

Review

Resilient and Sustainable Housing Models against Climate Change: A Review

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Abstract: Most of the world's population resides in urban areas, and it is expected that this will continue to be the case in the future. These urban areas face enormous challenges such as climate change, economic instability and inequality. Housing is considered a basic unit comprising cities, and, as such, this study contextualized the concepts of urban resilience and sustainability against climate change such that housing models that respond to these concepts could be identified. As a result of an extensive literature review, three resilient housing models and four sustainable housing models are presented and discussed with a focus on the main characteristics necessary for meeting urban resilience and sustainability against climate change. When analyzing the housing models considered resilient, the need to establish housing on safe land stood out and concrete was a common building material among these housing models. In addition, the use of alternative sources of water and energy supply was prioritized. On the other hand, sustainable housing models were developed by local entities and certified by various initiatives. In addition, these models account for the climatic specifications of their location, energy and water efficiency, and quality of the indoor environment, and promote the use of local materials and resources. The use of durable materials was considered a requirement for both resilience and sustainability. The results of this study are a contribution to the process of strengthening housing against the challenge posed by climate change in a timely and adequate manner considering both urban resilience and sustainability aspects.

Keywords: housing; urban areas; resilience; sustainability; climate change



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1. Introduction

Understanding of the role of housing in urban development has evolved significantly in recent decades, now established as an essential component of the social fabric. Thus, the right to housing is enshrined in several international human rights instruments, such as the Universal Declaration of Human Rights (art. 25.1) [1] and the International Covenant on Economic, Social and Cultural Rights (art. 11.1) [2], consequently defining the importance of adequate housing that has the security of tenure, availability of services, materials, facilities, infrastructure, affordability, habitability, accessibility, safe location and cultural adequacy [3].

Following this context, housing is highlighted as fundamental for human well-being and integration into the economic and social spheres [4], since it comprises the largest physical area within a city. However, as the world has entered the new millennium, development, urbanization and environmental alteration have converged and posed threats to humanity's quality of life [5], with developing countries increasingly feeling the effects of phenomena such as climate change, resource depletion, food insecurity and socioeconomic instability. Therefore, investing in the emergence of inclusive, safe, resilient and sustainable cities is paramount.

The general objective of this study is to identify housing models that respond to the concepts of urban resilience and sustainability and discuss their main characteristics against climate change. Following specific objectives, the first one is to define resilience and sustainability in the urban context. The second one is to conduct a comparative analysis of various housing models that meet the definitions of urban resilience and sustainability. Finally, based on the results, the third objective seeks to discuss the characteristics of resilient and sustainable housing in the context of climate change.

There are currently no studies focused on housing accounting for both resilience and sustainability. Consequently, this study sought to fill this gap in the literature. For this purpose, a qualitative methodology based on the systematic review of scientific information was employed, providing context to international events in terms of the resilience and sustainability of housing. As such, this study highlights significant scientific papers, international agendas and global initiatives that promote participation in the global development effort and urge cities to prepare for implementing plans for a more resilient and sustainable urban future.

2. Background

2.1. Cities and Climate Change

Over time, cities have been located at the crossroads of trade routes, built as an expression of social order, serving as hubs of defense, physical security and social continuity [6]. Today, they continue to be the engines of growth, as they offer important opportunities to improve human well-being [7] by constituting themselves as the main spaces of social and economic reproduction [8] that catalyze development [9].

However, cities also face significant challenges, such as accelerated population growth, poor urban planning, infrastructure deficit, pollution, overburdened urban services and the increase in their vulnerability to catastrophes resulting from climate change [9]. Therefore, this generation has the responsibility and opportunity to lead a change that incorporates adaptation and mitigation measures in cities, from their basic unit, i.e., housing, urging for consideration of the inherent weaknesses of current models and rebuilding them differently [10], with an emphasis on urban resilience and sustainability.

In this context, several studies point out how these challenges have been influenced and/or exacerbated by humankind. In terms of climate change, the Fifth Assessment Report of the IPCC or AR5 [11] indicates that human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases have been the highest in history. In 2020 alone, urban emissions from consumption-based accounting were estimated at 29 GtCO₂-eq, representing between 67% and 72% of global CO₂ and CH₄ emissions, respectively [12].

Currently, more than half of the world's population lives in urban areas, and by 2030, that number will increase to 60%, where developing countries will be home to 80% of the urban population [13]. Such is the case of Latin America and the Caribbean, which have undergone the process of very rapid urban expansion and are currently the most urbanized developing regions in the world [14]. Nevertheless, developing countries are characterized by high socioeconomic inequality, the presence of informal and precarious human settlements, high degrees of land tenure insecurity and large segments of the population dependent on the informal economic sector [15].

Consequently, this imbalance between development and the challenges faced by cities will only increase their vulnerability and reduce their competitiveness from economic, social and environmental points of view as externalities of productive activities [16]. As of 2022 alone, 32.6 million people were displaced as a result of climate change-related threats such as storms, floods and others (Figure 1) [17].

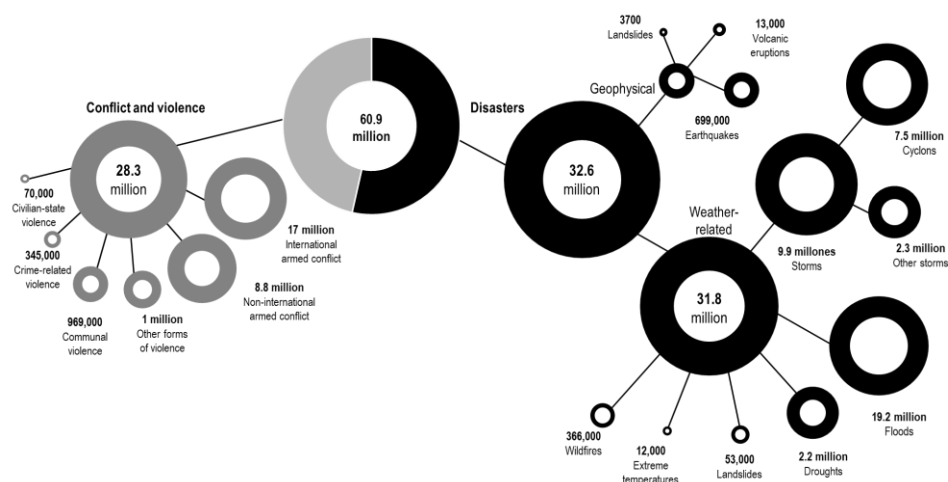


Figure 1. Internal displacements in 2022: breakdown by conflict, violence and disasters. Source: authors' own elaboration based on the Global Report on Internal Displacement 2023 [17].

In this sense, there is a need to address new strategies for supporting developing countries relating the issue of housing with a greater emphasis on resilience and sustainability. Thus, work is being carried out on the urban future from an integrated approach that ensures the growth and development of the potential of cities [10] and enriches the dialogue around housing as a key component of the urban fabric.

Therefore, this study considers the role of housing in the fulfillment of global agendas that collaborate as comprehensive, multisectoral and multi-stakeholder frameworks that seek to unlock the value of urbanization, ensure relevant human rights and empower cities. In addition, this study puts urban housing as the focus of greater attention for the successful implementation of resilient and sustainable development.

2.2. Transition to Resilience and Sustainability

In recent decades, there has been exponential growth in the funding and practice of research, frameworks and/or initiatives that seek to contextualize the balance between urban development and the environment. This can be traced back to the promulgation of the concept of sustainable development, introduced in the Brundtland Commission as a pathway to meeting the needs of the present without compromising the ability of future generations to meet their own needs [18]. Likewise, new international agreements and initiatives have been tools that, together or individually, have had far-reaching implications for the management of rapid urbanization and climate change.

However, in terms of housing, the progress made has focused mainly on the legalization of informal human settlements, the granting of subsidies, the promotion of the construction and improvement of substandard housing through self-construction, and the construction of housing in the category of social interest [19]. Therefore, it is necessary to expand the way we are approaching the subject and include its resilience and sustainability. Thus, the development of ideas with an integral and transversal perspective becomes a pressing task, enabling the enrichment of the research around housing.

It is therefore necessary to address more integral concepts than adaptation or mitigation, where housing is the axis for the creation of solutions to urban vulnerabilities to climate change [20]. Hence, the use of a perspective of resilience and sustainability applicable to urban areas is urged, where urban resilience is considered as the measurable capacity of any urban system to maintain continuity through all shocks and stresses such as floods, strong winds, landslides and other extreme weather events, while adapting positively and transforming toward sustainability [21]. Sustainability, on the other hand, applies to planning, development and construction processes that drive the protection and efficient use of natural resources in order to reduce potential environmental impacts [22].

Hence, by better understanding the definitions of resilience and sustainability, a close link is identified. This link creates the opportunity to establish synergistic strategies to tackle the impacts of climate change, disasters and other challenges affecting housing in urban areas. Housing is defined as an independent structure that has been built or reformed for the purposes of permanent or temporary accommodation for people, and that could be individual or collective. Following this definition, Figure 2 illustrates housing typology, where the permanent individual type is highlighted, since it specifies the type of housing that guides this study.

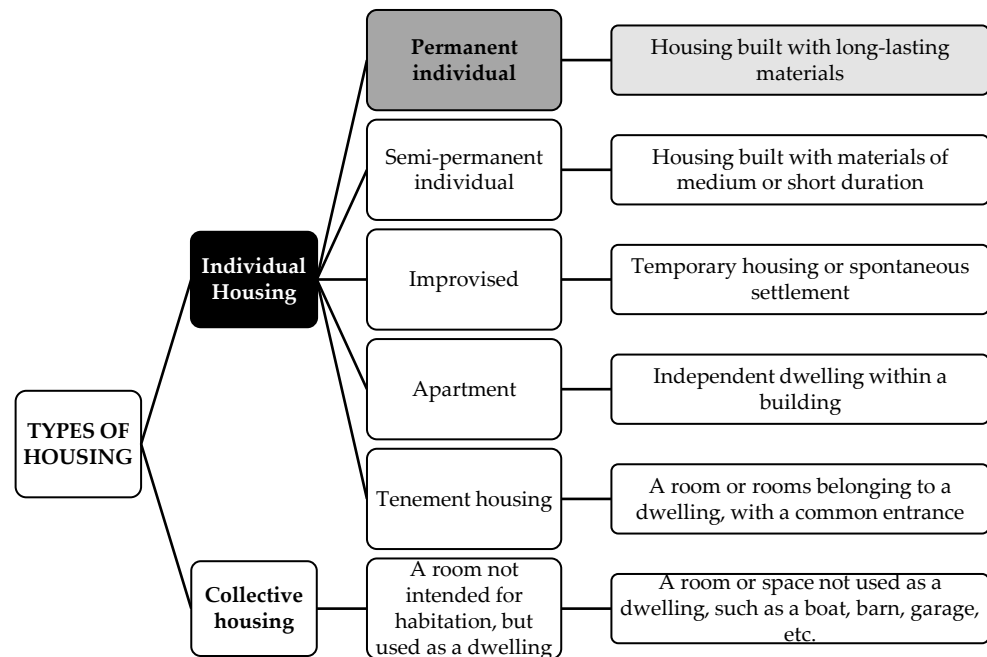


Figure 2. Panamanian housing as an example of housing typology that is used worldwide. Source: authors' own elaboration based on the document of definitions and considerations of the Population and Housing Census of the Republic of Panama [23].

Therefore, to implement a comprehensive strategy covering all dimensions of urban housing and a long-term perspective, this study used the definitions of resilience, sustainability and permanent individual housing discussed in this section. Thus, this study serves as a basis to identify current challenges and suggest the necessary changes to strengthen housing in terms of resilience and sustainability, helping advance the agendas of equality in its various dimensions and citizen rights.

2.3. The Role of Housing against Climate Change

Housing is a key component in the construction of the social tissue. It is not an isolated human right, but a tool that conditions the enjoyment of several other human rights, particularly in the spheres of work, health, social security, privacy and education [24]. However, the climate change crisis is having serious repercussions on all aspects of the enjoyment of human rights worldwide [25,26], such that, damage, migration and/or displacement caused by the increased occurrence of extreme weather events or long exposure events are becoming more frequent [27], forcing the establishment of substandard or even inhumane housing conditions [28].

Given this reality, one must be aware of the extent to which housing contributes to the exacerbation of climate change. All the phases that make up its construction, use and/or demolition have environmental repercussions since they are processes that consume resources (land use, water, energy and raw materials) and produce greenhouse gas emissions, the main cause of climate change [11,29,30]. Likewise, once they are in use, their design

will have an impact on the contribution of greenhouse gases through their energy, water and waste systems, among others [28].

Therefore, there is an evident need to develop clear and ambitious initiatives and policies that promote innovative solutions with a vision to achieve fair housing [31], with a particular focus on those that contribute to or are based on human rights and are resilient and sustainable against climate change. In this regard, this study generates information that facilitates an equitable and inclusive transition of housing against climate change issues that govern cities and the world at large.

3. Materials and Methods

Literature Review

This study was developed within a qualitative framework, aimed at collecting and deepening relevant data and information on housing and climate change, in order to identify the state of housing in the context of resilience and sustainability and analyze models for resilient and sustainable housing applicable to urban areas.

An extensive review of the specialized scientific literature published since 2015 was carried out, following the year of the 2030 Agenda and the Sustainable Development Goals promulgation [32]. After 2015, SDG 11 to make cities more inclusive, safe, resilient and sustainable was established as the focus of various investigations. Therefore, using relevant methodological references [33–37] and review studies (e.g., [38–41]) to collect and analyze data, four concrete methodological steps were established to frame the development of this study. One limitation of the literature review is the fact that not all papers and documents that could be pertinent to the study were open access for the author's use.

The first step of the study was to orient the study to the definitions of urban resilience and sustainability applicable to housing that, together with the selection of keywords, guided the selection of published papers and other relevant texts. In the second step, Scielo and Google Scholar were used as search engines for scientific–academic literature since they cover most scientific publications, and Google as a search engine for gray literature using a combination of Spanish and English keywords, thus capturing all the breadth and richness, as well as the emerging trends of the background at the international level through various reports, papers and other documents.

Once the information was compiled, step three, made use of quality criteria such as relevance, belonging and credibility for the inclusion and exclusion of papers and texts from the final database. Compliance with the selected study time, the non-duplication of information and the relationship of the texts with the objective of this study were verified. Accordingly, a manual inspection was carried out, topic by topic, starting with 135 general documents, of which 75 academic papers, books, book chapters and international frameworks were concluded and delimited, as they explicitly included the established criteria.

Finally, the fourth step employed qualitative content analysis as an adequate method to develop conceptual categories (Table 1) in harmony with the indicators proposed by [42] for resilient and sustainable housing, and textual data focusing on what is relevant and influential for the execution of the study were interpreted.

Table 1. Conceptual categories used for the literature review. Source: authors' elaboration.

Energy	Water and Sanitization	Built Form	Resources Management	Location	Comfort
Energy assessment of the house	Innovative water techniques applicable to housing	Resilient and sustainable building regulations and guidelines	Efficient use of resources and waste management	Security assurance and vulnerability analysis	Understanding the physical–social environment

Thus, the available selection of frameworks, scientific papers and government initiatives were integrated that serve as guides for evaluating and measuring the degree to which

housing meets conditions of resilience and sustainability. As a result, relevant studies to analyze and discuss as the basis for resilient and sustainable housing models for urban areas in the face of climate change were identified.

This study is focused on housing. It is recommended to expand the study to other types of projects, such as infrastructure or technology development, which would also contribute to the development of resilient and sustainable cities.

4. Results

When considering the current impacts, future effects and implications of adequate housing, incorporating resilience and sustainability characteristics is denoted as fundamental for risk reduction and the strengthening of housing in urban areas. For this reason, this exhaustive research of scientific papers, frameworks, indexes and standards applicable to housing analyzed each of the conceptual categories and managed to establish resilient and sustainable housing characteristics (Table 2), which already have proposed indicators [42].

Table 2. Key characteristics for resilience and sustainable housing according to the conceptual categories used for the literature review.

Energy [43–51]	Water and Sanitization [43–45,52]	Built Form [43,44,47,53,54]	Resources Management [43,44,47,53,55–57]	Location [57–59]	Comfort [43–45,50,52,59–61]
<ul style="list-style-type: none"> • Continuous access • Energy efficiency • Renewable energies 	<ul style="list-style-type: none"> • Continuous access • Water efficiency • Water reuse 	<ul style="list-style-type: none"> • Application of building codes and standards • Resistant materials • Housing management 	<ul style="list-style-type: none"> • Material Life Cycle Analysis • Use of eco-friendly or reused materials • Efficient use of resources 	<ul style="list-style-type: none"> • Safe land • Development of planned sites 	<ul style="list-style-type: none"> • Adaptability and accessibility

It has been observed that cities are seen as the first line of trenches in the fight against climate change [62]. Most studies focus on resilient and sustainable cities [62–68]. Regarding housing specifically, the studies that were found are either focused on resilience [69] or sustainability [43,70,71]. No studies on both resilient and sustainable housing were found.

Following this vision, some housing models were identified that meet the criteria of resilience and sustainability according to certifying and/or international bodies. Understanding these is a means of encapsulating a complex reality, as they use their conditions, but provide clarity and draw guidelines for countries interested in increasing their resilience and sustainability. In this sense, the models selected to illustrate resilient and sustainable housing are detailed below.

4.1. Resilient Housing Models

To understand the mechanisms used in other countries to comply with resilience guidelines, housing that has obtained recognition for resilience to the effects of climate change, such as floods, strong winds or natural disasters in general, is studied. The models found are illustrated in Figure 3 and compared in Table 3.



Figure 3. Resilient housing models: (A) Resilient House Antu [72]; (B) Spirited Bamboo [73]; (C) Resilient Link House [74].

Table 3. Characteristics of the resilient housing models found in the literature review. Source: authors’ elaboration based on cited literature.

Characteristics	Resilient House Antu: Caribbean Countries (Figure 3A) [72,75]	Spirited Bamboo: Caribbean Countries (Figure 3B) [73,75]	Resilient Liaison House: Puerto Rico (Figure 3C) [74]
Footage	43 m ²	50 m ²	50 m ²
Energy	This house did not include energy efficiency measures or alternative energy systems.	This house incorporates the use of solar energy to supply electricity to the house that, supported by passive cooling measures with the double-roof system, shade and insulation and incorporation of cross-ventilation, promotes thermal comfort.	This house has a portable solar power plant with the capacity to store 1.5 kilowatts (kW) per day.
Water and Sanitation	This house did not include water efficiency measures or alternative systems.	This house includes the collection of rainwater for reuse in a low-pressure drip irrigation system for crops within the field and/or with a UV filtration system for use as drinking water.	This house provides water and sanitation through a 200-gallon rainwater cistern that runs by gravity, making it usable even during power outages, as well as an underground greywater system.
Location and Resistance to extreme events	This house was designed according to the realities of the terrain, local capacities and the challenges evidenced by hurricanes Irma and Maria.	This house was designed according to local capabilities and evidenced challenges, such that it allows for resistance to earthquakes and strong hurricane winds.	This house respected the building codes in force in the country, while considering the needs of the user and the protection of the environment. In addition to considering the challenges received by the island: hurricanes, strong winds and floods.
Materials	This house uses common materials and low maintenance: wood, river stones and concrete, with a construction cost of USD 9962.00.	This house uses bamboo and concrete pillars as materials, with a construction cost of USD 8107.00.	This house uses common materials such as masonry and concrete panels with structural insulation on the roof.
Observation	This house participated in the Resilient Homes Challenge.	This house was awarded as the winner of the Resilient Homes Challenge.	This house won the XVI Biennial of Architecture and Landscape Architecture of Puerto Rico 2021 award, and the Green Builders 2022 Green Home of the Year.

4.2. Sustainable Housing Models

Sustainable housing boomed in the late 1980s with the idea of sustainable development, but it is through organizations such as LEED [76], BREEAM [77] and Green Star [78], among others, and their energy, water and material efficiency certifications, that have increased the quality of housing design, construction and operation. In this context, four case studies of sustainable housing are illustrated in Figure 4 and compared in Table 4.

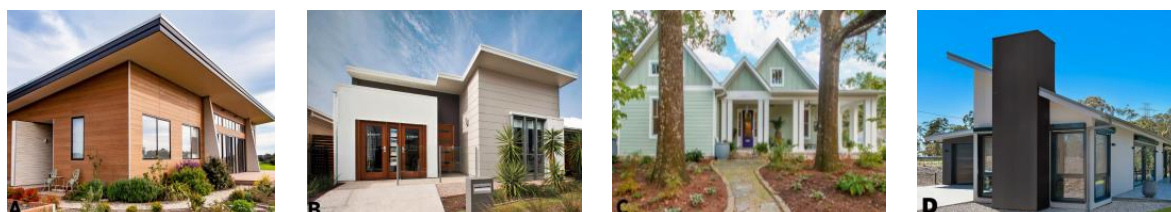


Figure 4. Sustainable housing models: (A) Harmony House [79]; (B) Caloundra [80]; (C) The Owen Residence [81]; (D) Sapphire Passive House [82].

Table 4. Characteristics of the sustainable housing models found in the literature review. Source: authors’ elaboration based on cited literature.

Characteristics	Harmony House: Australia (Figure 4A) [79,83]	Caloundra: Australia (Figure 4B) [80]	The Owen Residence: Estados Unidos (Figure 4C) [84,85]	Sapphire Passive House: Australia (Figure 4D) [82,86]
Footage	194 m ²	150 m ²	800 m ²	238 m ²
Energy	This house produces its electricity using a 14 kW photovoltaic system. In addition, it has a passive solar design that contemplates internal thermal mass, cross-flow ventilation and strategic window placement.	This house implemented the use of glass windows and doors with low emissivity, a 1.5 kW photovoltaic solar system and the exclusive use of thrifty appliances.	With the help of 42 solar panels and the exclusive use of Energy Star appliances, this house does not consume energy from the grid, even returning its surplus to it.	This house is 90 percent more energy efficient, with an average use of 1.66 kW per day to run. However, it has a zero-carbon classification, supplying its consumption within a 5 kW photovoltaic solar system with a 10 kW battery storage system.
Water and Sanitation	This house has enough storage for 27,000 L to meet all water needs, without the need to connect to the public network. Domestic wastewater is processed by a worm farm septic system, thus providing a chemical-free and relatively easy-to-maintain method.	The main water use is kept to a minimum by incorporating a 5000-L rainwater tank for reuse in bathrooms, laundry and gardens. In addition, high-efficiency plumbing is incorporated.	Opted for products with efficiency certification in everything related to plumbing. The design included eight barrels of rainwater to collect runoff from the roof and considered a landscape with unirrigated, drought-tolerant, site-appropriate landscaping and a fully permeable lot to maximize stormwater absorption and reduce runoff.	Rainwater is collected from the roof in a 22,000-L rainwater tank, which is connected to all internal fittings. The kitchen tap is the only tap connected to the main water supply. However, the entire plumbing system is highly efficient.
Location and Resistance to extreme events	This house considers climatic zones, adaptability to local needs and lifestyle.	This house considers climatic zones, adaptability to local needs and lifestyle.	This house considers the climatic zones and the resources of the locality.	This house considers climatic zones, adaptability to local needs and lifestyle. For example, it is the first Certified Passive House in Australia to meet the highest bushfire risk rating.

Table 4. Cont.

Characteristics	Harmony House: Australia (Figure 4A) [79,83]	Caloundra: Australia (Figure 4B) [80]	The Owen Residence: Estados Unidos (Figure 4C) [84,85]	Sapphire Passive House: Australia (Figure 4D) [82,86]
Materials	This house is clad in designer-finished fiber cement, an easy maintenance material. In addition, the walls have a 'self-cleaning' coating, whereby silica particles absorb water molecules from the air to form a protective film on the surface of the house.	This house model considers the quality and comfort of the inhabitants and the environment by using paints and laminates with low VOC, thermally more efficient materials and recycled materials, as well as materials that can be recycled, such that most of the house can be disassembled or reused at the end of its life span.	This house incorporates as many recycled materials as possible into the construction.	Any excavated materials were re-used on the site, with rocks also used for the building and landscaping. Local materials were used as much as possible.
Observation	This house illustrates a case study from "Your Home: Australia's Guide to Environmentally Sustainable Homes."	This house illustrates a case study from "Your Home: Australia's Guide to Environmentally Sustainable Homes."	This house has been widely highlighted since its construction, with a LEED Platinum certification, and is named one of three outstanding single-family homes by the U.S. Green Building Council (USGBC) in the 2018 LEED Homes Awards, where it also won Project of the Year.	This house is the first certified Passive House in the Blue Mountains and the first certified Passive House in Australia to also be built to Bushfire Attack Level Flame Zone (BAL-FZ) regulations, and the first house in New South Wales to receive Healthy House Australia certification.

5. Discussion

Each of the resilient and sustainable housing models was analyzed to establish actions and/or qualities in order to meet urban resilience and sustainability, such that there is a guide to comply with the new international agreements and initiatives that strive to strengthen populations in their search for sustainable development.

In this sense, when analyzing the housing models considered resilient [72–74], the need to establish housing on safe land stood out. The use of locally manufactured and quality materials was considered a requirement for resilience and sustainability. Regarding adequate materials, concrete was present in all resilient housing models. In addition, the use of alternative sources of water and/or energy supply was prioritized.

Sustainable housing models [79,80,82–86] were developed by local entities and have a certification that accredits them as sustainable. In addition to standing out for taking into account the climatic specifications of their location, they sought energy and water efficiency, took care of the quality of the indoor environment, promoted the use of materials and resources according to what is available locally and followed environmental regulations.

Therefore, the main characteristics that can be extracted are the use of renewable energy as the main source of energy and the incorporation of design in the orientation of the house to take advantage of natural light and ventilation that allow for energy savings, as well as the search for water efficiency by implementing mechanisms for reuse, harvesting and water treatment. Moreover, materials should come from sources with environmental certifications and/or have recycled content. In addition, locally produced materials were prioritized over imported materials, in order to reduce the carbon footprint of the house.

Overall, the housing models discussed in this study contribute not only to resilience and sustainability against climate change, but also to the comfort, health and well-being of their occupants.

It is essential to recognize that the focus on building resilient and sustainable housing implies a paradigm shift in the construction industry, which implies overcoming traditional practices and adopting new methods and technologies that promote energy efficiency, emissions reduction and conservation of natural resources, among other actions. For this reason, the implementation of resilience and sustainability features in housing comes with

significant challenges to overcome. The literature points out that although some countries have introduced climate action policies, implementation efforts are inadequate or non-existent [87], which leads to conflicts or technical ambiguities that hinder the widespread adoption of these policies.

Technical challenges linked to sector professionals are identified, as there is a lack of access to specialized training and resistance to change, which hinders the task of fully integrating housing considerations [88–90]. It is important to note that this barrier is cross-cutting in nature, as it can be linked to regulatory requirements or economic performance.

The implementation of local measures must be aligned to the local context. There are cultural challenges as well [91], such as denial or resistance to change, which prevents the inclusion and diversification of actions in favor of the environment. This situation prevents the appropriation and demand for initiatives that seek to mitigate and adapt to climate change from social foundations, such as housing.

6. Conclusions

It was established that housing is fundamental for human well-being and quality of life, including health, security and development in general. Therefore, this study helps establish the lines to follow for the implementation of local measures at a public and private level for resilient and sustainable housing.

Considering climate change and its impact on cities, especially housing, this study framed efforts to identify resilient and sustainable housing models and a comparative analysis of housing models that integrate these characteristics was presented.

It is expected that the results of this study will serve as a basis for the establishment of safe and efficient measures for urban housing from the incorporation of characteristics such as location on safe land, application of building codes and standards, use of durable materials, continuous access to water and energy, efficiency in the consumption of resources, water and energy, comfort, health and adaptability to climate change, among others.

Likewise, by considering the challenges due to climate change and involving the principles of urban resilience and sustainability, not only were the principles of adequate housing established by international law strengthened, but also actions to achieve the Sustainable Development Goals, the climate objectives of the Paris Agreement and work on the acceleration of cities that think of its basic unit, i.e., housing, were achieved.

Throughout the study, housing is highlighted as a fundamental axis for people's lives, health, safety and development in general. The challenges or barriers that prevent the establishment and implementation of local measures from governance systems to private innovation in this area are also discussed and used to compare the perceptions of the industry or civil society.

Alongside that, this study serves as inspiration for professionals from other disciplines who would like to follow up with complementary research in fields such as social, economic and/or political sciences.

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