growth enhances connectivity, making walking more convenient (Won & Jung, 2023). Population density often correlates with accessibility to amenities, enhancing walking opportunities (Gao et al., 2020). LST, influenced by factors like green spaces and building materials, affects thermal comfort and is further impacted by the urban heat island effect (Won & Jung, 2023). These characteristics contribute to spatial heterogeneity, impacting walkability and thermal comfort.

Macro-scale neighbourhood characteristics can be assessed objectively or subjectively. Objectively measured characteristics may not always align with individual perceptions of the environment. Behaviour change theories suggest that perceived built environment characteristics may correlate more strongly with health behaviours than objective measurements (Sallis et al., 2015). Subjectively measured characteristics reflect personal evaluations of the built environment, shaping the lived experience and influencing whether people perceive their neighbourhoods as walkable (Arellana et al., 2020). For instance, a diverse land-use mix, street connectivity, and retail density could enhance walking by providing varied destinations within walking distance and making walking more efficient and appealing (Hakimian & Lak, 2016).

Many studies on outdoor thermal comfort have developed universal indices to characterise comfort in both hot and cold climates. The primary indices include PET (Physiologically Equivalent Temperature), PMV (Predicted Mean Vote), UTCI (Universal Thermal Climate Index), and SET* (Standard Effective Temperature), all suitable for calculating heat and cold stress (Binarti et al., 2020). PMV classifies thermal sensation, while PET, UTCI, and SET* evaluate thermal comfort in degrees Celsius. PET, initially developed for Western and Central Europe, has a "neutral" scale of 24–26°C for hot climates, confirmed by 95% of studies (Matzarakis & Amelung, 2008). In cold climates, 89% of studies identified a neutral range of 15–20°C. Research in tropical climates, such as Taiwan and Egypt, reports higher PET values than those observed in Europe (Lin, 2009; Mahmoud, 2011), indicating that local urban climatic characteristics influence thermal perception and outdoor environment use.

Since neighbourhoods are integral to daily life and outdoor activities and vary with climatic conditions, associating thermal comfort with walkability could improve the creation of environments that support walking year-round (Peca Amaral Gomes et al., 2021). A pedestrian-friendly built environment can be achieved by implementing urban standards and continuously assessing walking conditions (Alawadi et al., 2021). Previous research has linked outdoor comfort to various built environment characteristics (e.g. Jia & Wang, 2021; Labdaoui et al., 2021). Despite advancements in measuring walkability, several practical issues related to pedestrian comfort remain unresolved, including 1) the absence of thermal comfort measurements at the neighbourhood scale and 2) the assessment of walkability considering thermal comfort. Therefore, building on prior research, this study aims to investigate the relationship between walkability, outdoor thermal comfort, and walking behaviour in Buraydah City, Saudi Arabia, focusing on walking frequency, duration, and PET values. Incorporating thermal comfort into walkability assessments at the neighbourhood macro-scale is essential for creating walkable and comfortable neighbourhoods. This study adopts a holistic approach by considering both measurable environmental characteristics and subjective experiences, using PET to evaluate thermal comfort—which is crucial for fostering year-round, sustainable walking behaviour.

2. Methodology

This empirical study, conducted in September 2023, focuses on Buraydah, a mid-sized Saudi Arabian city with over 700,000 residents (Saudi General Authority for Statistics, 2023), characterised by a hot-arid climate (BWh) according to the Köppen climate classification (Peel et al., 2007). It investigates the relationship between walking behaviour, neighbourhood walkability, and outdoor thermal comfort. Data collection involved surveys, microclimatic measurements, and Geographic Information Systems (GIS) analysis across three high-to-low walkable and comfortable neighbourhoods. The study aimed to understand how these characteristics collectively influence walking behaviours under Buraydah City's unique climatic conditions.

2.1 Selection of High-to-Low Walkable and Comfortable Neighbourhoods

Neighbourhood selection was based on objective built environment characteristics, including urban growth patterns, population density, and land surface temperature, chosen for their collective contribution to spatial heterogeneity, which influences both walkability and outdoor thermal comfort. Urban growth patterns were mapped to understand area development intensity, population density data was provided by Buraydah authorities, and land surface temperature was assessed using satellite imagery and morning time (7 am) pictures. These characteristics were crucial for selecting representative neighbourhoods with diverse environmental and urban diversity in Buraydah City. Accordingly, three neighbourhoods were selected to represent high-to-low walkable and comfortable neighbourhoods: 1. Al-Khabib (high), 2. Al-Fayziyyah (medium), and 3. Al-Nahda (low) (Figure 1). Table 1 details the characteristics of the selected neighbourhoods, emphasising the spatial and environmental diversity affecting walkability and outdoor thermal comfort.

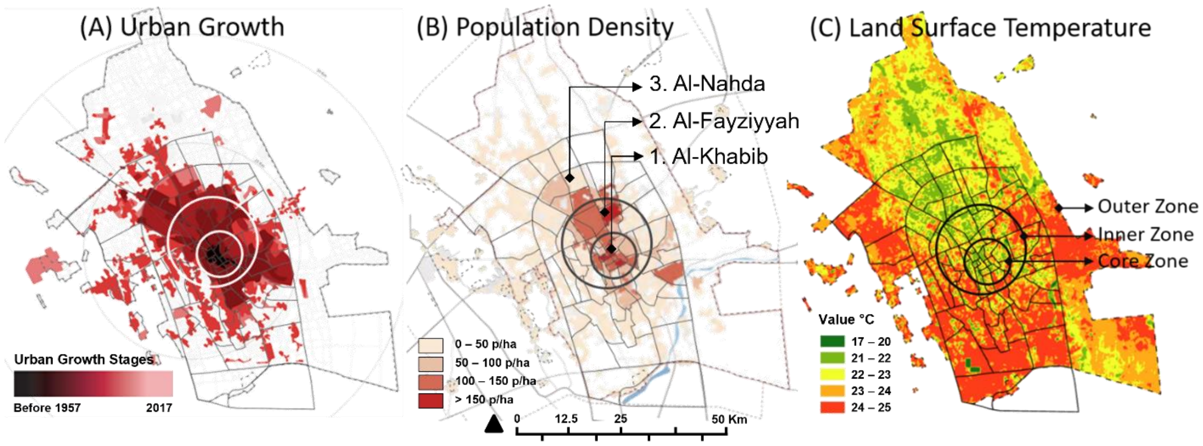

Figure 1: Maps showing the urban growth (A), population density (B), and the urban surface temperature (C) of Buraydah City with the three zones (Core, Inner, and Outer) and the selected neighbourhoods.

Table 1: The selected neighbourhoods' detailed characteristics.

Neighbourhood	Urban growth patterns	LST	Building Type	Land Area (hectare)	Total Population	**Population Density (p/ha)**
1. Al-Khabib	Core zone (1950s)	21-22 °C	3-4 Floor Buildings	114.71	21,790	**190 (High)**
2. Al-Fayziyyah	Inner zone (1990s)	22-23 °C	2-3 Floor Buildings	312.06	23,856	**76 (Medium)**
3. Al-Nahda	Outer zone (2010s)	22-23 °C	2-Floor, Villas	556.24	26,912	**48 (Low)**

2.2 Participant Recruitment

Participants were recruited using convenience sampling, employing street intercepts for their practicality and cost-effectiveness. This method enabled rapid data collection by engaging pedestrians in easily reachable locations. An online questionnaire was also employed to reduce selection bias and include individuals less likely to be reached in public, such as females in privacy-conscious environments like Saudi Arabia. This combined approach helped ensure a more diverse and representative sample. A total of 318 valid questionnaires were collected from the three selected neighbourhoods, including 209 from face-to-face interviews and 109 from online responses. The study targeted adults aged 18-65 residing in the selected neighbourhoods to achieve a broad and inclusive sample.

While convenience sampling can introduce selection bias, we used a mixed approach to help mitigate potential underrepresentation, especially among groups with privacy concerns. However, we recognise that this sampling method poses limitations for generalising the findings. We recommend that future studies adopt randomised sampling techniques where feasible to improve sample representativeness further and minimise potential biases.

2.3 Measuring Walking Frequency and Duration

Walking frequency and duration were measured using a validated self-report questionnaire, specifically the International Physical Activity Questionnaire - Short Form (IPAQ-SF), which has been extensively tested for reliability in similar environmental studies (Frehlich et al., 2018). Self-reported data provided a key advantage by capturing the purpose behind walking activities, whether for commuting or recreation—an aspect that is challenging to collect through objective measures alone. Such information is crucial for understanding the broader motivations and context of pedestrian behaviour, which play a role in interpreting patterns of urban walkability and thermal comfort perception.

While future studies may benefit from incorporating wearable devices to complement self-reported data and enhance accuracy, it is important to note that these devices may also introduce sampling bias, as seen in prior research. The cost and potential inconvenience associated with wearable devices can reduce participation from certain demographic groups, potentially affecting sample representativeness. Therefore, a balanced approach, combining self-report methods with wearable data, could provide comprehensive insights while addressing the limitations of each method individually.

2.4 Measuring Perceived Neighbourhood Walkability Built Environment Characteristics

To assess perceived neighbourhood walkability characteristics, the study used a questionnaire based on the Neighborhood Environment Walkability Survey (NEWS) by (Saelens et al. 2003) and improved by (Hakimian & Lak, 2016). This survey evaluates characteristics like residential density, land-use mix, and street connectivity. Participants rated these characteristics on a 5-point Likert scale from 'strongly disagree' to 'strongly agree,' with a neutral midpoint. Previous studies confirmed the survey's reliability and validity, making it suitable for this study.

A total of 318 participants completed the survey, providing data on perceived residential density, land-use mix, street connectivity, land-use intensity, and retail density. The average scores for each characteristic were calculated. Higher scores reflected more positive perceptions.

2.5 Measuring Outdoor Thermal Comfort

Outdoor thermal comfort was evaluated using site-specific climatic data, including air temperature, globe temperature, humidity, and wind speed, measured at pedestrian height (~170 cm) using handheld weather stations (Kestrel 5500 meters). Personal characteristics, such as clothing levels and metabolic rate, were estimated during participant interviews. The study employed the Physiologically Equivalent Temperature (PET) index to assess thermal comfort, calculated using RayMan Pro software with inputs including air temperature, wind velocity, relative humidity, and mean radiant temperature (Tmrt).

Tmrt is critical in determining thermal comfort, accounting for radiant heat exchange between the human body and the environment. Tmrt was estimated using Equation 1 (ASHRAE 2017):

$$Tmrt = ((Tg + 273.15)^4 \ + ((1.1 \times 10^8 \ v^{0.6})/(\varepsilon D^{0.4)}) \times (Tg - Ta))^{\frac{1}{4}} - 273.15 \qquad (1)$$

Where: Tg is the globe temperature (°C), Ta is the air temperature (°C), v is the wind velocity (m/s), D is the globe diameter (mm), and ε is the globe emissivity.

These values were recorded on each questionnaire form and later entered into RayMan Pro software to calculate PET. This detailed thermal assessment helped us understand the impact of environmental conditions on pedestrian comfort and walking behaviour.

2.6 Data Analysis: Utilising ArcGIS Pro, Excel, and SPSS

The analysis used Microsoft Excel and SPSS to explore the relationships between built environment characteristics, perceived walkability, thermal comfort, and walking behaviours in Buraydah City. Excel facilitated data management and basic statistical calculations, while ArcGIS Pro mapped high-to-low-walkable and comfortable neighbourhoods based on (population density, urban growth patterns, and land surface temperature) along with the spatial distribution of PET using Natural Breaks, categorising data into five comfort levels.

Statistical analysis in SPSS included an independent sample t-test to compare walking levels across high-to-low-walkable and comfortable neighbourhoods. Linear and multiple regression analyses examined relationships between perceived neighbourhood characteristics, daily walking, and PET values. The analysis differentiated between neighbourhoods of high-to-low-walkable and comfortable neighbourhoods, with a significance level of $p < 0.05$ used throughout to ensure the robustness of the findings.

3. Results

3.1 Sample Characteristics

Table 2 summarises the sample characteristics (age, gender, and ethnicity) across the selected neighbourhoods. The data reveals a predominantly male sample (80.5%) across all neighbourhoods. Al-Khabib has the highest male representation (99.0%), while Al-Nahda has the lowest (63.8%). The age distribution skews towards younger adults, with the 18-29 and 30-39 age groups being the most prominent overall. Notably, Al-Nahda boasts the highest concentration of younger adults (46.5%). Ethnicity and nationality showcase diversity, with significant representation from Saudi nationals, Arab non-Saudis, and South Asians. Al-Nahda has a higher percentage of Saudi participants (76.4%), followed by Al-Fayziyyah (66.3%). Conversely, Al-Khabib has a larger proportion of non-Saudi Arabs (65.7%) and South Asians (21.6%).

Table 2: Participants' sociodemographic characteristics in the three neighbourhoods and the total sample.

Personal Characteristics		Neighbourhood Type			Total sample
		Al-Khabib High-walkable	Al-Fayziyyah Medium-walkable	Al-Nahda Low-walkable	
Number of participants | (%)		102 (32%)	89 (28%)	127 (40%)	318
Gender (%)	Male	99.0	83.1	63.8	80.5
	Female	1.0	16.9	36.2	19.5
Age group (%)	18-29	24.5	25.8	46.5	33.6
	30-39	34.3	31.5	21.3	28.3
	40-49	31.4	22.5	20.5	24.5
	50-65	9.8	16.9	11.0	12.3
	> 65	0.0	3.4	0.8	1.3
Ethnicity/ Nationality (%)	Saudi	8.8	66.3	76.4	51.9
	Arab non-Saudi	65.7	24.7	15.0	34.0
	South Asian	21.6	9.0	8.7	12.9
	Other	3.9	0.0	0.0	1.3

3.2 Variations in Participants′ Walking Frequencies and Durations

The analysis reveals significant differences in walking frequencies and durations across the three neighbourhoods. In terms of walking frequencies, in Al-Khabib, a high-walkable and comfortable neighbourhood, nearly 90% of residents walk 6-7 days per week, whereas, in Al-Nahda, a low-walkable but comfortable neighbourhood, only 45% of residents walk this often, with half of the population walking minimally (0-5 days per week). Al-Fayziyyah, characterised as a medium-walkable and comfortable neighbourhood, shows intermediate walking frequencies, suggesting that features such as proximity to destinations and shading in denser areas play a role in encouraging more frequent walking even during hot weather (Figure 2, left).

Regarding walking durations, more than 60% of residents in Al-Khabib report long walks (over 41 minutes), while in Al-Fayziyyah and Al-Nahda, most residents report shorter walks (0-20 minutes), with approximately 60% and 40%, respectively (Figure 2, right). Although some residents in Al-Khabib take shorter walks, and some in Al-Nahda walk longer distances to reach amenities, the data suggests that the availability of closer destinations and shaded streets in high-walkable neighbourhoods like Al-Khabib potentially promotes longer walking trips. These findings highlight how different neighbourhood characteristics influence the frequency and duration of walking, emphasising the importance of urban planning elements such as connectivity and shade in encouraging walking as a regular daily activity.

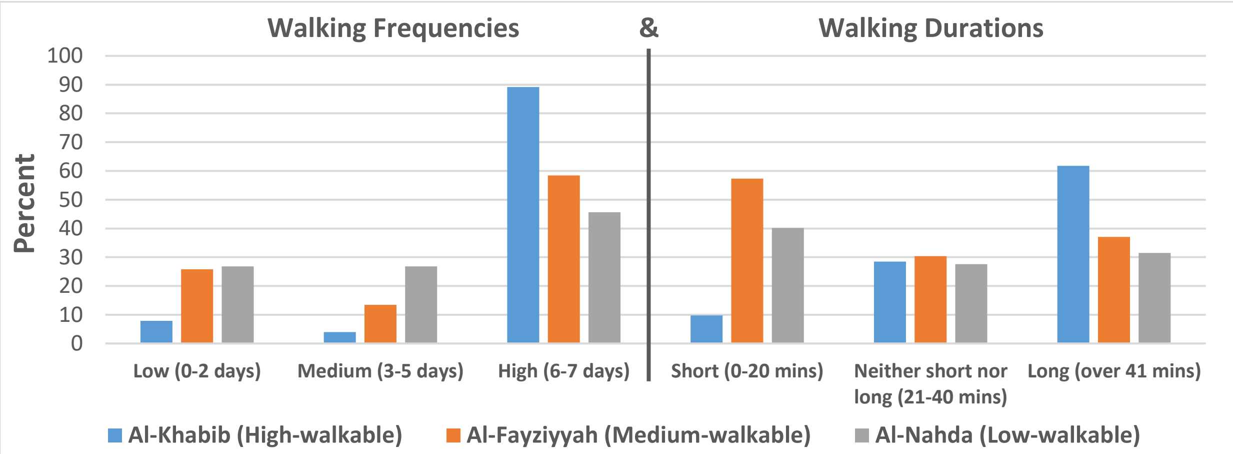

Figure 2: Long-term Walking frequencies and durations in the high-to-low walkable and comfortable neighbourhoods.

3.3 Variations and Spatial Distribution of Participants′ Estimated Outdoor Thermal Comfort PET.

The Estimated Physiological Equivalent Temperature (PET) varies significantly across the neighbourhoods of Al-Khabib, Al-Fayziyyah, and Al-Nahda, as indicated by the box plot in (Figure 3). Al-Nahda consistently records the highest PET values across all metrics, including minimum, maximum, mean, median, and standard deviation. Conversely, Al-Khabib generally exhibits the lowest PET values among the three neighbourhoods. Al-Fayziyyah falls between the other two neighbourhoods. The standard deviation reveals the degree of variability within each neighbourhood, with Al-Nahda showing the highest variability in PET. These findings suggest that residents of Al-Nahda may experience more extreme thermal conditions than those in Al-Khabib and Al-Fayziyyah, highlighting the importance of understanding and addressing local climate conditions for residents' outdoor thermal comfort.

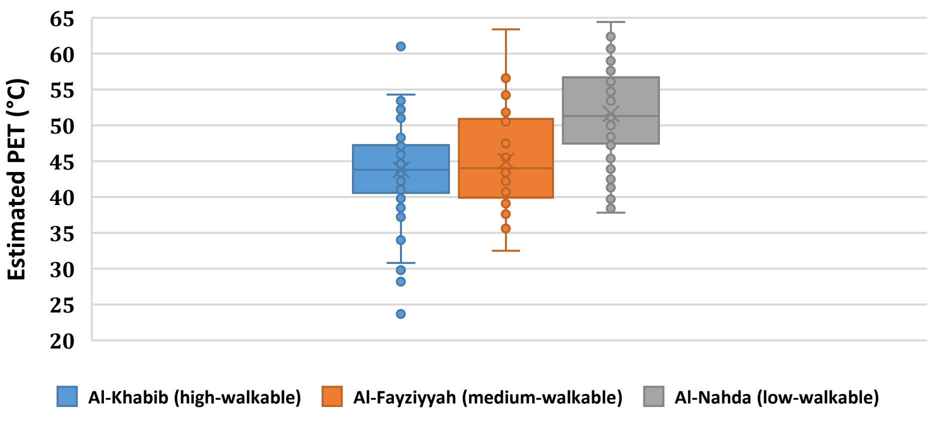

Figure 3: The estimated PET for the three high-to-low walkable and comfortable neighbourhoods.

Figure 4 depicts the spatial distribution of 209 face-to-face participants across three neighbourhoods—Al-Khabib, Al-Fayziyyah, and Al-Nahda—based on their Estimated PET. Each participant is represented by a coloured dot corresponding to five PET ranges: 24-34°C (dark green), 34-43°C (light green), 43-49°C (yellow), 49-55°C (orange), and 55-64°C (red).

In Al-Khabib, most participants fall within the cooler PET ranges of 24-34°C and 34-43°C, indicated by dark and light green dots. This suggests a relatively comfortable thermal environment, with fewer participants experiencing higher PET values (43-64°C), as represented by yellow, orange, and red dots. Thus, thermal stress is lower in this neighbourhood. Al-Fayziyyah exhibits a more balanced distribution across all five PET categories, indicating a diverse thermal environment in which participants experience a range of thermal conditions, from comfortable to high-stress levels. In contrast, Al-Nahda shows a concentration of higher PET values, particularly in the 43-64°C range, marked by yellow, orange, and red dots. This indicates that Al-Nahda experiences higher PET values, suggesting a less comfortable thermal environment. These findings highlight the heat stress risks for pedestrians and emphasise the importance of urban planning and design in improving outdoor thermal comfort in hot-arid climates.

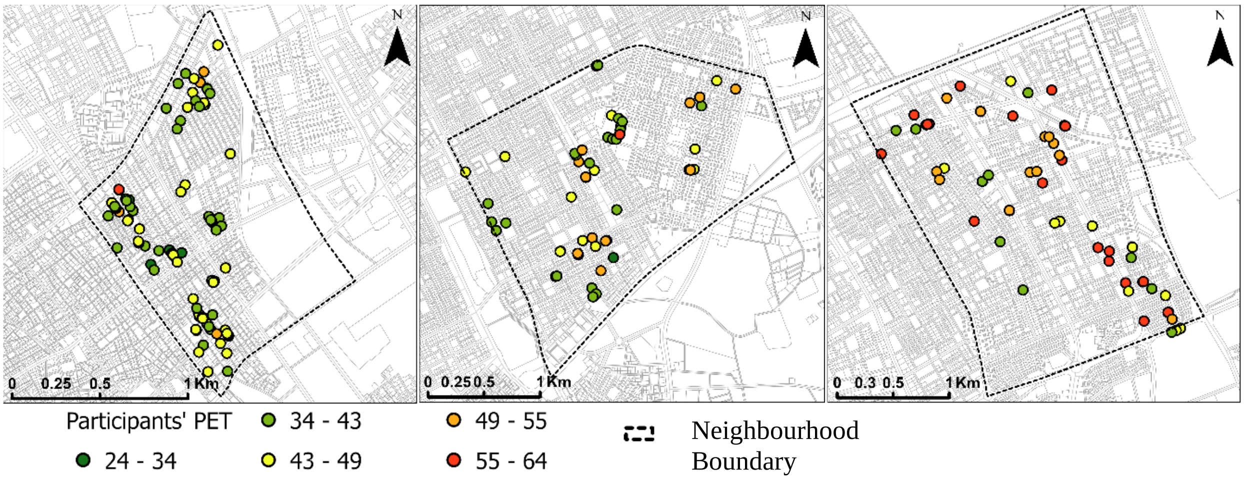

Figure 4: Spatial distribution pattern of face-to-face participants based on their PET among the three neighbourhoods (Al-Khabib, Al-Fayziyyah, and Al-Nahda), highlighting high, medium, and low-walkable-and-comfortable) respectively.

3.4 Comparison of Thermal Sensation Votes TSV vs Estimated Physiological Equivalent Temperature PET.

From 209 thermal comfort questionnaire responses, the correlation between PET and thermal sensation votes (TSV) was low ($R^2 = 0.0483$), suggesting PET alone does not strongly predict thermal sensation due to various influencing characteristics. To address this, PET values were categorised into 15 data bins of approximately 3°C each, with a mean thermal sensation vote (MTSV) assigned to each bin. This method showed a stronger relationship ($R^2 = 0.7995$) between MTSV and PET: MTSV = (-0.0347×PET) + 4.78. Figure 5 illustrates this linear regression, indicating an upper thermal comfort limit of approximately 49.9°C, with most responses (99%) within the 32.4°C to 64°C range. This identified upper limit appears high compared to other outdoor comfort studies in various climates.

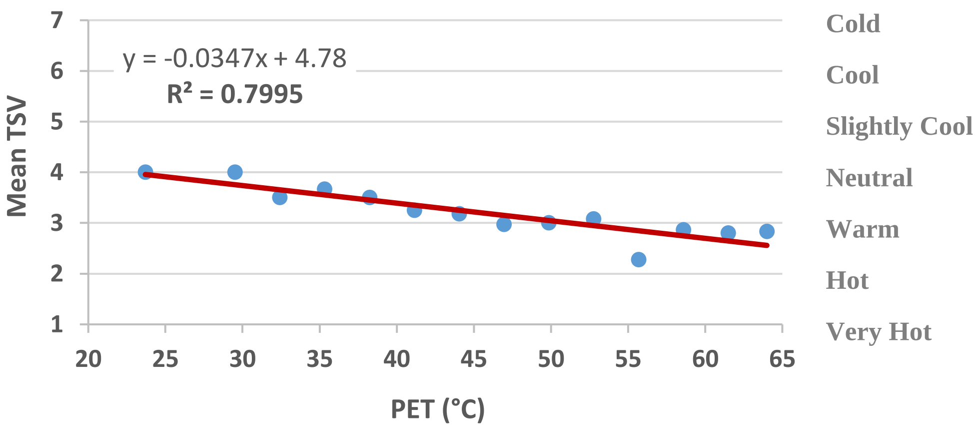

Figure 5: Mean thermal sensation votes (MTSV) vs PET outdoors of the total face-to-face questionnaire samples.

This discrepancy likely stems from two factors. First, hot-dry conditions like Buraydah's allow higher heat loss through sweat evaporation, increasing tolerance to heat. Second, residents of harsh climates, including low-income outdoor workers, may exhibit psychological adaptation to thermal stress (Alznafer, 2014). Most participants who rated conditions as "comfortable" were surveyed in shaded areas during cooler hours (mornings/evenings), with a smaller subset in the afternoon who had adapted to outdoor work conditions. Some participants also reported coming from sun-exposed areas, affecting their thermal votes, especially for "Neutral" and "Warm" categories.

Two minimum PET values (23.7°C, 29.5°C) were observed, with most values ranging from 32.4°C to 64°C, reflecting high summer daytime temperatures. These results suggest that while PET offers valuable insights, future studies could benefit from additional indices that consider individual adaptation and varying exposure conditions in extreme climates.

3.5 Variations in Participants' Perceived Neighbourhood Built Environment Characteristics.

Table 3 summarises how residents in the three Buraydah City neighbourhoods - Al-Khabib, Al-Fayziyyah, and Al-Nahda - perceive the walkability of their neighbourhoods. Scores range from (1) 'Strongly disagree,' least walkable, to (5) 'Strongly agree,' most walkable. Al-Khabib emerges as the neighbourhood with the most favourable perception of walkability, boasting an overall score of 4.5. This suggests that residents feel their area offers a good mix of residential density, land uses, street connectivity, and retail options, all of which contribute to a walkable environment. Al-Fayziyyah follows closely behind with a score of 3.9, while Al-Nahda rounds out the table at 3.7.

Table 3: Description of perceived walkability Characteristics of the questionnaire.

Perceived Walkability-Related Characteristics	Neighbourhood (M (SD))[a]			Total Sample
	Al-Khabib N= 102	Al-Fayziyyah N= 89	Al-Nahda N= 127	
Residential density	3.8 (1.52)	3.8 (1.28)	3.8 (1.19)	3.8 (1.33)
Land-use mix	4.8 (0.79)	4.3 (0.98)	3.9 (1.22)	4.3 (1.09)
Street connectivity	4.7 (0.92)	3.9 (1.21)	3.7 (1.27)	4.1 (1.22)
Land-use intensity	4.7 (0.79)	3.7 (1.08)	3.4 (1.34)	3.9 (1.24)
Retail density	4.6 (0.91)	3.6 (1.22)	3.7 (1.18)	4.0 (1.20)
Walkability's Total Scores	4.5 (1.08)	3.9 (1.21)	3.7 (1.32)	3.9 (1.36)

Note: Five characteristics of perceived walkability are related to macro-scale neighbourhood-built environments. [a]Response score: (1) strongly disagree and (5) strongly agree; M = Mean of total scores; SD = Standard Deviation of total scores; N = Number of participants.

3.6 Statistical relationships between high-to-low walkable and comfortable neighbourhoods & perceived neighbourhood walkability and walking & Estimated PET.

To calculate each participant's total weekly walking duration, the weekly walking frequency (days) was multiplied by the estimated daily walking time (minutes). Midpoint values were assigned to each time interval (e.g. up to 10 minutes = 5 minutes; 11-20 minutes = 15 minutes; etc.). For durations over 60 minutes, 90 minutes was used as an upper bound. The sample size was reduced from 318 to 283 participants, as some did not walk frequently or at all. Participants were distributed across the neighbourhoods: Al-Khabib (99), Al-Fayziyyah (74), and Al-Nahda (110).

3.6.1 High-to-Low Walkable and Comfortable Neighbourhoods and Participants' Walking & Estimated PET

Table 4 presents the average daily walking time in minutes for the selected neighbourhoods. Residents of Al-Khabib walk the most, averaging 58.4 minutes daily, followed by Al-Fayziyyah (36.7 minutes) and Al-Nahda (30.8 minutes). The average daily walking time across all neighbourhoods is 41.3 minutes, with a high standard deviation indicating significant participant variability.

A positive correlation exists between high- and low-walkable and comfortable neighbourhoods and daily walking time. Residents in high-walkable and comfortable neighbourhoods walk 13.58 minutes more daily than those in low-walkable and comfortable neighbourhoods (B = 13.580, t = 6.142, $p < 0.001$). However, with an R-squared of 0.107, this factor explains only 10.7% of the variation in daily walking, suggesting other characteristics may significantly influence walking.

Table 4: Difference between walking in high-to-low walkable and comfortable neighbourhoods.

Neighbourhood	Total Daily Walking		
	M (mins)	SD	Coefficients
Al-Khabib high-walkable (n=99)	58.4	32.4	B (13.6); SE (4.6); Beta (.327); t (6.1); and **P (<.001)**
Al-Fayziyyah medium-walkable (n=74)	36.7	33.9	
Al-Nahda low-walkable (n=110)	30.8	33.3	
Total sample (n=283)	41.3	35.2	

Note. M = Mean; SD = Standard deviation; B = Unstandardised Coefficient; SE = Standard Error; Beta = Standardised Coefficient. The values in **bold** type are significant.

In terms of PET, Table 5 illustrates the average PET values by high-to-low walkable and comfortable neighbourhoods. A regression model was used to examine the association between PET and all the selected neighbourhoods as the independent variables. The analysis, based on data from face-to-face participants only, included a sample size of 209 individuals: Al-Khabib (n=96), Al-Fayziyyah (n=58), and Al-Nahda (n=55).

The analysis revealed a negative relationship between high-to-low walkable and comfortable neighbourhoods and PET. The negative coefficient for the neighbourhood variable indicates that PET decreases as neighbourhood walkability increases. This relationship is statistically significant ($p < 0.001$), suggesting a low probability that the observed relationship is due to chance.

Table 5: Difference between PET in high-to-low walkable and comfortable neighbourhoods.

Neighbourhood	Estimated physiological equivalent temperature – PET (°c)		
	M	SD	Coefficients
Al-Khabib high-walkable (n=96)	43.8	5.7	B (-3.67); SE (.536); Beta (-.433); t (-6.902); and **P (<.001)**
Al-Fayziyyah medium-walkable (n=58)	45	6.5	
Al-Nahda low-walkable (n=55)	51.6	7.2	
Total sample (n=209)	46.2	7.1	

Note. M = Mean; SD = Standard deviation; B = Unstandardised Coefficient; SE = Standard Error; Beta = Standardised Coefficient. The values in **bold** type are significant.

The lower PET in high-walkable-and-comfortable neighbourhoods may be due to denser urban forms, where buildings provide shade, reducing sunlight and air temperatures, making these areas more comfortable than low-density neighbourhoods. However, the model's explanatory power is low, with an R-squared value of 0.187, indicating that high-to-low walkable and comfortable neighbourhoods account for only a small portion of the variation in PET across neighbourhoods. Other characteristics likely contribute significantly to PET variations.

3.6.2 Perceived Neighbourhood Walkability and Participants' Walking & Estimated PET

Table 6 indicates a significant positive relationship between perceived walkability (land-use mix, street connectivity, land-use intensity, and retail density) and total daily walking and a significant negative relationship with estimated PET. This suggests that people who perceive their neighbourhood to be more walkable walk more and are exposed to lower levels of PET, which was found to be strongly related to their thermal sensations in this study (section 4.3). However, perceived residential density did not show a significant correlation with either walking or PET.

The findings suggest that neighbourhoods with diverse land uses, better street connectivity, higher density, and more retail are perceived as more walkable. This perception is linked to increased walking and lower PET values.

Table 6: Relationships between perceived walkability characteristics and total daily walking & Estimated PET (°C)

Perceived Walkability-Related Characteristics	Total Daily Walking			Estimated PET (°C)		
	B	Std. Error	P (Sig.)	B	Std. Error	P (Sig.)
Residential density	-.774	6.015	.604	.395	.349	.259
Land-use mix	**10.795**	**1.720**	**<.001**	**-1,385**	**.582**	**.018**
Street connectivity	**5.330**	**1.589**	**<.001**	**-.981**	**.407**	**.017**
Land-use intensity	**5.792**	**1.557**	**<.001**	**-1.092**	**.401**	**.007**
Retail density	**5.176**	**1.620**	**<.002**	**-.959**	**.401**	**.018**
Overall perceived walkability	**9.466**	**2.217**	**<.001**	**-1.372**	**.596**	**.022**

Note. B = Unstandardised Coefficient; SE. Error = Standard Error; Sig = P-Value. The values in **bold** type are significant.

Different patterns emerged when comparing high-walkable and comfortable neighbourhoods with low-walkable and less comfortable ones. In Al-Khabib, land-use mix, land-use intensity, retail density, and overall perceived walkability were associated with higher daily walking. In contrast, in Al-Fayziyyah and Al-Nahda, only perceived land-use mix positively correlated with daily walking (Table 7). Moreover, when examined separately, no significant relationships were found between perceived walkability and PET across these neighbourhoods.

Table 7: Relationships between perceived walkability characteristics and total daily walking for each neighbourhood.

Perceived Walkability-Related Characteristics	Total Daily Walking		
	Al-Khabib	Al-Fayziyyah	Al-Nahda
	B; (SE); P	B; (SE); P	B; (SE); Sig
Residential density	.088; (2.14); P .967	-3.183; (2.80); P .259	.087; (2.48); P .972
Land-use mix	**15.10; (3.82); P .001**	**9.817; (3.54); P .007**	**5.18; (2.39); P .033**
Street connectivity	5.601; (3.46); P .108	3.833; (2.97); P .200	-.019; (2.23); P .994
Land-use intensity	**12.77; (3.91); P .001**	1.004; (3.35); P .765	-.598; (2.21); P .788
Retail density	**9.655; (3.42); P .006**	2.002; (2.95); P .498	-1.84; (2.50); P .462
Overall Perceived Walkability	**12.845; (4.53); P .006**	4.677; (4.66); P .318	1.02; (3.31); P .758

Note. B = Unstandardised Coefficient; SE. Error = Standard Error; Sig = P-Value. The values in **bold** type are significant.

4. Discussion

This study investigated how spatial variations in high-to-low walkable and comfortable neighbourhoods—considering urban growth patterns, population density, and land surface temperature—affect perceived walkability, walking behaviour, and outdoor thermal comfort (PET) in Buraydah City, Saudi Arabia. Consistent with previous research (Jia & Wang, 2021; Mouada et al., 2019; Tan et al., 2018; H. Wang & Yang, 2019), this study found that participants from high-walkable and comfortable neighbourhoods walked more and had lower PET levels than those from low-walkable and comfortable neighbourhoods. These findings emphasise the importance of walkable environments in promoting physical activity. Additionally, the lower PET levels observed in high-walkable neighbourhoods suggest that urban characteristics such as shaded streets and proximity to various amenities can enhance outdoor thermal comfort and make outdoor walking more feasible, especially in hot climates.

The positive association between perceived neighbourhood characteristics—including land-use mix, street connectivity, land-use intensity, and retail density—and total daily walking aligns with the broader literature on walkability. These characteristics are crucial in shaping the perception of neighbourhood quality, which subsequently influences walking behaviour (Sallis et al., 2016). Interestingly, perceived walkability was also inversely related to estimated PET, suggesting that well-designed, high-density environments can contribute to outdoor thermal comfort by offering shaded areas, reducing exposure to extreme heat and providing cold spots at a close distance (e.g. shops), allowing for more relief from the extreme heat. This relationship was more pronounced in high-walkable neighbourhoods, where higher density and mix of uses contribute to higher walking levels and improved thermal conditions. These findings are in agreement with the work of (Mouada et al., 2019; Won & Jung, 2023), who reported similar associations between neighbourhood characteristics, walking behaviour, and thermal comfort.

However, when individual neighbourhoods were analysed separately, significant relationships between perceived neighbourhood characteristics and PET were not observed. This suggests that while overall walkability may enhance outdoor thermal comfort, the effect of individual neighbourhood characteristics on thermal conditions may vary across different local contexts. The lack of significant findings could also imply that subjective perceptions of thermal comfort are influenced by a complex interplay of factors, including microclimate elements, personal comfort preferences, and social norms, which may not directly correlate with physical neighbourhood characteristics. This highlights the need for urban planners to consider objective and subjective characteristics when designing interventions to promote walkability and outdoor thermal comfort.

The study's findings also support the idea that perceptions of the built environment influence walking behaviour. High-walkable and comfortable neighbourhoods positively influenced individuals' perceptions of their neighbourhoods, potentially shaping their walking habits and comfort levels. According to Bandura's social cognitive theory (1986) (Sallis et al., 2015), the built environment shapes behaviour through both perceptions and sensations, making the perceived quality of the neighbourhood as crucial as its objective characteristics.

The results of this study demonstrate that neighbourhood characteristics such as land-use mix, retail density, and street connectivity are crucial determinants of walkability and outdoor thermal comfort. Urban planners and policymakers should consider these characteristics in future urban development projects, particularly in hot-arid climates like Buraydah City. Enhancing shaded areas, creating mixed-use neighbourhoods, and designing connected streets can potentially increase physical activity levels while improving thermal comfort.

The study presents valuable insights for future urban planning and policy. Creating walkable neighbourhoods in regions with extreme climates involves balancing thermal comfort and accessibility. Enhancing shade through tree planting or infrastructure and encouraging mixed-use development can promote comfort and walkability. Although this study offers important findings, there are opportunities for further research. Longitudinal studies could help reveal how walkability and thermal comfort improvements impact walking behaviour over time. Additionally, incorporating objective measures of walking activity and detailed microclimatic assessments could provide a more comprehensive understanding, reducing potential biases from self-reported data.

The study's findings, while relevant to cities in hot-arid climates like Buraydah, should be interpreted with caution when applied to different climatic regions or urban morphologies. The environmental and urban characteristics specific to Buraydah City influenced pedestrian behaviour and thermal comfort, particularly regarding high summer temperatures and limited green infrastructure. We suggest that future research could extend these findings to cities with varying climates and urban forms to assess the broader applicability of the study conclusions. This approach could provide a more holistic understanding of walkability and thermal comfort across diverse urban environments.

5. Conclusions

This study provides valuable insights into the relationships between neighbourhood walkability, thermal comfort, and pedestrian behaviour in Buraydah City, Saudi Arabia. It enhances understanding of the built environment's objective and perceived characteristics that encourage walking. As one of the first studies in a hot-arid region examining adults' daily walking in relation to outdoor thermal comfort using PET, it underscores the significant impact of neighbourhood design and microclimate characteristics on walking behaviour and thermal comfort levels.

The findings demonstrate that residents of high-walkable neighbourhoods walk more frequently and experience greater thermal comfort than those in low-walkable neighbourhoods, highlighting the benefits of walkable urban environments. Enhancing characteristics such as residential density, land-use intensity, and retail density in low-walkable neighbourhoods is recommended to encourage more walking and improve comfort. Effective microclimate management—such as creating shaded streets through compact developments—plays a crucial role in mitigating urban heat effects, thereby supporting more walkable and livable communities in hot climates. These findings are crucial for urban planners and policymakers to create more sustainable and livable environments, especially in hot-arid climates like Buraydah City.

The study highlights the need for tailored urban planning and design. Low-walkable neighbourhoods could benefit from mixed-use developments, while high-walkable neighbourhoods might be enhanced by adding more green spaces. Urban design principles prioritising walkability and thermal comfort can promote healthier lifestyles. Future research should examine the impact of neighbourhood characteristics, socioeconomic factors, and seasonal variations on walking behaviour using longitudinal studies and advanced tools like GIS and remote sensing.

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Conflict of interest.

The author(s) declare(s) that there is no competing interest.

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