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Enabling the Built Environment for Sustainable Living and Climate Resilience

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ABSTRACT:
Climate crises and a myriad of anthropogenic hazards have induced multitude of diverse impacts on the built environment. These complex and interconnected crises bring impacts on the functionality and integrity of the built environment in various material and immaterial manners, exacerbating the already intense socioeconomic conflicts. Sustainable solutions, if properly planned and implemented, can help build more holistic crises resilience in the built environment by enhancing the capability and capacity to increase preparedness and agility of the built environment to disruptions.
This paper aims to provide a better understanding about the research progress on sustainability and resilience of the built environment in response to climate changes. It reviews the impacts of climate crisis on the functionality and integrity of the built environment and examines the importance of integrating resilience in sustainability solution in the built environment.
A framework is proposed to unveil how sustainability solutions with an integration of resilience can provide a more solid approach to accelerate the adaptation to and mitigation of climate change impacts within the built environment. Apart from optimising biodiversity and natural resources-based-solutions, sustainable built environment also facilitates powerful partnerships via social transition for environmental governance and human. Sustainability isn't about decarbonising the built environment. Instead, sustainability would contribute by making systemic changes in the built environment for increased resilience to climate changes and socioeconomic challenges.

Keywords: Sustainability, built environment; climate change, resilience, adaptation, systematic review

1. Introduction

According to WMO (2024), the global average near surface temperature in 2023 was 1.45± 0.12°C above the 1800-1900 mean and 2023 broke a record and reached the highest temperature in the observational record of 174 years. In addition to the new high temperature threshold, the year 2023 also broke a record of every single climate indicator. Concentrations of greenhouse gases including carbon dioxide, methane and nitrous oxide hit a new high record, while ocean heat content and sea level reached recorded observed highs (WMO, 2024). Polar ice shields continue to melt, and Antarctic Sea ice extent hit a new low record too. Profound negative ecological impacts of climate change have become more apparent now and they are likely to intensify in the coming years if no immediate and proper action is taken to reduce carbon emissions.

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A myriad of anthropogenic hazards including coastal erosion, land subsidence, saltwater intrusion, soil salinization and groundwater pollution, have induced multitude of diverse impacts on the built environment (Qi & Liu, 2017). Climate change crises such as extreme temperatures, droughts, flooding, precipitation changes, sea level rise, heatwaves and warming, cyclones and strong winds are happening at a greater speed and intensity than before. These have brought unprecedented implications to human, buildings, infrastructure and the surrounding. Uncontrolled climate crisis is threatening the people's lives and impacting all aspects of phenology – cyclic and seasonable natural phenomena of animal and plant life. Climate variability could lead to expansions, reductions, or extinctions of some species that in turn result in biodiversity loss.

Human activities have great influences on changing the natural ecosystem and Earth's system. Human-induced climate crises are anthropogenic disasters or natural disasters aggravated by human actions or inactions. Anthropogenic hazards refer to hazardous events caused by intentional human activities, inactions, negligence, or errors. Anthropogenic hazards may trigger and catalyse more climate change disasters, further burdening the society and natural ecosystems. For instance, burning of fossil fuels and human activities increased the greenhouse gas concentrations, leading to the global temperature rise and a lack of precipitation – increases the risks of severe droughts. Extensive studies and reports demonstrated that climate crises are primarily human induced (IPCC, 2023; Scott et al., 2021). Current carbon dioxide concentrations are higher than at any time over the past two million years and far exceed the natural multi-millennial changes between glacial and interglacial periods over the past eight hundred thousand years (IPCC, 2023). It is unequivocal that observed increases in greenhouse gas concentrations since 1750 are attributed to greenhouse gas emissions resulted from human activities (IPCC, 2023).

Built environments are increasingly exposed to climate stresses and cascading effects. The impacts of climate changes on built infrastructure could be catastrophic and long lasting since the built assets are designed for a long lifespan. Once built assets are created, the physical form and land use patterns would be locked in for generations. Extreme climate events and disastrous shocks result in tremendous damage to the built environment and infrastructure, hence increasing the vulnerability of people and urban systems to climate disturbances (Al-Humaiqani and Al-Ghamdi, 2023). In wake of ever -increasing climate hazards, the global discourse needs to focus on climate adaptation to increase the capacity and capability of the built environment to cope with potential future climate disturbances.

The built environment is an important nexus for climate change mitigation and adaptation. However, current sustainable built environments are designed to produce lower environmental impacts but not to respond to the ever-increasing impacts of the environment (Roostaie et al., 2019). There is growing number of studies calling for the need to foster resilience and sustainability in the built environment (Al-Humaiqani & Al-Ghamdi 2023; Tanguay & Amor, 2024; Roostaie et al., 2019). Despite of this, resilience appears to receive less attention and momentum in the current methodological solutions against climate change shocks and stresses within the built environment.

This paper aims to provide a better understanding about the research progress on sustainability and resilience of the built environment in response to climate changes. It reviews the impacts of climate crisis on the functionality and integrity of the built environment and examines the importance of integrating resilience in sustainability solution. A framework is proposed to unveil how sustainability solutions with an integration of resilience can provide a more solid approach to accelerate the adaptation to and mitigation of climate change impacts within the built environment.

This paper is structured as follows: first, the methods used to collect and analyse data are explained in Section 2.0. In Section 3.0, we present the findings and discuss the various aspects of resilience and sustainability studies in the built environment. A conceptual framework integrating sustainability and resilience principles is presented in Section 4.0.

2. Methods and data analysis

A systematic literature review of peer reviewed studies was conducted to enable the collection of evidence of the topic under study, providing a coherent synthesis of existing knowledge using a clearly defined and accountable protocol. The systematic literature review is comprised of four stages: (1) searching process for studies according to the defined plan; (2) screening of the samples by applying inclusion and exclusion criteria; (3) filtering the screened samples by reviewing the abstracts; and (4) reviewing the final samples. Figure 1 depicts the systematic literature review process.

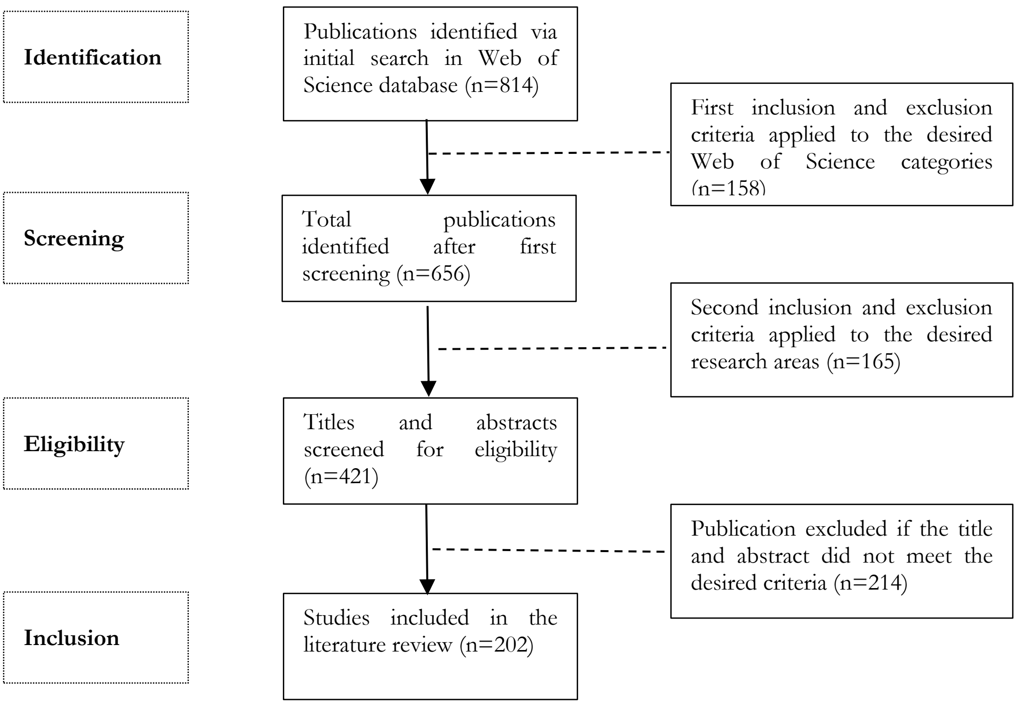

Figure 1: Systematic literature review process

The search process was carried out in the database of Web of Science. The document type was limited to "articles" and "proceeding papers". The keywords used in the search were ((resilien* and sustainabl* and built environment) and (climate adapt*). Two sets of inclusion and exclusion criteria were defined to limit documents to the desired categories and research areas to screen the first and second samples of publications. After applying the inclusion and exclusion criteria, 421 publications were identified. Titles and abstracts were then screened for eligibility of which 214 results were excluded. For example, studies with a narrower focus on agriculture, marine and structure or system design were not considered. A total of 202 publications were included in the final analysis.

Studies on sustainability and climate resilience of the built environment were dominated by developed countries. The top ten countries with the most publications are United States of America (33), United Kingdom (29), China (23), Australia (22), Italy (14), Canada (12), Sweden (11), Germany (9), Belgium (7) and Netherlands (7). Figure 2 depicts the dispersion of sustainable and climate resilient studies, where the darker colour indicates a higher number of publications. Developing countries such as Bangladesh, Fiji, Indonesia, Nigeria, Ghana and Brazil are observed to be relatively active in publishing sustainability and climate resilient studies in the recent years, whereas they are listed as the top 25 countries. This shows an increasing trend in these developing countries to combat climate change risks, with more efforts dedicated to climate resilient and sustainability research.

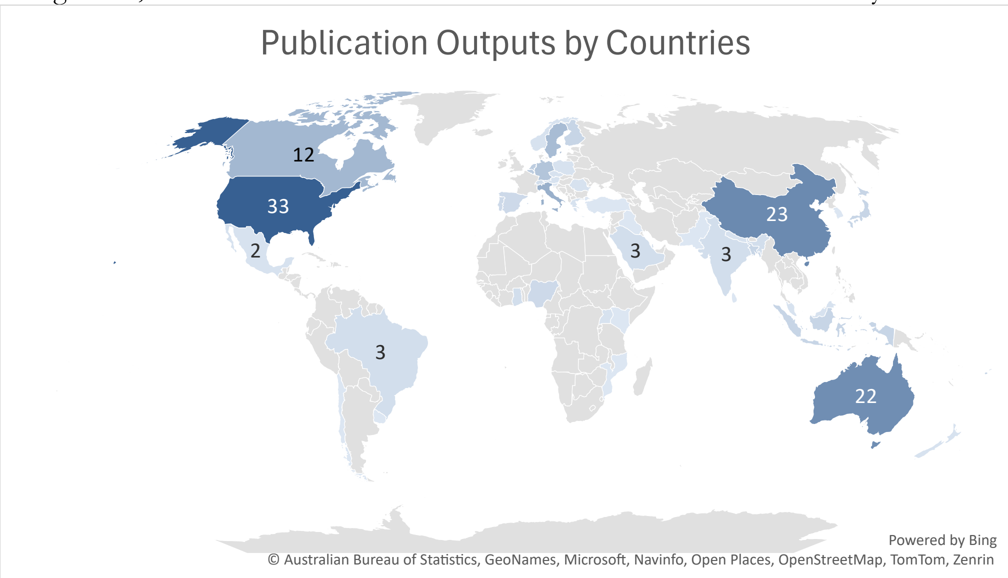

Figure 2: Publication outputs by country

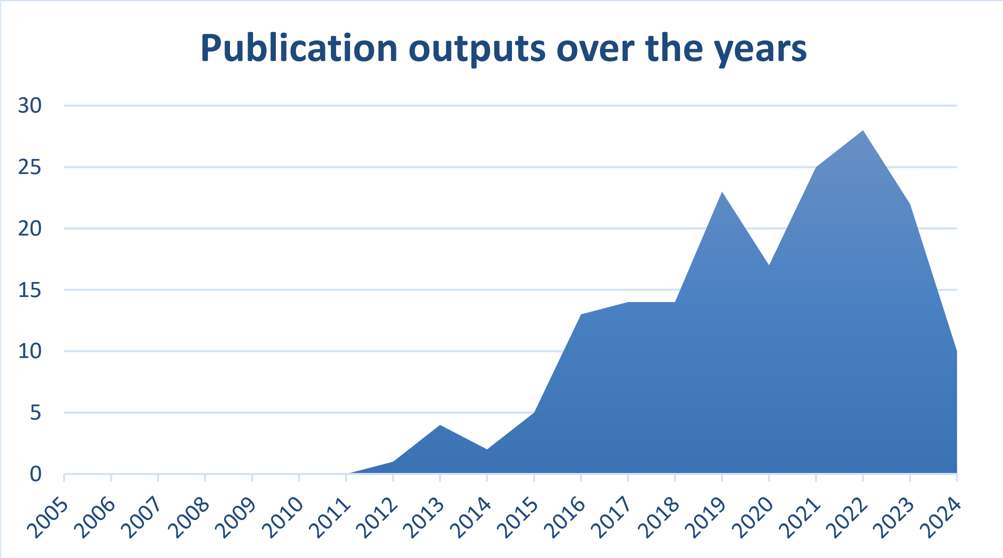

Figure 3: Publication outputs over the years

Figure 3 indicates a steady increase in publications on this topic starting from 2015, with a slight but notable drop in 2020, likely attributable to the Covid-19 pandemic. This overall upward trend highlights growing interest in the subject over the past decade, reflecting the escalating urgency of enhancing global climate resilience. The number of publications peaked in 2022 (28), coinciding with the release of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report: *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. This report emphasized the critical importance of Climate Resilient Development, underscoring the need for inclusive governance, adequate resources, technology, information, and financing to achieve this goal (IPCC, 2022). The report's findings align with those of the United Nations, which noted that the years 2015 to 2022 were the eight warmest on record, despite the cooling effect of a La Niña event in the last three years (WMO, 2024). Given the severity of the climate crisis, it is expected that more studies will continue to emerge globally in the coming years, focusing on ways to enhance climate resilience more effectively. Therefore, it is crucial to assess the current direction of existing research and explore how sustainability solutions for the built environment can be better designed to adapt more effectively to climate change impacts.

3. Results and discussion

3.1 Climate Crises on Functionality and Integrity of the Built Environment

The built environment refers to all kinds of man-made or modified structures created for living, working, and recreational purposes, and they comprise of the infrastructure used to deliver services such as water energy, sanitation, and transportation systems (EPA, 2023). The built environment includes all types of buildings (covering residential, commercial, industrial, educational, institutional buildings and mixed-use buildings), open spaces, roads, utilities, and infrastructure.

Potential risks of climate variability on the built environment vary in accordance with regions, making it important to give contextually specific and appropriate adaptation measures of built environment (UNEP, 2021). The impacts of climate disruptions can be examined at two levels: the urban scale and the building scale. At the urban scale, buildings and infrastructure are subject to risks of flooding (fluvial, pluvial and coastal), coastal erosion and heat stress (Scott et al., 2023; UNEP, 2021). Nearly 410 million people living in coastal areas will be exposed to coastal flooding and sea level rise by 2050 (UNEP, 2021). At the building scale, multitudes of climate risks are associated with the building fabrics and structure including precipitation (increased water penetration and indoor moisture content), more intensive freeze-thaw cycles, subsidence (more variable water content in soil), damage from intensified storminess and wind, increased weathering arising from driving rain, snow loads, temperature, and impacts on indoor quality and thermal comfort (Scott et al., 2023; Temmer & Venema, 2017).

One of the most significant climate impacts on the built environment is urban heat island effects. Urban heat island effects caused higher temperature in urban areas than outlying areas by amplifying the effects of extreme heat events. This has further increased vulnerability and climate risks of elderly populations and disadvantaged groups who are sensitive to extreme heat. Higher average temperatures brought by urban heat island effects also increase active cooling demand that leads to a spiral of further global energy demand (Poulsen Rydborg & Brunsgaard, 2021). According to UNEP (2021), about 1.6 billion inhabitants in more than 970 cities will experience extreme high temperatures by 2050. Urban heat island effect is particularly noticeable during summer period and urban overheating can cause extreme discomfort and even mortality among elderly and very young children (Scott et al., 2021). The effects of urban heat island can be substantial, ranging from 2°C -4°C to outer suburbs and 15°C to rural areas or park lands (UNEP, 2021).

In addition to heat stress, urban heat island effects also induce air pollution and more convective rainstorm events, making local hydrology such as flooding more extreme (IPCC, 2023). Flooding then overwhelms stormwater systems, corrodes structures, scours foundation and put ageing infrastructure at risks of failing. Deforestation for urban development has destructed the ecological balance and natural defences such as wetlands and coastal swamps, further aggravating global warming effects. Cyclones and storms become more frequent and intensified due to climate change. Flooding and sea level rise cause scouring and would compromise the integrity of building foundations. These complex and interconnected climate crises bring impacts on the functionality and integrity of the built environment in various material and immaterial manners, exacerbating the already intense socioeconomic conflicts.

Urban development triggers the exposure of multitudes climate risks to vulnerable groups in a more extensive manner, in which they are subject to further environmental inequality and social inequity. For instance, Rachunok and Nateghi (2021)'s study outlined the relative degradation risks faced by Bay County due to changes in income inequality. Peck et al. (2022) also found a lack of environmental and social equity in the current flooding paradigms and ecosystem-based adaptation, where socioeconomic vulnerability experienced more stresses but received less protective infrastructure for flood protection prior to Hurricane Katrina. Kamei et al. (2021) also described that sustainable building technology and materials are still limited within the relatively high-income groups, although net zero and energy efficiency could have been mainstreamed in the building sector nowadays. This has shown a widening divide of socioeconomic conflicts in wake of increasing climate risks and low energy security in the context of built environments.

However, urban areas are the main engine of economic growth, and they contributed significant to a nation's gross domestic product (GDP). In the United States, about 91% of the GDP comes from urban areas and the five largest in the country are responsible for 23% of the country's GDP (EPA, 2023). According to World Bank (2023), about 4.4 billion people - 56% of the world's population live in cities or urban areas as of 2023 and this number will increase by 1.5 times to 6 billion. This means that nearly two-thirds of the global population projected to live in cities or urban areas by 2050, highlighting the urgency of creating a more sustainable and climate resilient built environment. Following the population growth in urban areas, new urban built-up areas are expected to be increased by 1.2 million km^2 by 2023, adding pressure to the already exhausted land and natural resources (World Bank, 2023). Inappropriate urban development has also aggravated the urban heat island effects, hence increasing risks to coastal erosion, flooding, and heat stress.

Functionality of the built environment is to provide services and goods for the development of society and economy at local to global levels. A network of interconnected systems of the built environment supports the flow of these goods and services for neighbourhoods and cities. Climate change poses multiple and far-reaching risks to interrupt the systems by affecting the supply chain and limiting access of people to these goods and services. This would in turn threaten the quality of life and human health, worsening social and economic inequality.

The built environment is an important nexus for climate change mitigation and adaptation. The indoor environment provided by the built assets can serve as a buffer against an extreme outdoor environment, thereby protecting occupants and ensuring the occupant health and wellbeing. Integration of sustainability and resilience in built assets can help to ensure the built assets works in harmony with exiting planning and design, while meeting the required functionality with an appropriate level of risk tolerance to respond to climate change.

3.2 Climate Resilience and Adaptation

Climate crises brought devastating consequences on socioeconomic development, such as food and water insecurity, economic disruptions, and productivity losses. They have adverse effects on mankind and aggravate other stresses and social distress such as disease, political conflicts, financial crisis, and environmental degradation.

Building resilience in the built environment has become a necessity to proactively address and respond to the current and future climate challenges. Resilience is the ability of an organisms, human, or system to prepare and plan for, absorb, recover from and more successfully adapt to adverse effects (Hong et al., 2023). It also refers to the capacity to tolerate disturbances through characteristics and measures to reduce, counteract damages and disruptions, hence maintaining the desired level of normality, stability or equilibrium for effective functioning (Stead, 2014). Resilience can be enhanced by both mitigation and adaptation measures. Because the goal of mitigation is to reduce the impacts to the minimum, mitigation measures can be the same across all types of impacts as the aim is increase the overall system robustness (Stead, 2014). Meanwhile, adaptation primarily focuses on the increase of rapidity of recovery of a system. Therefore, the deployment of adaptation strategies is often dependent on the impacts of climate change (Stead, 2014).

Adaption is defined as an approach for addressing current and future risks posed by a changing climate to reduce the vulnerability of our environment, society and economy and increase resilience (Scott et al., 2021). Adaptation is often considered along with the concept of "adaptive capacity" which considers the ability to adapt to the potential harms, leverage existing opportunities and respond to impacts (UNEP, 2021). The essence of adaptive capacity in the context of built environments is to embody positive change irrespective of short term or long tern changes, contributing to the place's ability to recover from the impact of s shock or disruption (Scott et al., 2021).

Both mitigation and adaptation are central to reduce risks associated with climate change. In the built environment, mitigation measures are given much greater emphasis than adaptation measures to tackle climate risks (Scott et al., 2021). Adaptation in the built environment appears to be in infancy stage and more efforts need to be mobilised and scaled up to deal with the growingly intense climate change impacts. Although adaptation has been established on the political agenda due to climate policy, adaptation has not accepted as an equal to mitigation (Stead, 2014). Stead (2014) attributed it to the long-time political difficult position to present adaptation policies due to its implied failure in reducing impacts. Another reason could be the traditional division between adaptation and mitigation in which they involve different actors that operate activities at varying spatial and temporal scales. Mitigation activities tend to involve key actors at the national and international levels, while local actors are more often involved in adaptation activities (Stead, 2014). Nonetheless, adaptation started to gain its momentum in various policy discourse across Europe, and some countries have incorporated adaptation into their policy agenda in the past decades. As a leading city in the Netherlands in climate change adaptation initiatives, Rotterdam incorporated climate adaptation in its local plans and strategies, in which climate-proof development measures were identified to minimise the probability and consequences of flooding and stimulate recovery (Stead, 2014).

Adaptation and mitigation shall be integrated and work in complementary to increase resilience of buildings and infrastructure to climate change. It is important to integrate local climate adaptation measures to develop a conducive environment to improve climate resilience. Adaptation measures require a robust and geographically tailored evidence. Local landscape, governance capacity and vulnerability assessment shall therefore be embedded when developing locally rooted design and implementation methods.

3.3 Sustainability Solutions for A More Resilient Built Environment

UNEP (2021) proposed a three-phases of time in developing climate resilient interventions of sustainable built environment: 1) prior to the event; 2) during the event and 3) a period of time after the event. Prevalent resilient interventions are primarily based on phase 1 and 2 that emphasise preventive sustainable solutions before the climate events and reactive solutions during the climate disasters.

A resilient city is one that can withstand future shocks and stresses while promoting sustainable development, well-being and inclusive growth (OECD.org, 2010). This requires a sustainable network of physical systems and human communities that can adapt to needs and learn from experiences, minimising the impact of disasters (Godschalk, 2003). In line with this, it is crucial to ensure that the physical built environment is well-designed with sustainable solutions to be capable of resistance or change when subject to a hazard event (Haigh and Amaratunga, 2011).

Sustainable solutions, if properly planned and implemented, can help build more holistic crises resilience in the built environment by enhancing the capability and capacity to increase preparedness and agility of built environments to disruptions. Because climate change is in a continuous and dynamic state, it is critical to develop a locally contextualised sustainable strategies that consider locations, characteristic of built assets, user groups, microclimate and surrounding environment.

Community-based and human factor approaches are seen to be an enabling factor to enhance resilience against climate hazards. For example, Mekonnen et al. (2019) highlighted the importance of integrating traditional community knowledge with modern scientific approaches to effectively design sustainable climate change adaptation and natural resource management strategies. Such integration can drive impactful changes that promote sustainable development while enhancing both livelihood and landscape resilience in the face of climate change in Ethopia. Similarly, a study in Nigeria by Effiong et al. (2023) emphasized that one of the key actions for enhancing climate adaptation is improving stakeholder engagement processes and integrating traditional knowledge and practices into planning efforts. This approach promotes more inclusive, community-based solutions for effective climate resilience.

A well-designed sustainable built environment is sensitive to local topography, culture, and climate conditions for improved resilience (Goh and Chong, 2023). Climate adaptation strategies identify risks and critical elements for necessary adjustments in the built assets. Both passive and active measures coupled with social transition strategies can be used to create more climate resilient and sustainable built environments. Properly designed and insulated building envelopes can improve the thermal performance by removing unnecessary heat gain from buildings during summer and reducing heat loss during winter (Hong et al, 2023). For example, traditional mosque designs in Indonesia exemplify how structures, materials, and designs are well-adapted to the local climate and environment. These mosques are characterised by low embodied energy due to the use of local materials and enhanced earthquake resilience through the Saka guru system, which relies on mortise and tenon joints (Sari et al., 2024). Similarly, a comparative study of net-zero office buildings in Brussels found that active cooling combined with natural night ventilation was the most effective strategy during heat waves, highlighting the importance of integrated design guidelines that align passive and active measures to improve climate resilience (Amaripadath et al., 2023)

Passive design strategies consider the site location, building typology, site orientation, building form, materials, building configuration and layout as well as the surrounding environment to leverage the natural resources for an optimum climate adaptive capacity. Existing or planned elements in the neighbourhood such as trees, shrubs and other building forms in the surrounding areas could serve as natural shield and offer shading or adversely block the sun when it is required (UNEP, 2021). Appropriate orientation of openings and spaces is a form of passive solar design to receive the required heat gain and daylights from the sun, depending on the location and season. Reflective surfaces and solar radiation are also a means used to maximise the cooling potentials of building in hot climates.

Building orientation, form, and internal configuration can be strategically designed to optimise wind flow and natural ventilation. Buildings can benefit from orienting windows and opening within 15 degrees from equator and should be oriented with the longest axis oriented in an east-west direction (UNEP, 2021). Shallow building depths enable effective cross-ventilation, which is particularly beneficial for improving airflow in dwellings located in hot and humid climates (UNEP, 2021). This is demonstrated in a study from Slovenia, where bioclimatic design strategies adapted to global warming were found to enhance residential buildings' resilience to overheating while reducing cooling demands (Pajek & Kosir, 2021). Additionally, Hanby & Smith (2012) recommended building evaporative cooling, based on simulations of a case study in Southeast England, as a viable low-energy technique that remains relevant for future climate scenarios.

As described in Poulsen Rydborg and Brunsgaard (2021)'s study, relying completely on passive means might not be able to provide the required thermal comfort level to users. Active design measures such as energy optimisation and renewable energy are required to ensure the constructed built assets meeting the required energy efficiency and environmental footprints. Simple mechanical systems can also help cool homes during extreme heat events by using relatively small amounts of energy. Low energy active solutions such as ceiling fans, portable fans, evaporative coolers and portable air conditioners or heats can improve the air circulations and avoid a space from overheating, hence raising the upper boundary of occupant comfort level (Hong et al., 2023).

The use of renewable energy sources like solar radiation holds transformative potential as a global adaptation strategy to enhance a country's socioeconomic resilience against droughts and climate change, as illustrated by the proposed smart grid photovoltaic generation program in Northeastern Brazil (Nobre et al., 2019). Similar approaches are reflected in case studies from Nepal and India, where granular technology was applied for power distribution. In Nepal, a tribrid power generation system—integrating distributed solar, hydro, and wind energy—was implemented to enhance the resilience of a remote village community of around 500 people. Meanwhile, in Chhattisgarh, India, off-grid solar PV systems were deployed to power 900 health centers (Mohanty, Pal, & Roy, 2024).

Frangible architecture is an intentional design approach to give way in face of extreme events such as high winds, large flooding and storms to reduce damages to built assets, hence offering protection to life and property (UNEP, 2021). Traditionally, fail-safe design approaches are employed to design buildings and infrastructure in compliance to legal safety standards. This traditional fail-safe method is inflexible and perpetuating lock-in, in which it could bring more catastrophic failures when it stretched beyond its designed capacity (Helmrich & Chester, 2022). To be climate-resilient, there is a need to consider interactions between infrastructure and the surrounding ecosystem. Safe-to-fail design increases the adaptative capacity of built assets to embrace the complexity and uncertainty of happenstance of extreme events by expecting and containing such occasions. Simulations and observations from past actual cyclonic disasters shown Geodesic dome structures suffer less destruction than rectilinear structures, due to their hemispherical form in resisting winds (UNEP, 2021). Round-shaped housing and optimum aerodynamic orientation design are more effective to resist storm effects, hence minimising damages to cyclones and storms (EPA, 2023). This also highlights the urgent need for applying parametric design in the built environment to create sustainable and resilient spaces, along with the development of guidelines to serve as protocols for future research (López-López et al., 2023).

Strong and resilient materials would also help increase the durability and strength of built assets against extreme events. Selecting suitable materials is also a key to enhance climate resilience of built environments. Strong materials can increase the ability of building to resist damage from extreme weather such as storms, high winds, and extreme temperature. Hurricane resistant windows and reinforced concrete structures can resist extreme shocks and maintain the integrity of building structures. Buildings subject to high flooding risks should use materials that withstand moisture damage to reduce working of moisture up into walls (UNEP, 2021). Homes in hot humid climates should use materials that can reduce heat gain through increased thermal resistance and promote quick heat loss while building materials that reduce heat loss through thermal resistance can perform well in cold climate regions (UNEP, 2021). Selecting appropriate materials can also significantly reduce carbon footprints of the built environment. One example is the use of bamboo houses for social housing in Colombia, which were shown to have only 40% of the carbon footprint of conventional brick houses (Rincón et al., 2023).

Nature is a powerful solution to climate crises. Appropriate allocation of green spaces and urban forests can help alleviate heatwave risks as vegetation and plants can cool the surrounding environment by offering shade and releasing water through their leaves (UNEP, 2021). Trees and vegetations are also best to address the disruptions brought by drought and flooding because the roots of plants can recharge groundwater and allow water to penetrate to soil during heavy rainfalls (UNEP, 2021). For instance, Russo (2023) incorporated ecological planting systems into urban regeneration projects in the United Kingdom, the Netherlands and Russia to create dynamics, biodiverse landscapes that enhance aesthetic and functional aspects of urban spaces. Apart from green infrastructure, blue infrastructure such as ponds, wetlands, rivers, lakes and streams, estuaries, seas and oceans can also bring climate adaptation co-benefits. Surface water has a lower surface temperature, thereby creating a larger cooling effect per unit area than vegetated areas and buildings (UNEP, 2021). Table 1 shows a summary of references based on the types of sustainable solutions in the context of the built environment.

Table 1: Summary of references based the types of sustainable solutions in the built environment

Sustainable Solutions	References
Passive design	Amaripadath et al, 2023; López-López et al., 2023; Pajek & Košir, (2021); Rehman,et al, 2024; Shastry, Mani & Tenorio (2016); Silva et al., 2022; Xiao, Yuizono & Li, 2024;
Active design	Amaripadath et al., 2023; Miao et al., 2024; Mohanty, Pal, & Roy, 2024; Nobre et al, 2019; Pajek & Košir, 2021; Poulsen Rydborg & Brunsgaard, 2021; Rehman,et al, 2024

Strong and resilient materials	Sari et al., 2024; Rincón et al., 2023
Nature-based solutions	Bruins et al., 2019; Carro et al., 2018; Ferreira et al., 2024; Hautamäki et al, 2024; Helmrich & Chester 2022; Kabisch et al., 2026; López et al, 2019; Meerow et al, 2021; Rochell et al, 2024; Russo, 2023; Thomson & Newman, 2021; Van Oijstaeijen et al, 2022
Frangible architecture	Helmrich & Chester, 2022
Users/Human-oriented approach	Carro et al., 2018; Effiong et al., 2023; Mekonnen et al., 2019; Rehman et al., 2024

4. A Framework Capacity and Capability for Increased Agility of Built Environments for Sustainable Living and Improved Climate Resilience

Technical or engineering solutions to climate change are known as hard adaptation measures. Nevertheless, climate resilient measures must be implemented at a systemic level across a series of complex human-environment systems, involving a multitude of interrelated "soft" dimensions such as social, economic, institutional, individual and political dimensions (Scott et al., 2019). Soft adaptation is increasingly important to enhance resilience and adaptative capacity of societies by altering behaviours, regulations and management systems for buy-in at all levels of governance (Scott et al., 2019). All built environment stakeholders and decision makers including end users shall engage with their role, exert influence and implement change to activate meaningful adaptation and resilience solutions in the built environment (WorldGBC, 2022). Coordination and synergy of individual actions and institutional responses for enabling adaptation at urban and building scales are essential to increase climate resilience of the built environment. For example, a case study of ecosystem-based adaptation (EbA) in Kiyu, Uruguay demonstrated that restoring coastal ecosystems required building the capacity of municipal staff and stakeholders, facilitating knowledge exchanges with national decision-makers and scientists, and integrating EbA approaches into the strategies of subnational coastal governments (Carro et al., 2018).

Human factors play a key role in enhancing climate resilience and adaptation of the built environment. Behavioural adaptation is important to improve building resilience performance, particularly in the absence of active design strategies. The ability to act depends on the occupants' physical abilities, cognitive abilities as well as psychosocial development. Understanding the needs and expectations of occupants can reduce the adaptation gaps and potential maladaptation to climate disruptions. Numerous studies (Goh, 2022; Goh & Chong, 2023; Mohanty et al., 2024; Rehman et al., 2024) have emphasised the imperative of engaging users and communities in co-creating and co-designing sustainable and resilient built environment. The people's perception and demand about the living environment would determine the acceptance and use of urban spaces (Russo, 2023).

Human-centric approaches come into play to help enhance climate adaptation of built environment. The importance of human-climate-building interactions is acknowledged by UNEP (2021) in which the adaptive principle lies in the human responses within the built environment. Occupant behaviours and characteristics would shape the energy use pattern and demands, and these can potentially affect the adaptative capabilities of built environments (Goh, 2022). Because human-centric approaches emphasise human needs, interests, cognitions, attitudes, and behaviours, they would empower users to harness sustainable building features effectively, hence adapting to the environment in accordance with dynamic changes of physical, physiological, and psychological requirements (Goh and Chong, 2023).

Flexibility is recognised as an essential attribute of resilience (Al-Humaiqani & Al-Ghamdi, 2023; Chester et al., 2021; Goh & Chong 2023; Radhakrishnan et al, 2019, Stead, 2014) and it offers a powerful way to increase agility of built environments in responding to climate risks and their associated socio-economic challenges. Improved flexibility of built assets helps reduce vulnerability and increase the ability to adapt and adjust to continuously evolving future events (Chester et al., 2021). Although flexibility is recognised as a key component of resilience qualities in the built environment system, Al-Humaiqani and Al-Ghamdi (2023)'s study revealed that the current integration of flexibility into decision making process remains inadequate. Flexible design strategies such as design for disassembly, deconstruction, and recyclability can enhance the reusability and recyclability of buildings and infrastructure (Goh, 2022). These innovative circular economy strategies would reduce the landfill burdens and carbon footprints, hence offering potential savings on disposal fees and demolition costs.

To bolster climate resilience, it is crucial to construct the built environment in accordance with fundamental characteristics that define sustainable solutions. To incorporate resilience, adaptative capability and sustainability into the built environment, a systemic approach shall be taken to advocate for a shift of integrating both hard adaptation and soft adaptation strategies. Community cohesion and social transition that are embedded in human-centric solutions shall be prioritised to proactively engage community to adapt to climate change. Synergistic actions among stakeholders need to be taken simultaneously to make systemic change for building climate resilience. Using two case studies from India and Nepal, Mohanty et al. (2024) contends that private investment cannot promise the success of building community resilience in absence of an active role of the public sector. They urged the public sector to create a database of sites for distributed energy generation systems with a diverse mix of local renewable sources and build awareness among local community members for community participation. The public sector and the private sector shall work in concert to mobilise resources to increase resilience of community against climate extremes.

The importance of having improved policies and regulations for long-term resilience has also been underscored by literature (Rehman et al., 2024; Silva et al., 2024). For instance, Rehman et al. (2024) emphasised the need of improved policy and building codes to provide guidelines to society, businesses, authorities as well as end users for long-term energy resilience of buildings. As the policy maker, the government has a role to play in facilitating the implementation of climate resilient strategies in the built environment by enforcing regulations.

This paper advocates for a value proposition that harnesses innovative design strategies, technical measures, nature-based solutions, and human-centric approaches to fortify the resilience and adaptability of built environments. Figure 4 illustrates the value proposition using a framework to future proof our built environment for sustainable living and climate resilience.

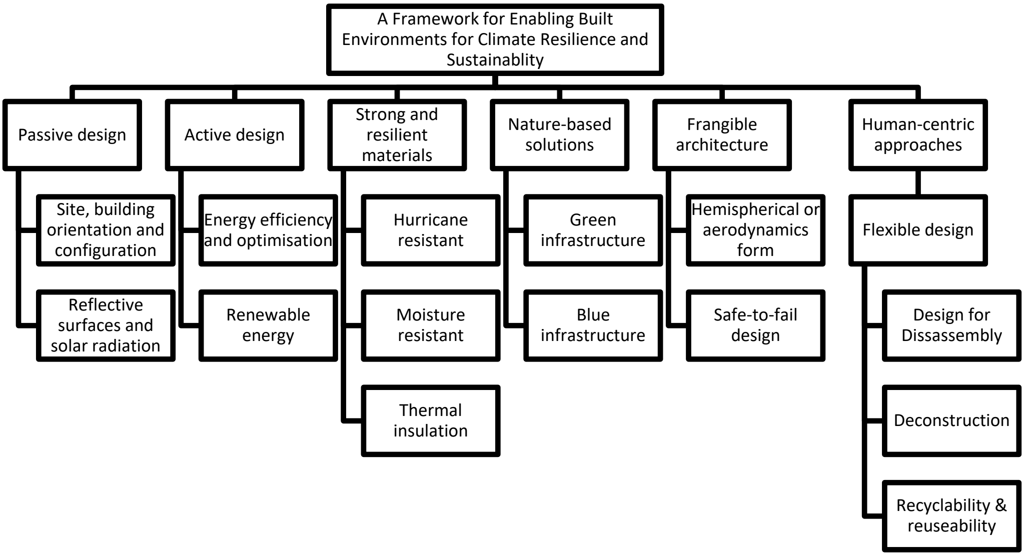

Figure 4: A framework for enabling built environments for sustainable living and improved climate resilience

5. Conclusion

The built environment represents a key to lead the climate resilience agenda for sustainable living. It provides an enabling environment to mitigate climate impacts and reduce vulnerabilities of the people and places to the climate extremes. To future proof our built environments, it is critical to consider both climate adaptation and resilience as complementary approaches to the climate mitigation measures. Climate adaptation measures need to be placed on par with mitigation measures to ensure the scale, scope and severity of climate change impacts can be reduced to a minimum, thereby increasing climate resilience.

This paper examines the impacts of climate crises on the built environment from the perspectives of functionality and integrity. It also presents how sustainability solutions can help build climate resilience and adaption into the built environment. However, measures of climate adaptation and resilience would not be successfully implemented if there is no institutional leadership and behavioural changes in the society. Sustainability isn't about decarbonising the built environment but a social transition towards sustainable development. Sustainable communities would contribute to make systemic changes in the built environment with increased resilience to climate changes and socioeconomic challenges. Future study should investigate and evaluate long term impacts of implementing sustainability and climate adaptation measures within the built environment, along the shift of international, regional, national and local climate policies. Future research shall also explore the effectiveness of various sustainability strategies in enhancing resilience, with a discussion on methodological approaches to measuring their impact over time.

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