Ground-level documentation of heat stress exposure and response strategies in informal settlements in Tshwane, South Africa

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Abstract

Purpose – The adverse impacts of climate change coupled with rapid informal urbanization in the Southern African region are increasing the vulnerability of already sensitive population groups. Consequently, these urban regions are highly vulnerable to urban heat island effects and heatwaves due to exogenous and endogenous factors. While the dynamic interplay between the built environment, climate and response strategies is known, this paper highlights the lived experience of informal settlement residents. It presents work from a project undertaken in Melusi, an informal settlement in Tshwane, South Africa, as a multi-disciplinary project focusing on improving the local resilience to climate change associated heat stress.

Design/methodology/approach – Following a mixed method approach, a semi-structured observational analysis of the spatial layout and material articulation of selected dwellings along with the continuous monitoring and recording of their indoor environments were undertaken.

Findings – The paper presents the research results in terms of the dwelling characteristics, as spatial and material-use strategies and documented heat stress exposure in these structures. The findings highlight that informal dwellings perform poorly in all cases due to endogenous factors and that inhabitants experience extreme heat stress conditions for between 6 and 10 h daily during the peak summer period.

Originality/value – Currently, there are little empirical data on the heat stress residents living in informal settlements in Southern Africa are experiencing. This article provides insight into the indoor environments of informal dwellings and hopes to contribute future guidelines or heat health policies.

Keywords Adaptive capacity, Climate change adaptation, Heat stress, Informal urbanism, Thermal comfort, Informal dwellings

Paper type Research paper

1. Introduction

The correlation between heat stress, climate change driven temperature increases, urban heat island effects and the built environment is widely known and extensively researched (Kimemia *et al.*, 2020; Di Leo *et al.*, 2016; Orimoloye *et al.*, 2017; Peng *et al.*, 2012; Scott *et al.*, 2017). Yet the majority of the studies focus on how this phenomenon manifests in formal

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urban settings. While the formal urban environment is representative of multiple cities globally, in the Southern Hemisphere, specifically the Southern African context, informality as a typical perpetual urban growth model also requires attention (Pieterse, 2019). Unfortunately, due to their legal status these informal urban sectors are often ignored (Dovey, 2015; Satterthwaite *et al.*, 2020), resulting in limited empirical data and a ground-level understanding of the built environment in these contexts. Developing local adaptive capacities, to lower user vulnerability, must align with local practices to improve the appropriateness and sustainability of proposed adaptation measures (Simpson *et al.*, 2021). Yet the lack of data of these informal settlements limits our ability to develop and leverage response strategies that lower local heat stress vulnerabilities. This study aims to address this by analysing the ground-level empirical data of local indoor temperatures and thermal control response measures undertaken by residents of the Melusi informal settlement in Tshwane, South Africa.

It is well known that the built environment is a contributory factor to public health and wellbeing (WHO, 2018). While several studies have addressed this link through policy suggestions, design guidelines and capacity building initiatives (Lavin *et al.*, 2006; Renalds *et al.*, 2010), more focus on the assessment and implementation of response strategies in informal settlements is needed (Weimann and Oni, 2019).

As part of a larger research project, the *Architecture and Public Health Nexus* project undertaken in Melusi, this paper presents the findings from one objective of this project. The larger research project aims to expand our understanding of public health and wellbeing in informal urban contexts. It follows an inter- and trans-disciplinary approach to develop more focused, appropriate assessment measures to identify feasible, locally appropriate and rapid response measures. This paper unpacks ground-level, empirical data of the indoor thermal environments collected from a sample of dwellings located in an informal settlement and how these relate to the dwellings' spatial and material characteristics. The findings contribute to the current climate change adaptation discourse, in particular exploring measures to improve the resilience of informal environments.

2. Literature review

The current and future effects of climate change have been widely reported (IPCC, 2021). While a myriad of impacts are expected in South Africa, higher temperatures are of particular concern as the average temperature in the Southern African region is projected to increase by 1.5–2 times the global average temperature increase (DEA, 2013). In addition, extreme weather events will become more prevalent in Africa with intense heat waves set to occur more frequently from 2045 onwards (Russo *et al.*, 2016). In Tshwane the number of extreme heat days, temperatures above 35 °C, are projected to increase to 48.54 days per year by 2050 (City of Tshwane, 2022). These exogenic drivers are also coupled with the endogenic factors, such as current urban forms, built-up density, loss of vegetation, building materials and anthropogenic heat sources (Li *et al.*, 2022; Seto and Shepherd, 2009), resulting in increased urban heat island impacts and heat stress. These higher temperatures ultimately affect the user wellbeing causing heat cramps, exhaustion, heat syncope, heat strokes and potentially death (Kimemia *et al.*, 2020). It specifically affects vulnerable individuals such as children, the elderly and pregnant women (Razzak *et al.*, 2022; Roos *et al.*, 2021).

The interaction between climate change, built environment and public wellbeing has been studied extensively (Watts *et al.*, 2015), unfortunately limited work has been undertaken in the informal built environment (Weimann and Oni, 2019). In the African context this is of specific concern as this continent is set to experience exponential urban growth, yet the lack of research, limited formal planning and rapid growth of these cities place them under significant risk to disaster events (IPCC, 2022; Li *et al.*, 2022). Furthermore while initiatives to upgrade informal settlements exist, little attention is given to the physical, mental and social wellbeing of residents in informal settlements during these upgrades (Weimann and Oni, 2019). This does not mean that these marginalised communities are completely ignored, as some studies have highlighted and investigated this urban phenomenon (Dovey, 2015; Pieterse, 2019; Satterthwaite *et al.*, 2020; Taylor *et al.*, 2020). The recent vulnerability analysis of the City of Tshwane also identifies these informal settlements as highly vulnerable to disruptions and extreme weather events (COT; CSIR, 2021). While acknowledging the plight of these marginalised sectors is welcome, limited fine grain, ground-level data of the informal settlements in Tshwane and the larger Southern African region are available.

Recently studies focusing on heat stress in informal settlements have done pioneering work in these communities. Studies by Adegun and Ayoola (2022), Baruti and Johansson (2020) and Bek *et al.*, (2018) analyse heat stress and the urban heat island impacts in informal communities in Nigeria, Tanzania and Egypt, respectively. Informal, unplanned neighbourhoods are noted to be between 1 and 4 °C hotter than adjacent formal neighbourhoods (Bek *et al.*, 2018). Furthermore, Adegun and Ayoola (2022) find that the urban poor, often in informal settlements, are more vulnerable and affected by higher temperatures due to their limited capacity to acquire active cooling solutions such as air conditioning. Baruti and Johansson (2020) report that inhabitants in Dar es Salaam typically use behavioural heat stress management measures such as congregating in shaded outdoor spaces and using hand fans, yet they note in informal settlements the public space quality is typically poor with limited vegetation and shading.

There is an increasing focus on improving informal settlements with several studies proposing interventions such as informal settlement upgrade initiatives (Huchzermeyer, 2006; Ntema *et al.*, 2018; Saad *et al.*, 2019). While limited work on the health and wellbeing of residents during such upgrades has been undertaken thus far, Shortt and Hammett (2013) analysed the general health conditions in informal settlements in Cape Town highlighting improved wellbeing, specifically mental wellbeing, reported after such a process. Similarly selected studies focus on heat stress in poorer communities in South Africa, field projects documenting the thermal conditions of low cost dwellings in rural and urban regions in South Africa highlight the risks that climate change driven temperatures pose and call for national heat health plans and early warning systems as response measures (Kapwata *et al.*, 2018; Naicker *et al.*, 2017). Some studies have started postulating solutions, such as the work of Kimemia *et al.* (2020) and Nutkiewicz *et al.* (2022) which specifically consider technological improvements to the facades of informal dwellings to lower heat stress exposure. These studies undertook controlled simulations and the adaptation of typical informal dwellings (Kimemia *et al.*, 2020) and digital simulations of these dwellings (Nutkiewicz *et al.*, 2022). While simulation studies are valuable, the discrepancies between the reality and simulated conditions are often highlighted (Hugo and du Plessis, 2020), prompting us to collect empirical data in an existing informal context and consider the heat stress exposure of the residents.

3. Research methodology

This project is based on a Pragmatism paradigm and sets out to document reality as closely as possible. This required the use of a mixed method research design, involving semi-structured observational analyses and collecting empirical indoor environmental data of selected dwellings. The study area, Melusi (S25°43'28.524", E28°7'24.333"), is an informal settlement located in Tshwane, South Africa. The settlement was established in 2008 and has grown rapidly since its inception. It is estimated to accommodate 27,000 residents at an approximate density of 160 residents per hectare, more than seven times the density of the surrounding formal neighbourhoods. The most dwellings are constructed from corrugated metal sheeting and are self-built. A non-probability sampling method was used to identify, analyse and monitor nine dwellings. The selected homes are located in the densest (built-up) section of the settlement. Furthermore a convenience sampling approach was used to identify willing participants to finalise the sample selection. The sample represents a typical informal housing typology constructed from corrugate sheeting fixed to a timber substructure using limited thermal insulation (Plate 1). This is representative of several informal settlements in Southern Africa (Dovey, 2015; Kimemia *et al.*, 2020).

The data was collected by a student cohort, and the field work was undertaken during multiple site visits. This involved semi-structured observational analyses that included structured surveys, open-ended photographic and drawing analyses and using reflexive diaries. The indoor environment was monitored by developing a low-cost, solar powered monitoring system. The sensors documented, amongst others, dry-bulb, wet-bulb temperatures and relative humidity. These sensors were installed in a shared room, typically the living room or kitchen, that is often used and installed between 1,000–1,600 mm above ground level. The data collection system includes an enclosed printed circuit board that houses an Esspressif ESP32 microcontroller, DS3132 real-time clock module, SD card, power management circuit and battery. Attached to this is a series of sensors that measure dry-bulb temperature, wet-bulb temperature and relative humidity (Table 1). SSN-22-USB loggers were added to limit any data losses and the sensors were calibrated to ensure the interpolation of the data. The SSN-22-USB loggers measured the dry-bulb temperature and relative humidity (Table 1). The data were captured using a user-activated Wi-Fi data transferring method and were downloaded intermittently.

A local weather station was installed in the community to collect the local micro climatic data. An HP200 Wi-Fi wireless weather station was used, it functions between −30 and +65 °C, 0–99% relative humidity and wind speeds of up to 30 m/s. It was located in an open vegetated area with no overshadowing and within 800 m of the sample dwellings.

Plate 1.
Example of a typical dwelling that were selected for the study

Table 1.
Sensor infrastructure information and accuracy

Measurement	Device	Range	Accuracy
Dry bulb temperature	Bosch BME280	0–65 °C	±0.5 °C
	Maxim DS18B20	−10 – 85 °C	
Wet bulb temperature	Maxim DS18B20	−10 – 85 °C	±0.5 °C
Relative humidity	Bosch BME280	20–80% RH	±3%
Dry bulb temperature	SSN-22-USB	−35 – 80 °C	±0.3 °C
Relative humidity	SSN-22-USB	0–100% RH	±3%

The spatial and material data collected during the observational analysis phase were translated using a CAD programme to accurately document each dwelling which were subsequently translated into the quantitative building parameters and analysed using descriptive statistics (Figure 1). Similarly, the indoor environment data were also analysed using descriptive statistics. The thermal comfort and heat stress were considered using the humidex index (Table 2). The humidex index was developed by Masterson and Richardson (1979) [23] for Canadian conditions, but has been used extensively in studies globally (Rana *et al.*, 2013), similarly by several studies in South Africa (Kimemia *et al.*, 2020; Orimoloye *et al.*, 2017). Although it is not a perfect heat stress indicator, it is convenient to use in contexts with data limitations as it only requires air temperature and relative humidity. The wet-bulb, dry-bulb temperatures and relative humidity were used to derive the saturated vapour pressure employed in the humidex calculations as developed by Sirangelo *et al.* (2020).

Research ethics approval (UP 363/2020) has been obtained prior to collecting any data and the dwellings were defined with non-identifiable codes to retain the owners' anonymity. The dwellings are defined with a numeric identifier, H1 to H9. In terms of research limitations, the data collection in informal conditions has proven to be more complicated than expected. Due to intermittent sensor disruptions, only selected data were available to analyse the indoor environment. At times when the relative humidity data were missing a method employed by Huang *et al.* (2013) was used to derive the missing data. Finally, the findings are only applicable to the residential typology documented in the study and is not representative of all indoor thermal conditions in Southern Africa.

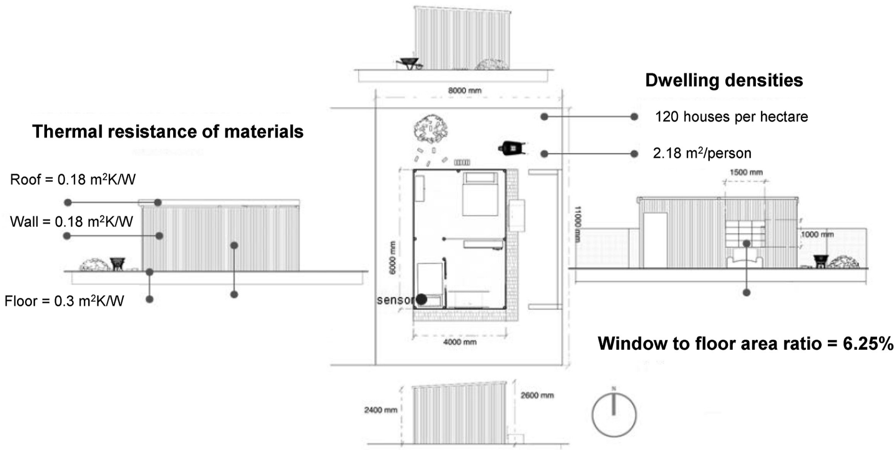

Figure 1.
Example of a sample dwelling translated into a CAD drawing to define the dwelling's performance characteristics

Table 2.
Humidex index and indicators as defined by United States National weather service

Humidex index Index range	Warning	Possible health impairments
21–25	Less evident	Fatigue with prolonged exposure
26–32	Caution	Fatigue
33–37	Extreme Caution	Muscle cramps, sunstroke, heat exhaustion
38–48	Danger	Sunstroke, heat failure, sun burn, skin rashes, fainting
>49	Extreme Danger	Heatstroke, heart failure, skin rashes

Source(s): Referenced in Orimoloye *et al.* (2017)

4. Findings and discussion

4.1 Observational analysis of selected dwellings

A selection of nine dwellings were analysed in terms of their spatial, material characteristics and their indoor environment (defined as H1 to H9). From the observational analysis, limited critical differences were documented and the findings are representative of typical corrugated houses built in Southern African informal settlements. The most important differences are the building orientation, and the dwelling and user densities, while similar construction and layout responses were noted throughout the sample selection (Tables 3–6).

The dwellings sizes are generally small and, in some cases, concerning in terms of their feasibility to accommodate the building occupants. The dwelling sizes range from 12.9 to 54.5 m^2 (mean floor area: 31.5 m^2) (Table 4). As a result, the occupancy density also differs significantly ranging from 3.2 to 13.6 m^2/person (mean occupancy density: 6.3 m^2/person) (Table 2). The occupancy density fluctuates during the day, but points to a generally high user density leading to high indoor heating loads. These densities are often achieved by allocating multiple functions to living rooms or kitchens. Eight of the dwellings clearly demarcate the bedrooms from the rest of the house, while one dwelling only had a single space functioning as both kitchen and bedroom (Table 4).

In terms of the site and building layouts, the sites on which the dwellings are located are generally small and spatially optimised. The building footprint coverage of the sites range from 31 to 80% (mean coverage: 47%), while the dwelling density, at a site scale, ranges from 58–222 dwellings per hectare (mean density: 121 d/ha) (Table 3). Notably this does not represent the settlement as a whole and over the study period (18 months) multiple buildings have been added and removed on these sites.

Importantly, the orientation of the sites and units are planned according to access, space availability and the general urban layout. As a result, limited dwellings have north/south aspects for solar control optimisation (Table 3). While these dwellings' orientation is not optimal for solar gain and control, they are also poorly insulated with limited glazing and solar control (Tables 4 and 5). Finally, the vegetation coverage is low, ranging from none (0%) on many sites to a maximum of 15% (considered an outlier in the sample group). The mean vegetation coverage is 4.0% (Table 3).

Unit	Coverage %	Dwelling density (units per hectare)	Site aspect[1]	Building aspect[1]	Vegetation coverage %	Parameter structures and enclosure overshadowing[2]
H1	44	63	73° (East)	73° (East)	2.5	39% @ 3 m (h)
H2	27	114	90° (East)	90° (East)	0	50% @ 2 m (h)
H3	65	168	0° (North)	90° (East)	0	75% @ 2 m (h)
H4	80	222	11° (North)	11° (North)	4	50% @ 2.5 m (h)
H5	23	58	270° (West)	270° (West)	7	30% @ 2.5 m (h)
H6	62	159	352° (West)	352° (West)	2.4	50% @ 2.3 m (h)
H7	36	92	90° (East)	0° (North)	5	27% @3 m (h)
H8	31	58	270° (West)	270° (West)	15	10% @ 2.5 m (h)
H9	58	156	270° (West)	270° (West)	0	53% @ 2.6 m (h)

Note(s): 1: Aspect refers to the orientation with 0° representing true north
2: The surrounding structures on the parameter and boundary walls were defined in terms of the percentage of parameter which is enclosed and what the typical height of the parameter structure or wall is

Table 3. Site and dwelling layout

Unit	Floor area (m^2)	Floor area to volume ratio %	Window to floor area ratio %	Occupant density (m^2/person)	Number of rooms	Types of rooms
H1	54.5	42.5	8.3	13.6	3	• Living Room and Kitchen • Main • 2 Bedrooms
H2	24	37.9	6	2.2	2	• Living Room, Kitchen and Bedroom • Bedroom
H3	36	38.5	10	7.2	4	• Living Room • Kitchen • 3 Bedrooms
H4	25.9	43.7	9.1	5.3	5	• Living Room and Kitchen • 3 Bedrooms Restaurant
H5	40	40	0	10	3	• 2 Bedrooms • Kitchen and living
H6	37.5	42.9	2.2	4.6	5	• Living Room and Kitchen • 2 Bedrooms • 1 Rental Room
H7	22.5	43.5	8.9	7.5	2	• Living Room, Kitchen and Bedroom • Bedroom
H8	30	38.5	0	3.3	3	• Kitchen and Living • 2 Bedrooms
H9	12.9	39.7	13.9	3.2	1	• Bedroom and Kitchen

Table 4.
Dwelling scale layout and volume

Unit	*R*-Value: Wall (m^2K/W)	*R*-Value: Roof (m^2K/W)	Reflectivity fraction	Shading window	Shading building	Air leakage
H1	0.175	0.202	0.3	Noted	Noted	Leaky, multiple gaps
H2	0.175	0.175	0.5	–	–	
H3	0.18	0.201	0.6	–	–	
H4	0.19	0.19	0.3	Noted	Noted	
H5	0.175	0.28	0.6	–	–	
H6	0.19	0.19	0.3	Noted	Noted	
H7	0.275	0.202	0.3	–	Noted	
H8	0.19	0.19	0.4	–	–	
H9	0.19	0.19	0.6	Noted	–	

Table 5.
Material use and application

The window to floor area ratio (WFA) of the various dwellings are generally low, with two of the units being windowless (H5 and H8) (Table 4). Notably, the one dwelling with a WFA of more than 10% has the smallest floor area and still only has a single window. In terms of shading, only 4 of the 9 units use some form of solar control. Three of these coordinated the outdoor shaded area with the window openings to ensure that these are shaded (Tables 5 and 6).

Table 6.
Climate control strategies noted in the dwellings

Unit	Climate control strategies and practices	Open covered spaces	Coverage proportion[1] %
H1	• Heater in the bedroom • Curtains used to cover the internal walls • Veranda shades large portion of the house and two large windows	Noted	23
H2	• None	None	0
H3	• Curtains used to cover the internal walls	None	0
H4	• Veranda used as shading and outdoor space • Shading of Western wall with shade netting	Noted	48
H5	• Swimming pool cover as interior wall insulation • Newspaper and plastics used to fill the gaps between walls and roof	None	0
H6	• Veranda used a shading and outdoor space	Noted	14
H7	• Insulation board used in the walls of the main bedroom	None	0
H8	• None	None	0
H9	• None	None	0

Note(s): 1: The proportionate segment of the total building footprint that functions as a covered veranda

Yet their ultimate impact on the indoor environment is limited as all the dwellings are constructed from corrugated iron sheeting with limited to no thermal insulation (dwellings H4 and H7 use self-made insulation from found objects) (Tables 5 and 6). While the South African National Standards (SANS) define the minimum thermal resistance for lightweight walls in the Tshwane region as 1.9 m^2K/W (SABS standards Division, 2022), the thermal resistance value (*R*-value) of the documented dwelling walls ranges from 0.175 to 0.19 m^2K/W. One dwelling attempted some form of self-made insulation which was assumed through observation as having an *R*-value of 0.275 m^2K/W (H7) (Table 5). Similarly, the thermal resistance of the roof structures ranges from 0.19 to 0.28 m^2K/W, while the national standard for this region requires roof insulation of 3.7 m^2k/W (SABS Standards Division, 2022) (Table 5). The envelope finish of the various dwellings varies from new zinc coated sheeting to older sheeting with darker rust discolouring, only two of the dwellings are painted a beige (off-white) colour. Notably the neighbourhood has significant dust pollution, therefore the albedo rates of the dwelling envelopes are assumed to be low.

Finally, limited indoor climate control practices were observed. Four of the dwellings use shade netting to shade the structures themselves, while three of these also use verandas to provide covered outdoor spaces and shade the structures (Table 6). While the limited occupation of these outdoor spaces was observed, this can be attributed to the time of the site visits. It was noted that other shaded outdoor spaces such as taverns and shops are extensively used. In one of the dwellings the covered outdoor space account for 48% of the total floor area (H4), this space is used to run a take-a-away shop and is significantly more comfortable.

The observational analysis noted that the dwellings' construction, material use, layout and site coverage are similar with little variation. The building aspects, outdoor spaces and user densities presented the only significant differences. In terms of climate control practices using open covered spaces proves to be effective, yet limited use of mechanical cooling/ ventilation strategies (such as fans) was observed.

4.2 Indoor environment findings

The analysis of the indoor environmental data was undertaken in selected dwellings. Due to the pragmatist nature of the study, with the emphasis on documenting the living conditions of the informal settlement dwellers, several data limitations had to be addressed (see Section 3). This paper discusses the findings from data collected over selected seven-day periods.

Due to data limitations experienced during the 12 months data collection period, the study analysed selected dwellings for specific periods during the summer and winter solstices and the equinox periods. Furthermore, the study also considered the indoor thermal conditions during January which is typically the hottest month of the year. Notably the analysis did not always consider the same houses from the sample selection. While this do not allow for the easy comparison of the various dwellings' performance, the findings reveal a general lived experience of the inhabitants. Each of the analysis periods have at least five dwellings representing the thermal performance and as noted in Section 4.1 that the dwellings closely represent a general typology found in informal settlements. Limited variation in the performance of the dwellings were also noted (see Section 4.1), providing us with empirical data of the inhabitants' overall heat stress exposure.

The analysis of the mean indoor dry-bulb temperatures reveals consistent temperature conditions within the various dwellings; in June (winter) the range is 15.6–16 °C, in September (spring) it is 19.3–22.4 °C, in December (summer) it is 21.5–26.1 °C, in March (autumn) the range is slightly lower being 20.8–23.6 °C, while January (midsummer) representing one of the hottest months the range is between 24–28 °C (Tables 7 and 8). Given the dwellings' poor thermal insulation, the diurnal temperature swings are significant with concerning maximum dry-bulb temperatures of above 35 °C noted in June (H2), September (H3, H5 and H7), while in December, March and January such maximum dry-bulb temperatures were documented in all the dwellings except in H8 (Table 6). Temperatures of above 40 °C were documented in

Documentation period	Unit	Mean (°C)	Min (°C)	Max (°C)	Standard deviation	Kurtosis	Skewness	Count
June (7 Days)	H1	15.6	4.8	31.0	7.8	−1.27	0.35	672
	H2	15.7	3.0	36.9	7.5	−1.22	0.19	672
	H4	15.6	4.8	31.0	7.6	−1.22	0.35	672
	H5	15.9	4.8	30.4	7.0	−1.11	0.42	672
	H7	16.0	3.5	32.6	8.6	−1.27	0.44	672
	H8	15.9	5.8	26.6	6.1	−1.35	0.18	672
September (7 Days)	H3	22.4	11.8	39.8	7.3	−0.65	0.77	672
	H5	19.3	5.8	36.0	7.2	−0.73	0.20	672
	H6	20.2	9.6	34.5	5.9	−0.74	0.60	672
	H7	22.0	10.6	40.7	7.7	−0.75	0.69	672
	H8	19.6	8.2	31.7	6.7	−1.22	0.27	672
December (7 Days)	H1	26.1	16	46	8.4	−0.96	0.65	672
	H2	23.0	14.7	38.5	6.5	−1.06	0.52	672
	H3	25.1	16.4	43.1	7.1	−0.98	0.62	672
	H4	24.9	14.4	43.8	8.0	−1.05	0.56	672
	H5	24.9	16.6	38.2	5.9	−1.00	0.48	672
	H6	24.1	15.0	40.1	6.6	−0.94	0.57	672
	H7	25.4	15.6	43.5	7.6	−1.18	0.51	672
	H8	22.5	15.0	33.0	4.7	−1.11	0.35	672
	H9	25.6	14.2	44.0	9.7	−1.24	0.53	672
March (7 Days)	H1	22.9	13.9	38	5.5	−0.17	0.87	672
	H2	20.8	12.4	35.3	5.2	−0.01	0.91	672
	H3	22.6	12.8	38.7	5.5	0.24	0.95	672
	H4	23.6	12.2	38.6	7.0	−1.10	0.40	672
	H5	23.2	14.4	38.0	5.0	0.24	0.93	672
	H7	23.5	13.0	41.0	6.6	−0.03	0.96	672
	H8	21.6	15.5	33.1	4.6	−0.43	0.64	672

Table 7. Dry bulb temperature descriptive statistics for the various analysis periods

September (max: 40.7 °C), December (max: 46 °C), March (max: 41.0 °C) with the highest temperatures documented in January (max 48.5 °C) (Tables 7 and 8 and Figure 2).

Figure 2 represents the 24-h period during which the maximum dry-bulb and wet bulb temperatures were documented (H1 and H7). As expected, the maximum temperatures were documented in the afternoons with high solar exposure, during these periods indoor dry-bulb temperatures of 48.5 °C (H1) and 45.9 °C (H7) were documented. During the same period the local ambient temperatures were 31.2 °C and 32.5 °C, respectfully. Given the poor thermal insulation, the indoor temperatures quickly dissipate after sunset. While these excessive indoor temperatures are not retained, it is concerning that indoor temperatures of above 30 °C were documented on those specific dates from 09:00 to 18:00 (H7) and 08:00 to 19:00 (H1) (Plate 1).

Heat stress is considered one of the principal climate change related impacts expected in the Southern African interior and is of particular concern in Tshwane (COT; CSIR, 2021). The humidex index was used to understand the heat stress experienced in these dwellings. While high peak temperatures were only documented for short periods, the percentage and level of exposure to excessive heat stress were calculated over the 7-day analysis period (168 h). It is noted the that indoor environmental conditions worsens to concerning heat stress conditions during the summer and autumn periods (Table 9). As expected, the heat stress exposure shifts from low temperatures with limited heat stress exposure in winter and early spring (June and September), to conditions presenting “Caution” to “Danger” in December (73–93% of the time). Concerningly, by January the indoor conditions become critical with 45–53% of the time representing “Extreme Caution” to “Extreme Danger” conditions (Tables 9 and 10). The high diurnal swing is also important to note, even during the cooler winter period the indoor environments slips into “Caution” and “Extreme Danger” conditions with outliers representing high heat stress exposure for 18–28% of the time (Table 9).

While the study did not set out to specifically document heat wave events. In Table 11, the poor performance dwellings during comparatively cooler and hotter periods are presented.

Table 8.
Dry bulb temperature descriptive statistics for the hottest month

Documentation period	Unit	Mean (°C)	Min (°C)	Max (°C)	Standard deviation	Kurtosis	Skewness	Count
January (7 Days)	H1	28.0	18.5	48.5	8.9	−0.82	0.82	672
	H2	24.4	16.0	40.0	6.7	−0.90	0.67	672
	H3	26.6	17.5	43.2	7.7	−1.07	0.7	672
	H4	26.9	16.8	42.9	7.9	−1.08	0.62	672
	H5	26.3	17.7	41.5	6.1	−0.81	0.69	672
	H6	26.1	17.7	44.1	7.2	−0.84	0.73	672
	H7	27.4	17.4	45.9	8.6	−0.99	0.73	672
	H8	24.0	16.3	34.7	4.9	−1.11	0.48	672

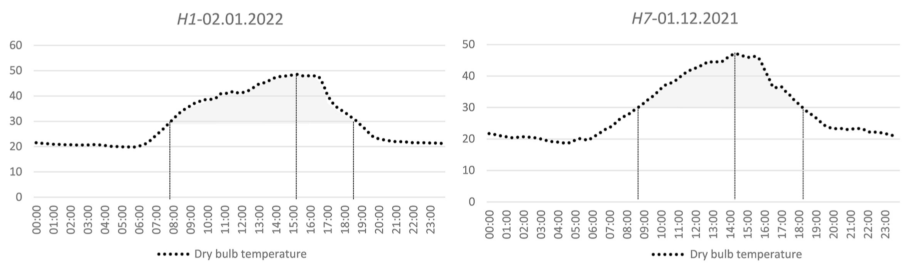

Figure 2.
Dry-bulb temperatures documented over a 24-h period (H1 and H7)

		Humidex	Humidex Exposure: Percentage of hours					
Documentation Period	Unit	Mean	No Concern	Less Evident	Caution	Extreme Caution	Danger	Extreme Danger
			< 20	21-25	26-32	33-37	38-48	>49
June (7 Days)	*H1*	16.4	*65 %*	15 %	20 %	0 %	0 %	0 %
	H2	20.1	*53 %*	14 %	19 %	12 %	2 %	0 %
	H4	16.7	*65 %*	16 %	19 %	0 %	0 %	0 %
	H5	21.1	*53 %*	12 %	16 %	14 %	4 %	0 %
	H7	22.2	*55 %*	8 %	8 %	11 %	18 %	0 %
	H8	20.6	*53 %*	13 %	28 %	6 %	0 %	0 %
September (7 Days)	*H3*	25.1	*34 %*	29 %	19 %	15 %	2 %	0 %
	H5	30.5	*25 %*	12 %	*22 %*	12 %	20 %	9 %
	H6	21.3	*55 %*	24 %	21 %	0 %	0 %	0 %
	H7	24.6	*42 %*	22 %	18 %	15 %	3 %	0 %
	H8	27.2	*29 %*	19 %	19 %	14 %	18 %	0 %
December (7 Days)	*H1*	32.9	0 %	23 %	*34 %*	13 %	*30 %*	0 %
	H2	31.3	0 %	27 %	*32 %*	21 %	19 %	0 %
	H3	33.2	0 %	7 %	*50 %*	16 %	*27 %*	0 %
	H4	31.9	1 %	26 %	*32 %*	15 %	*27 %*	0 %
	H5	32.6	0 %	7 %	*50 %*	24 %	19 %	0 %
	H6	31.6	0 %	20 %	*39 %*	21 %	21 %	0%
	H7	32.8	0 %	22 %	*33 %*	14 %	31 %	0 %
	H8	30.8	0 %	17 %	*47 %*	33 %	3 %	0 %
	H9	32.6	0 %	24 %	*33 %*	11 %	*32 %*	0 %
March (7 Days)	*H1*	29.7	3 %	18 %	*54 %*	21 %	4 %	0 %
	H2	28.3	3 %	32 %	*45 %*	17 %	2 %	0 %
	H3	30.5	3 %	14 %	*52 %*	22 %	9 %	0 %
	H4	29.7	7 %	26 %	*33 %*	22 %	11 %	0 %
	H5	30.6	1 %	13 %	*57 %*	22 %	7 %	0 %
	H7	31.2	3 %	16 %	*46 %*	19 %	16 %	0 %
	H8	28.8	3 %	22 %	*56 %*	19 %	0 %	0 %

Note(s): Largest proportion of heat stress exposure highlighted and in italic text

Table 9. Humidex analysis of the indoor environment of sample group

		Humidex	Humidex Exposure: Percentage of hours					
Documentation Period	Unit	Mean	No Concern	Less Evident	Caution	Extreme Caution	Danger	Extreme Danger
			< 20	21-25	26-32	33-37	38-48	>49
January (7 Days)	*H1*	35.7	0 %	1 %	*52 %*	14 %	28 %	6 %
	H2	34.0	0 %	5 %	*49 %*	16 %	30 %	0 %
	H3	35.7	0 %	0 %	*51 %*	15 %	34 %	0 %
	H4	35.2	0 %	2 %	*45 %*	19 %	33 %	0 %
	H5	35.0	0 %	1 %	*47 %*	20 %	32 %	0 %
	H6	34.6	0 %	1 %	*54 %*	12 %	32 %	1 %
	H7	35.9	0 %	2 %	*50 %*	13 %	27 %	8 %
	H8	33.7	0 %	1 %	*51 %*	24 %	25 %	0 %

Note(s): Largest proportion of heat stress exposure highlighted and in italic text

Table 10. Humidex analysis of the indoor environment for the hottest month

Two weeks in March were documented that had a 2.8 °C difference in mean ambient temperature (18.6 vs 21.4 °C), resulting in the local maximum ambient temperature differing with 1.3 °C (29.7 vs 31.0 °C). Considering the worst and best performing dwellings, in terms of

Table 11.
Dwelling performance comparison (10–16 March vs 16–22 March)

		10–16 March	16–22 March
Local weather	Mean (°C)	21.4	18.6
	Min (°C)	15.7	10.7
	Max (°C)	31.0	29.7
H7	Mean (°C)	26.1	23.5
	Max (°C)	43.9	41.0
	Humidex Mean	34.8	31.2
	Humidex Exposure (*Caution -Extreme Caution)*	67%	66%
	Humidex Exposure (*Danger -Extreme Danger)*	31%	16%
H8	Mean (°C)	24.4	21.6
	Max (°C)	35.0	33.1
	Humidex Mean	32.5	28.8
	Humidex Exposure (*Caution -Extreme Caution)*	87%	75%
	Humidex Exposure (*Danger -Extreme Danger)*	10%	0%

their mean humidex conditions (H7 and H8), we see both dwellings shifting into higher temperature regimes (Table 11). In H7 the "Danger" to "Extreme Danger" conditions increase from 16% to 31% over a seven-day period, representing 52 h over a full week. The better performing dwelling, H8, experiences a 10% shift from "Danger" to "Extreme Danger" conditions. While the hotter period, 10 to 16 March, was not defined as a heat wave event as per the South African National Weather service criteria (SAWS, 2022) notably during the small temperature increases both dwellings shift into much more dangerous heat stress regimes.

Finally, considering the general humidex exposure of the dwellings from November (2021) to June (2022), the mean temperatures range from 22.0 to 25.5 °C, while the mean humidex conditions range from 29.2 to 33.5. While the mean humidex conditions are not considered that high, the inhabitants of these dwellings experience "Extreme Caution" to "Extreme Danger" conditions for between 30–45% of the time. On the other hand, the data proves concerning as the midsummer data in January reveal that 25–35% of the time represents "Danger" to "Extreme Danger" heat stress conditions (Table 10). This typically translated to extreme heat stress exposure for between 6 and 10 h per day, preventing the safe inhabitation of the dwellings during the day time. This supports the findings from Kimemia *et al.* (2020) noting in their study that approximately 50% of a study period exceeds the critical heat stress threshold.

4.3 Discussion of findings

The analysis of the dwellings documented in an informal settlement in Tshwane, South Africa, point towards similar spatial and material conditions and congruent indoor environments. As noted, the maximum temperatures vastly exceed the ambient thermal conditions and due to the limited thermal control strategies documented in the dwellings we can assume that endogenic factors drive much of the documented heat stress conditions. Importantly, these conditions were not documented during heatwave events and the current climate change data point to significant future temperature increases (DEA, 2013), these exogenic conditions will only serve to increase the heat stress risk of these communities.

The indoor environmental analysis reveals concerning high temperatures throughout the sample group regardless of orientation, position, or context. While mean dry-bulb temperatures of above 24 °C were documented in January, low winter temperatures of below 10 °C were also noted in June. Although temperatures below freezing (<0 °C) were not documented, the thermal fluctuations due to the poor insulation result in discomfort and high energy needs in a poorly serviced and under-resourced community. Yet more concerning is the hidden impact of high thermal conditions and increased heat stress. The fact that 45% of the analysis period (November to July) present “Extreme Caution” to “Extreme Danger” conditions, means that during heatwave events these dwellings will have no capacity to lower the inhabitants’ exposure to heat-related risks.

While the spatial and material variations between the households are limited, the fact that some dwellings do not have windows or that two dwellings are painted with lighter colours has little impact on their indoor environmental performance. The poor thermal resistance proves to be detrimental and will require significant adjustments to address the high indoor temperatures. Whether this only requires thermal insulation in the roof structures or the complete overhaul of the building envelopes will need to be tested. To make such adjustments will certainly not be simple and will require the participation and ‘buy-in” from homeowners. In addition, as none of the dwellings have proven to perform better, this will effectively require that the majority of the residences in the settlement be reconstructed. The scale of this problem is extensive, as this study area represents a typical Southern African informal settlement (Kimemia *et al.*, 2020). In addition, associated research findings, from previous research, have noted that the same community perceives heat stress (and the high indoor temperatures) as a negligible problem. This highlights the community’s vulnerability as they need to navigate multiple risks, but also the potential of heat stress as a hidden disturbance that will slowly become unmanageable as future global average temperatures increase. Finally, the findings also put to question the relevance of heat stress indicators, such as the humidex index developed for alternative climatic conditions, yet one should take care to not dismiss these high thermal conditions with indifference due to the supposed higher tolerance of the inhabitants as these high thermal conditions still have adverse health impacts (Kimemia *et al.*, 2020; Wright *et al.*, 2021).

The findings reveal the need for the wholescale adaptation of the dwellings which might prove both socially and economically unfeasible. This calls for alternative solutions to address these current and future heat stress risks. The vulnerable population sectors to heat stress, i.e. young, elderly and pregnant women, typically have little agency to reconfigure their dwellings. Developing thermal refuges in these informal settlements might be the only feasible approach to lowering the locals’ exposure to heat stress and supporting vulnerable sectors of society. This calls for the development of local heat wave and urban heat island infrastructure and response strategies as advocated by the South African National Heat Health Guidelines (National Department of Health, 2020). These strategies include adapting specific public spaces (community centres, clinics or preschools) to lower heat stress exposure, integrating open public spaces with ecosystem services and improving local knowledge regarding heat stress and appropriate practices to lower its risks.

5. Conclusions

As an analysis of the ground-level heat stress exposure and response measures of selected dwellings in informal settlements in South Africa, the findings highlight the high level of exposure that the residents endure as well as the dwellings’ limited capacity to lower the current and future exposure to heat stress. While the findings are not unexpected, in contrast to Nutkiewicz *et al.* (2022) analysis of informal settlements in South Africa, the level of heat stress exposure and maximum temperatures are alarming, calling for innovative response measures. This will require multiple tactics to address the dwellings’ performance, but more importantly integrate neighbourhood-wide response measures to provide rapid and effective solutions.

Upon reflection, due the pragmatist approach of this study, it was fundamental to document the empirical data of the dwellings located within their informal context. Yet, due to the unregulated, rapidly changing and underserviced nature of these settlements the collection and long-term stability of these indoor sensors were often compromised. This resulted in difficulties in accessing sites and collecting the data, ultimately, resulting in data gaps. This prompted us to reconsider the nature of data deemed feasible to use and how we process the data to present a single overview of the findings. The inclusion of multiple houses assisted in presenting a more complete understanding of the heat stress exposure that the inhabitants endure on a daily basis.

As the data represents a 12-month data collection period and extremely high temperatures were often noted during the day, with more comfortable conditions after sunset, understanding therefore the correlation between the high temperatures, user patterns and lived experiences will be required to fully understand the user sensitivity to the heat stress exposure. In addition, this project will also aim to develop a community resilience plan, which will be co-created in collaboration with the community members. This is specifically needed as the extent of the response measure will need to be community-wide and grounded within the context.

As future research, similar studies can be undertaken in informal settlements located in different climate regions to collate more data regarding regional heat stress exposure in informal settlements. This can aid in developing appropriate national heat health response policies with more targeted interventions accounting for climatic, settlement morphology and building typology differences in these settlements.

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