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Article

Evaluating Heat Stress Vulnerability and Adaptation in Malaysia: Integrating System Thinking as a Public Health Intervention

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Abstract: Climate-induced heat stress poses escalating threats to public health, particularly among vulnerable populations in tropical countries. This study applies a systems thinking approach to evaluate heat stress vulnerability and adaptation capacity in Malaysia, focusing on high-risk urban and rural communities. A mixed-methods design was used, integrating physiological biomarkers (e.g., HSP70 expression, core body temperature), principal component analysis (PCA), and participatory stakeholder input into causal loop diagrams (CLDs) to model system dynamics. Distinct urban and rural CLDs were developed to map feedback loops and identify leverage points across five dimensions: environmental exposure, physiological response, housing quality, behavioral adaptation, and policy intervention. Findings revealed contrasting pathways of vulnerability. In urban settings, poor housing infrastructure and weak policy enforcement exacerbated chronic indoor heat exposure. In rural areas, prolonged outdoor work and infrastructural deficits were key contributors. Despite stronger adaptive behaviors in rural populations, systemic limitations impeded resilience. This study highlights the importance of targeting interventions to context-specific system structures. The integrated framework offers a transferable model for diagnosing heat-health risks and guiding equitable public health adaptation strategies in other tropical regions experiencing similar vulnerabilities.

Keywords: system thinking; causal loop diagram; public health adaptation; heat stress

1. Introduction

Climate change has emerged as one of the most pressing global public health threats, with escalating ambient temperatures increasingly contributing to heat-related illnesses, hospitalizations, and premature deaths [1]. In tropical countries like Malaysia, where baseline temperatures are already high, the intensification of extreme heat events poses a significant threat to both public and occupational health [2]. Vulnerable groups—such as outdoor workers, the elderly, and individuals with pre-existing medical conditions—are disproportionately affected, often due to limited access to adaptive resources and compounded by socio-economic and environmental disparities [3,4].

Current assessments of heat stress vulnerability and adaptation in Malaysia tend to be fragmented and reactive. Many rely on isolated climatic or demographic indicators, offering a narrow view of the multifactorial and systemic dynamics that drive heat-related health outcomes [5]. These approaches overlook the complex interplay of environmental, physiological, behavioral, and socio-economic variables that characterize real-world vulnerability scenarios [6,7]. There is thus a critical need to adopt more integrative frameworks that capture the multifaceted nature of heat-health risks [8,9].

Systems thinking has emerged as a promising holistic framework in public health research, enabling the mapping of causal relationships, feedback loops, and intervention leverage points within complex systems [10]. Applied to heat stress, it facilitates a deeper understanding of how environmental exposures translate into health outcomes and provides a pathway for designing proactive, strategic, and equity-centered interventions. However, its application within the Malaysian context remains limited, particularly in integrating physiological evidence and community-based participatory insights.

While some studies have examined heat-related biomarkers such as cortisol levels or core body temperature, few have incorporated these physiological indicators into broader systems-level models. This creates a gap in capturing the full spectrum of heat-health dynamics. Furthermore, the lack of participatory modeling approaches has restricted the inclusion of community knowledge, which is vital for contextualizing adaptive behaviors and institutional responses [11].

This study addresses these gaps by integrating systems thinking with empirical biomarker data and participatory stakeholder input. Specifically, we developed causal loop diagrams (CLDs) that synthesize physiological responses, environmental conditions, and socio-behavioral feedback loops to evaluate heat stress vulnerability and adaptive capacity in Malaysia. By generating differentiated CLDs for urban and rural populations, this study offers a nuanced understanding of the structural and systemic determinants of vulnerability.

Ultimately, this research advances both the theory and practice of systems thinking in environmental public health. It provides a replicable model for diagnosing systemic vulnerabilities and guiding evidence-informed, locally relevant public health adaptation strategies in tropical regions experiencing climate-induced heat stress.

2. Methodology

2.1. Study Design

This study employed a mixed-methods design that integrates empirical physiological and biomarker data within a systems thinking framework to evaluate heat stress vulnerability and adaptation in Malaysia. Rather than replicating previous biological assessments, this study expands their utility by embedding them into a dynamic systems model. This approach allows for the identification of feedback loops, structural leverage points, and interdependent factors influencing heat-health outcomes in real-world settings.

2.2. Data Sources and Physiological/Biomarker Integration

Physiological and biomarker data were obtained from a cross-sectional investigation conducted between July and September 2022 in selected urban and rural areas of Klang Valley, Malaysia. Detailed methodologies regarding participant recruitment, exposure classification, and data collection are available in the following three peer-reviewed publications:

a) "Heat stress-induced heat shock protein 70 (HSP70) expressions among vulnerable populations in urban and rural areas Klang Valley, Malaysia", which explored HSP70 gene and protein expression in response to ambient heat exposure [12];
b) "Association between physiological responses and heat shock protein 70 (HSP70) expressions in the vulnerable populations of Kuala Lumpur", which examined associations between physiological indicators (core body temperature, blood pressure, and heart rate) and HSP70 expression [13];
c) "Assessment of heat stress contributing factors in the indoor environment among vulnerable populations in Klang Valley using principal component analysis (PCA)", which employed principal component analysis (PCA) to identify vulnerability indicators related to indoor heat exposure [14].

The focus of these studies was on high-risk groups identified as vulnerable to heat stress, rather than the general population. Eligible participants included senior citizens (aged 60 years and above), individuals from low-income households (representing the bottom 40% of income in Malaysia), and those with diagnosed health morbidities such as hypertension, diabetes, or respiratory conditions. These criteria were selected to reflect populations with reduced physiological adaptability and/or limited access to structural adaptation resources. To ensure stable environmental exposure profiles, participants were required to have resided in their current homes for at least one year. Additional inclusion criteria specified that participants must have reported experiencing symptoms of heat stress while at home within the previous seven days, such as dizziness, excessive sweating, fatigue, or headaches. Exclusion criteria included pregnancy and individuals under the age of 13, due to differing physiological baselines and ethical considerations. This population framework was consistently applied across the three peer-reviewed studies from which the current systems analysis draws its empirical foundation. Focusing on these groups allowed for a more accurate and targeted evaluation of how systemic factors, such as poor housing infrastructure, limited passive cooling strategies, and occupational exposure, manifest within those most physiologically and socially vulnerable to heat in both urban and rural Malaysian communities.

These publications, therefore, provide the empirical foundation and quality assurance for data integrated into the present systems-based analysis.

2.3. Systems Thinking Approach: Causal Loop Diagramming (CLD)

To operationalize the systems thinking approach, we adopted a participatory modeling method centered around causal loop diagramming (CLD), a qualitative systems mapping technique widely used in environmental and public health research. The CLD construction process involved four key steps: (1) variable selection, (2) conceptual framework development, (3) stakeholder validation, and (4) model refinement.

(1) Variable Selection Criteria

Variables included in the CLD were identified based on triangulated evidence from three prior peer-reviewed studies (Refer to Table 1). A variable was eligible for inclusion if it (i) was empirically associated with heat stress (via physiological or behavioral indicators), (ii) appeared as a statistically significant factor in PCA results, or (iii) was repeatedly emphasized during stakeholder engagements. The goal was to ensure all variables reflected either a measurable exposure, sensitivity factor, or adaptive capacity indicator. Recurring elements such as core body temperature, HSP70 expression, housing type, and hydration behavior were prioritized as nodes within the system.

(2) Conceptual Framework Development

These findings informed the drafting of a preliminary conceptual CLD that mapped interactions between heat exposure, physiological response, socio-environmental context, and institutional dynamics. Directionality of causal links was initially based on literature consensus and refined iteratively during the next stages.

(3) Stakeholder Engagement and Participatory Modeling

Three (3) stakeholder workshops were conducted in Klang Valley, involving a total of 21 participants representing community leaders, public health officers, elderly citizens, outdoor workers, and academic researchers. Each session followed a structured facilitation model based on the Iceberg Framework and group model building techniques. Workshop procedures included,

- Step 1: Individual Reflection & Group Brainstorming – Participants were first asked to identify personal or observed experiences with heat stress symptoms and coping strategies.
- Step 2: Mapping Contributors and Consequences – Using sticky notes and thematic clusters, participants worked in small groups to list factors contributing to heat stress and resulting impacts.
- Step 3: Identification of Feedback Loops – Participants were guided to link variables through causal relationships, identifying whether the connection was reinforcing or balancing in nature.
- Step 4: Validation and Expansion of the Draft CLD – The initial conceptual CLD was presented and collaboratively modified by the group, with attention to missing links, local terminology, and context-specific conditions.

To ensure robust qualitative input, facilitators used semi-structured prompts such as:

- "What tends to happen next when heat stress symptoms increase in your environment?"
- "What factors make it easier or harder for people to adapt to heat?"
- "How do local institutions respond to rising heat risk, and how timely are these responses?"

All workshop discussions were audio recorded and thematically analyzed. Variables and connections with the majority consensus were retained in the final CLD. Minority perspectives were noted for future research consideration.

(4) Model Refinement and Validation

During the workshops, system components were iteratively classified into archetypal feedback structures such as reinforcing loops (e.g., dehydration and cumulative heat strain), balancing loops (e.g., adaptive behaviors like rest and hydration), and time-delayed loops (e.g., lag between exposure and policy response). Biomarker findings—notably elevated HSP70 protein expression and increased core body temperature—were used as quantitative anchors to validate and contextualize key variables. For example, elevated biomarker levels among low-income urban residents were used to model a reinforcing loop linking poor housing conditions, chronic heat exposure, and biological strain.

The resulting CLD was then digitized and cross-validated against the PCA-derived vulnerability indicators publication sources. This step ensured that the system model reflected statistically robust components of exposure, sensitivity, and adaptive capacity. Relevant PCA-derived indicators (e.g., housing materials, building age, medication use) were translated into system components and linked to physiological health outcomes within the diagram. The finalized CLD was digitized using Vensim software, cross-validated with PCA results, and refined through internal peer review to ensure logical coherence, alignment with empirical data, and applicability for public health diagnostic purposes.

2.4. Summary of CLD Variable Mapping

To enhance transparency and support the validity of the CLD structure, Table 1 summarizes key CLD variables included in the system model, along with their descriptions, data sources, and validation approaches.

2.5. Final CLD Review and Use as a Diagnostic Tool

The completed CLD underwent internal review to ensure logical consistency, inclusion of relevant feedback mechanisms, and identification of actionable leverage points. While this study did not proceed to quantitative simulation, the CLD could serve as a diagnostic tool for uncovering emergent dynamics and informing targeted, evidence-based public health interventions aimed at improving heat-health resilience in Malaysia.

Table 1. Mapping of Key CLD Variables, Descriptions, and Data Sources.

CLD Variable	Description	Data Source	Validated by
Heat Stress Exposure	Intensity and duration of environmental heat	[12,13]	Physiological and biomarker evidence (HSP70, core temperature)
Vulnerable Housing	Quality of the built environment and ventilation	[14]	PCA-based statistical analysis; spatial housing data
Dehydration	Hydration practices and stress response	Stakeholder workshops	Biomarker indicators; participant narratives

Policy Response Delay	Time lag in institutional adaptation measures	Stakeholder workshops	Repeated themes across multi-stakeholder inputs
Adaptive Behaviors	Rest, hydration, and protective actions	Community narratives	Triangulated with literature and stakeholder consensus

3. Results

3.1. Overview of System Map and Core Variables

The final Causal Loop Diagrams (CLDs) synthesize insights from physiological biomarker analysis, participatory stakeholder input, and environmental vulnerability indicators into two system models—one representing urban heat stress vulnerability, and the other rural. These diagrams serve as conceptual tools that visually map feedback loops across five interconnected dimensions: (i) environmental exposure, (ii) physiological response, (iii) housing and infrastructure, (iv) behavioral adaptation, and (v) institutional and policy influence.

Both CLDs integrate the expression patterns of HSP70 gene and protein as physiological indicators of heat stress adaptation, with urban populations exhibiting elevated protein expression linked to acute thermal exposure, while rural populations demonstrated persistent gene activity, suggestive of chronic physiological strain. This biomarker distinction validates the inclusion of both acute and latent heat stress responses within each system map.

(i) Urban Heat Stress Causal Loop Diagram (CLD)

As shown in Figure 1, the urban heat stress CLD reflects a highly interdependent system driven by poor housing conditions, delayed policy response, and insufficient individual adaptation capacity. This CLD underscores how structural, behavioral, and policy shortcomings create a reinforcing cycle of vulnerability in urban environments, even when adaptive intentions are present.

- Reinforcing Loop R1 begins with poor housing conditions, such as low ceiling height, inadequate insulation, and aging infrastructure, that cause heat accumulation indoors. Prolonged exposure leads to dehydration and biological strain, marked by increased HSP70 protein expression, signaling cellular stress. This loop is compounded by limited passive cooling options and contributes to chronic physiological stress. While protective feedback mechanisms may regulate HSP70 gene activity, the loop continues as housing remains structurally unchanged.
- Reinforcing Loop R2 is centered around adaptive behaviors (e.g., rest, hydration), which initially help counteract heat exposure. However, these behaviors are undermined by fatigue, often caused by delayed or insufficient institutional responses, such as lack of early warnings or poorly enforced rest policies. This fatigue suppresses further adaptive behaviors, thereby intensifying dehydration and stress. The loop thus reinforces itself through declining behavioral resilience.
- Balancing Loop B1 represents the intended homeostatic response to heat through adaptive behaviors (hydration, rest). These behaviors initially help stabilize

dehydration and HSP70 levels. However, their effectiveness is reduced by economic limitations, workplace expectations, and overdependence on mechanical cooling, often inaccessible to low-income residents. As a result, the balancing loop remains weak and often fails to offset the two reinforcing loops.

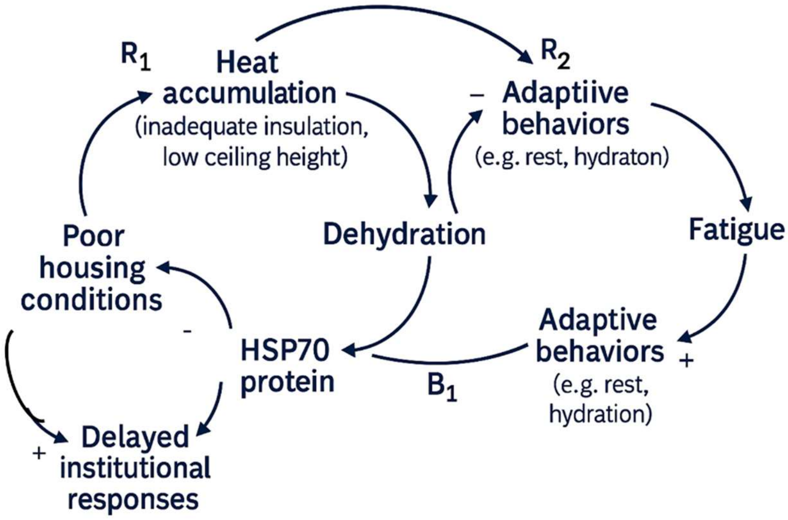

Figure 1. Causal Loop Diagram (CLD) for urban vulnerable populations. Reinforcing loops (R1, R2) illustrate compounding vulnerabilities due to housing and policy delays. Balancing loop (B1) represents adaptive behaviors constrained by social and economic limitations.

(ii) Rural Heat Stress Causal Loop Diagram (CLD)

The rural heat stress CLD, shown in Figure 2, captures a complex system of vulnerability anchored by labor-intensive occupations, deteriorated infrastructure, and limited institutional support. It highlights how physiological stress accumulates through reinforcing feedback loops while partial mitigation is attempted through behavioral adaptation. This diagram demonstrates that while rural populations may engage in more proactive adaptive behaviors, their effectiveness is often neutralized by persistent structural and resource barriers.

- Reinforcing Loop R3 begins with direct outdoor exposure associated with physically demanding work. This leads to elevated core body temperature, which is further exacerbated by substandard roofing and lack of ceiling insulation—resulting in higher internal heat retention. As temperature rises, HSP70 gene expression is triggered, indicating cellular stress but without adequate physiological adaptation. The loop reinforces itself as structural conditions persist.
- Reinforcing Loop R4 is initiated by long-term exposure, aging infrastructure, and underlying health conditions, which continuously activate HSP70 gene transcription. However, the body’s ability to produce protective HSP70 protein remains limited. This reinforces chronic physiological strain without effective buffering.
- Balancing Loop B2 involves physical activity and hydration, which rural residents often practice out of necessity. These behaviors can help reduce heat strain, but are constrained by systemic barriers such as poor water supply and

limited healthcare access. As illustrated in the CLD, the intended balance is undermined, leading to only partial mitigation of heat-related health risks.

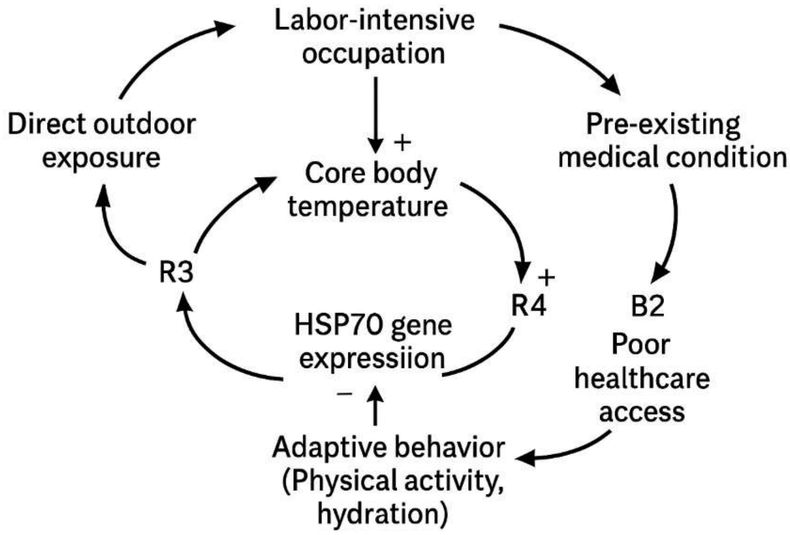

Figure 2. Causal Loop Diagram (CLD) for rural vulnerable populations. Reinforcing loops (R3 and R4) depict biological strain driven by occupational exposure and infrastructure decay. Balancing loop (B2) suggests partial mitigation via physical and hydration practices, hindered by systemic resource gaps.

3.2. Stakeholder Validation and Community Insights

The participatory workshops revealed a consistent narrative of vulnerability among outdoor workers and elderly participants as tabulated in Table 2, but with notable contrasts between urban and rural contexts.

In urban settings, stakeholders highlighted:

- Over-reliance on mechanical cooling, such as fans and air-conditioners, especially in poorly ventilated high-rise flats.
- Concerns over rising utility costs which discourage the continuous use of cooling appliances.
- A lack of employer enforcement on mandatory rest breaks or hydration policies in indoor workplaces.
- Beliefs that older buildings retain more heat and contribute to chronic discomfort, particularly during evening hours.

In rural settings, the dominant concerns included:

- Extended periods of exposure due to agricultural work with limited shaded rest areas.
- Unreliable access to clean drinking water, especially in hilly or remote zones.
- Acceptance of heat discomfort as a normal part of life, contributing to underreporting of symptoms.
- Cultural norms favor endurance and productivity over safety during hot weather.

Participants in both settings contributed to the refinement of loops involving behavioral norms, access barriers, and institutional response delays. These qualitative insights added layers of realism to the CLD structure.

Table 2. Key Community Insights Identified during Stakeholder Workshops.

Theme	Urban Stakeholder	Rural Stakeholders
Cooling practices	Use of fans, air-conditioning system; concerns about electricity cost	Limited use of fans; rely on natural ventilation
Water access	Generally accessible but not prioritized during work	Intermittent; affected by infrastructure or geography
Occupational behavior	Sedentary indoor work; less hydration enforcement	Outdoor manual labor; long hours under direct sun
Cultural attitudes	Perceived need to maintain productivity indoors	Cultural emphasis on physical endurance
Institutional gaps	Delayed response from authorities on heatwave alerts	Minimal engagement from health officers or local leaders

3.3. Integration of Biomarker Data and PCA Evidence

Biomarker evidence from the referenced studies provided essential physiological grounding to both urban and rural CLDs, validating feedback loops associated with heat-related stress. In urban populations, elevated HSP70 protein levels reflected a stronger cellular response to prolonged heat exposure, particularly in enclosed environments with inadequate ventilation. Conversely, rural populations exhibited lower protein expression, suggesting a more limited adaptive physiological response to heat despite comparable gene activity. HSP70 gene expression, while consistent across settings, appeared to reflect longer-term health factors rather than immediate thermal stress. These biomarker trends support the interpretation that HSP70 protein serves as a sensitive marker of acute thermal strain, while gene expression may indicate underlying vulnerability or chronic adaptation pathways. Their combined use enhanced the physiological relevance of key CLD variables, particularly in relation to core body temperature, dehydration, and housing quality.

As shown in Table 3, PCA findings strengthened the empirical foundation of the CLDs by identifying robust, context-specific vulnerability domains. In urban areas, principal components emphasized health morbidity, medication use, and poor ceiling design. For rural populations, key vulnerability indicators included ceiling unavailability, low-quality roofing, and prolonged residential exposure. These findings guided variable inclusion and directionality within each system map, ensuring that both CLDs were grounded in quantitative, data-driven evidence. Together, the biomarker and PCA results reinforced the rationale for constructing separate CLDs and demonstrated how physiological and environmental data can be integrated into systems-based diagnostics for targeted public health interventions.

Table 3. Summary of PCA-Derived Vulnerability Components.

Component Theme	Urban Model Dominant Variables	Rural Model Dominant Variables
Health & Medical Risk	Health morbidity, medicine intake	Health morbidity, medicine intake
Structural Housing Risk	Ceiling height, building age	Ceiling availability, roof material
Social-Behavioral Risk	Educational level, gender, water intake	Physical activity, income, occupation type

3.4. Summary of CLD Insights for Public Health Intervention

The urban and rural system models revealed context-specific leverage points for public health intervention, grounded in differences in environmental exposure, housing infrastructure, and behavioral adaptation capacity as shown in Table 4.

In urban settings, priority should be given to retrofitting existing housing stock to improve thermal insulation and ventilation. The chronic nature of indoor heat exposure in urban environments, coupled with high dependency on mechanical cooling, underscores the need for passive cooling strategies and the enforcement of hydration and rest policies within indoor workplaces. Targeted subsidies may also help alleviate the financial burden of air-conditioning use, especially for vulnerable low-income groups. Furthermore, the integration of physiological biomarker surveillance into occupational health systems can offer real-time indicators of heat stress and inform timely intervention.

In rural areas, the most impactful leverage points include upgrading basic infrastructure such as water supply systems and the provision of shaded work shelters for outdoor workers. Given the physical intensity of agricultural labor and the longer duration of exposure, interventions should focus on strengthening behavioral adaptation through community-led health promotion programs. Rural-specific heat-health warning systems tailored to the local climatic context could enhance preparedness and response. Mobilizing community health volunteers to monitor hydration and detect early signs of heat-related illness may improve health outcomes in remote settings.

Both CLDs reinforce the notion that heat stress vulnerability is not merely a function of ambient temperature but arises from systemic and modifiable determinants. Thus, a systems-thinking perspective is essential to designing integrated, context-sensitive public health adaptation strategies.

Table 4. Summary of Leverage Points Identified in Urban and Rural Heat Stress Systems.

Leverage Point Category	Urban Recommendation	Rural Recommendation
Housing and infrastructure	Improve ventilation; insulate buildings	Replace roofing; install ceiling

Occupational health	Mandate hydration breaks	Provide rest areas and shaded shelters
Public health surveillance	Integrate biomarkers in screening	Launch rural symptom reporting systems
Community education	Promote AC use efficiency and hydration awareness	Mobilize village health committees

These leverage points will be explored further in the Discussion as part of a broader public health adaptation strategy.

4. Discussion

4.1. Systems Thinking in Heat Stress Evaluation

This study offers a novel and integrated application of systems thinking to assess heat stress vulnerability in Malaysia, using causal loop diagrams (CLDs) to map the interconnections between environmental exposures, physiological responses, housing conditions, behavioral adaptations, and institutional dynamics. By incorporating physiological biomarker data, stakeholder insights, and PCA-derived vulnerability indicators, this systems framework captures the non-linear and emergent dynamics that traditional assessments often overlook [15].

The dual-CLD approach effectively illustrates how heat vulnerability manifests differently in urban and rural settings. While both populations are exposed to rising temperatures, the pathways of sensitivity and adaptive capacity differ based on structural, behavioral, and socio-economic contexts. This contextual modeling highlights the role of feedback loops and systemic barriers that either reinforce vulnerability or offer opportunities for targeted interventions.

(i) Urban Heat Stress Vulnerability and Intervention Leverage

The urban CLD reveals a complex and reinforcing system of vulnerabilities in which substandard housing infrastructure, insufficient policy implementation, and constrained individual coping behaviors collectively elevate physiological stress levels among vulnerable groups. Central to this vulnerability is the chronic accumulation of indoor heat within poorly ventilated, low-ceiling dwellings, leading to sustained elevations in core body temperature and HSP70 protein expression—biomarkers indicative of acute cellular stress responses. Reinforcing loop R1 illustrates how inadequate insulation and structural design trap heat indoors, exacerbating thermal discomfort and biological strain. Reinforcing loop R2 further compounds this vulnerability through the delayed or absent institutional responses, such as the lack of timely public advisories or thermal safety regulations in low-income residential zones. Balancing loop B1 represents behavioral countermeasures such as hydration and rest; however, these are often undermined by socioeconomic constraints, including energy insecurity, lack of awareness, and social expectations that discourage rest in high-density urban work environments [16].

In terms of intervention leverage, the urban system suggests multiple actionable entry points. Structural interventions, such as subsidized housing retrofits that enhance passive ventilation and thermal insulation, could break the reinforcing cycle of heat accumulation. Behavioral interventions should target education and awareness campaigns promoting heat-risk literacy and hydration practices. From a governance standpoint, policy reforms mandating minimum thermal safety standards and employer-enforced hydration breaks are critical. Moreover, integrating physiological biomarker monitoring (e.g., HSP70 profiling) into routine public health surveillance can serve as an early warning mechanism for identifying heat-related risks in high-density urban populations. These leverage points, if strategically implemented, can shift the system from vulnerability reinforcement toward resilience and adaptive capacity.

While the previous discussion has identified multiple entry points for intervention, realizing meaningful change requires alignment across structural, behavioral, and institutional domains. Integrated urban planning and public health policies must prioritize the retrofitting of vulnerable housing units to promote passive cooling, alongside the institutionalization of occupational safety measures such as mandated hydration breaks and indoor thermal comfort standards. Furthermore, embedding physiological biomarkers like HSP70 into surveillance systems can enhance early detection and targeted response to heat-related illnesses. Equally important is addressing entrenched social norms and economic barriers that inhibit adaptive behaviors, such as reluctance to rest during peak heat hours or constrained access to cooling devices due to high electricity costs [17]. These layered interventions, when coordinated effectively, can transform the urban heat vulnerability landscape into one of resilience and adaptive readiness.

(ii) Rural Heat Stress Vulnerability and Intervention Leverage

In contrast, the rural CLD highlights a distinct yet equally concerning vulnerability system, predominantly shaped by intensive outdoor labor, deteriorating housing infrastructure, and limited institutional support. Rural populations are frequently engaged in agricultural and manual labor under prolonged direct sunlight, which significantly elevates core body temperatures. Although HSP70 protein expression appeared slightly lower compared to urban counterparts, sustained HSP70 gene activity points to chronic physiological strain, possibly due to less effective thermoregulatory adaptation mechanisms. Reinforcing loop R3 underscores the direct heat load resulting from extended outdoor exposure and inadequate roofing or ceiling insulation, while loop R4 captures the interplay between persistent infrastructural neglect, pre-existing health conditions, and socioeconomic constraints that prevent effective behavioral or structural adaptation.

This system of vulnerability is further exacerbated by systemic inequities in access to potable water, healthcare services, and heat-mitigation infrastructure such as shaded shelters. Despite these challenges, rural communities exhibited comparatively stronger intrinsic coping behaviors, including more frequent hydration and higher physical resilience. However, these behaviors alone are insufficient to counteract the systemic stressors embedded in their environments.

Intervention leverage in rural settings must therefore be multifaceted. Structural upgrades to housing, such as provision of insulated ceilings and improved roofing materials, are foundational. Occupational interventions should focus on creating shaded rest areas and scheduling labor to avoid peak heat hours. Institutional support must be enhanced through mobile healthcare delivery, rural-specific heat warning systems, and empowerment of local health volunteers to conduct heat risk education and symptom monitoring. Furthermore, context-specific behavior change campaigns should be co-developed with community leaders to reinforce adaptive practices that are culturally resonant and practically feasible. Collectively, these strategies can disrupt the reinforcing vulnerability loops and foster systemic resilience across rural heat-stressed populations.

While rural populations demonstrated relatively stronger behavioral adaptations, such as increased hydration and sustained physical activity, these strategies alone were insufficient to mitigate the entrenched systemic deficits. Inadequate access to clean water, absence of protective occupational policies, and deteriorated housing structures continue to undermine adaptive capacity. These deficits reflect structural inequities and institutional neglect, compounding physiological vulnerability despite intrinsic resilience.

To effectively leverage interventions in rural settings, strategies must prioritize scalable infrastructure solutions such as cost-effective ceiling insulation, weather-resilient roofing, and improved water delivery systems. Occupational health safeguards, including mandated shaded rest zones and flexible work scheduling during extreme heat periods, are essential. Additionally, health promotion must be localized through culturally attuned education programs and strengthened by training community health volunteers to monitor and respond to early signs of heat-related illness. Implementing hyper-local early warning systems tailored to environmental and labor conditions will further reinforce community-level preparedness and response.

4.2. Broader Implications and Applicability to Tropical Settings

This study reinforces the need to disaggregate vulnerability by socio-geographic context and population subgroups. By applying a systems-based framework, we demonstrate that heat stress vulnerability is not a linear function of temperature alone but a product of structural, physiological, and social determinants. The approach is scalable and adaptable to other tropical countries facing similar climatic and socio-economic challenges.

For instance, researchers in southern Brazil used systems thinking to understand the quality of the public health system [18], noting that public health systems are complex environments with many interacting actors. They argue that it is important to take a holistic perspective when implementing information systems and information technology in such environments [19]. In Vietnam, system thinking has also been used to manage the impacts of climate change. It shows that understanding the complexities and interactions between various factors is crucial for effective decision-making and policy development [20]. Likewise, studies in India have emphasized the role of informal labor, inadequate rest policies, and limited institutional heat-risk frameworks—echoing the structural constraints observed in Malaysian rural populations [10]. These parallels underscore the broader applicability of CLD-based approaches in diagnosing system-level vulnerabilities and guiding targeted interventions across varied tropical contexts.

Governments and public health agencies can leverage this framework to identify leverage points, allocate resources more effectively, and co-design context-specific adaptation strategies. The participatory and data-driven nature of the model enhances its relevance, particularly in low- and middle-income settings where local realities often dictate health outcomes [21].

4.3. Methodological Contributions and Future Directions

This research contributes methodologically by bridging quantitative and qualitative data through systems thinking. Integrating biomarkers like HSP70 into CLDs introduces a physiological layer often absent in public health modeling. The use of PCA further validates variable selection and system mapping.

Future studies should operationalize these qualitative CLDs into simulation models such as system dynamics or agent-based models to test intervention scenarios under various climate futures. Longitudinal studies could also improve understanding of delayed feedback mechanisms and cumulative exposures. Integrating mobile health technologies and real-time environmental monitoring may enhance responsiveness and facilitate adaptive governance.

In conclusion, this study advances the application of systems thinking for diagnosing and addressing heat stress vulnerability in tropical climates. By developing differentiated, empirically grounded CLDs for urban and rural communities, we offer a replicable and policy-relevant framework to inform equitable, evidence-based public health interventions in an era of escalating climate risks.

4.4. Limitations

This study has several limitations that should be acknowledged. First, while integrating biomarker and PCA data into the systems thinking framework improves conceptual robustness, the causal loop diagrams (CLDs) remain qualitative and exploratory in nature. The feedback relationships, interaction pathways, and leverage points identified were based on participatory inputs and cross-sectional evidence, rather than tested through quantitative simulation. Future studies could address this limitation by translating the CLD into a stock-and-flow system dynamics model to simulate different intervention scenarios, test feedback sensitivities, and quantify long-term effects under various heat exposure and policy conditions. Model validation could involve historical trend comparison, parameter estimation from empirical datasets, or scenario calibration using real-time physiological or environmental monitoring data.

Second, the sample population focused on vulnerable groups within selected urban and rural communities in Klang Valley, which may not represent the full demographic or geographic diversity of Malaysia. Third, potential recall bias and subjective interpretation during stakeholder workshops could have influenced the reliability of some qualitative insights, particularly in identifying causal linkages and system boundaries. Fourth, the use of HSP70 as a biomarker provides acute physiological insight but does not fully capture the range of chronic health outcomes or cumulative exposures associated with prolonged heat stress. Finally, the cross-sectional nature of the study limits the ability to track delayed feedback loops, long-term adaptation pathways, or evolving risk profiles over time.

5. Conclusion

This study presents a novel application of systems thinking to identify and interpret heat stress vulnerability in Malaysia by focusing on high-risk urban and rural populations. Through the development of separate CLDs informed by physiological biomarkers, PCA-based vulnerability dimensions, and stakeholder narratives, we offer a context-sensitive diagnosis of heat-health risk pathways. The models underscore the systemic nature of vulnerability, shaped by structural, environmental, behavioral, and institutional dynamics that differ significantly between urban and rural settings.

Our findings emphasize the need for geographically targeted and equity-driven public health interventions, particularly in tropical countries facing rapid urbanization and climate variability. The framework developed here provides a scalable tool for diagnosing systemic heat vulnerability and guiding adaptation planning in other low- and middle-income countries with similar socio-environmental conditions. By prioritizing vulnerable populations and identifying specific leverage points, this study contributes to the evolving field of climate resilience and public health systems. Future work should aim to translate these conceptual models into dynamic simulations to test policy interventions and enhance decision-making under climate uncertainty.

Author contributions: Conceptualization, VH and LFL; methodology, VH; software, VH; validation, VH, SNM and LFL; formal analysis, VH, NSAMS; investigation, VH, NSAMS; resources, VH, SNM, NSAMS; data curation, VH and LFL; writing—original draft preparation, VH and SNM; writing—review and editing, VH and SHM; visualization, VH; project administration, SHM; funding acquisition, VH. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This research received ethical clearance from the Ethics Committee for Research Involving Human Subjects, Universiti Putra Malaysia (Reference No.: JKEUPM-2022-222). Prior to participation in the study, written informed consent was obtained from all participants, ensuring compliance with ethical guidelines.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are publicly available in the International Journal of Environmental Health Research repository at https://doi.org/10.1080/09603123.2024.2340125, the Scientific Reports repository at https://doi.org/10.1038/s41598-024-67110-w and Journal of Exposure Science and Environmental Epidemiology at https://doi.org/10.1038/s41370-025-00764-4. Further datasets can be obtained from the corresponding author on reasonable request.

Conflict of interest: No potential conflict of interest was reported by the author(s).

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