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EDITED BY
Christos H. Halios,
Public Health England, United Kingdom

REVIEWED BY
You Peng,
Eindhoven University of Technology, Netherlands
Ali Soltani,
Flinders University, Australia
Farzad Hashemi,
University of Texas at San Antonio, United States

*CORRESPONDENCE
Azadeh Lak,
a_lak@sbu.ac.ir

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A conceptual framework to mitigate the adverse effects of surface urban heat islands through urban acupuncture: a two-phase scenario of diagnosis and prescription at the neighborhood scale

S. Mohammad Reza Moussavi A., Azadeh Lak* and Nasibeh Tabrizi

Department of Architecture and Urban Planning, Shahid Beheshti University, Tehran, Iran

Rising temperatures, a major global environmental challenge, negatively impact health, the environment, society, and the economy. Surface Urban Heat Islands (SUHI), exacerbated by urbanization and climate change, intensify vulnerabilities for urban areas and residents. Urban planning and design aime to reduce these vulnerabilities through large-scale and small-scale interventions. However, addressing the significance of the capillary effects resulting from small-scale interventions and bottom-up community engagement is important. Urban acupuncture (UA) is an emerging approach in contemporary urban planning and design that focuses on small-scale interventions to mitigate the effects of SUHIs at the community level. This study develops a framework for mitigating the impacts of SUHIs through UA implementation in urban design. The proposed framework consists of two key phases: diagnosis and prescription. During the diagnosis phase, we analyzed heat-vulnerable points to identify indicators contributing to the development and exacerbation of the SUHIs. Then, we employed the Matrix of Cross Impact Multiplications Applied to a Classification (MICMAC) technique to comprehensively assess 75 influential indicators related to urban structure across various aspects and scales, focusing on the mesoscale. Among them, 30 leading indicators were identified, of which environmental and morphological indicators emerged as significant catalysts. Moving on to the prescription phase, we developed a UA-based framework called the "5 Wh Question" which addresses five fundamental questions: why, who, what, how, and where. Our findings can provide comprehensive solutions for policymakers and urban planners to address the identified heat-vulnerable points.

KEYWORDS

surface urban heat islands (SUHIs), UHI, urban acupuncture, mitigating, neighborhoods, urban design

1 Introduction

The 21st century faces the critical challenge of climate change, which poses significant threats to the global environment and human activities (Loukaitou-Sideris, 2020). One specific consequence of this challenge is global warming, which has made cities and residents increasingly vulnerable, primarily due to the continuous growth of urban populations (IPCC, 2021). SUHIs, a direct result of the intertwining of global warming and urbanization (Sailor, 2011), harm urban environments by increasing health problems and mortality rates (Jonescu et al., 2023), worsening weather conditions, causing economic hardships, and leading to the degradation of urban infrastructure (Bank World, 2021). The increasing prevalence of SUHIs and environmental neglect pose a growing threat to regions worldwide, with a particular focus on cities and their residents (Yang et al., 2023). In response to this threat, the World Meteorological Organization (WMO) has designated the slogan for 2022 as “Early Warning, Early Action” (Vahlberg et al., 2022). Consequently, urgent measures must be promptly implemented through localized interventions to create immediate synergistic effects. These efforts should focus on specific areas and contribute to urban cooling initiatives (Stangel, 2023).

In recent years, extensive research has explored strategies to mitigate SUHI and associated urban heating in the built environment (Hayes et al., 2022; He, 2022; Fadhil et al., 2023; Irfeey et al., 2023). However, the implementation of large-scale and costly measures, faces numerous challenges, such as creating extensive green space areas, which may not be feasible in compact and densely populated cities (Rosso et al., 2023), particularly in arid urban areas. Furthermore, existing literature tends to consider the implementation of small-scale interventions for specific projects, often overlooking their potential for broader impact on the entire neighborhood or city. Moreover, the bottom-up approach involving community participation has received limited attention (Bartesaghi-Koc et al., 2021; Han et al., 2023).

Some urban planning and design approaches, such as Urban Acupuncture (UA), Tactical Urbanism, DIY (Do-It-Yourself), LQC (Lighter, Quicker, and Cheaper), and Pop-Up, have recently gained significant traction among urban planners and designers. All these small-scale approaches are considered “Punctual Urbanisms,” which differ in two dimensions: first, in terms of who is implementing them, involving various public and private participation. Second, the implementation may be based on event interventions, installations, or increment interventions (Landgrave-Serrano et al., 2021). Numerous studies have examined the effectiveness of small-scale interventions in mitigating the impacts of SUHI, investigating the role of tactical urbanism, pocket parks, green roofs, and cooling pavements (Nieuwenhuijsen, 2021; Rosso et al., 2023). Previous research has focused on small-scale mitigation measures and strategies, such as green roofs, walls, and reflective and permeable pavements (Shao and Kim, 2022; Zhao et al., 2022; Wang et al., 2023). However, these interventions have primarily been implemented at specific projects within urban areas (Bartesaghi-Koc et al., 2021; Ampatzidis et al., 2023). Consequently, more attention should be given to comprehensively understanding the broader effects of these strategies on the urban fabric.

Moreover, using and integrating local knowledge, expertise, and ideas are crucial for achieving more effective and responsive outcomes—an aspect that has not been extensively explored in the literature on SUHI mitigation (Boros and Mahmoud, 2021). Consequently, there is a need for an approach that can achieve a significant impact through small-scale, prompt, and bottom-up interventions to empower public participation (Zhang et al., 2022a; González et al., 2023). The bottom-up approach is characterized by its local, citizen-initiated, low-budget, and temporary nature, which is often reinforced through partnerships with local institutions or governments (Dias et al., 2018; Arefi and Kickert, 2019). This approach is also called Grassroots and Open-Source (Landgrave-Serrano et al., 2021). Given that SUHI represents hotspots of vulnerability for urban dwellers, urban acupuncture (UA) could help these areas by contributing to city-wide cooling through specific interventions (Müller et al., 2023; Zhang and Yuvan, 2023). Therefore, this research aims to develop a comprehensive conceptual framework to address the existing research gap and identify more suitable small-scale interventions by employing UA theory. The proposed framework addresses two fundamental questions: a) How to identify heat-vulnerable points within urban areas, and b) How to effectively mitigate the vulnerability of these points, which have a rapid and capillary impact in neighborhoods, by considering social, economic, and cultural goals.

Consequently, we used urban acupuncture (UA) to mitigate urban heat and the impacts of SUHIs at the neighborhood scale. The main goal of this study is to mitigate the adverse effects of SUHIs by creating neighborhood-scale policies within a comprehensive framework. Through small-scale interventions and a bottom-up approach, the goal is to create capillary effects throughout the urban fabric, thus preventing heat spread. This has been identified as a research gap in previous studies (Boros and Mahmoud, 2021; Nieuwenhuijsen, 2021; Rosso et al., 2023). To fill this gap, we developed a conceptual framework based on urban design and UA principles. This framework encompasses a two-phase scenario: a diagnosis phase aimed at identifying the key drivers of SUHIs and a prescription phase focused on implementing appropriate interventions. Our findings consist of principles and approaches based on UA that could assist planners, urban designers, and policymakers in addressing the impacts of SUHI.

This study is structured as follows: Section 2 provides a detailed explanation of the theoretical background of SUHIs and UA. The Supplementary Material section also offers a brief summary of both topics. Section 3 outlines the research methodology, ensuring transparency and rigor. Section 4 presents the results and discussion, divided into two parts: diagnosis and prescription. Each part contributes to the development of an urban design framework informed by the theoretical background, highlighting the originality and depth of the conceptual framework. Section 5 presents the conclusions of the study, summarizes its limitations, and suggests future research directions. This study captivates readers by presenting a compelling conceptual framework that contributes to urban design knowledge.

2 Theoretical background

2.1 Surface urban heat Island (SUHI)

Urban heat islands (UHI) refer to the temperature differential between urban and rural areas, which affect surface and atmospheric levels. This phenomenon is mainly caused by human activities, such as energy consumption, transportation, and urbanization (Oke, 1982; Sailor, 2011). UHIs in different urban layers are divided into surface urban heat island (SUHI) and atmospheric urban heat island (AUHI). SUHIs, which are much more intense than AUHIs, are influenced by urban design and the features of urban surfaces such as streets and roofs. These surfaces absorb and release heat more than other spaces (US EPA, 2008; Kong et al., 2021). These phenomena can result in elevated levels of air pollution, increased energy demands for cooling, and a higher incidence of heat-related illnesses (Sailor, 2011; Bank World, 2020).

The formation and intensification of SUHIs can be attributed to multiple factors operating at various scales. Previous studies have classified these factors into two distinct groups: climatic factors (uncontrollable) and urban morphological factors (controllable) (Che-Ani et al., 2009). These factors have also been examined at two scales: the urban canopy layer (UCL), which includes surface geometry, thermal characteristics, surface condition, natural heat, and the urban greenhouse gas effect, and the urban boundary layer (UBL), which encompasses aspects such as pollution boundaries, sensible heat flow, natural heat, and continuity (Oke, 1982). Furthermore, factors have been analyzed based on their temporal effects, distinguishing between those with short-term impacts, such as airflow speed and cloud cover, long-term effects, such as green areas, building materials, and sky visibility factors, and factors with periodic influences, such as solar radiation and human heat production sources (Riswan et al., 2008).

Mushtaha et al. (2021) categorized these factors into environmental, urban, and building-related aspects. However, these classifications only cover some factors contributing to SUHIs associated with various components of the urban environment. Furthermore, organizing these factors within the context of urban components can help urban designers and planners better understand SUHIs and develop more effective strategies and policies. These factors can influence six key aspects of urban design: socioeconomic aspects, land use and activities, transportation and accessibility, urban morphology, townscape, the structure of urban spaces, and environmental considerations (Golkar, 2005). A summary of these factors is presented in Supplementary Appendix Table A1. It is worth noting that the morphology aspect of this study explores the hierarchical arrangement of the constituent components. These components encompass various scales, including the overall size and texture of the city, and the buildings and materials (Kropf, 1996).

In urban planning and design, various strategies have been developed to mitigate the impacts of SUHIs and, contribute to local and global climate improvements. These strategies reduce energy consumption and decrease ambient temperatures (Tian et al., 2021). Various studies have proposed different classifications of strategies to mitigate the effect of SUHIs. For example, mitigation strategies have been classified into three groups: roof strategies, non-roof strategies, and covered parking strategies (Khare et al., 2021). Nuruzzaman, (2015) also suggested that the impacts of SUHIs could be mitigated through two approaches: increasing the reflectivity of urban surfaces (albedo) and promoting greater evaporation and transpiration.

Moreover, Deilami et al. (2018) divided mitigation strategies into internal and external categories. Internal strategies primarily focus on building-related aspects, align more with architecture and energy considerations, and are somewhat outside the scope of urban design and planning (Deilami et al., 2018). External strategies can also be categorized into four groups: increasing urban albedo, promoting green city policies, optimizing urban ventilation, and implementing environmental management measures (Deilami et al., 2018). Furthermore, Tian et al. (2021) identified several strategies for mitigating the impacts of SUHIs, such as implementing urban greening, using cooling materials, incorporating water bodies, enhancing urban ventilation, and optimizing urban morphology.

Historically, approaches to addressing heat-related issues have consistently emphasized the importance of aligning solutions and strategies with the local environment rather than working against it (Hamza-Goodacre, 2019; Cong et al., 2023). Recently, there has been a growing emphasis on engaging individuals and local communities in addressing these issues (Qi et al., 2022), highlighting the importance of community participation in addressing urban heat challenges. For instance, nature-based solutions offer a cost-effective approach that provides environmental, social, and economic benefits while promoting resilience (Mccormick, 2020).

In summary, extensive research has been conducted to mitigate the impact of SUHI, encompassing macro and micro-scale interventions (Su et al., 2021a; Müller et al., 2023; Zhang and Yuan, 2023). Loukaitou-Sideris (2020) argues that the success of large-scale interventions relies on the stability and adaptability of small-scale interventions, such as green and permeable infrastructure (Fadhil et al., 2023; Semenzato and Bortolini, 2023). However, the catalytic potential and significance of strategies, and bottom-up engagement of communities in small-scale interventions, have received comparatively less attention. Consequently, the urban acupuncture approach, which is characterized by the principles and attributes outlined in Section 2.2, emerges as a promising method to effectively address these challenges within urban design and planning.

2.2 Urban acupuncture

UA is a socio-environmental approach that departs from conventional large-scale urban regeneration initiatives. Instead, it focuses on more community-driven, locally focused, and cost-effective strategies (Balicka et al., 2021). Drawing inspiration from acupuncture therapy, UA identifies and address stress points within a community, much like treating diseases (Lerner, 2014). The premise of this approach is that small interventions can profoundly influence the urban environment (Vassiljev et al., 2020). In the UA projects, local individuals predominantly assume the role of implementers, using a bottom-up approach. They achieve capillary and incremental effects on a larger scale despite limited financial resources and time constraints (Pissourios, 2014; Pak, 2017).

Jamie Lerner advocates for UA to revitalize important areas and their surroundings, focusing on sustainability, mobility, and social inclusivity. Interaction and participation are integral to UA, and education is crucial in achieving this objective (Lerner, 2014). Manuel de Sola Morales sought to comprehend urban expansion and play an active role in its development. Cities are often perceived as having a physical shell composed of various elements such as structures, textures, and contrasts (streets, open spaces, gardens, and walls). The interaction between residents and these urban elements shapes the urban experience, transmitting energy through key points. This process fosters a collective identity based on cultural references, which transform into social structures (Solà-Morales, 2008).

Marco Casagrande expanded the acupuncture approach by introducing novel dimensions and emphasizing vegetation (Casagrande, 2012; Yimeng, 2015; Casagrande, 2020). The study mentioned that UA can be understood as a bio-urban approach that integrates sociology and urban design principles with the traditional Chinese medicine concept of acupuncture. This study acknowledges nature as a dynamic force interwoven with local knowledge and self-organizing social initiatives within the urban environment. This holistic approach restores cities to their original essence by harmonizing with nature (Casagrande, 2020). Ryan proposes the term Eco-Acupuncture (EcoA), emphasizing the shortcomings of international and national responses to climate change. Instead, local institutions, with their inherent creativity, can respond effectively to the challenges posed by climate change (Ryan, 2013). Iaconesi and Persico, (2017) explored the concept of digital UA (DUA), reevaluating user authentication and its relevance in the era of universal communication. Thus, in the information age, there has been a shift in the definition of public and private spaces. This transformation has impacted our perception, the efficient utilization of public spaces, and citizenship rights (Iaconesi and Persico, 2014).

On the other hand, Casanova and Hernandez., 2015 incorporated acupuncture principles into public spaces, providing strategies and interventions to revitalize urban life through three main themes: time-based strategies, citizen participation, and substitution (Casanova and Hernandez, 2015; Yimeng, 2015). Finally, Urban Environmental Acupuncture (UEA) suggests that enhancing non-green spaces and implementing nature-based solutions can have a positive impact on sustainable development by reducing SUHIs and improving the comfort and quality of urban spaces (Starzewska-Sikorska et al., 2022; Stangel, 2023).

Biophilic Urban Acupuncture (BUA) integrates biophilic design principles into the UA framework. This approach reduces stress by transforming frequently ignored everyday spaces into visually appealing and interactive environments, thus improving people's moods and mental wellbeing (Reinhold, 2018). Urban Blue Acupuncture (UBA) also emphasizes the importance of water bodies and spaces and their interconnection with UA (Bell et al., 2020). Therefore, informal and potentially underutilized urban blue spaces can be repurposed for recreational activities with minimal infrastructure and management (Balicka et al., 2021). This approach illustrates the positive benefits of the "less is more" and "small is powerful" principles, encompassing their unique criteria and principles (Vassiljev et al., 2020).

In addition, Urban Dark Acupuncture (UDA) incorporates UA principles to address the preservation of darkness. This approach emphasizes that strategically important locations within cities can be improved through the intentional use of darkness. These designated areas, such as squares, bridges, and memorial sites, serve as platforms for delivering educational content to users. UDA also aims to raise awareness about the significance of preserving the night sky and the intrinsic values linked with darkness (Stone, 2018) in order to reduce the negative effects of artificial lighting in urban areas. This aligns with sustainability and efforts to mitigate climate change (Amilawangi, 2020). A summary of the objectives, principles, and tools of each type of UA is presented in Supplementary Appendix Table A2.

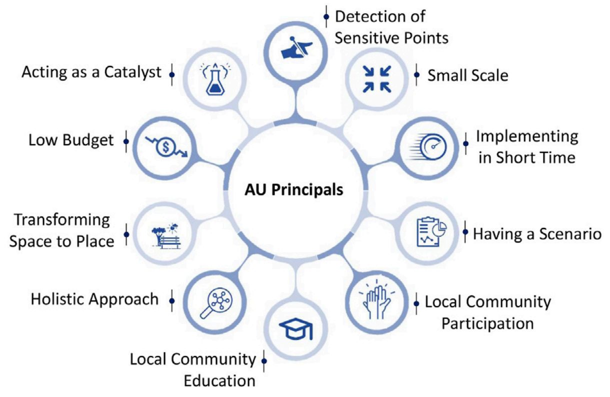

FIGURE 1
Principles of UA.

Figure 1 illustrates the most fundamental principles of UA. One of the crucial principles shared by various perspectives in UA is the identification of sensitive points. This initial step is similar to identifying key points of a patient's body for treatment (Lerner, 2014; Salman and Hussein, 2021; Tromp, 2021). A distinguishing characteristic of UA interventions is their implementation within small-scale projects with low budgets (Radstaak, 2012). This approach achieves a significant impact by implementing small-scale pilot projects (Nassar, 2021).

Furthermore, presenting a scenario constitutes another fundamental principle of UA (Nassar, 2021). Well-designed scenarios promote resident engagement and participation, creating a domino effect and contributing to an enhanced quality of life and a sense of solidarity. This scenario and suggested interventions should be implemented promptly (Lerner, 2014). UA plays a crucial role in promoting a dynamic that facilitates adaptability and transformation (Prins, 2013), by increasing residents' awareness and understanding of urban interventions. Consequently, citizens must be trained to understand and perceive their environment (Nassar, 2021). Furthermore, this training can be successful when the local community actively participates in the process, with the people themselves assuming leadership in driving this approach forward (Lerner, 2014; Nassar, 2021; Tromp, 2021).

UA embraces a holistic approach that integrates various economic, environmental, infrastructural, historical, and political elements within a unified framework to transform a space into a meaningful place. It revitalizes the area by replenishing energy instead of depleting it (Prins, 2013; Salman and Hussein, 2021). Ultimately, the main goal of UA is to act as a catalyst, using small-scale urban projects to initiate reactions that improve the overall functioning of the urban environment (Tromp, 2021). The selection of catalysts in UA depends on various factors, including the purpose, planning, size, shape, and land use of the surrounding areas. Incorporating green spaces is a crucial catalyst among these factors (Radstaak, 2012).

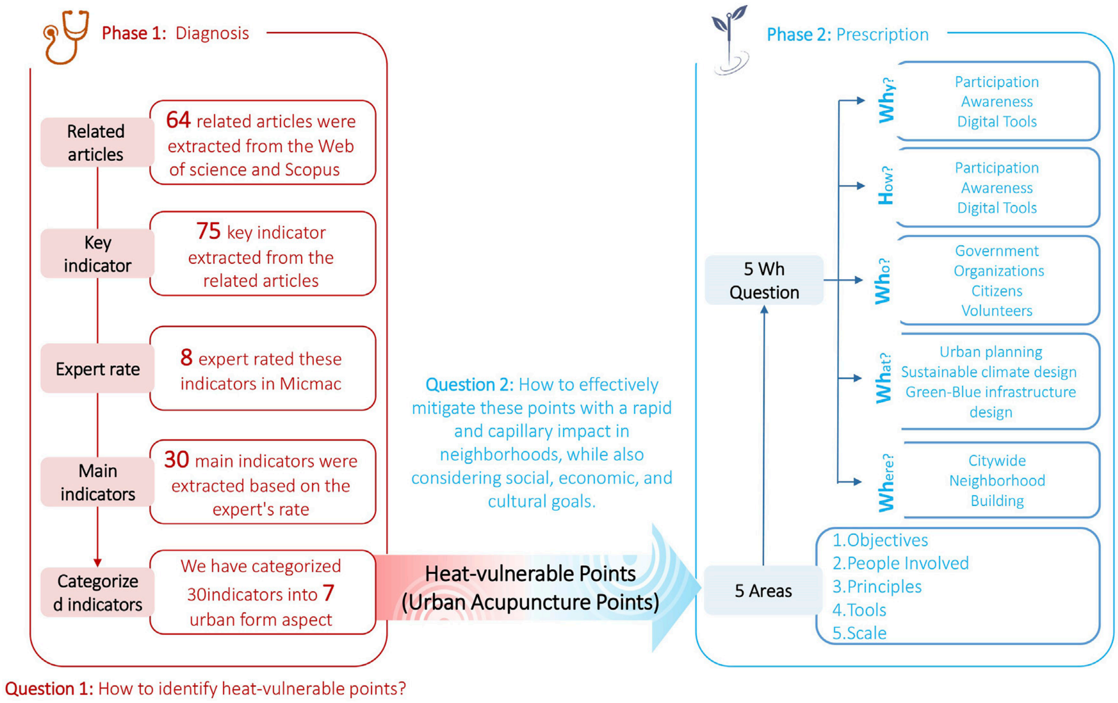

FIGURE 2
Conceptual framework in a glance.

Based on the principles and characteristics outlined in the previous section, UA demonstrates the potential to address the second question of this research. Through the rapid implementation of small-scale interventions, this approach can expand its influence throughout the neighborhood or city by promoting social, cultural, and economic objectives.

We can examine UA on three distinct levels in this study: (**a**) The initial level involves the semantic similarity between UA and acupuncture in medicine. At this level, the main focus is identifying key and sensitive points, particularly pinpointing areas with the highest heat accumulation, indicating their vulnerability to heat stress (Radstaak, 2012). (**b**) The second level pertains to the physical similarity between UA and medical acupuncture, encompassing principles such as implementation in a short time, small-scale interventions, catalyst functionality, and a holistic approach (Landgrave-Serrano et al., 2021). (**c**) The third level involves a parallel process in which the urban fabric is compared to the human body. By implementing interventions at specific locations within the city, it is possible to influence on broader area on a larger scale. By targeting identified vulnerable areas, interventions can yield comprehensive benefits, extending their impact to the broader urban context.

3 Methodology

We developed a conceptual framework comprising a two-phase scenario for addressing the issue of SUHI by implementing UA. The first phase, known as "diagnosis," entails creating a framework to identify the acupuncture points most vulnerable to heat accumulation based on SUHI's formation and intensification indicators. These identified points serve as heat-vulnerable points that store the most heat. In the second phase, known as "prescription" the research proposes a framework employing acupuncture principles and approaches to develop strategies for mitigating SUHIs (Figure 2).

To address the first phase and answer the first research question, a thorough literature review was conducted through a desk study. This involved searching the Scopus and Web of Science databases, carefully reviewing article titles, keywords, and abstracts, and removing duplicate entries. A total of 64 articles were analyzed qualitatively. Subsequently, duplicate or overlapping indicators were eliminated, and 75 essential indicators were extracted (See Supplementary Appendix Table A1). Eight experts from different fields carefully reviewed all the extracted indicators. This group included experts in urban climate, thermal comfort, UHI, urban resilience, public health, urban design, urban morphology, and urban and regional planning (See Supplementary Appendix Table A3). The panel comprised six academic professors and two senior experts from different regions, including Iran, Australia, Japan, and Ireland. Their thorough evaluation resulted a final set of 75 consolidated indicators.

The next step, involved identifying the main drivers contributing to the formation and intensification of SUHI by developing an interpretive structural framework, which established a comprehensive understanding of the interrelationships among various indicators influencing SUHI formation and intensification. Subsequently, the Matrix of Cross Impact Multiplications Applied to a Classification (MICMAC) technique, a structural analysis method developed by Michel Godet and

François Bourse (Chandramowli et al., 2011), was used to reveal the indirect relationships between these indicators. The MICMAC technique facilitated a detailed examination of the interdependencies within the system.

MICMAC analysis is a forward-looking structural analysis technique used to examine indirect relationships (Saxena et al., 1990). This analytical approach involves creating a chart that categorizes indicators into four clusters based on their driving force and dependency power: Autonomous indicators are relatively isolated from the system and show weak dependence on other indicators. Dependent indicators show the highest level of reliance on other indicators. Linkage indicators are characterized by their volatility and significant influence on other indicators. Finaly, Independent indicators are minimally influenced by other indicators and deserve special attention because of their strong association with key indicators (Ahmad et al., 2019). The MICMAC software can integrate qualitative indicators and explore diverse and unfamiliar future scenarios. This approach begins with a problem description and then identifies of indicators to investigate the interrelationships. It quantifies these relationships on the basis of dynamism and dependence among the current indicators (Janssen et al., 2019; Kaur et al., 2019; Naghibi et al., 2023). The crucial foundation of MICMAC is experts' opinions on the issue (Patel et al., 2021). Impact strength varies between 0 and 3, as measured on a four-point scale (Godet, 2000). We used MICMAC foresight software (Version 6.1.2, 2004/2003) to visualize the results.

Thus, we created a 75 × 75 matrix for comparing the drivers. The eight previously mentioned experts carefully analyzed and scored each pair of indicators on the basis of their influence and dependence. The scores were compiled and averaged to determine the relative importance of each indicator. Statistical analysis was then conducted using MICMAC software to measure the relative weights and analyze the complex hierarchical interrelationships among the selected indicators associated with the formation and intensification of SUHI. It is worth mentioning that MICMAC uses four numbers (0, 1, 2, and 3) to determine the level of influence or dependence between each pair of drivers (i and j) (Ahmad et al., 2019). The assigned numbers were interpreted as follows:

- 0: No influence or dependence between drivers, indicating independence and no impact on each other.
- 1: Weak influence or dependence, representing limited interaction and correlation.
- 2: Moderate influence or dependence indicates, a significant level of interaction and influence.
- 3: Strong influence or dependence, suggesting a substantial impact and strong correlation.

This systematic approach allowed for the identification and characterization of the interdependencies among the drivers, providing insights into their relative importance and influence within the studied system (Ahmad et al., 2019; Rad et al., 2023).

During the second phase, known as the prescription phase in the scenario, a literature review was conducted by analyzing relevant documents, books, and articles about various types of UA in the Scopus and Web of Science databases. In this regard, 65 articles on UA and its various types were obtained by searching titles, keywords, and abstracts. After excluding non-English and irrelevant articles and conducting a thorough examination, 23 articles were carefully selected to extract their underlying principles, tools, and objectives. Based on the findings, the objectives, principles, and tools associated with each type of UA were categorized to establish a comprehensive conceptual framework (See Supplementary Appendix Table A2).

4 Results and discussion

4.1 First phase: Diagnosis

The UA approach's core principle involves identifying sensitive points, similar to the initial step of pinpointing specific points on a patient's body for treatment (Solà-Morales, 2008; Salman and Hussein, 2021). The first phase in this scenario involves the critical task of identifying these sensitive points (heat-vulnerable points in urban areas). Subsequently, after conducting a comprehensive literature review and using the MICMAC technique, we identified the key indicators contributing to the formation and intensity of SUHI. Overlaying these indicators helps to identify the sensitive points. Regarding the aspects of urban form (Golkar, 2005), we categorized the extracted indicators into seven: socio-economic (3 indicators, 4%), land use and activity (4 indicators, 5.3%), transportation and accessibility (17 indicators, 22.6%), morphological aspect (22 indicators, 29.3%), townscape and city image (1 indicator, 1.3%), the structure of the urban spaces (4 indicators, 5.3%), and environmental aspect (24 indicators, 32%). In the following, we proceeded with the analysis using MICMAC:

4.1.1 Reliability and stability of the MICMAC analysis

To determine the influence and dependence of each indicator, it is crucial to differentiate between significant indicators and those that can be disregarded (Naghibi et al., 2023). We visually represented indicators using graphical depiction and categorized them into four clusters: autonomous, dependent, linkage, and independent with the help of MICMAC analysis. The layout of indicators on a diagram helps evaluate the system's overall stability. When examining the indicators contributing to the formation and intensification of SUHI, the spatial distribution of these indicators on a two-dimensional plane shows an L-shaped pattern (Figure 3). This pattern indicates a relatively stable system (Naghibi et al., 2023). Table 1 presents the reliability rate of the direct matrix, indicating its level of validity. The table shows that over 90% of the indicators are suitable, indicating a high level of validity. Table 2 provides a comprehensive summary of the matrix specifications.

4.1.2 Interpretation of the map of indicators' typologies

Figure 3 illustrates the significant influence of the "green spaces" indicator in the Linkage quadrant on other indicators. Numerous studies agree that the presence or absence of green spaces is the primary indicator contributing to the formation or mitigation of SUHI (Balany et al., 2020). Several indicators significantly influence land surface temperature (LST). LST serves as a widely used indicator for studying SUHI to the extent that numerous studies

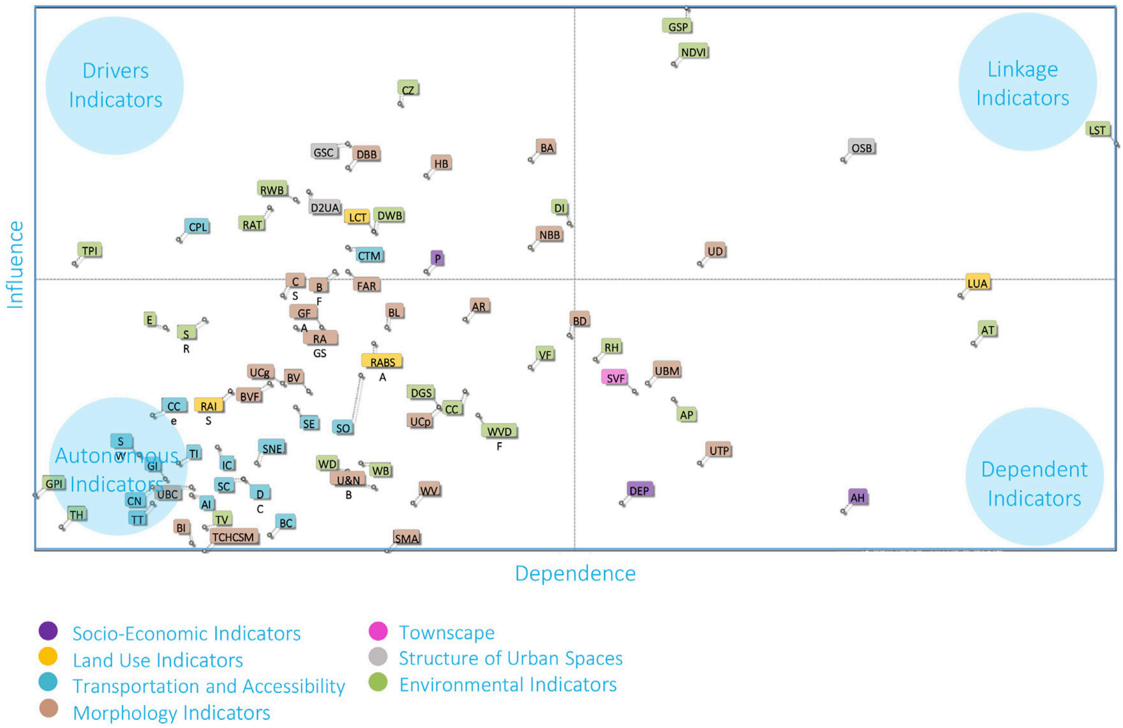

FIGURE 3
Direct Influence/Dependence Map based on Aspects of Urban Form.

TABLE 1 Study of the stability of the system.

Iteration	Influence (%)	Dependence (%)
1	91	95
2	98	97

use LST interchangeably with SUHI (Lu et al., 2021a; Ghanbari et al., 2023; Hamed Fahmy et al., 2023). The indicators of open public spaces and urban density also demonstrate significant dependence and influential potential, contributing to their effectiveness (Ahmad et al., 2019). Open public spaces play a crucial role in mitigating or reducing the intensity of SUHI by creating ventilation spaces and facilitating wind flow (Lee and Kim, 2022). An increase in density, marked by taller buildings, reduces the height-to-width ratios of streets to buildings and reduces vegetation coverage, correlated with heightened magnitudes of SUHIs (Chapman et al., 2018).

Driver-quarter shows present low dependence have possess high, indicating that they exert strong influence to a lesser extent (Ahmad et al., 2019). Among the indicators in this quarter, the climate zone has the most significant influence on the other indicators. The climatic zone contributes to variations in urban greenery and directly impacts urban morphology. It determines building density and spacing and is even influenced by materials (Azhdari et al., 2018; Yang et al., 2022). Therefore, the climate zone indicator directly impacts the SUHI. For example, nearby high mountains can obstruct wind flow or reduce the intensity of the SUHI effect by increasing wind speed (Kim et al., 2018).

Furthermore, indicators related to urban morphology significantly influence other indicators. Metrics such as the distance between buildings, building height, number of buildings per block, and building aggregation all make significant contributions to the formation and intensification of SUHI within the urban morphology (Xi et al., 2021; Zhang et al., 2022b; Gao et al., 2022; Simon et al., 2023). These scenarios directly influence density, population, and energy consumption, leading to either an increase or decrease in the intensity of SUHIs (Su et al., 2021b). Furthermore, adjusting these indicators is expected to improve the effectiveness of urban ventilation and open spaces in mitigating the effects of SUHI (Simon et al., 2023).

Autonomous indicators demonstrate low dependence, often staying separate from the system because of their weak connections, even when altered, without causing significant changes within the system (Ahmad et al., 2019). Consequently, by excluding this quadrant, the indicators from the remaining three quadrants (30 indicators in total) can be considered influential

TABLE 2 Overview of the properties of the matrix for direct influences and dependencies.

Matrix size	Number of iterations	Number of zeros	Number of ones	Number of twos	Number of threes	Number of P	Total	Filling rate (%)
75	2	4050	909	474	192	0	1575	28

TABLE 3 The main driver of SUHI formation and intensification for detecting heat-vulnerability points (based on results from MICMAC).

NO	Driver	Code	Layer	Influence	Dependence	Total strength	References
1	Land Surface Temperature	LST	Environmental	59	88	147	Masson et al. (2020), Lu et al. (2021a), Kim and Brown (2021), Ghanbari et al. (2023), Hamed Fahmy et al. (2023)
2	Green Space Proportion	GSP	Environmental	76	55	131	Soltani and Sharifi (2017), Kleerekoper et al. (2018), Ke et al. (2021)
3	Open Public Spaces	OPS	Structure of Urban Spaces	57	67	124	Kim and Brown (2021), Lee and Kim (2022)
4	Degree of Greenness	NDVI	Environmental	65	58	123	Kleerekoper et al. (2018), Ke et al. (2021), Chen et al. (2023), Tabrizi et al. (2023)
5	Land Uses and Activity	LUA	Land Use	40	76	116	Che-Ani et al. (2009), Lu et al. (2021b)
6	Air Temperature	AT	Environmental	34	77	111	Kim and Brown (2021)
7	Urban Density	UD	Morphology	66	44	110	Sobstyl et al. (2017), Chapman et al. (2018)
8	Building Aggregation	BA	Morphology	57	43	100	Che-Ani et al. (2009), Zhang et al. (2022a)
9	Climate Zone	CZ	Environmental	64	33	97	Masson et al. (2020), Yang et al. (2022)
10	Height of Buildings	HB	Morphology	49	46	95	Che-Ani et al. (2009), Kim and Brown (2021), Xi et al. (2021)
11	Number of Buildings per Block	NBB	Morphology	55	35	90	Che-Ani et al. (2009), Gao et al. (2022)
12	Dryness Index	DI	Environmental	46	43	89	Masson et al. (2020), de Almeida et al. (2021), Kim and Brown (2021)
13	Green Space Coherence	GSC	Structure of Urban Spaces	59	29	88	Ke et al. (2021), Kim and Brown (2021)
14	Distance Between Buildings	DBB	Morphology	56	29	85	Che-Ani et al. (2009), Simon et al. (2023)
15	Air Pollution	AP	Environmental	27	54	81	Masson et al. (2020), Kim and Brown (2021), Ulpiani (2021)
16	Urban Block Morphology	UBM	Morphology	29	52	81	Che-Ani et al. (2009), Li et al. (2020a)
17	Anthropogenic Heat	AH	Socio-Economic	13	67	80	ESMAP (2020a), Wang et al. (2018)
18	Relative Humidity	RH	Environmental	32	48	80	Kim and Brown (2021), Feinberg (2022)
19	Land Cover Type	LCT	Land Use	48	31	79	Ritu (2023)
20	Distance to Urban Area	D2UA	Structure of Urban Spaces	53	26	79	de Almeida et al. (2021), Kim and Brown (2021)
21	The Distance to the Centroid of Any Nearby Water Body	DWB	Environmental	48	31	79	C40 Cities (2016), Kleerekoper et al. (2018), Nassar et al. (2016)
22	Sky View Factor	SVF	Townscape	28	51	79	Dirksen et al. (2019), Kim and Brown (2021)
23	Population	P	Socio-Economic	43	35	78	Manoli et al. (2019), Su et al. (2021b), Kim and Brown (2021), Kong et al. (2021), Chen et al. (2023)
24	Rivers and Other Water Bodies	RWB	Environmental	52	25	77	C40 Cities (2016), Kleerekoper et al. (2018), Lin et al. (2023)
25	Choice of Travel Mode	CTM	Transportation	46	29	75	Ruefenacht and Acero (2017), Kamruzzaman et al. (2018)
26	Urban Tissue Pattern	UTP	Morphology	19	56	75	Sobstyl et al. (2017), Simon et al. (2023)
27	Relative Area of Trees	RAT	Environmental	51	23	74	EPA (2016), Kleerekoper et al. (2018)
28	Demand for Electric Power	DEP	Socio-Economic	14	50	64	Che-Ani et al. (2009), Su et al. (2021a)

(Continued on following page)

TABLE 3 (*Continued*) The main driver of SUHI formation and intensification for detecting heat-vulnerability points (based on results from MICMAC).

NO	Driver	Code	Layer	Influence	Dependence	Total strength	References
29	Characteristic Path Length	CPL	Transportation	47	16	63	Rajagopalan et al. (2014), Sharifi (2019), Erdem et al. (2021), Chenary et al. (2023)
30	Topographic Position Index	TPI	Environmental	44	8	52	Emran et al. (2018), Masson et al. (2020)

indicators in the formation and intensification of SUHI (Table 3). According to Figure 3, which categorizes each aspect of the urban form with distinct colors, the environmental aspect encompasses the highest number of indicators (12 indicators, 40%). Hence, the most significant indicators relate to blue-green spaces. Research has demonstrated that urban blue and green spaces and vegetation play crucial roles in mitigating the effects of SUHIs. These are considered to be the most effective strategies for reducing SUHI intensity (Balany et al., 2020; Ke et al., 2021).

Subsequently, the urban morphological aspect was the most influential in SUHI formation (9 indicators, 23.5%), followed by the structure of urban spaces and demographic-economic aspects (3 indicators, 10%). Notably, open public spaces, and lower population density can mitigate SUHIs. Population size correlates with increased energy demand and consequent anthropogenic heat production, directly influencing the intensity of SUHI (Wang et al., 2018; Su et al., 2021a). Transportation-related indicators comprise approximately 23% of all indicators examined. Surprisingly, only a small proportion of the indicators, (2 indicators; 6.5%) are associated with transportation and accessibility. Transportation aspect indicates that travel mode choice can either mitigate or intensify the effects of SUHIs (Kamruzzaman et al., 2018). Moreover, land use allocation, including commercial, residential, industrial, green spaces, and airports, can have distinct impacts on SUHIs. These impacts arise from the generation of anthropogenic heat and its influence on land cover and building morphology (Lu et al., 2021b).

Additionally, the “word clouds” illustrating the indicators offer valuable insights into the significance of influencing and dependent indicators in the formation and intensification of SUHIs across various urban form aspects at different urban scales (macro, meso, and micro), as highlighted in Figure 4. Notably, the micro and mesoscales show greater abundance and prominence. This underscores the importance of implementing interventions at the urban design scale and in neighborhood settings to mitigate the effects of SUHIs.

4.1.3 Interpretation of the map of indicators’ typologies

An overview of the key indicators identified in our study is presented in Table 3, encompassing 30 indicators distributed across seven urban form aspects. Among the top ten indicators, several critical indicators emerged, ranked by their influence and dependence. These include land surface temperature, the proportion and percentage of green space, the quantity of open public spaces, land use type and activity, and urban density. Furthermore, we have provided a potential directed graph illustrating the relationships between these indicators in Figure 5. The graph visually represents the total strength of the drivers, which is determined by combining the influence and dependence scores obtained from the MICMAC analysis (Table 3). The size of the node corresponds to the total strength.

The thickness and number of connection lines also indicate the strength and type of the relationships between these drivers. This graph analysis reveals that the proportion of green space and urban density significantly influence other indicators, while the remaining indicators greatly impact SUHIs. Moreover, the results highlight the significant influence and dependence of open public spaces, emphasizing their importance in our study, particularly during the second phase of the scenario, namely, prescription. Our findings are consistent with existing literature highlighting the importance of small-scale interventions in urban open public spaces (Hoogduyn, 2014; Müller et al., 2023).

In the first phase, we identified drivers with a high level of generalizability across diverse contexts. However, it is essential to note that additional research may be necessary to adapt the indicators to the specific design context for addressing different climatic conditions. This adaptation can be accomplished by integrating and tailoring the indicators within the conceptual framework or during the design process to correspond with the specific climate of the study area. Furthermore, future studies should explore the relationship between the impacts of SUHI and suggested mitigation strategies. Thus, our findings can serve as a basis for initiatives, offering suitable tools to mitigate the adverse effects of SUHI on communities.

As mentioned, we developed a comprehensive framework in the first phase to address various social, economic, climatic, and sociological aspects in urban areas. Identifying heat-vulnerable points in urban areas may vary depending on different approaches, necessitating the identification of primary influencing indicators before conducting the study. These indicators are significante in the following phase, which involves implementing and adopting mitigation tools. For instance, in the suburban and rural regions of Ahmedabad, India, where most households are from low-income groups, interventions in the physical aspect are less significant (Vellingiri et al., 2020). These interventions stem from the substantial time and financial commitments required for morphological interventions, which diverge from the principles of UA, and impose a burden beyond the residents’ means.

In addition, we analyzed indicators contributing to the formation and intensification of SUHI by drawing on previous research. Through MICMAC analysis, we have successfully identified the primary drivers that influence the development of SUHIs. We can accurately identify key points within the urban fabric by pinpointing and overlaying these indicators. These identified points were labeled as “heat-vulnerable points” in the second phase.

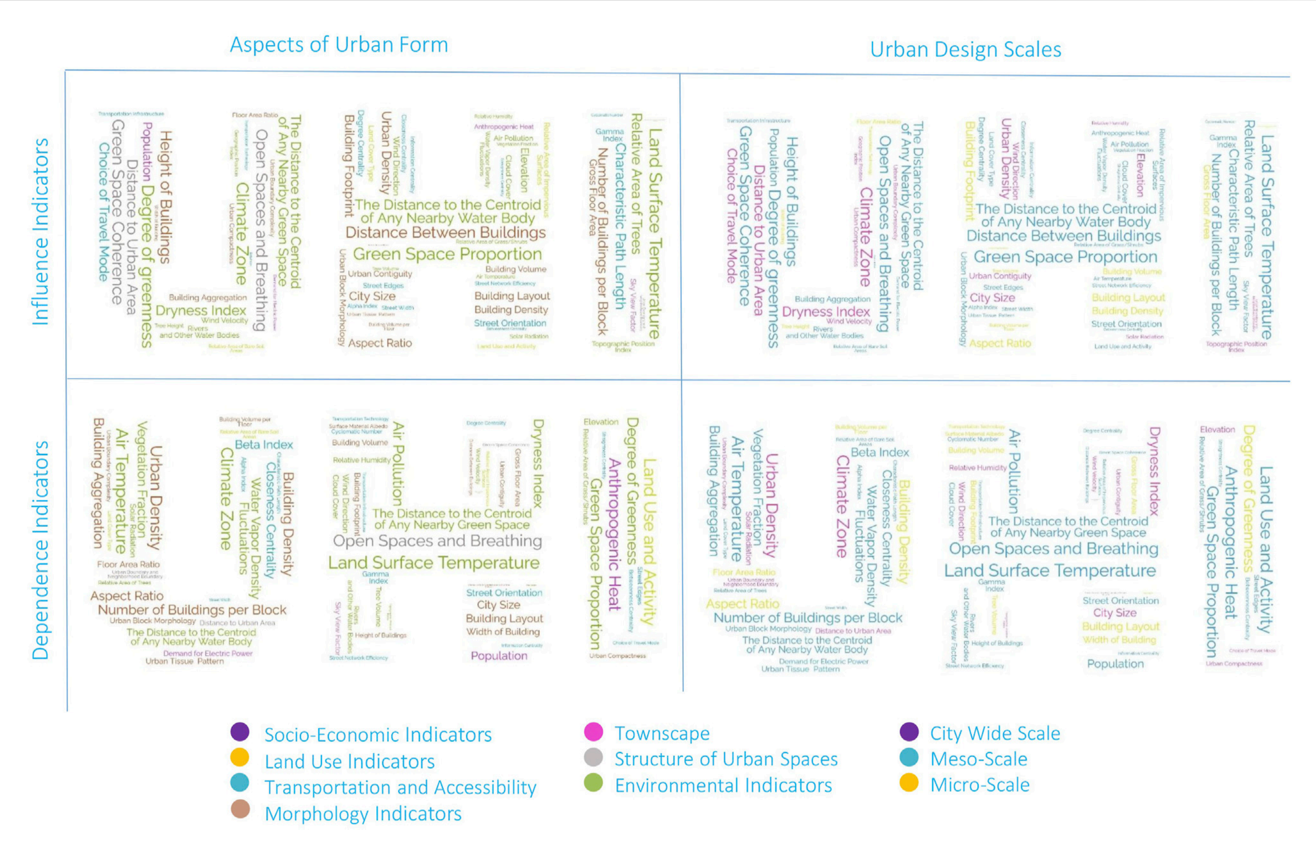

FIGURE 4
List of Indicators Sorted by Influence and Dependence based on Aspects of Urban Form and Scales (The larger the Size of the Word, the Greater the Effect of the Indicators).

These areas are crucial intervention points where residents are vulnerable to heat-related risks and damages. By strategically implementing acupuncture interventions at these key points, it is possible to regulate the temperature in the targeted area, thus reducing the effects of SUHIs and improving residents' wellbeing. The concept of "heat-vulnerable points" is significance as it encompasses the social aspect and emphasizes the bottom-up approach within the framework of the UA (Lerner, 2014; Nassar, 2021; Tromp, 2021).

4.2 Second phase: prescription

In the second phase, we needed to address the urban area by prescribing interventions through selected points. A comprehensive review of acupuncture types and existing studies revealed five common themes demonstrating their potential effectiveness in mitigating SUHI effects and promoting catalytic change (Ryan, 2013; Reinhold, 2018; Margono and Zuraida, 2019; Amilawangi, 2020; Casagrande, 2020; Balicka et al., 2021). Based on these findings, we developed the "5 Wh Question" framework to address various dimensions of SUHI reduction. This framework offers a holistic approach to addressing SUHI challenges, incorporating a set of inquiries that direct each acupuncture project, including goals, key stakeholders, guiding principles, relevant tools, and suitable scales. Supplementary Appendix Table A2 presents the questions based on the "why, who, what, how, and where," as shown in Figure 6.

4.2.1 Why

Due to the detrimental impacts of SUHI (ESMAP, 2020a), it was essential to prioritize the primary and secondary objectives to mitigate the adverse effects. During the prescription phase, we considered three secondary objectives, environmental, social, and economic, that require attention from the beginning of the intervention. Furthermore, depending on the nature and scale of each acupuncture project, various goals could be established before its start.

In addition, within the scope of environmental objectives, an acupuncture project may include secondary objectives such as reducing greenhouse gas emissions (Saporito, 2017; Charles-Guzman, 2020; Rodríguez González et al., 2023), minimizing energy consumption (Charles-Guzman, 2020), promoting water and energy recycling (Saporito, 2017), and fostering connections between diverse communities and the natural environment, as well as biodiversity (Palacios, 2020).

Furthermore, urban cooling initiatives could also serve social objectives, depending on the specific needs of the project. For instance, the Ahmedabad cooling project in India aimed to promote social justice and equality for low-income communities by involving residents in using cost-effective roof painting techniques (Vellingiri et al., 2020). Here, social interaction is a

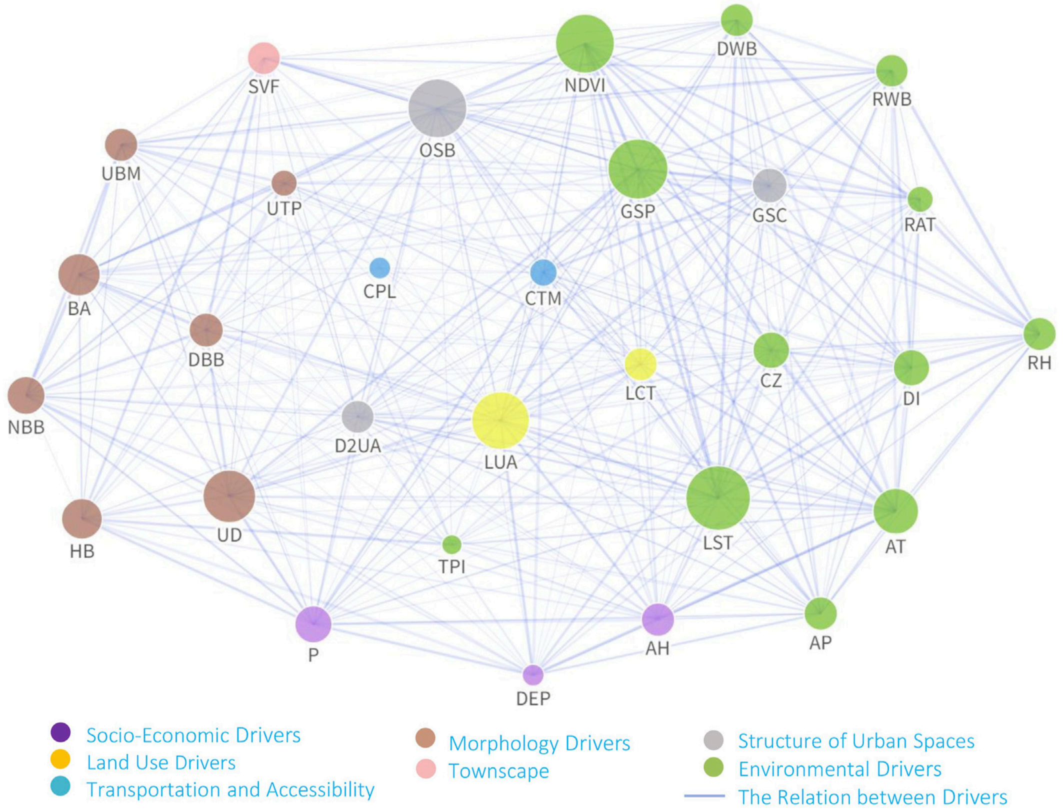

FIGURE 5
Potential direct graph of the main drivers of the formation and intensification of SUHI (based on results from MICMAC).

pivotal principle within the concept of UA (Lerner, 2014; Nassar, 2021; Tromp, 2021), warranting consideration in urban cooling projects (Saporito, 2017; Palacios, 2020; Bank World, 2021). Additionally, vulnerable people, such as children, older adults, and individuals with disabilities who are more vulnerable to heat-related risks (Huang et al., 2023), should be included as a specific focus within social objectives (Bank World, 2021).

Finally, it is crucial to consider the economic aspects of the project, especially at the meso, micro, and local levels. Prioritizing economic objectives, such as increasing local employment opportunities (Saporito, 2017; Charles-Guzman, 2020) and facilitating easy access to locally sourced food (Saporito, 2017; Palacios, 2020), are crucial factors that deserve attention.

4.2.2 Who

Acupuncture projects involve various stakeholders, from government leaders and organizations to private property owners. Therefore, the focus of this question pertains to the individuals involved in the interventions, including diverse groups. Acupuncture interventions offer a concrete opportunity for civic engagement by involving individuals with different levels of familiarity with urban design and planning in transforming or creating urban spaces. Furthermore, they facilitate connections between citizens and local authorities, extending beyond traditional settings such as public meetings and fostering city-wide collaborations (Landgrave-Serrano et al., 2021). Implementing these small-scale projects requires the involvement of various actors, including individual stakeholders, local businesses and retailers, and community groups. These initiatives can be initiated by government entities in the public sector to promote social participation or sponsored by private sector entities such as businesses, developers, or corporate organizations (Landgrave-Serrano et al., 2021). Crucially, these projects often begin with a bottom-up approach and frequently emerge from the community (Balicka et al., 2021).

Consequently, once the project's objectives have been established, it becomes imperative to identify the project's implementers and consider the interests of each involved group. It is crucial to align these interests with the project's goals and provide the necessary support to ensure compatibility and successful execution. For example, the OrtiAlti project in Turin, Italy, serves as a case in point, where a bottom-up approach to regeneration was pursued (Saporito, 2017). In this endeavor, the local government properly considered the legal and financial concerns of private property owners and achieved significant environmental, economic, and social breakthroughs through their collaboration, which proved mutually beneficial for all involved parties.

4.2.3 What

Based on the principles of UA, we identified heat-vulnerable points to mitigate the adverse effects of SUHI in selected points. As previously discussed, the ten principles of UA, illustrated in Figure 1, help guide the implementation of projects targeting these vulnerable

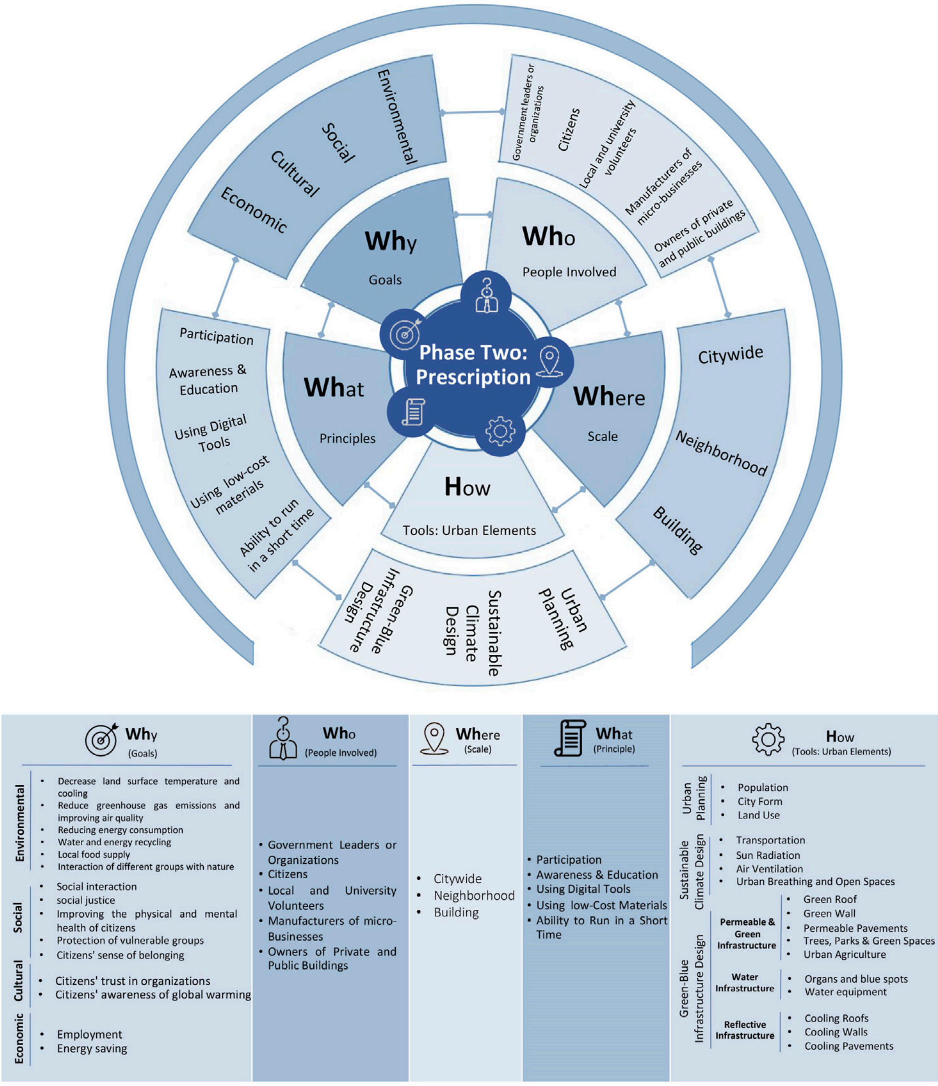

FIGURE 6
5wh question model. Prescription: The second phase to mitigate and prevention of SUHI impacts.

points. Concurrently, the framework emphasized citizen participation (Saporito, 2017; Charles-Guzman, 2020; Palacios, 2020) and the crucial aspects of informing and training residents (Charles-Guzman, 2020; Bank World, 2021), helping to raise citizens' awareness about the consequences of SUHIs and potential solutions to mitigate them. Additionally, it can be beneficial to consider the principles of various UA approaches (See Supplementary Appendix Table A2).

4.2.4 How

Finding the appropriate method to implement our framework requires a thorough response based on the previous inquiries. After identifying the acupuncture points and establishing objectives, selecting appropriate strategies to mitigate SUHI at critical points in urban areas became crucial. These strategies were designed to effectively mitigate SUHIs at the identified points by implementing cooling measures. To summarize the studies on mitigating SUHIs, the tools can be categorized into three main groups: (a) urban planning, (b) sustainable climate design, and (c) green-blue infrastructure design.

1) The tools associated with urban planning primarily focus on the urban form and population, addressing the city-wide scale (Su et al., 2021b; Kang et al., 2022; Amir Siddique et al., 2023). At this scale, urban form is associated with city size, compactness, boundary complexity, and contiguity (Su et al., 2021a; Kang et al., 2022). However, considering the acupuncture projects primarily operate on a small scale with community engagement, two other tools become more significant within our framework.
2) Sustainable climate design consists of three types of interventions: transportation, urban geometry, and creation of urban green open spaces. Strategies aimed at reducing traffic, such as the establishment of bicycle and pedestrian pathways, and strategies focused on minimizing heat flux, including the design of infrastructure, bus stations,

materials, and the configuring walkways, as well as choosing building and surface material, are related to transportation interventions within citizen participation (Ruefenacht and Acero, 2017). Furthermore, urban geometry offers numerous opportunities to mitigate neighborhood and small-scale urban temperatures, particularly considering shade and wind flow as crucial factors (Gago et al., 2013). In meso and micro-scale design, indicators such as building layout, arrangement of urban elements, building height, and sky view factor significantly influence shade and wind flow (Kim and Brown, 2021; Kong et al., 2021). Noticeably, the creation of urban green open spaces is great importance. These green spaces can regulate temperature, cool the surrounding air, and create cool islands in different areas, particularly in urban centers where SUHIs are more common (Ruefenacht and Acero, 2017). This element is intricately linked to other urban elements. Open and permeable urban spaces serve multiple purposes, including urban agriculture, improving community engagement, and providing local food production (Ladan et al., 2022).

3) Green-blue infrastructure design plays a crucial role in mitigating the adverse impacts of SUHIs, particularly on a small scale. Designing green-blue infrastructure involves interconnected green infrastructure, water bodies, and reflective infrastructure. Numerous studies have provided substantial evidence of the beneficial effects of connected blue-green infrastructure in mitigating SUHIs by contributing to urban cooling (Del Serrone et al., 2022; Fadhil et al., 2023; Semenzato and Bortolini, 2023). Urban elements such as green roofs, walls, connected pavements, green spaces (trees, parks), and urban agriculture are practical measures that can yield positive outcomes, especially when implemented through community engagement and across various spatial scales (Shao and Kim, 2022). Furthermore, the design of water bodies, such as fountains, water features, and water installations in public spaces, contribute significantly to the cooling of the surrounding areas (Ampatzidis et al., 2023). With active community participation, urban water acupuncture interventions can transform public spaces into vibrant, interactive, and cost-effective environments (Bell et al., 2020; Vassiljev et al., 2020). Moreover, it is worth noting that roofs make up approximately 25%–30% of urban surface area, while sidewalks account for approximately 40% (US EPA, 2008). Consequently, implementing reflective infrastructure, such as cool roofs, walls, and pavements, offers practical and economically viable interventions for mitigating the SUHI effect. These interventions offer significant potential for community participation by changing surface albedo. It enables local community members and various organizations, such as students and universities, to actively engage by volunteering to paint the roofs and streets within the neighborhood (Charles-Guzman, 2020).

4.2.5 Where

Finding the appropriate scale and locations for more effective interventions requires analysis to be conducted across three scales: city-wide (macro), neighborhood (meso), and building (micro). Figure 7 illustrates the relationship and importance of scales and various urban elements to mitigate SUHIs. The micro-level scale shows the strongest correlation with reduction strategies and interventions. The chart also highlights the relative importance of each mitigation strategy on the basis of its scale. However, UA principles emphasize the significance of small-scale interventions (Nassar, 2021), highlighting the increased importance of neighborhood and micro-scale strategies. In contrast, urban planning strategies are more closely associated with city-wide approaches.

Thus, in the Prescription phase, addressing the mitigation of SUHI effects through UA involves five fundamental questions. In a similar context, Meerow et al. (2017) established a link between the concept of urban resilience and the ability of an urban area to adapt to various challenges and shocks, such as natural disasters, economic recessions, and social disruptions. This study has raised five crucial questions related to the urban resilience framework aligned with our own. These questions include identifying the stakeholders or those affected by resilience planning, determining the primary goal of enhancing urban resilience, deciding where the focus of resilience planning should be directed, considering whether the emphasis should be on short-term or long-term resilience, and understanding the fundamental policies regarding resilience and its importance for urban areas. Therefore, our framework in the second phase offers an integrated approach to address the complex and multifaceted issues of SUHIs while enhancing urban resilience. Enhancing the physical, social, and institutional adaptability of cities reduces their vulnerability to heat, thereby reinforcing their resilience to climate change (Keith and Meerow, 2022). This issue further emphasizes the importance of small-scale interventions and active community participation in studies that enhance urban heat and resilience.

Figure 8 presents a comprehensive overview of the interconnected nature of various dimensions (scale, tools, principles and people involved) within the prescription phase. Green-blue infrastructure, particularly at the neighborhood scale, plays a crucial role in mitigating the impacts of SUHIs. Conversely, mitigation strategies related to urban planning mainly focus on a city-wide scale. Given that UA projects frequently involve citizen participation, it is crucial to acknowledge the vital role of local authorities and organizations.

Additionally, within the hierarchical structure of project implementation, individuals at lower levels demonstrate higher efficiency. However, the connection between the people involved, principles, and urban elements at various scales depends on the primary and secondary goals of urban projects.

As addressed in the “Why” question, the framework acknowledges the incorporation of extra goals within each UA project. These goals, aimed at urban cooling as the primary objective, encompass three main dimensions: environmental, social, and economic. Contrary to initial expectations based on the literature, our framework revealed a relatively little emphasis on goals focused on physical interventions. This difference can be attributed to several factors, including: (a) Implementing physical interventions requires more time and financial investment, which contradicts the principles of UA for low-cost and short-term projects. (b) In densely populated cities, pursuing large-scale physical goals presents challenges such as land use allocation,

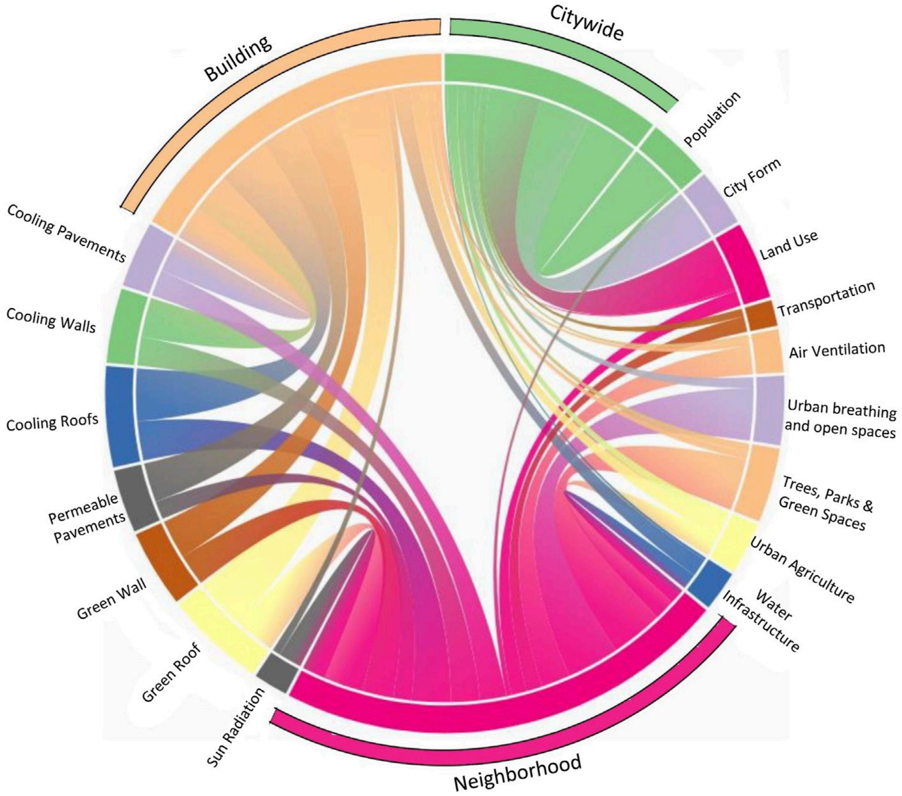

FIGURE 7
The relations between scales and SUHI mitigating tools.

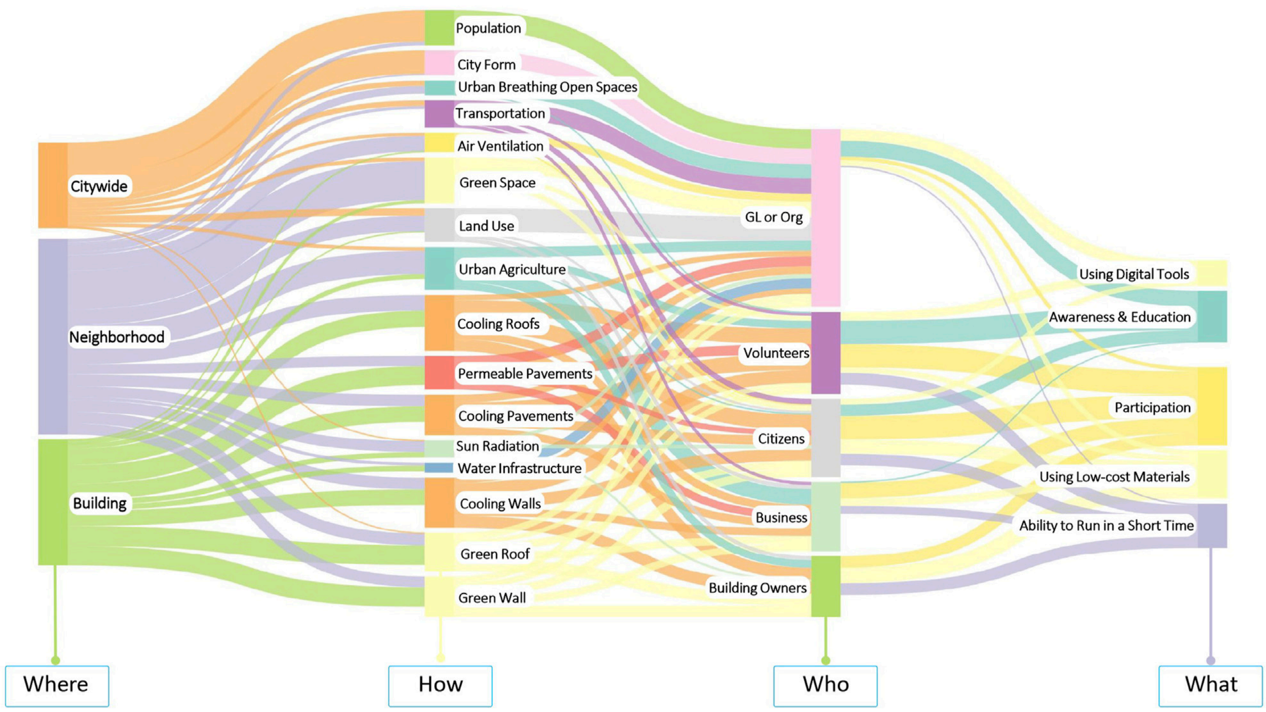

FIGURE 8
The relations between the different dimensions of the second phase.

security provision, and navigating bureaucratic procedures, which contradicts the principle of small-scale UA projects. (c) By adhering to the principles of UA, small-scale physical interventions can be incorporated into three goals. In addition to environmental, social, and economic goals, the cultural aspect could be considered another secondary goal. This goal involves raising community awareness of the adverse effects of heat and implementing strategies to mitigate these effects. Furthermore, it strengthens trust between the community and higher-level institutions and organizations.

Finally, the framework plays a crucial role in the practicality of the research findings, particularly in developing countries with limited socioeconomic status and financial capacity. The findings indicate that physical interventions play a lesser role compared to other interventions, supporting this claim. In these scenarios, small-scale actions at specific points can be highly effective, such as using lost spaces or rooftops for urban agriculture or organizing events to raise residents' awareness about urban heating. These initiatives not only contribute to the local economy and job creation but also increase the sense of community and community cohesion through participation. Integration of government, NGOs, and community involvement is of utmost importance. The government serves as a facilitator by developing policies and establishing regulations. For instance, after identifying lost spaces, the government can lease the land to locals for urban agriculture while providing education and awareness. This approach ensures local food production and income generation for the community. Additionally, the government can assist low-income families in setting up affordable cooling solutions in their homes by offering low-interest loans. NGOs can contribute by providing small budgets for projects such as enhancing public spaces and, painting pavements and roofs to mitigate urban heating. However, community participation is crucial at every stage. Implementing this framework can result in a range of elements, spaces, and events that have broad effects, not only in cooling the neighborhood and improving the environment but also in increasing positive social and economic impacts.

4 Conclusion

Rapid urban population growth has posed a significant challenge for cities as they grapple with the harmful effects of surface urban heat islands (SUHI), which negatively impact urban environments and the wellbeing of residents. Devising effective strategies to mitigate these impacts while actively engaging the community is complex. Based on urban design principles, we introduce a framework that connects the principles of urban acupuncture (UA) to facilitate community participation in implementing small-scale solutions.

Our framework was developed to address the research questions and consists of two distinct phases: diagnosis and prescription. During the diagnosis phase, we identified heat-vulnerable points within urban areas, effectively addressing the question "a." This was accomplished by using a comprehensive set of 30 primary indicators identified through MICMAC analysis, encompassing various aspects of urban form such as socioeconomic aspects, townscape, land use, transportation, morphology, structure of the urban spaces, and the environment. To address question "b," the prescription phase focuses on the identified heat-vulnerable points through urban acupuncture (UA) projects. Each project is guided by five key questions that determine secondary objectives, stakeholders, scale, and principles. Our framework for mitigating SUHI is categorized into urban planning, sustainable climate design, and green-blue infrastructure design.

By implementing this two-phase scenario based on UA principles, the framework empower designers, planners, and urban managers to identify heat-vulnerable points within urban settings. This facilitates the development of practical measures to mitigate SUHI impacts at the meso and microscales while involving the community. There were limitations in clarifying the first phase of the scenario. Acknowledging that using MICMAC in the first phase introduces specific associated challenges that require consideration is essential. Cultural biases among experts may influence the comparison of indicators, potentially compromising the validity and reliability of the key drivers. While the existing body of literature and statistical data analysis support the results, it is worth noting that different experts may draw diverse comparisons.

Future research should also aim to develop our framework into an operational model that can be applied to various scales for assessing geographic locations or evaluating different urban areas in mitigating the impacts of SUHI. Thus, our framework, utilizes the acupuncture method for identifying heat-vulnerable points, and provides practical practices for designers, planners, and urban managers. For future studies, there is an opportunity to expand the framework's application to macroscales, such as citywide. However, it should be noted that our current research primarily focuses on the mesoscale and microscale because of the nature of urban acupuncture and its emphasis on small-scale interventions, especially in neighborhoods.

Additionally, our study can contribute to the development of an urban design guideline document aimed at transforming identified heat-vulnerable points into a series of cooling oases. These oases serve as multifunctional spaces to address environmental goals and integrate social, cultural, and economic objectives through bottom-up community participation. According to our findings, creating these cooling oases provides, valuable guidance for urban designers and planners to improve livability and sustainability in cities in the era of urban resilience. Integrating environmental considerations with social, cultural, and economic dimensions contributes to a comprehensive approach to urban design, and fosters resilient communities.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://mega.nz/file/icABjZrT#m8OL25_puvtKPGOtbh7v7eYJVvPYr46XseSr_f6kQps.

Author contributions

SM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. AL: Conceptualization, Data curation, Methodology, Project administration, Supervision, Validation, Writing–original draft, Writing–review and editing. NT: Data curation, Formal Analysis, Methodology, Validation, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1324326/full#supplementary-material

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