TYPE Original Research
PUBLISHED 13 November 2025
DOI 10.3389/fbuil.2025.1653057



OPEN ACCESS

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RECEIVED 24 June 2025 REVISED 30 August 2025 ACCEPTED 01 October 2025 PUBLISHED 13 November 2025

CITATION

Sabah FY (2025) Global approaches to affordable housing: comparative insights from developed and developing countries and the case of Palestine.

Front. Built Environ. 11:1653057. doi: 10.3389/fbuil.2025.1653057

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Global approaches to affordable housing: comparative insights from developed and developing countries and the case of Palestine

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Affordable housing remains one of the most pressing global policy challenges, with strategies and constraints differing significantly between developed and developing contexts. This study employs a comparative policy analysis of six case countries United States, Germany, Japan, India, Brazil, and South Africa to examine how diverse socio-economic and political settings shape housing strategies. The analysis focuses on key factors influencing affordability, including regulatory frameworks, financial mechanisms, community participation, and innovation in addressing local needs. In Palestine, the interaction of political conflict, land restrictions, and economic constraints creates a unique and highly constrained housing environment that requires context-specific responses. The study indicates that developed countries benefit from structured public-private partnerships and robust regulatory frameworks, whereas developing countries rely more on community-driven initiatives and flexible financing models. Lessons from this comparative analysis can inform global policymakers by emphasizing resilience, inclusivity, and sustainability in housing policies, with particular relevance for improving affordability in conflict-affected and economically constrained settings such as Palestine.

KEYWORDS

affordable housing, comparative analysis, developed countries, developing countries, Palestine

1 Introduction

Affordable housing is a fundamental component of human wellbeing and social stability, yet it remains a persistent global challenge. Governments worldwide struggle to provide adequate housing that is both accessible and affordable, with the issue shaped by economic, political, social, and environmental factors. This paper addresses the pressing question of how different contexts developed and developing countries design and implement housing policies to meet affordability needs.

The relevance of this study lies in its comparative scope: it examines policy experiences in six countries, identifying strategies that have proven effective and highlighting lessons that can inform global practice. By including Palestine as a unique case study, the paper contributes new insights into how political conflict, economic constraints, and land restrictions complicate housing provision in ways rarely explored in existing literature.

The main objective of this work is to advance understanding of affordable housing strategies across diverse contexts and to demonstrate how these experiences can inform both academic debate and policy design. In doing so, the paper contributes to the ongoing development of housing policy scholarship by linking global comparative analysis with the specific realities of Palestine.

2 Concept and context of housing affordability

Housing affordability is a multifaceted and subtle concept, particularly when comparing countries with very different housing markets and financing structures (Biljanovska et al., 2023). According to Adegoke and Agbola (2020), it is typically defined by the capacity of households to access housing services, focusing on the relationship between household incomes and the costs of housing, including both purchase prices and rents. Similarly, MacLennan and Williams (1990) define "affordability" as securing a certain standard of housing at a cost that does not, in the opinion of a third party (usually the government), place an unreasonable burden on household income. Whitehead (1991) further emphasizes that affordability is often assessed by the proportion of household income spent on housing, with a threshold beyond which housing costs are considered unaffordable.

The challenge of housing affordability is particularly pronounced in communities experiencing increased housing demand, driven by factors such as net population growth, immigration, and the rise in low-income renter households, including senior households and households of color (Anacker, 2019). These challenges are often exacerbated by insufficient government programs (Schneider and Morduch, 2017). Addressing these issues is difficult for several reasons: reducing household expenditures is challenging; increasing household incomes is equally difficult; and both expenditures and incomes tend to grow slowly over time. Consequently, many policymakers are hesitant to take immediate action, as evidenced during the foreclosure crisis and the Great Recession. This inaction has led to severe social consequences, including suicides, sudden evictions (Desmond, 2016), increased crime rates (Lacoe and Ellen, 2015), and health crises (Currie and Tekin, 2015).

In developed countries, the availability of resources, institutional frameworks, and economic stability enables the implementation of sophisticated housing policies. These typically include a combination of public housing projects, subsidies, and private-sector partnerships aimed at improving housing affordability (World Bank, 2019a). In contrast, developing countries often face greater challenges, including rapid urbanization, informal settlements, limited financial resources, political instability, and a lack of a holistic and viable sustainability framework for housing development (Arnott, 2008; Pasalar et al., 2021). Therefore, these countries must innovate and adapt strategies to their specific contexts in order to meet housing needs effectively.

Palestine offers a particularly compelling case study due to its ongoing political conflict, economic constraints, and the unique challenges associated with its status. The housing sector is heavily influenced by land restrictions, resource limitations, and sociopolitical instability. Empirical local studies, such as household

surveys in Jenin, indicate that affordability is dominated by financial constraints, down-payment and pre-construction payment requirements, and limited market offers (Sabah, 2024a).

3 Affordable housing in developed countries

Developed countries have established various frameworks to ensure housing affordability. These frameworks often involve a mix of direct government intervention, regulatory measures, and incentives for private sector participation. According to Anacker (2019) Public awareness of housing affordability and affordable housing has recently increased. In the United Kingdom, this issue was a focal point for the main political parties during the general elections of 2015 and 2018. Prime Minister Theresa May has also addressed the national housing crisis in several speeches, highlighting various new programs and approaches aimed at tackling the problem. The Home Building Fund supports small developers who face challenges in securing conventional funding from the private sector. The updated National Planning Policy Framework, released in July 2018, establishes guidelines for the creation of locally prepared housing and development plans, with the goal of accelerating the construction of more affordable homes (Ministry of Housing, Communities and Local Government, 2018). This section delves into the strategies employed by the United States, Germany, and Japan, providing a detailed analysis of their approaches and the outcomes achieved.

3.1 Public housing and subsidies in the United States

The U.S. Department of Housing and Urban Development (HUD) plays a central role in improving housing affordability for low-income and vulnerable populations. Its most significant initiatives include public housing projects, the Section 8 Housing Choice Voucher Program, and the Low-Income Housing Tax Credit (LIHTC). Public housing projects provide rental units for eligible families, the elderly, and persons with disabilities, managed by local Public Housing Agencies (PHAs) under federal oversight. The Section 8 program assists households through vouchers that cover a portion of rent in the private market, with tenants contributing according to their income. The LIHTC program, introduced in 1986, incentivizes private developers to construct affordable units through federal tax credits, leading to the creation of millions of homes nationwide (U.S. Department of Housing and Urban Development HUD, 2021; McClure, 2019; Richter et al., 2019).

Despite these programs, low-income households often face limited flexibility in reducing fixed expenses such as taxes, healthcare premiums, rent, and mortgage payments, leaving them highly vulnerable to financial stress and housing insecurity (Desmond, 2016). Furthermore, housing affordability is not only shaped by income and subsidies but also by local building regulations. While government initiatives have sought to ease restrictive rules such as outdated codes, lengthy design reviews, and excessive development

standards health, safety, and welfare requirements remain non-negotiable. Although these regulations improve long-term housing safety, they also raise housing costs, underscoring the persistent challenges faced by low-income households even with federal support programs (Carson, 2018).

3.2 Germany's social housing and rent control

In Germany, the Federal Government introduced rent control laws in March 2013, which were implemented by selected municipalities experiencing significant rent increases starting in June 2015. The impact of these laws has been mixed (Deschermeier, et al., 2016; Kholodilin, 2016). In the summer of 2014, the Federal Government, together with states, municipalities, and associations, formed an affordable housing coalition, which released its final report in November 2015. According to Anacker (2019), regarding housing affordability, the coalition recommended increasing housing assistance for renters and analyzing the implications of high housing costs.

To boost the affordable housing stock, the coalition proposed several measures, including establishing and increasing subsidies for housing construction by states and municipalities to support sustainable building rehabilitation, reducing property taxes on newly purchased homes, selling federally owned properties at discounted prices, encouraging municipalities to sell lots particularly in urban areas subsidizing states and municipalities to lower the asking prices of properties, increasing the affordable housing stock for students and apprentices, improving, establishing, and streamlining legal and construction standards, increasing housing density, allowing mixed-use developments, promoting flexible parking regulations, reforming noise and fire regulations, encouraging collaboration among developers and stakeholders, and establishing policies and programs that support aging in place. These recommendations aim to address various aspects of housing affordability and availability, fostering a more sustainable and inclusive housing market.

Germany's approach to affordable housing combines social housing with stringent rent control measures. The country's social housing program is designed to provide affordable rental housing for low-income households. This program is funded through a mix of federal, state, and municipal resources and involves both public and private sector participation. Social housing units in Germany are typically built and managed by municipal housing companies or private developers, and are rented out at below-market rates to eligible households.

The rent control measures in Germany are also robust, with strict regulations on rent increases and tenant protections. The Mietpreisbremse, or "rent brake," is a policy that limits rent increases in areas with tight housing markets, ensuring that rents remain affordable. Additionally, Germany's housing policy emphasizes the importance of maintaining a high standard of living in social housing units, which are often located in well-serviced neighborhoods with access to public transportation, schools, and healthcare facilities. This holistic approach ensures that low-income households can live in decent conditions and integrate into the broader community (Kadi and Musterd, 2015).

Beyond national policies, several municipalities have implemented complementary measures to further enhance housing affordability. In other experiences in Germany, some cities, such as Hamburg and Berlin, have applied and combined organization, urban planning, land allocation, and public housing, while reducing obstacles to construction, in order to increase housing supply and improve housing affordability (McClure, 2019; Richter et al., 2019).

3.3 Japan's private sector incentives

Japan's housing policy heavily involves the private sector, with the government providing various incentives to encourage the construction of affordable rental housing. The country faces unique challenges due to its limited land availability and high population density, particularly in urban areas such as Tokyo. To stimulate private sector participation, the government offers tax incentives, low-interest loans, and subsidies for developers who build affordable rental units. The Housing Supply Corporation, a government-affiliated entity, plays a key role in financing and facilitating these projects. One notable aspect of Japan's approach is the emphasis on quality and sustainability, as affordable housing units are designed to be durable, energy-efficient, and adaptable to changing needs. This focus on long-term sustainability helps ensure that housing remains affordable and livable over time (Hirayama, 2010).

In parallel with government incentives, the Japanese mortgage market has undergone a significant transformation, shifting from primary to secondary markets, with greater private sector involvement in financing and issuance, including the development of Mortgage-Backed Securities (MBS) markets. These changes created further incentives for private actors to participate in housing finance, offering important lessons for emerging Asian countries seeking to enhance private sector engagement. Over time, the government has also gradually shifted toward neoliberal policies, reducing the number of public rental apartments while increasing the supply of private rental units. As a result, the proportion of people living in owner-occupied homes has declined, while more people reside in rental housing, particularly rental apartments, indicating that many low-income groups (LIGs) face housing affordability challenges (Forrest and Hirayama, 2018; Kobayashi, 2016).

On the supply side, various studies such as Kishioka et al. (2013) have shown that the private sector faces challenges in providing low-rent housing (LRH), which is often limited in quantity and characterized by poor housing conditions, particularly in older wooden structures. Furthermore, the supply of LRH has declined due to the reduction of older wooden apartment buildings without bathrooms. Building on these findings, the present study examines LRH in Osaka Prefecture, focusing on different room types as a sub-market, to provide insights into how private sector incentives influence housing affordability and availability (Yoshida and Kato, 2022).

A comparative analysis of affordable housing strategies in developed countries reveals both differences in implementation and insights into program success under specific socio-political and economic conditions. Institutional and Financial Frameworks:

Developed countries benefit from strong institutional capacity and robust financial mechanisms. For example, the LIHTC program in the U.S. mobilizes private sector participation through federal tax incentives, while Germany combines social housing with rent control to stabilize markets. These mechanisms directly impact indicators such as rent-to-income ratios and homeownership rates. Quantitatively, countries with stronger frameworks show homeownership rates between 61% and 65% and rent overburden rates below 33%, highlighting effectiveness compared to countries with weaker institutions.

3.3.1 Public-private partnerships (PPPs)

PPPs are central to scaling affordable housing. In the U.S., private developers leverage LIHTC incentives, and in Japan, government loans and subsidies promote quality rental unit construction. Financial risk-sharing and incentives emerge as key determinants of program effectiveness, with housing satisfaction rates in Japan reaching 82%. Community Participation: While generally limited in developed countries, incorporating resident feedback has measurable benefits. For instance, pilot participatory planning programs in Germany improved housing satisfaction by 5-8 percentage points and reduced complaints related to housing design. This demonstrates that even modest community engagement can enhance sustainability and alignment with local demand. Regulatory and Policy Measures: Legal frameworks such as Germany's Mietpreisbremse effectively maintain affordability by controlling excessive rent increases. These policies underscore the need to adapt regulatory mechanisms to local housing market dynamics to prevent unintended outcomes like displacement.

3.3.2 Transferability of lessons to palestine

Direct replication of developed country programs is not feasible due to different socio-political contexts. However, lessons from financial incentives, structured PPPs, and regulatory safeguards can inform tailored strategies. For example, Palestine could adapt LIHTC-style tax incentives and PPP frameworks while accounting for land restrictions, funding limitations, and socio-cultural needs. Linking these measures to Palestinian indicators (Supplementary Tables A3–A5), such as down-payment requirements, overcrowding (~25%), and donor dependence (~30%), ensures that policy adaptation is quantitative, contextual, and actionable.

4 Affordable housing in developing countries

Developing countries face distinct challenges in addressing affordable housing needs. Rapid urbanization, informal settlements, limited financial resources, and political instability are common issues that these countries must navigate. Despite these challenges, many developing countries have implemented innovative and effective housing strategies. This section explores the approaches taken by India, Brazil, and South Africa, highlighting their successes and ongoing challenges.

4.1 Slum upgrading and in-situ development in India

India faces a growing need for affordable housing, with approximately one in six urban Indians living in informal settlements. In response, the Ministry of Housing and Urban Poverty Alleviation (MoHUPA) launched the *Pradhan Mantri Awas Yojana* (PMAY) in 2015, aiming to make India slum-free by 2022. While ambitious, the program has been criticized for its limited people-centered focus: beneficiaries are often perceived as passive, empowerment measures are scarce, access to benefits is restricted, and long-term impacts are neglected (von Puttkamer, 2015).

To address the broader challenge of urban informal settlements, India's housing strategy has evolved to include comprehensive programs such as the *Jawaharlal Nehru National Urban Renewal Mission* (JNNURM). This flagship initiative emphasizes slum upgrading and *in situ* development, improving living conditions within existing slums rather than relocating residents. Key components include the provision of basic infrastructure—water supply, sanitation, electricity, and waste management—as well as land tenure regularization to ensure residents' legal security (Mahadevia, 2011).

The success of JNNURM is partly attributed to its participatory approach, involving residents in planning and implementation to tailor solutions to community-specific needs. However, challenges remain, including the need for sustained funding, political commitment, and effective governance. Studies indicate that weak institutional coordination and inadequate monitoring can lead to outcomes favoring private developers over slum residents, exacerbating social inequalities (Mahadevia and Narayanan, 2008; Dutta, 2024). Moreover, despite improvements in cities such as Mumbai, Delhi, and Bangalore, slum upgrading programs have achieved only limited success in reducing urban poverty.

Overall, India's experience demonstrates that slum upgrading and *in situ* development can be effective strategies for improving the living conditions of low-income urban residents. However, comprehensive planning, participatory implementation, and sustained institutional support are essential for long-term success (ESID, 2015).

4.2 Brazil's Minha Casa Minha Vida program

Effectively addressing the multifaceted challenges of the built environment in Brazil requires cultivating adaptability and resilience across diverse contexts. Social housing should be understood as a critical component of a comprehensive urban system, necessitating interventions that encompass physical, cultural, economic, political, and environmental dimensions. In this regard, the *Programa Minha Casa Minha Vida* (PMCMV—My House My Life Program), implemented by the Brazilian government since 2009, represents a strategic initiative aimed at reducing the national housing deficit (Cardoso and Aragão, 2018). The program was introduced in response to the proliferation of informal housing constructed without adequate technical oversight and

primarily relies on standardized solutions for large-scale housing production (Dalla Vecchia and Medvedovski, 2021).

The housing units provided under PMCMV follow a standardized typology, ranging from 32 to 37 m² and constructed using structural masonry. Each unit typically includes a living room, two bedrooms, a bathroom, a kitchen, and a laundry area. This typology is consistently applied to both single-story houses and apartment units across Brazil's diverse contexts. However, after several years of occupancy, residents have often modified these units—removing walls or constructing additional single-story rooms—frequently without technical guidance. Several national and local studies have highlighted the challenges faced by residents of PMCMV social housing, noting that these standardized models often fail to account for local social, economic, cultural, climatic, and environmental conditions (Amore et al., 2015; Formoso et al., 2011; Dalla Vecchia and Kolarevic, 2020).

In particular, Villa et al. (2022), through two case studies, identified factors that negatively affect the adaptive capacities of these communities. Poor quality of construction materials and building techniques was linked to environmental discomfort and adverse health outcomes. Additionally, the layout of the houses frequently limited opportunities for expansion and long-term adaptation. The study also highlighted the insufficient quality of public spaces, which undermines community engagement and social interaction. Furthermore, the implementation of housing sites often neglected residents' access to local work opportunities, thereby restricting the overall functionality and resilience of the developments.

Despite these challenges, the PMCMV program has achieved significant accomplishments. By offering subsidies and financing options for low- and middle-income families, the program has enabled homeownership at a scale previously unseen in Brazil, constructing millions of housing units and substantially reducing the housing deficit. Its phased approach targets different income groups, providing substantial subsidies for the lowest income households and more modest support for middleincome groups, complemented by favorable mortgage terms. The program also incorporates social and economic integration measures, such as community facilities and services within housing developments, which contribute to the broader functionality of these communities (Cardoso and Aragão, 2018). Nevertheless, the program continues to face criticism regarding the quality and location of housing units, project completion delays, and financial sustainability, highlighting the need for continuous improvements to enhance adaptability and resilience.

4.3 South africa's integrated housing strategy

South Africa's approach to affordable housing remains deeply influenced by its apartheid legacy and the enduring spatial inequalities that it created. This history has produced stark urban duality, where elite areas maintain "world-class" standards, while townships and informal settlements house the majority of urban and rural poor populations (de Satgé and Watson, 2018; Madell and Karam, 2022). Understanding this historical context is essential to grasp the challenges faced by contemporary housing policies and the

rationale behind initiatives aimed at creating more inclusive urban environments.

Building on this legacy, inclusionary housing policy has emerged as a key tool for restructuring cities. By promoting compact and integrated developments, it requires private developers to provide affordable housing within their projects (Klug et al., 2013). Although national-level legislation targeting the gap market in established urban centers has not yet been fully enacted, the principle of inclusionary neighborhoods is embedded in the Constitution, the National Housing Act, and the Breaking New Ground (BNG) strategy for integrated and sustainable human settlements (Republic of South Africa, 2004). According to Turok et al. (2024), the essential conditions for effective and inclusive residential development include an engaged civil society, broad-based support from both officials and political leaders, economic feasibility that does not impose excessive risk on real estate investors, and a strong legal framework to minimize disputes, prevent disruptions, and institutionalize necessary reforms. Moreover, further research is needed to understand the political, social, and institutional factors that influence the implementation of the Inclusionary Housing Policy (IHP).

The national Framework for Inclusionary Housing Policy (Republic of South Africa, 2007) comprises two complementary approaches. Under the voluntary, deal-driven approach, municipalities may identify projects to actively pursue in collaboration with private sector partners. In such cases, municipalities can contribute publicly owned land and expedite development approvals, provided the developer allocates a substantial portion of the project to affordable housing. Complementing this, expanding affordable housing options across diverse tenure forms-including both ownership and rental-is central to promoting inclusionary cities. While private ownership has historically offered secure tenure, affordability constraints exclude many lower-income households, making rental housing a critical tool for flexibility across life stages. Over 25% of South African households live in rental accommodation, and government rental supplements help maintain affordability for low-income families while facilitating partnerships with private developers, particularly in inner-city areas where both rental and ownership opportunities exist (Budlender and Royston, 2016; Gardner and Trust, 2008; Mbuyisa, 2019).

Beyond the IHP, South Africa possesses a wide range of tools to restructure cities and enhance both the location and affordability of housing. Critical frameworks include public housing policies, spatial planning, land use management, and development incentives. Leveraging publicly owned land, infrastructure incentives, and financial support—including subsidies and tax benefits—can further strengthen these efforts. Given the inherent risks and complexities, the state must actively pursue collaborative partnerships with the private sector, NGOs, and communities to expand affordable housing—especially amid weakened state capacity caused by corruption, recession, COVID-19, fiscal crises, and widespread service delivery protests (Madell, 2025).

Finally, national housing policy, articulated through the Reconstruction and Development Programme (RDP) and later the BNG strategy, seeks to redress historical injustices and provide decent housing for all. While the RDP focused on mass housing construction to meet urgent post-apartheid needs, it became clear

that a more integrated and sustainable approach was necessary. Introduced in 2004, the BNG strategy emphasizes the creation of integrated human settlements, combining housing with social and economic infrastructure. This approach aims to develop vibrant, sustainable communities rather than isolated housing projects, incorporating mixed-income developments, public-private partnerships, and essential services. Despite notable achievements, including millions of housing units delivered since the end of apartheid, challenges persist in improving housing quality, ensuring sustainable funding, and addressing ongoing spatial and economic inequalities (Charlton and Kihato, 2006).

Comparative analysis of affordable housing strategies in developing countries reveals distinct challenges and innovative solutions shaped by socio-economic and institutional contexts.

Institutional and Financial Frameworks: Unlike developed countries, developing countries often face limited institutional capacity and financial resources, which affect housing outcomes. For instance, Brazil's Minha Casa Minha Vida program relies on government subsidies and financing options to achieve a high homeownership rate (~73%), while India's JNNURM focuses on slum upgrading and land tenure regularization to reduce informal housing (~25%) and overcrowding (~28%). South Africa emphasizes mixed-income developments and public-private partnerships (PPPs) to address both housing deficits (~2.3 million units) and spatial inequality. These cases illustrate that innovative financial mechanisms and institutional support are critical for improving affordability under constrained resources.

Public-Private Partnerships (PPPs): PPPs play a pivotal role in scaling affordable housing delivery where government capacity is limited. In South Africa, the integration of PPPs within the Integrated Housing Strategy enabled significant housing delivery and promoted spatial integration, demonstrating the importance of resource pooling and risk-sharing in developing contexts. Community Participation: Participatory approaches, such as India's *in situ* slum upgrading, enhance local ownership, cultural sensitivity, and long-term sustainability. Although participation levels vary, community engagement has measurable outcomes, including improved living conditions and social cohesion, which are crucial when formal housing markets cannot meet demand.

Regulatory and Policy Measures: Land tenure regularization, policy-driven subsidies, and housing allocation mechanisms are key regulatory tools in developing countries. These frameworks help mitigate informal settlement growth and ensure access for low-income households, though challenges such as bureaucracy and implementation delays persist.

Transferability of Lessons to Palestine: Developing country strategies highlight the importance of context-specific, resourceefficient solutions. For Palestine, lessons include:

- Implementing subsidy-based and mixed-income models akin to Brazil, adapted for local market constraints.
- Promoting community-driven planning and participatory development, following India's model.
- Leveraging PPPs to pool limited financial and technical resources, as in South Africa.

By aligning these lessons with Palestinian indicators (e.g., down-payment and pre-construction payment requirements,

overcrowding ~25%, donor dependence ~30%), policymakers can design tailored affordable housing strategies that address socio-economic, political, and land constraints effectively.

5 The case of Palestine

Palestine presents a unique and complex case for affordable housing due to its political situation, economic constraints, and social dynamics. The Israeli-Palestinian conflict, ongoing occupation, and resulting restrictions on land use and movement have profound implications for housing development. This section examines the specific challenges and strategies in Palestine, highlighting the role of local and international efforts in addressing housing needs. The quest for affordable housing stands as a formidable challenge in Palestine, where socio-economic, political, and environmental factors converge to exacerbate the housing crisis. With a population characterized by rapid urbanization, limited land availability, and the enduring repercussions of the Israeli-Palestinian conflict, the shortage of adequate and affordable housing looms large, particularly for marginalized communities. This introduction sets out to elucidate the multifaceted nature of the affordable housing crisis in Palestine, delineating the overarching challenges and complexities inherent in addressing this pressing issue. The demand for housing in Palestine consistently outpaces the available supply, precipitating inflated housing prices and soaring rental costs (Rabie, 2020; Haas, 2022). Factors such as population growth, internal migration, and the return of Palestinian refugees further amplify the housing demand, exacerbating the strain on existing housing infrastructure (Shaheen and Salim, 2012; Khatam and Haas, 2018). However, the supply of affordable housing remains grossly inadequate, particularly in urban centers where the majority of the population is concentrated. This disparity between demand and supply underscores the urgency of devising sustainable solutions to bridge the housing gap.

Compounding the housing crisis is the pervasive housing backlog, with scores of families enduring substandard living conditions characterized by overcrowding, inadequate amenities, and precarious housing arrangements (Barakat et al., 2004; Sabah, 2024a). The lack of affordable housing options compels many Palestinians to reside in informal settlements devoid of basic necessities, perpetuating cycles of poverty and marginalization. The persistence of the housing backlog underscores the imperative for concerted efforts to address the root causes of housing insecurity. In response to the affordable housing crisis, various approaches have been undertaken by Palestinian authorities, international organizations, and grassroots initiatives. Government-led interventions encompass subsidies, low-interest loans, and policy reforms aimed at enhancing affordability and accessibility (Sabah, 2024a; Sabah, 2024b). However, formidable barriers obstruct progress, including land scarcity, bureaucratic impediments, and infrastructural deficiencies. Moreover, the efficacy of implemented strategies remains variable, necessitating closer scrutiny and innovation (Abdelhamid, 2006; Sabah, 2024b). This manuscript endeavors to provide a comprehensive analysis of the affordable housing crisis in Palestine, spanning demand and supply dynamics, housing backlog, adopted strategies, their efficacy, and case studies of affordable housing initiatives within Palestinian cities. Through

an exhaustive examination, it seeks to elucidate the urgent need for innovative, context-sensitive solutions to address the housing crisis and ensure housing security for all Palestinians.

5.1 Situation of affordable housing in Palestine

In Palestine, the quest for affordable housing is entrenched in a complex web of socio-economic, political, and environmental challenges. The high population density, rapid urbanization, and limited land availability exacerbate the shortage of suitable housing units, particularly for low and middle-income families (Shaheen and Salim, 2012; Haas, 2022). Urban areas, in particular, grapple with acute housing shortages due to the concentration of the population and the strain on existing infrastructure. The demand for housing consistently outstrips the available supply, resulting in inflated housing prices and soaring rental costs (Itma, 2014). Factors such as population growth, internal migration, and the repatriation of Palestinian refugees contribute to the burgeoning housing demand. However, the supply of affordable housing remains grossly inadequate, perpetuating cycles of housing insecurity and exacerbating socio-economic disparities. Compounding the housing crisis is the enduring impact of the Israeli occupation and restrictive land use policies, which further constrain Palestinians' access to land for housing purposes (Helu, 2012). The fragmentation of Palestinian territories, coupled with the expansion of Israeli settlements, further exacerbates land scarcity and impedes efforts to develop affordable housing solutions. The housing backlog looms large over Palestine, with thousands of families enduring substandard living conditions characterized by overcrowding, inadequate amenities, and precarious housing arrangements (Asfour and Zourob, 2017; Sabah, 2024b). Informal settlements, lacking basic necessities such as water, electricity, and sanitation facilities, proliferate in response to the acute shortage of affordable housing options. This backlog continues to grow unabatedly, perpetuating cycles of poverty and marginalization within Palestinian communities.

5.2 Demand and supply dynamics

The dynamics of housing demand and supply in Palestine are intricate, shaped by a combination of demographic trends, urbanization patterns, and political factors. The demand for housing consistently surpasses the available supply, leading to inflated housing prices and acute affordability challenges (Al-Sa et al., 2006; Rabie, 2020). Several factors contribute to this imbalance, exacerbating housing shortages and perpetuating socio-economic disparities within Palestinian communities. Population growth is a significant driver of housing demand in Palestine, exerting pressure on existing housing stock and infrastructure. Internal migration from rural to urban areas, coupled with the return of Palestinian refugees, further amplifies the housing demand, particularly in densely populated urban centers (Asfour, 2012). This demographic influx strains housing resources, exacerbating affordability challenges and perpetuating cycles of housing insecurity. Urbanization trends also play a pivotal role in shaping housing demand dynamics in Palestine. Rapid urbanization, fueled by population growth and rural-to-urban migration, has led to the concentration of the population in urban enclaves (Hussein et al., 2010). As a result, urban areas face acute housing shortages, with demand outpacing the pace of housing construction and development. Conversely, the supply of housing in Palestine struggles to keep pace with burgeoning demand, leading to a pronounced housing deficit. Limited land availability, exacerbated by the Israeli occupation and restrictive land use policies, constrains the development of new housing units (Khamaisi, 1999). Additionally, bureaucratic hurdles, infrastructure deficiencies, and financing challenges further impede efforts to expand the housing supply, exacerbating affordability challenges for Palestinian households.

The interplay between housing demand and supply dynamics underscores the urgency of addressing the housing crisis in Palestine through comprehensive policy interventions and targeted investments. Efforts to expand the housing supply must be coupled with measures to enhance housing affordability, improve infrastructure, and address land tenure issues (Chitti and Moser, 2019; Sabah, 2024b). Moreover, fostering sustainable urban development practices and promoting inclusive housing policies are essential to ensure equitable access to housing for all segments of the population.

5.3 Housing backlog

The housing backlog in Palestine is a pressing issue, characterized by a substantial shortage of adequate and affordable housing units, particularly in urban areas. Thousands of families are forced to endure substandard living conditions, including overcrowding, inadequate amenities, and precarious housing arrangements (Abu-Ghazalah, 2008; Sabah, 2024b). This backlog persists due to a combination of demographic pressures, political constraints, and socio-economic challenges, exacerbating housing insecurity and perpetuating cycles of poverty within Palestinian communities. Population growth and urbanization are significant drivers of the housing backlog in Palestine. The rapid increase in the population, coupled with internal migration from rural to urban areas, strains existing housing resources and infrastructure (Asfour, 2012; Khatam and Haas, 2018). Moreover, the return of Palestinian refugees further exacerbates housing demand, compounding the pressure on already limited housing stock. Political factors, including the Israeli occupation and restrictive land use policies, also contribute to the housing backlog in Palestine. Land scarcity, exacerbated by restrictions on Palestinian land use and settlement expansion, impedes efforts to develop new housing units and expand existing infrastructure (Ibrahim, 2014; Haas, 2022). The fragmentation of Palestinian territories further complicates housing development efforts, perpetuating spatial inequalities and hindering equitable access to housing resources. Socio-economic challenges, including poverty, unemployment, and income inequality, further compound the housing backlog in Palestine. Many Palestinian households struggle to afford adequate housing due to limited financial resources and lack of access to formal housing finance mechanisms (Enshassi et al., 2017). As a result, informal settlements

proliferate, with families residing in makeshift dwellings lacking basic amenities such as water, electricity, and sanitation facilities.

Addressing the housing backlog in Palestine requires a comprehensive approach that addresses the underlying systemic issues and fosters collaboration between governmental, non-governmental, and international stakeholders. Efforts to expand the housing supply must be coupled with measures to enhance housing affordability, improve infrastructure, and promote sustainable urban development practices (Saleh et al., 2023). Moreover, initiatives aimed at addressing poverty, unemployment, and income inequality are essential to ensure equitable access to housing resources for all Palestinians

5.4 Approaches to affordable housing in Palestine

Various approaches have been adopted to address the affordable housing crisis in Palestine, encompassing governmental initiatives, international collaborations, and community-driven projects. These approaches aim to alleviate housing insecurity, enhance housing affordability, and improve access to adequate housing for Palestinian households. Government-led initiatives play a pivotal role in addressing the affordable housing challenge in Palestine. These initiatives often involve subsidies, grants, and lowinterest loans to facilitate housing construction and acquisition for low and middle-income families (Abureesh, 2023; Sabah, 2024a; Sabah, 2024b). Additionally, governments may enact policy reforms aimed at streamlining the housing development process, reducing bureaucratic hurdles, and promoting investment in affordable housing projects. International collaborations and partnerships are instrumental in augmenting governmental efforts to address the affordable housing crisis in Palestine. International organizations and donor agencies provide financial assistance, technical expertise, and capacity-building support to enhance housing infrastructure and expand housing opportunities for Palestinian communities (Hamid, 1999; Barakat et al., 2004). These collaborations often focus on developing affordable housing projects, improving housing standards, and promoting sustainable urban development practices. Community-driven initiatives play a crucial role in addressing localized housing needs and fostering community empowerment in Palestine. Grassroots organizations, non-governmental organizations (NGOs), and community-based associations often spearhead initiatives aimed at addressing specific housing challenges within Palestinian communities (Budeiri, 2014). These initiatives may involve the construction of social housing units, rehabilitation of informal settlements, or provision of housing-related services such as legal assistance and housing advocacy. Despite the implementation of various approaches, formidable barriers persist, hindering efforts to address the affordable housing crisis effectively. Land scarcity, bureaucratic hurdles, infrastructure deficiencies, and political constraints remain significant challenges that impede progress in expanding the supply of affordable housing in Palestine (Sabah, 2024b). Additionally, socio-economic disparities, income inequality, and poverty exacerbate housing insecurity, necessitating comprehensive approaches that address the root causes of housing vulnerability.

5.5 Effectiveness of affordable housing strategies

While various strategies have been implemented to address the affordable housing crisis in Palestine, assessing their effectiveness remains crucial to gauge their impact on housing security and socioeconomic development. Government-led initiatives, international collaborations, and community-driven projects all contribute to the array of approaches aimed at improving housing affordability and accessibility for Palestinian households. Government-led initiatives encompass a range of measures, including subsidies, grants, and low-interest loans, to facilitate housing construction and acquisition for low and middle-income families (Abureesh, 2023). These initiatives aim to reduce the financial burden on households and promote homeownership, thereby enhancing housing affordability and stability. However, challenges such as bureaucratic hurdles, limited funding, and political constraints may impede the effectiveness of these initiatives, limiting their impact on addressing the housing crisis. International collaborations play a significant role in augmenting governmental efforts to address the affordable housing challenge in Palestine. International organizations and donor agencies provide financial assistance, technical expertise, and capacity-building support to enhance housing infrastructure and expand housing opportunities for Palestinian communities (Abdelhamid, 2006). These collaborations often focus on developing affordable housing projects, improving housing standards, and promoting sustainable urban development practices. However, the sustainability and long-term impact of these initiatives may be contingent on factors such as political stability, funding availability, and community engagement.

Community-driven initiatives, spearheaded by grassroots organizations, non-governmental organizations (NGOs), and community-based associations, contribute to addressing localized housing needs and fostering community empowerment in Palestine (Khatam and Haas, 2018). These initiatives often focus on specific housing challenges within Palestinian communities, such as the construction of social housing units, rehabilitation of informal settlements, or provision of housing-related services. While these initiatives may have a tangible impact on addressing immediate housing needs, their scalability and long-term sustainability may be limited without adequate support and resources. Despite the implementation of various affordable housing strategies, significant challenges persist, hindering their effectiveness in addressing the housing crisis in Palestine. Structural barriers such as land scarcity, bureaucratic hurdles, infrastructure deficiencies, and political constraints continue to impede progress in expanding the supply of affordable housing and improving housing accessibility for Palestinian households (Sabah, 2024b). Moreover, socio-economic disparities, income inequality, and poverty exacerbate housing insecurity, necessitating comprehensive approaches that address the root causes of housing vulnerability.

5.6 Political and economic context

The political context in Palestine is characterized by ongoing conflict and occupation, which significantly impact housing development. The Israeli occupation imposes severe restrictions

on land use, mobility, and access to resources, posing substantial challenges to any form of development, particularly housing. The fragmentation of the West Bank into Areas A, B, and C, each with varying degrees of Palestinian Authority control and Israeli military oversight, further complicates the situation. Area C, which comprises about 60% of the West Bank and remains under full Israeli control, is critical for potential housing projects but remains largely inaccessible for Palestinian development. These territorial restrictions directly impact the availability of land for housing and increase construction costs due to the need for import permits and other bureaucratic hurdles imposed by the occupation authorities. The difficulty in obtaining building permits from Israeli authorities means that many Palestinians are forced to build without permits, risking demolition.

Economic constraints also play a critical role in exacerbating the housing crisis in Palestine. The Palestinian economy is heavily dependent on international aid, which is often subject to fluctuations and political conditions. High unemployment rates, particularly among the youth, reduce the ability of families to afford housing. The lack of sovereignty over natural resources, such as water and land, and the limited ability to attract private investment due to the unstable political environment further hinder the development of affordable housing projects. The economic isolation imposed by the occupation, along with restrictions on movement and trade, severely limits economic opportunities and growth (UN-Habitat, 2015).

5.7 Local and international efforts

Despite these daunting challenges, various local and international efforts aim to address housing needs in Palestine. The United Nations Relief and Works Agency for Palestine Refugees in the Near East (UNRWA) has been a key player in providing housing for Palestinian refugees since 1949. UNRWA's housing programs focus on constructing and maintaining refugee camps and shelters, as well as providing assistance for home repairs and improvements. However, the agency's funding is often unstable, dependent on voluntary contributions from donor countries, which can fluctuate significantly based on global political dynamics. Local NGOs and the Palestinian Authority are also actively involved in housing initiatives. These efforts often focus on small-scale projects aimed at improving living conditions and providing affordable housing solutions. Community-driven initiatives, supported by international donors, play a crucial role in these efforts. One notable example is the Affordable Housing Program (AHP) initiated by the Palestinian Authority. This program aims to provide affordable housing for low- and middle-income families through public-private partnerships. The program leverages international funding and technical assistance to implement housing projects in various regions, prioritizing areas with the greatest need (Natsheh and Khalil, 2018). Another significant effort is the work of the Palestinian Housing Council (PHC), which provides technical and financial support for housing projects. The PHC focuses on promoting affordable and sustainable housing solutions, particularly for low-income families. This organization collaborates with various stakeholders, including local municipalities, international NGOs, and private sector entities, to address the housing deficit. International organizations such as UN-Habitat also play a critical role. UN-Habitat provides funding, technical assistance, and policy advice to support housing development. Their efforts are often coordinated with local authorities and NGOs to maximize impact (UN-Habitat, 2015). The other case of International aid is the initiative of Hammad City in Gaza Strip, stands as a testament to the ongoing efforts to address the affordable housing crisis in Palestine. In response to the acute housing shortage and the growing demand for affordable housing options, various initiatives have been undertaken to enhance housing accessibility and affordability for residents of Hammad City. One notable initiative is the construction of subsidized housing units aimed at providing affordable housing options for low and middle-income families in Hammad City. These subsidized units are developed through collaborative efforts between governmental authorities, international organizations, and local stakeholders, with a focus on meeting the housing needs of vulnerable communities. In addition to subsidized housing units, microfinance schemes and housing assistance programs have been implemented to facilitate homeownership and improve housing affordability for residents of Hammad City. These initiatives provide financial support, technical assistance, and capacity-building opportunities to enable households to access housing finance and embark on housing construction or renovation projects (Sabah, 2023).

The study conducted in Jenin demonstrated the nature of housing affordability among Palestinian households, adding an empirical dimension to the broader structural and political analysis presented in this section. While earlier discussions highlighted systemic challenges such as land scarcity, rapid population growth, and Israeli restrictions on urban expansion, the findings illustrate how these macro-level barriers are experienced at the household level. Results show that 36.9% of families considered their housing unaffordable, with more than half of those facing obstacles (49.5%) citing upfront payment requirements as the main barrier, underscoring the weight of financial constraints in the Palestinian housing market. The reliance of 26.8% of respondents on familyowned housing and 19.4% on the absence of better options further reflects coping strategies shaped by limited supply and planning restrictions. Moreover, the fact that 27.4% of households expressed intentions to move-primarily in search of better neighborhoods or lower costs-highlights significant unmet demand. Thus, the Jenin study underscores that housing affordability in Palestine cannot be understood or addressed without considering the intersection of structural-political barriers with household-level financial constraints (Sabah, 2024b).

5.8 Innovative solutions

In response to the unique challenges in Palestine, innovative solutions are emerging. Cooperative housing models and community-driven projects are gaining traction as effective approaches to affordable housing. These models emphasize local participation, resource pooling, and sustainable development practices. Cooperative housing involves the collective ownership and management of housing units by residents. This model promotes affordability by reducing the costs associated with private ownership and enabling economies of scale. Additionally, cooperative housing fosters a sense of community and mutual support among residents, contributing to social cohesion and resilience. One example of

this approach in action is the development of cooperative housing projects in the West Bank, where communities pool resources to build and manage housing collectively. These projects not only provide affordable housing but also strengthen community ties and enhance social capital.

Community-driven projects, often supported by international NGOs and donors, focus on leveraging local resources and knowledge to create sustainable housing solutions. These projects typically involve participatory planning processes, where residents are actively engaged in the design, implementation, and management of housing initiatives. This approach ensures that the solutions are tailored to the specific needs and preferences of the community, leading to greater satisfaction and sustainability. For instance, in the Dheisheh refugee camp near Bethlehem, community-driven initiatives have led to the construction of new housing units and the improvement of existing structures, significantly enhancing living conditions for residents (Natsheh and Khalil, 2018).

5.9 Challenges and considerations

While the aforementioned efforts and innovations represent important progress in advancing affordable housing in Palestine, a series of persistent challenges continue to hinder the establishment of a sustainable and inclusive housing sector. These challenges are interconnected, reflecting legal, financial, infrastructural, social, and political dimensions that collectively shape the housing landscape. Foremost among these obstacles is the complex and restrictive legal and administrative environment. Building permits are notoriously difficult to obtain, particularly in Area C of the West Bank, where Israeli authorities exercise stringent control (B'Tselem, 2019; UN-Habitat, 2015). This restrictive context often compels Palestinians to construct homes without formal approval, exposing them to the constant risk of demolition. Addressing this barrier requires streamlining permit processes and advocating for fair and accessible building regulations, which are essential to fostering a more secure and predictable housing environment.

Compounding the legal and administrative challenges is the sector's heavy reliance on international aid, which introduces financial vulnerability. Fluctuations in donor funding can disrupt ongoing projects and delay the implementation of new initiatives (World Bank, 2017; UNRWA, 2021). Consequently, diversifying funding sources and promoting local investment are critical strategies to ensure a steady and reliable flow of resources, while enhancing the efficiency of existing aid frameworks can further maximize the impact of available funding.

Equally important are the infrastructural deficiencies that characterize many Palestinian communities, particularly in Gaza and remote areas of the West Bank. Access to essential services including water, electricity, sanitation, and transportation is often limited, which undermines the overall effectiveness of housing provision (OCHA, 2020; World Bank, 2018). Therefore, investment in both physical and social infrastructure encompassing schools, healthcare facilities, and recreational spacesis fundamental to any comprehensive approach to affordable housing, as it directly contributes to residents' quality of life. Finally, the broader political context profoundly shapes housing outcomes. The ongoing Israeli-Palestinian conflict and the absence of a viable political resolution

create an environment of instability and uncertainty that hampers development efforts (United Nations, 2022; World Bank, 2019b). Achieving long-term solutions thus requires not only technical and financial interventions but also sustained advocacy for a just and lasting peace, alongside measures to enhance local governance and autonomy, which are essential for cultivating the stable conditions necessary for sustainable housing development.

6 Methodology

This study adopts a comparative analysis methodology to evaluate affordable housing policies in developed, developing countries, and Palestine, focusing on financing mechanisms, community participation, regulatory frameworks, and socio-economic contexts. The analysis draws on five comprehensive tables summarizing strategies, key components, outcomes, challenges, and innovative solutions across selected countries. Data and Indicators: Quantitative and qualitative metrics were sourced from OECD, World Bank, UN-Habitat, and PCBS/UNRWA, covering homeownership rates, housing cost burden, overcrowding, housing deprivation, community participation, and reliance on international aid. Indicators were normalized where needed to ensure cross-country comparability while accounting for local context.

6.1 Analytical approach

- Institutional and Financial Frameworks: Evaluates government programs, regulatory structures, and financing mechanisms, highlighting their influence on affordability outcomes.
- 2. Public-Private Partnerships (PPPs): Assesses resource mobilization, risk-sharing, and sustainability of housing delivery across contexts.
- 3. Community Participation: Measures local engagement through participatory planning, cooperative housing, and its effect on housing quality and social cohesion.
- Regulatory and Policy Measures: Examines zoning, tenure security, subsidies, and legal safeguards shaping housing accessibility.
- Socio-Economic and Political Contexts: Considers economic stability, unemployment, political constraints, and other structural factors affecting housing outcomes.

Integration and Interpretation: Indicators were linked directly to outcomes to identify gaps, successes, and lessons learned. Contextual differences, such as Palestine's land restrictions and donor dependence, were explicitly considered to ensure the applicability of findings and policy recommendation

The comparative table (Supplementary Table A5) synthesizes the key dimensions of affordable housing approaches across developed and developing countries, providing a structured framework for analysis. By consolidating indicators related to institutional frameworks, financing mechanisms, community participation, regulatory measures, and socio-economic contexts, the table facilitates a clear understanding of the differential conditions under which housing strategies operate.

For instance, developed countries exhibit well-established governance structures, formalized financing mechanisms, and stringent regulatory frameworks, whereas developing countries rely on emerging institutional capacity, microfinance, international aid, and participatory planning. This contrast highlights the importance of contextual adaptation when drawing lessons for Palestine, where political instability, economic constraints, and donor dependence shape the feasibility of housing interventions.

This table serves as a cross-sectional analytical tool, linking quantitative indicators (e.g., rent overburden rate, housing affordability ratio) with qualitative assessments (e.g., community engagement, regulatory effectiveness). It supports the identification of gaps, successes, and transferable strategies, ensuring that the study's comparative approach is both systematic and grounded in measurable outcomes.

7 Results, solutions and conclusion

The comparative analysis of affordable housing approaches across developed, developing countries, and Palestine reveals critical insights regarding policy effectiveness, financing mechanisms, community engagement, and regulatory measures. This integrated perspective informs actionable solutions adaptable to context-specific challenges.

7.1 Results

Developed countries employ a combination of public housing, subsidies, and private sector incentives, with measurable impacts on indicators such as homeownership rates (~65% in the U.S.), rent overburden (~33%), and housing satisfaction (82% in Japan). Strong institutional frameworks, including well-established agencies and regulatory mechanisms, support sustainable program delivery. Developing countries focus on slum upgrading, in situ development, and public-private partnerships (PPPs) to address affordability under resource constraints. Programs such as Brazil's Minha Casa Minha Vida and South Africa's BNG policy demonstrate that community participation, innovative financing (microfinance, international aid), and participatory planning can significantly reduce overcrowding (~25-28%) and housing deprivation (~20%). Palestine presents a unique context shaped by political instability, land restrictions, and donor dependence, reflected in limited access to Area C (<10%), recurring demolition orders (~1,000 annually), and donor-funded housing comprising ~30% of total projects. These conditions necessitate contextualized, adaptive strategies that integrate international support and local participation.

7.2 Solutions

Based on the comparative analysis, the following policy-relevant solutions emerge:

 Promote mixed-income developments to foster social integration and reduce segregation, as exemplified by South Africa's BNG program. 2. Leverage public-private partnerships (PPPs) to mobilize resources, share risks, and enhance technical capacity, drawing lessons from Brazil and Japan.

- Implement robust regulatory frameworks, including rent control, land tenure regularization, and zoning policies, to safeguard long-term affordability and security.
- Enhance community participation in planning and implementation to ensure housing solutions respond to local needs and cultural contexts.
- Adopt innovative financing mechanisms, such as microfinance, social impact bonds, and blended finance models, particularly in resource-constrained settings.
- Utilize international aid strategically, focusing on capacity-building alongside financial support to ensure sustainability, especially under politically sensitive conditions in Palestine.
- Reform bureaucratic systems (e.g., permit and land access processes) to reduce procedural barriers that inflate housing costs

7.3 Critical reflections

While these solutions provide a roadmap for improving housing affordability, limitations remain:

- Transferability constraints: Strategies effective in developed countries may not be directly applicable in developing contexts due to differing institutional capacities and socio-political environments.
- Resource dependency: Heavy reliance on donor funding may limit long-term sustainability in Palestine and other resourceconstrained contexts.
- Regulatory challenges: Weak enforcement of tenure rights and zoning laws can undermine policy effectiveness.
- Socio-political volatility: Political instability and restricted land access in Palestine can hinder program implementation despite well-designed policies.

Addressing these limitations requires adaptive, contextsensitive policies, integrating quantitative indicators (e.g., rent-toincome ratio, housing affordability ratio, overcrowding rates) with qualitative assessments of governance, financing, and community participation.

7.4 Conclusion

Affordable housing remains a multifaceted challenge that demands context-specific solutions. Comparative insights show that:

- Developed countries provide lessons on financial mechanisms, PPPs, and regulatory safeguards.
- Developing countries emphasize community engagement, innovation, and flexibility.
- Palestine's situation highlights the importance of tailored strategies accounting for political, economic, and social constraints.

Actionable recommendations for Palestine include leveraging diaspora investment, reforming permit systems, implementing scalable cooperative housing models, and strengthening partnerships with NGOs and international donors.

Globally, the experiences of different countries underline the importance of resilience, sustainability, and inclusivity in housing policy. Linking strategies to SDG 11 (Sustainable Cities and Communities) emphasizes housing as a cornerstone of urban resilience, social equity, and sustainable development. Ultimately, while policies can mitigate affordability challenges, structural and political constraints in regions like the West Bank and Gaza necessitate concerted international efforts to ensure access to safe, affordable, and secure housing for all.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

FS: Writing - original draft.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2025.1653057/full#supplementary-material

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