Discover Cities

Research

Enhancing Urban Climate Resistance Through the Application of Selected Strategies and Technologies

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Abstract

Adapting cities for climate resilience is crucial as climate change increases the frequency and severity of extreme weather events. This study outlines a comprehensive set of resilience strategies aimed at enhancing urban resilience across four key domains: water, food, shelter, and energy. These strategies, applicable to both new and existing neighborhoods, range from simple, short-term measures to complex, long-term initiatives. A three-pronged evaluation framework, consisting of three platforms, is introduced to assess these strategies where criteria are initially selected based on their impact on strategy adoption and implementation. This framework employs hypothetical scores and weights that can be adjusted for specific urban contexts through detailed studies. Key outcomes of the evaluation conducted in the first platform include a systematic method to rank strategies based on six criteria: cost, infrastructure impact, scalability, regulatory and zoning challenges, community acceptance, and maintenance needs. For example, community gardens and rainwater harvesting systems are highly scalable and accepted, whereas green roofs require more investment and maintenance. The second and third platform of the framework facilitate the identification of strategies that enhance resilience across each of the resilience domains, as well as across several domains. The results highlight the top-performing strategies under different weighted scenarios. Strategies like green roofs strategy scores high in domains like water management, due to its capacity to absorb and manage stormwater, and energy, by providing natural insulation that reduces heating and cooling demands. Additionally, green roofs contribute to food production when utilized for urban agriculture and enhance shelter by improving building durability and increasing biodiversity This data-driven framework supports the strategic prioritization of resilience strategies, enhancing urban planning and investment decisions globally. Its modularity ensures adaptability to diverse urban settings and climatic issues.

Abbreviations

AI:	Artificial Intelligence
BIPV:	Building integrated photovoltaics
CSA:	Community-supported agriculture
GHG:	Greenhouse gas (emissions)
PV:	Photovoltaic
RD:	Resilience domain
RS:	Resilience strategy
WSUD:	Water sensitive Urban design
WEF:	Water-energy-food

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1 Introduction

Enhancing the resilience of cities and, more broadly, of societies, to cope with the consequences of climate change and emergencies has become increasingly critical. Climate change is already affecting many parts of the world, with its impacts ranging from frequent and severe extreme weather events to extreme temperatures and prolonged droughts. Improving resilience requires concerted action at different levels, ranging from individual, to community, to national and global, and across different public and private domains. The proposed methodologies can be tools in assisting in this rigorous effort, to formulate resilience-oriented regulations.

Several definitions of resilience exist. In this work, resilience is defined as the capability to deal with shocks and stresses while continuing to meet the essential needs of the community (e.g. [1]). Conceptual studies recognize that various plans and strategies need to be developed to increase the aptitude of communities to manage risks and adapt to changes [2]. A climate-resilient society would be low-carbon, prepared to deal with the realities of a changing climate. This requires both mitigation (reducing greenhouse gas GHG) emissions and adaptation to existing and imminent climate threats. These strategies are complementary, not exclusive, and function together to enhance the capacity of urban systems to respond to and recover from adverse conditions. Spatial design strategies in communities and neighborhoods play a critical role in adapting to climate change. Such domains as water management, food availability, shelter, and energy can benefit from enhanced design strategies to ensure urban sustainability and protection of fundamental human rights [3, 4]. Ultimately, sustainability acts as the guiding principle, ensuring that efforts to build resilience contribute to the long-term environmental, social, and economic health.

Resilience of selected urban systems to climate and natural disasters was studied in diverse literature. For instance, Salimi, & Al-Ghamdi [5] present a review of key impacts of climate change in urban areas of the Middle East, and of climate change adaptation strategies to enhance the resilience to climate change-driven events. The relationship between buildings, water, energy and food is evident; resilience of one system relates to that of the others. Daher et al. [6], developed a common framework that combines water-energy-food (WEF) nexus literature with different types of shocks.

Responsible planning of new urban form, or restoration of existing areas, can reduce significantly the impacts of different shocks and disturbances. Strategic infrastructure programmes relating to water, energy, shelter and food supply can be designed and built to adapt to disasters. Water management facilitates the mitigation of shocks and disturbances ranging from drought to flooding. Food production can be enhanced by urban agriculture and sustainable farming, securing food supply. Resilient shelter design mitigates against shocks such as extreme weather and ensures the habitability of structures. Reliable power supply is ensured by strategic infrastructure design and the use of renewable energy technologies and smart grids reducing the frequency and impact of shocks like blackouts.

Research in urban planning underscore a multidimensional approach to enhancing urban resilience through technological innovation, ecological balance, and cultural wisdom. For instance, Bueno et al. [7] demonstrate the critical role of resistance–capacitance (RC) network models in predicting and enhancing the energy performance of buildings within varied urban climates. Chondrogianni and Stephanedes [8] assess urban planning methods through the lens of bioclimatic design, emphasizing the need for urban spaces that not only achieve ecological balance but also remain resilient against climatic changes. Their evaluation sheds light on planning strategies that effectively integrate environmental considerations to improve urban resilience. Marshall and Twill [9] delve into the potential of Indigenous knowledge to inform climate resistance strategies, advocating for a regenerative approach to urban planning. Their research highlights methods of blending traditional ecological insights with contemporary planning practices to create sustainable urban landscapes that are well-adapted to future environmental challenges.

A myriad of tools had been developed to assess urban resilience. For instance, Tyler and Moench [10] reviewed diverse concepts and theories to illustrate methods of developing operational frameworks for practitioners. This framework summarizes theoretical and empirical knowledge of resilience factors, and proposes methods to translate those concepts into practice. Mehryar, Sasson, and Surminski [11] analyzed 27 tools for measuring urban climate resilience and conducted semi-structured interviews with experts from over 100 cities. This study highlights that about one-third of the analyzed tools support the implementation of resilience actions, while the rest focus on knowledge sharing and raising awareness. They identified that some tools are more effective in influencing transformational decision-making by providing proactive strategies, long-term climate information, and participatory planning, focusing on smart architecture, risk reduction integration in urban policies, incentives for risk reduction, and enforcement mechanisms.

This document focuses on taking proactive measures to enhance the resilience of urban areas and communities. It explores various design strategies and technologies to enhance the overall resilience of existing and new communities, based on current and avant-garde solutions, and compiles them in a comprehensive database. The study introduces a novel framework designed to enhance urban resilience by systematically evaluating and prioritizing the identified strategies across key urban domains. A flexible scoring system adaptable to local contexts is utilized to assess these strategies, based on six resilience criteria including cost, maintenance, and scalability. The novelty of the framework consists of enabling the integration of strategies across multiple domains, allowing to assign priorities based on specific objectives and to identify optimal combinations of strategies that address multiple resilience goals simultaneously. This data-driven approach provides a strategic, adaptable toolkit supporting informed decision-making in urban resilience planning, tailored to the unique challenges and resources of diverse urban settings.

This approach addresses a clear research gap by offering a quantifiable and strategic tool to assess and implement resilience strategies that align with the needs and resources of urban environments. The framework's versatility allows for both specific and broad applications, aiming to achieve comprehensive resilience goals effectively.

2 Approach

The main objective of this study is to enhance urban resilience by developing and implementing a comprehensive evaluation framework that systematically assesses and prioritizes a wide array of resilience strategies across key urban domains. The approach followed in this work consists of four stages. The first stage is an overview of various initiatives applied around the world to enhance the resilience of urban areas in specific domains, termed resilience domains (RD). These domains are water management, food supplement, shelter and energy. The four RDs are selected based on their fundamental role in urban resilience since each of them represents a critical aspect of urban functionality and sustainability, essential for maintaining the quality of life and safety under the pressures of climate change. In Stage 2, potential resilience strategies (RS) are extracted for each of these domains and are briefly discussed. These strategies integrate sustainable design principles and advanced technological components, ensuring that the solutions are both long-term and seamlessly incorporated into urban settings. The third stage (Sect. 4) proposes a framework for analysing strategies, employing a three-pronged approach, consisting of the following platforms: A) Analysis of RS in each resilience domain (RD) according to six main criteria: Cost, infrastructure impact, scalability, regulatory and zoning challenges, community acceptance and maintenance needs; B) Conducting an analysis across all listed strategies and resilience domains, to highlight strategies that can enhance simultaneously many RDs; and C) proposing a method to rank the best resilience strategies found in B, against criteria proposed in A. The six criteria are selected due to their significant influence on the adoption and effectiveness of resilience strategies. This selection was informed by methodologies from similar studies, such as the international Energy Agency (IEA) Task 63 [12], where criteria were derived through detailed questionnaires that gathered insights from a spectrum of experts. Further, a comprehensive review of literature across various disciplines validated the importance of some of these criteria, noting their critical roles in the successful implementation of sustainable and resilience practices even though they may not always be combined in previous studies.

Stage 4 presents a discussion of the results, and recommendations to enhance the resilience of urban developments. The main stages of the work are illustrated in Fig. 1.

3 Urban design strategies

This section presents an overview of various urban design strategies implemented in each of the resilience domain mentioned above, to enhance the resilience of various cities around the world. Based on these specific cases, an inventory of generalized strategies is developed for each of the resilience domains and presented in Sect. 3.2.

3.1 Review of resilience initiatives

3.1.1 Water

Worldwide examples of water management range from renewal projects to city-wide efforts led by residents. These examples highlight the potential of infusing water management with urban design to promote liveable, sustainable, and resilient cities. Integrating water features into the design of urban environments provides benefits that were confirmed in many cities, boosting sustainability, biodiversity, and livability.

New York City's High Line, converted from an elevated railway, embodies various sustainable landscaping and water management features, including permeable pathways, along with terraced and flooded beds that slow and drain storm

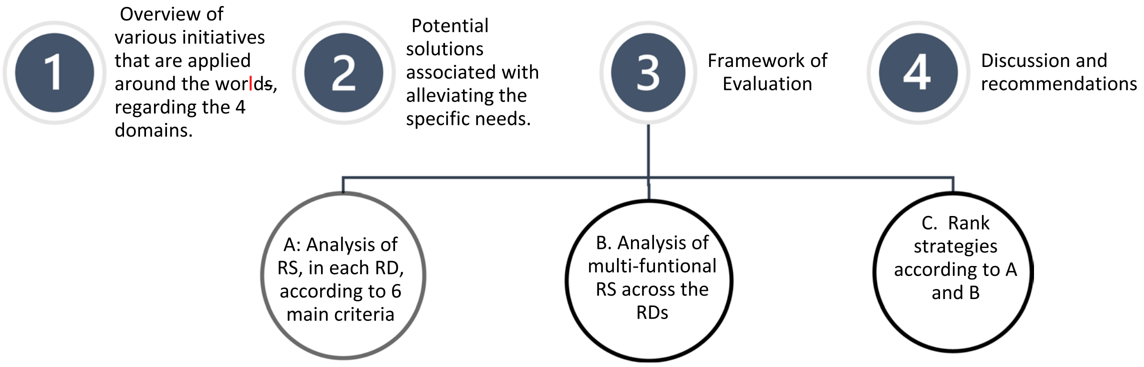


Fig. 1 Diverse stages of the methodology

water to minimise its impact on the heavily paved city, providing a cooling green space [13]. Singapore's Bishan-Ang Mo Kio Park transformed a concrete canal into a naturalized river, increasing flood resilience, promoting biodiversity, and creating new recreational space [14]. Lübeck in Germany has blended historic and modern features, planted green roofs and laying permeable pavements and sophisticated drainage systems to mitigate the impact of rain and floods [15].

Programs such as Melbourne's Living Rivers in Australia retrofit urban landscapes with rain gardens, wetlands, and other water-sensitive urban design features to control stormwater sustainably [16]. The Netherlands' Room for the River program diminishes flood risk through the restoration of natural flood plain, dike relocation, new side channels, among other techniques.

Portland, Oregon's Green Streets program incorporates green infrastructure, such as curb extensions, raingardens, and tree planting, to manage stormwater flows, mitigating flooding and lowering city temperatures [17, 18]. China is redesigning its urban areas under the Sponge City Initiative, which incorporates green roofs, wetlands and permeable pavements to absorb and reuse rainfall, significantly reducing flooding [19].

3.1.2 Food

Food production in urban areas should be a fundamental part of any agenda to tackle food deserts, improve food security and urban resilience. Producing food closer to urban consumers reduces the impact of supply chain failures, cuts transportation emissions from traditional agriculture, and can supply cities with fresh and nutritious food. Examples of successful integration of urban food production in cities around the world are presented below.

One of the global systems undertaking an effort to make urban food security is the Milan Urban Food international pact, where 159 cities worldwide are committed to develop sustainable and resilient food systems [20]. This pact aims at improving access to safe and nutritious food for all city dwellers, especially vulnerable populations, within a human rights-based framework [21]. The global movement will focus on reducing food loss and waste, protecting biodiversity and adapting to and mitigating climate change.

In some cities in the United States community gardens are a popular form of urban agriculture. Not only do they provide fresh produce but also educational value and open spaces in the city where communities can come together [22, 23]. In Tucson, Arizona researchers have developed models of hypothetical farms that could be placed on brownfield sites and publicly owned vacant land to address food deserts [24]. This approach includes rainwater harvesting and the use of reclaimed water for irrigation, demonstrating a sustainable and resource-efficient method of urban farming. In Detroit, a city that has struggled with food deserts, urban farmers are using aquaponics—a system that combines fish farming with hydroponics (growing plants in water, rather than soil) [25]. Fish waste provides organic food for the plants, and the plants naturally filter the water for the fish. This closed-loop system is efficient and suitable to be located indoors or set up in underutilized urban spaces. In Brooklyn, rooftop hydroponic farms are designed to produce leafy greens year-round [26]. These farms use hydroponic technology, where water is enriched with nutrient components in its tank of roots, to grow leafy greens year-round. They use less water and no pesticides, as compared with agricultural watering.

Innovative strategies for growing food in urban neighborhoods, particularly integrating agriculture into buildings, are gaining interest. One such concept is the Vertically Integrated Greenhouse, which hydroponically grows plants in small pockets on a vertical frame, housed within a building's double-skin façade [27]. Singapore, a city-state with sparce agricultural land, is widely implementing vertical farming to enhance its food security [28]. Sky Greens is one example, that grows leafy vegetables in tall A-frame towers where crops rotate on hydraulic systems, ensuring even exposure to sunlight [29]. Not only does this method use less water and energy than traditional cultivation practices, but it also allows for enhanced utilisation of space.

Paris has veered in recent years towards rooftop gardening with initiatives like "Parisculteurs". Dozens of initiatives have been created including rooftop gardens, community-supported agriculture (CSA), and hydroponic farms in urban settings [30]. The small town of Todmorden in UK has initiated the "Incredible Edible" project, in which unused public areas are turned into edible landscapes [31]. Fruit trees, vegetable patches, and herb gardens are planted in spaces like parks, hospital grounds, and even along railway tracks, making fresh food freely available to everyone. Tokyo, with its restricted land space, has seen the emergence of mobile urban farms [32]. Old shipping containers are employed to create portable farms that can be moved to different locations. LED light systems and hydroponic pipes are fitted inside the containers to cultivate vegetables including lettuce, herbs and other leafy vegetables.

Urban farming isn’t limited to plants. There’s a rising trend in cities like New York City and Portland, Oregon, for raising chickens, primarily for egg production [33, 34]. This practice complements community gardening due to the fertilizer produced by chickens. However, regulations on keeping chickens vary significantly between cities. In addition, urban beekeeping is attracting interest globally, in major cities [35]. One function of this form of farming is to help with pollination.

As this experimentation within cities adds to the agricultural-ness of urban life, local food production might increase and become more sustainable.

3.1.3 Shelter

Designing urban shelters for the enhancement of disaster resilience can lead to the development of spaces that enable residents to withstand emergencies, including both natural and man-made disasters, as well as reinforce the resilience of urban areas and facilitate community recovery and sustainability [36, 37].

In different parts of the US, research on temporary shelters is developed for fast erection in response to hurricanes and tornadoes [38–40]. These structures, which are modular and portable, can offer a highly mobile rapid-response shelter that can be deployed quickly for individuals and families displaced by disasters. These designs may include features such as solar power for on-site energy independence, integrated water collection systems, and durable materials that can withstand high winds and debris impacts.

Shelter construction systems should be innovative, rapidly deployable and designed to address the specific needs of disaster-stricken populations. They should lay the groundwork for more permanent solutions. Developed in association with the UN Refugee Agency (UNHCR), IKEA’s Better Shelter is a flat-pack housing unit designed for portability and ease of assembly without additional tools [41, 42]. These shelters are fitted with solar panels, and generate electricity on site, leading to better living conditions. Better Shelters have been erected in places such as Africa and the Middle East in the wake of conflicts and floods.

Another example is the utilization of shipping containers [43]. For example, after the Christchurch New Zealand earthquake in 2011, shipping containers were swiftly converted into temporary houses [44]. These structures were kitted out with insulation, windows, and doors, providing quick, safe and inexpensive shelter. Many solutions for shipping container modifications have been made with timber, glass and plastic fittings. The flexibility of container housing allows for various configurations, providing an adaptable habitat for a family according to their needs [45, 46]. This approach demonstrates a novel use of existing resources in disaster response, highlighting the potential for adaptive reuse in emergency housing.

3.1.4 Energy

The design of urban energy systems can ensure secure and reliable energy supply during and after natural disasters or catastrophic events, thus preserving basic services and facilitating recovery efforts, minimising the impact on citizens [47]. Below are worldwide examples highlighting innovative urban energy system designs and measures taken to reinforce disaster resilience.

Microgrid design and implementation are explored in varied capacity in different cities. Several cities in the US are exploring the development of community microgrids to operate independently of the larger utility grid [48]. These microgrids are aimed at providing power to a specific area even when the main grid is down. Microgrids are increasingly tying into renewable energy sources such as rooftop solar panels and wind turbines and are combined with energy storage systems to generate a clean, decentralised, resilient energy source [49].

In Japan, following the 2011 earthquake and tsunami, Tokyo Electric Power Company (TEPCO) is implementing a smart energy network, employing technologies such as advanced metering infrastructure, providing real-time monitoring and control of the energy network [50]. This capability enables faster response to outages and better management of energy supply during emergencies. it enhances the ability to integrate renewable energy sources, reducing overall reliance on centralised facilities that could become vulnerable in disasters.

Other examples, such as Copenhagen district heating, employ centralised systems to promote disaster resilience, providing significant energy for the city [51]. Not only do systems like these use waste heat from electricity generation or renewable energy sources to improve energy efficiency, but they may also distribute it through insulated pipes across the city, making the heating more resilient to energy supply disruptions. As the system becomes more redundant by multiple energy sources, it becomes increasingly resilient to extreme weather events.

Utilities in various cities around the world are installing advanced grid automation and artificial intelligence (AI) technologies to provide greater resilience for its national energy infrastructure [52]. Real-time monitoring and automated contingency support are possible, enabling real-time fault response and disaster mitigation. AI algorithms can forecast maintenance needs and identify weak points in the grid before they can lead to failures. This enhanced resilience can provide greater security of supply at critical moments.

3.2 Design strategies

This section is a generalisation of the specific implementations detailed in Sect. 3.1 into general guidelines for design approach. It presents various resilience strategies associated with the considered resilience domains.

3.2.1 Water

Design strategies for incorporating water elements in neighborhoods to mitigate flooding and reduce heat involves a multifaceted approach. Design strategies for water management in neighborhoods are crucial for both reducing flood risks and mitigating urban heat. These strategies often involve a combination of natural and engineered solutions, integrating water management with urban planning and landscape design. The combination of green infrastructure and next-generation water management is a key part of building ecologically sustainable cities able to withstand the impacts of hydrological extremes. Main strategies of water management are described in Fig. 2a and b. They are divided into 3 main categories: green infrastructure, urban water bodies and engineered solutions, as described below.

Green Infrastructure These include: rain gardens and bioswales which use vegetation and mulch to absorb and filter stormwater runoff from impervious surfaces, leading to the reduction of the load on the stormwater infrastructure and promoting urban cooling through evapotranspiration; permeable pavements that allow water infiltration and mitigate surface runoff and promote groundwater recharge; green roofs and living walls with vegetation layers that capture rainwater and provide thermal insulation and mitigate runoff and urban heat island effects, while improving building energy efficiency; targeted expansion of urban forestry that contributes to the absorption of stormwater, provides shade, reduces urban temperatures and increases air quality.

Urban Water Bodies Stored in constructed wetlands and retention ponds, such water is released slowly to reduce flood risk, provide ecosystem services and urban recreational amenities. Restored river stream and floodplain systems can reduce flood risks and restore aquatic ecosystems.

Engineered Solutions These structures and walkways are built at higher levels than known flood levels, so they continue to function when flood waters rise. Water sensitive urban design (WSUD) integrates the full urban water cycle into city planning. It includes water treatment measures that use natural systems or combine them with technological systems. It also builds flood resilience by ensuring that urban water can be absorbed and processed by natural systems and the water table. Rainwater harvesting involves capturing and storing rainwater for non-potable uses to reduce the burden on potable water supply and municipal infrastructure. It also reduces flood risks. Climate-responsive design involves responding to the local climatic conditions of a city to improve the urban microclimate and its comfort using such features as shaded walkways and evaporative water features, such as reflecting pools and splash pads. Integrated Flood Management refers to practices that combine engineered and nature-based solutions, to flood defence with integrated land and water management to build the resilience of cities and their inhabitants to climate change, taking into consideration the complex and dynamic nature of the urban water cycle. Such strategies and practices are what facilitate urban adaptations that are not only resilient to climatic variability but also critical to urban sustainability and innovative

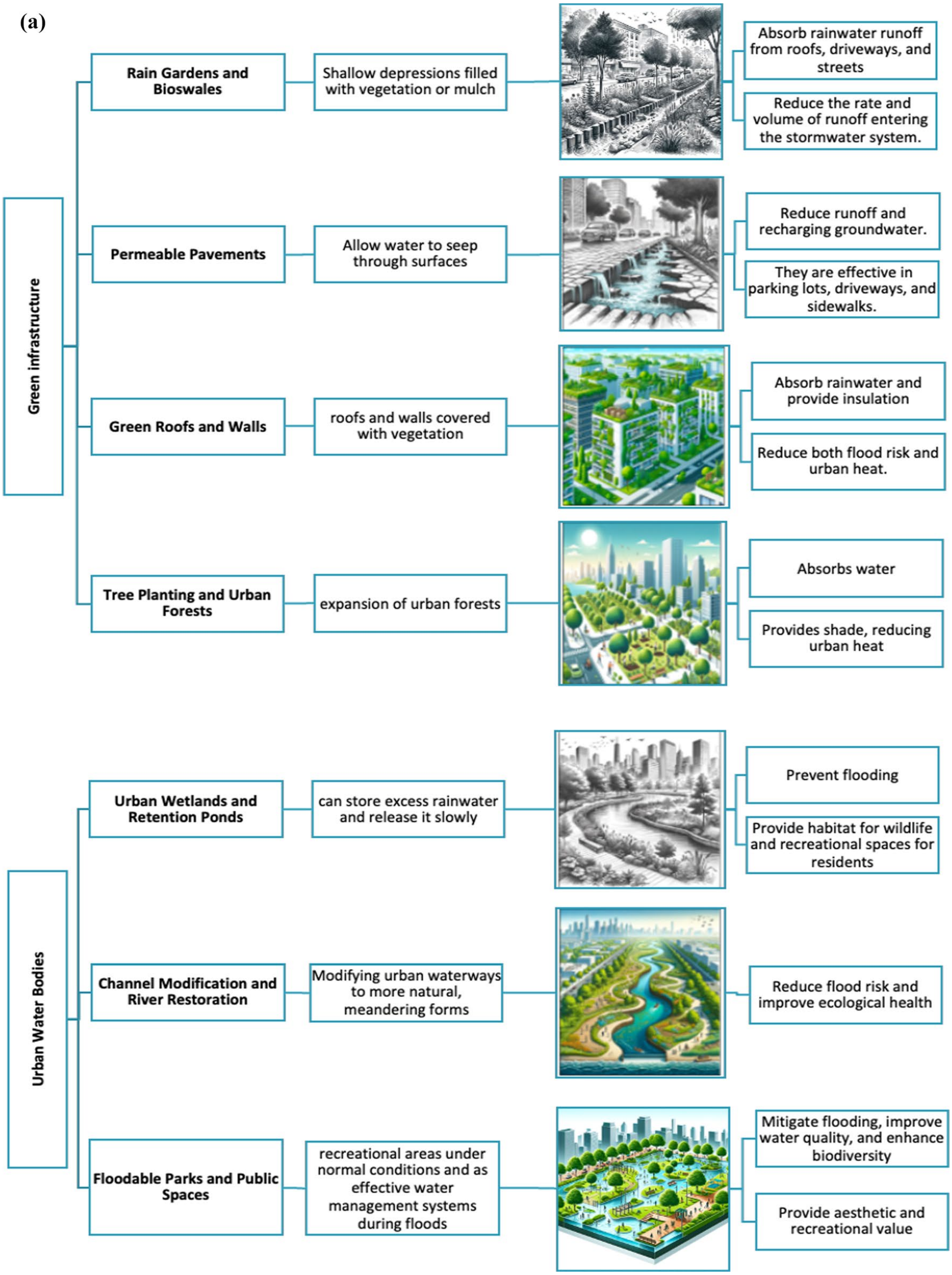


Fig. 2 **a** Water strategies, illustrations produced using AI tools. **b**, Water strategies (ctd.)

environmental stewardship. They are at play in Portland, Berlin, Fukuoka and Rotterdam, among other cities, and are integral to the development of livable and resilient metropolises.

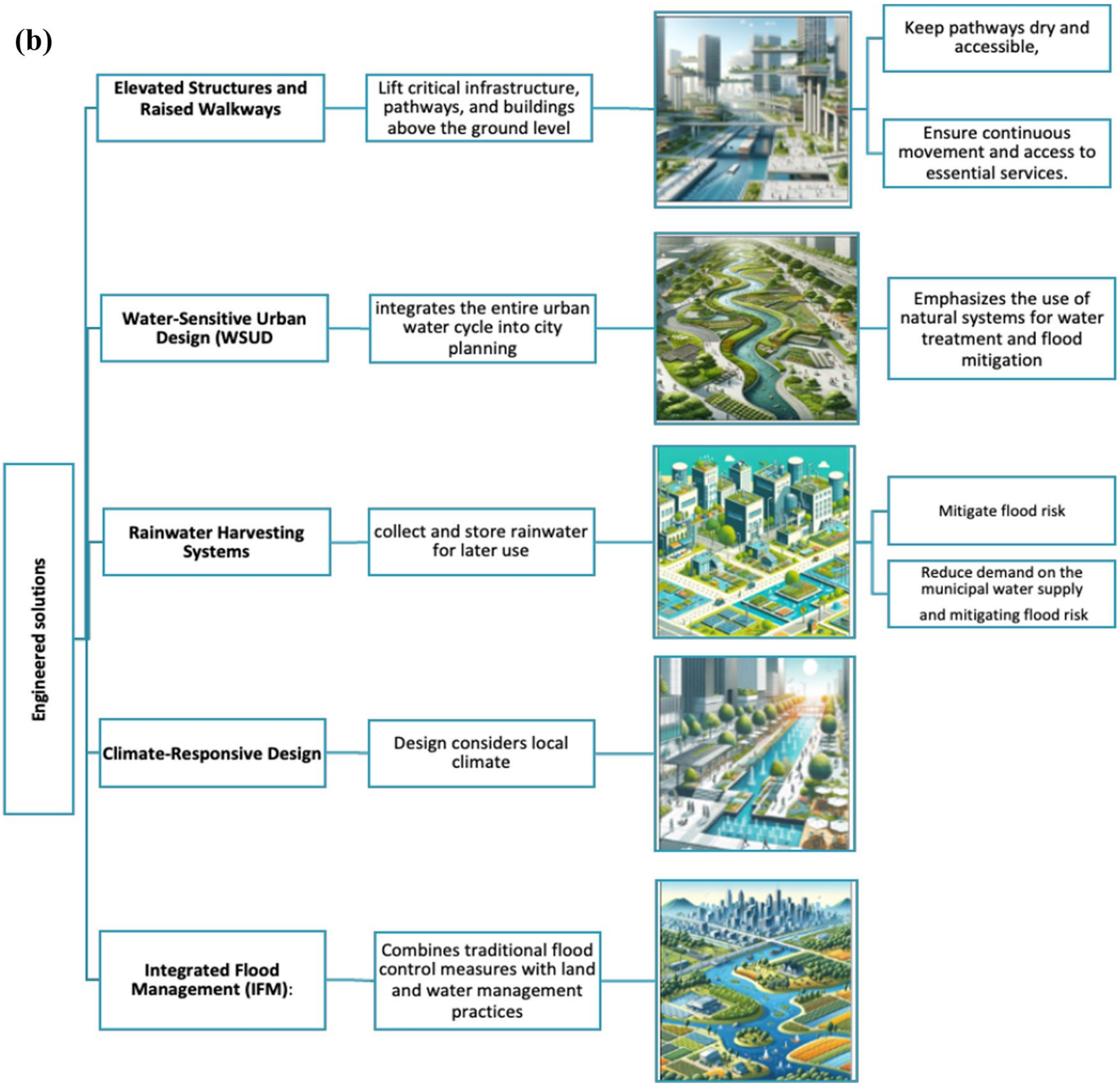


Fig. 2 (continued)

3.2.2 Food strategies

Urban agriculture integrates sustainable food production strategies into city fabric. It plays a key role in reducing food deserts and enhancing local food security. This approach can transform underutilised urban space to create productive community gardens and farms.

Various urban structures can be employed for Agricultural practices. For instance, rooftops and vertical surfaces, can be exploited to create gardens and build greenhouses, enhancing the energy efficiency of the building, and alleviate the urban heat island effect, as well as food deserts.

Innovative technologies and soil-less methods can be implemented in cultivation techniques like vertical farming and hydroponics. Such techniques optimize resource use and minimize ecological impacts.

Other potential strategies include transforming public spaces such as parks and riverbanks into edible landscapes that increase urban biodiversity and provide accessible fresh produce. Complementing agricultural strategies with urban livestock raising and mobile agriculture, can introduce biodiversity and adaptability. This incorporates small-scale livestock operations such as beekeeping and transportable cultivation units that conform to urban spatial constraints.

Furthermore, locally oriented food distribution systems, such as farmers' markets and food hubs, provide a direct connection between producers and consumers. They reinforce local economies while reducing distribution-related transportation emissions and ensuring the seasonal availability of locally grown produce. Locally produced food reduces reliance on long supply chains, enhances food security, and supports sustainable urban ecosystems.

Some strategies that can be implemented to enhance food resilience are summarized in Fig. 3a and b. They are classified under 4 main categories: Urban agriculture models, urban livestock, dynamic and flexible agriculture, and local food distribution systems.

3.2.3 Shelters

Urban shelter designs for disaster resilience combine urban planning, building design and technology, and community engagement. This approach should focus on many factors such as integrating hazard-sensitive zoning of land use and risk profiles, integrated green plots, and zones to absorb natural disasters, and dual-purpose or transformative community centres that can be used for regular and emergency purposes.

Shelter design can incorporate modular construction that can be quickly deployed, sustainable materials that minimise environmental impact, and resilient infrastructure that allows critical services to remain functional throughout a disaster. Community strategies should enhance preparedness through education and participatory design to ensure that shelters meet local needs.

Smart city technologies for improved disaster response, include mobile structures for rapid shelter in the aftermath of a disaster; and adaptive reuse of buildings combining multi-use facilities. A summary of various strategies to enhance sheltering potential is presented in Fig. 4a and b.

3.2.4 Energy

Resilient urban energy design aims to minimise the dependence on conventional power grids by using a wide range of renewable and energy-efficient production and management strategies. These strategies include the utilization of renewable energy sources such as decentralized photovoltaic systems on roofs and facades of buildings, small-scale wind turbines that can be incorporated in various urban settings, and mini-hydro systems using local water bodies. Building-integrated photovoltaics (BIPV) incorporates photovoltaic material into structural elements such as windows and facades and can improve energy generation while also reducing the need for traditional building materials. Other renewable energy systems include geothermal systems to exploit ground temperature, and community biogas facilities to convert organic waste to energy.

Efficiency and storage play a key role in enhancing energy resilience of communities. Passive solar design, advanced insulation, and energy-efficient appliances, along with smart grid technologies, improve the efficiency of electricity distribution and grid reliability. Furthermore, energy storage systems store electricity from peak renewable energy periods to reduce grid fluctuations or outages.

Incorporating green infrastructure in urban planning, such as green roofs and spaces, can improve air quality and help to reduce the urban heat island effect. They can also be designed to integrate various renewable energy technologies (e.g. PV systems, solar thermal collectors, etc.).

Community microgrids which are independent of centralised power networks, can combine a diversity of renewable energy sources. Such localised energy systems can isolate individual buildings and neighbourhoods from the grid, and thus improve resilience in the event of power outages.

These approaches collectively improve energy efficiency, resilience and environmental sustainability, decreasing both the carbon footprints and ecological footprints of urban communities. A summary of various energy strategies is presented in Fig. 5a, b.

4 Framework of evaluation

This section presents a 3-pronged approach to evaluate the various resilience design strategies, discussed above. The approach is composed of 3 platforms (see Sect. 2). The criteria selected in platform 1, are determined based on their potential impact on the adoption and implementation of these strategies. The scores and weights are hypothetical, based on rational assumptions, but primarily aimed at illustrating the proposed methodology. These scores can be modified according to specific applications, employing methodical studies to obtain reliable information that allows a robust ranking of various resilience strategies.

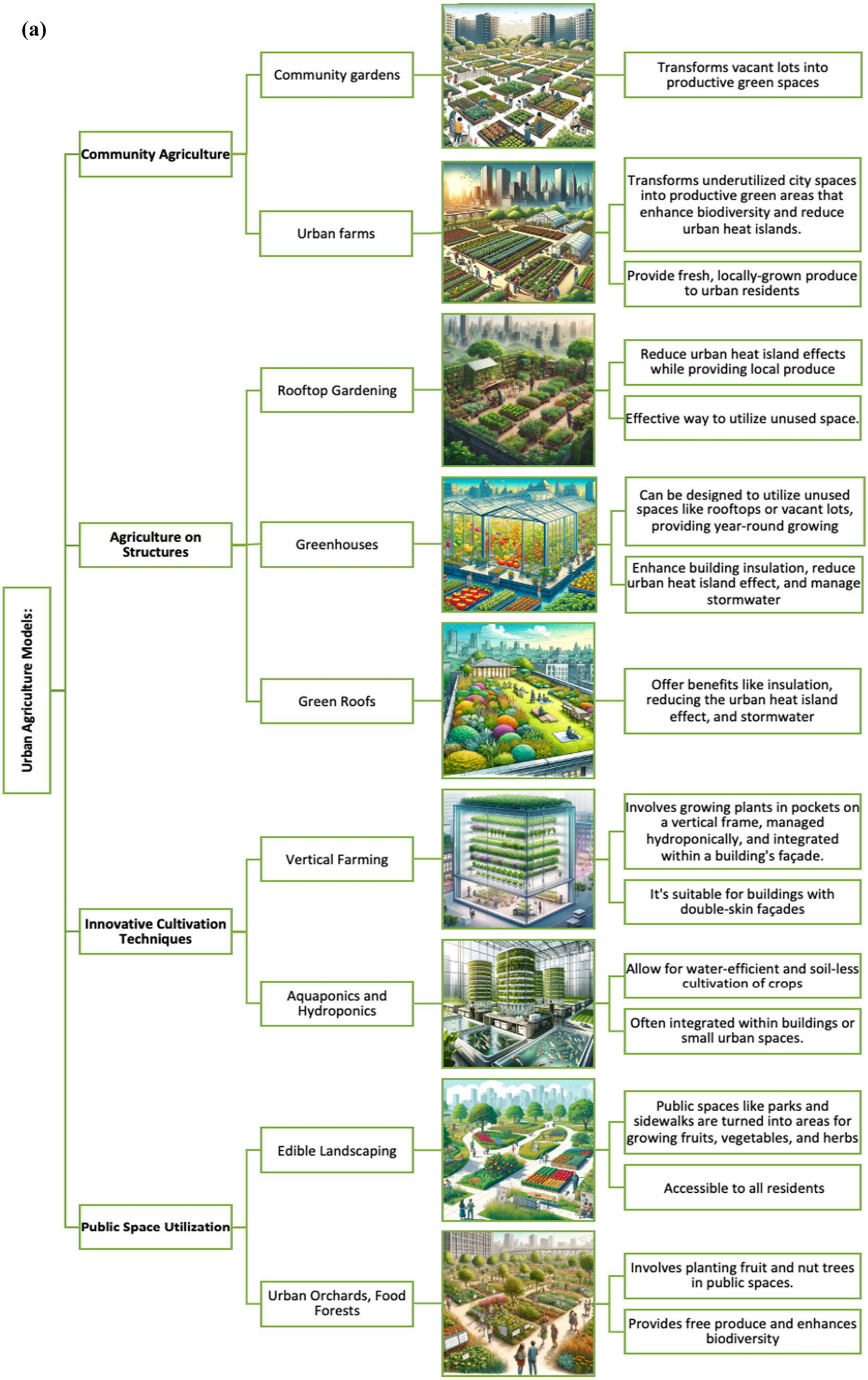


Fig. 3 **a** Food strategies; Illustrations produced using AI tools. **b**, Food strategies (ctd.)

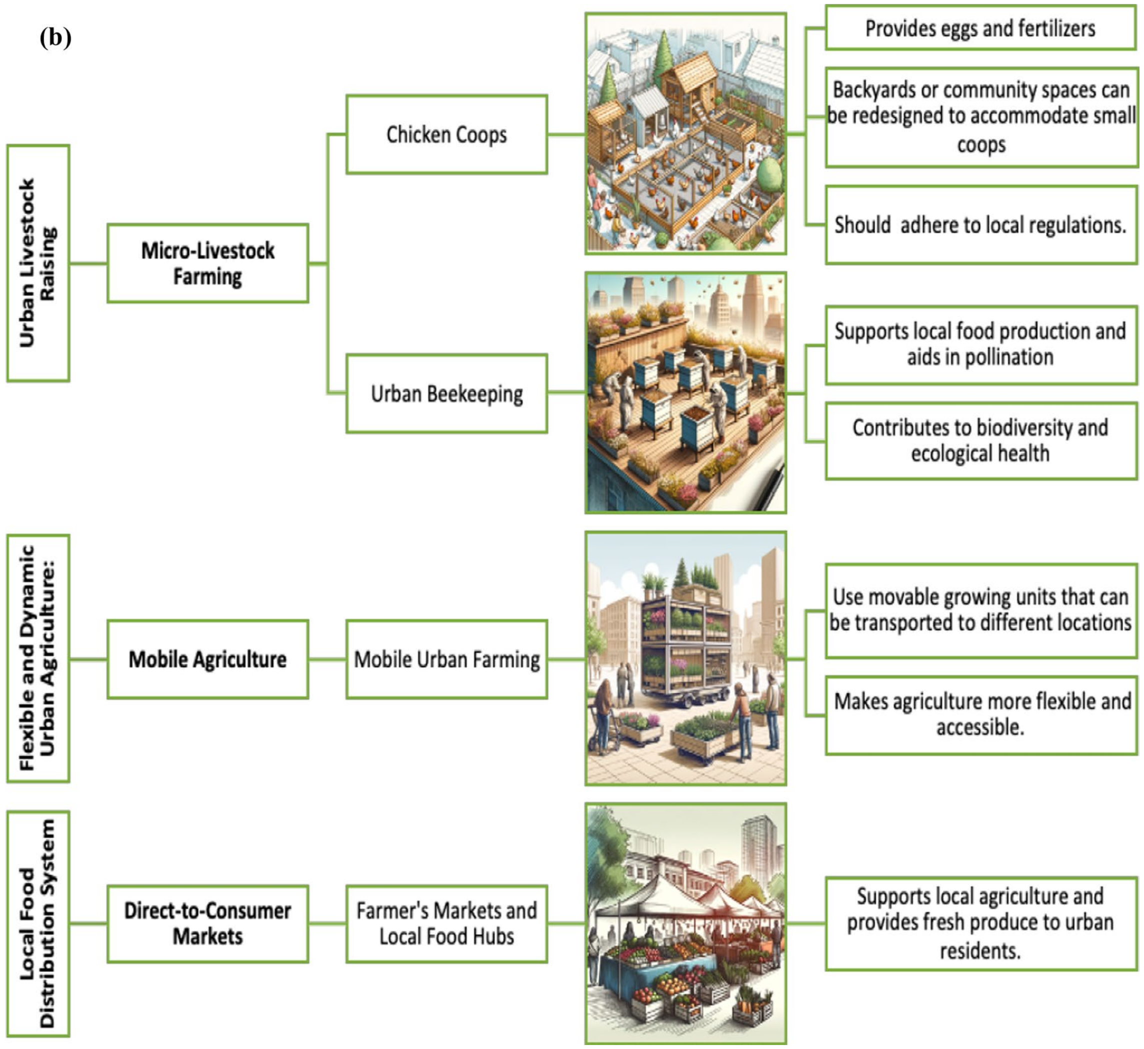


Fig. 3 (continued)

4.1 Ranking strategies

This section presents a method to evaluate the proposed RS based on specific criteria. This method aims to provide a tool for comparing various available strategies for a specific RD, and to rank those that are most favorable.

4.1.1 Criteria for Ranking

Six resilience criteria (RC) are employed to evaluate various aspects that can play a key role in the adoption and implementation of these strategies. These criteria are summarized in Table 1 below.

The ranking of each of the resilience strategies (RS) across the six resilience domains (RD) are presented in the following and summarized in Figs. 6, 7, 8, 9, 10, 11, 12, 13 as hexagons, where the apices represent the RDs and internal concentric hexagons the rankings, with values indicated for the cost RD.

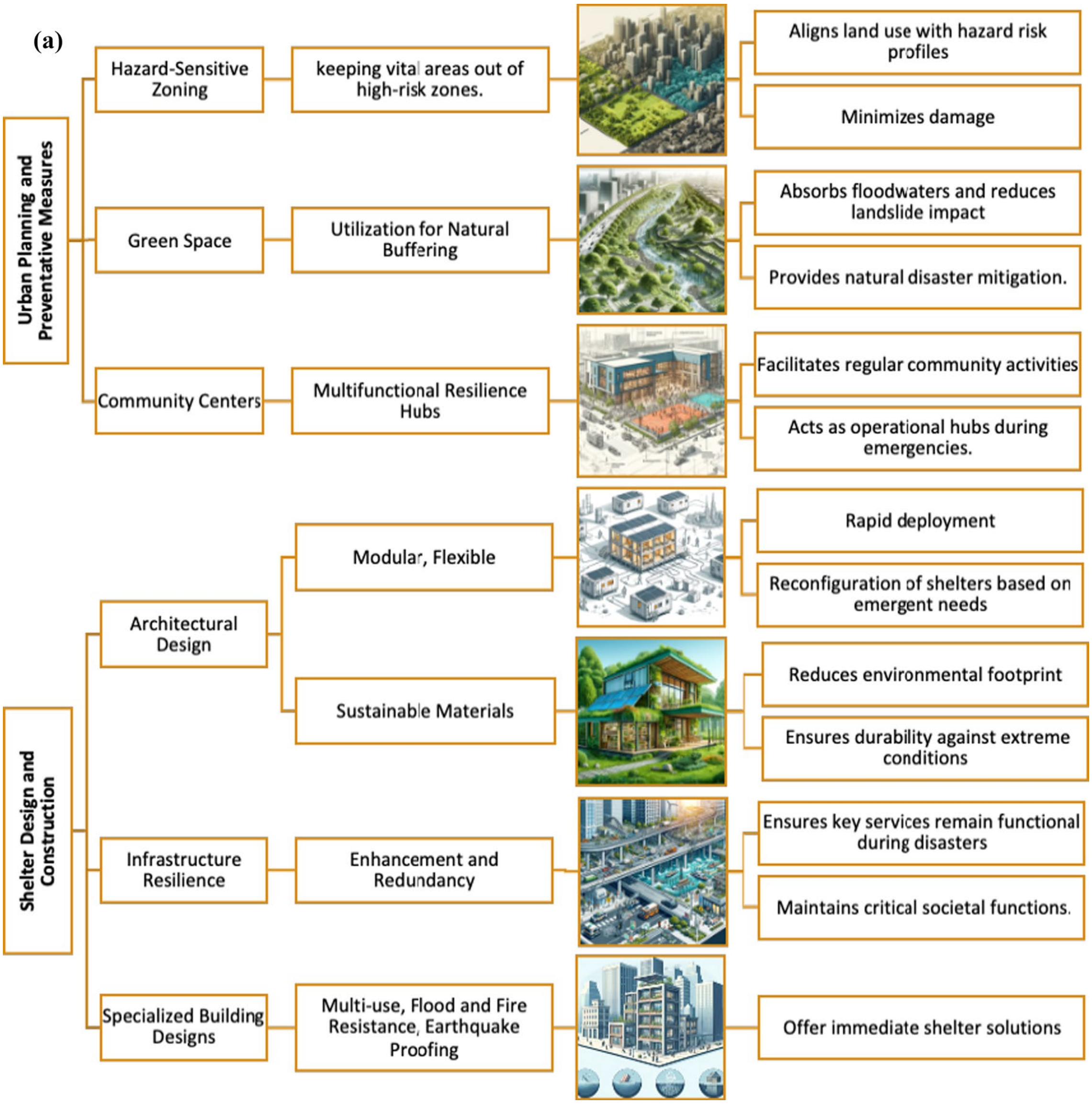


Fig. 4 **a** Shelter strategies; Illustrations produced using AI tools. **b**, Shelter strategies (ctd.)

4.1.2 Water

Twelve water RS are evaluated for water management, as shown in Fig. 2. Each of these strategies is evaluated against the 6 criteria presented above. Ranking (1–5) is assigned to these RS, from simplest to most complex to implement. This evaluation is assumed to consider qualitative and quantitative aspects that, in actual applications, could be derived from existing studies, expert opinions, and case studies.

The graph in Fig. 6 shows the ranking of each of the strategies across the different evaluation criteria. For example, rainwater harvesting system has low infrastructure impact, high scalability, and high community acceptance, while green roofs and walls have comparatively high cost, high maintenance needs, high infrastructure impact, but high community acceptance. Other strategies such as floodable parks, urban wetlands and channel modification can be comparably more costly, need higher maintenance and have higher infrastructure impact as a significant modification needs to be applied to the existing infrastructure.

Figure 7 presents a comparison of the evaluation of all the water RS presented in Fig. 2 (Sect. 3.2), with respect to all the criteria. The graph shows for example that strategies such as climate responsive design, water sensitive urban design, channel modification, elevated structure and integrated flood management have the low community acceptance and

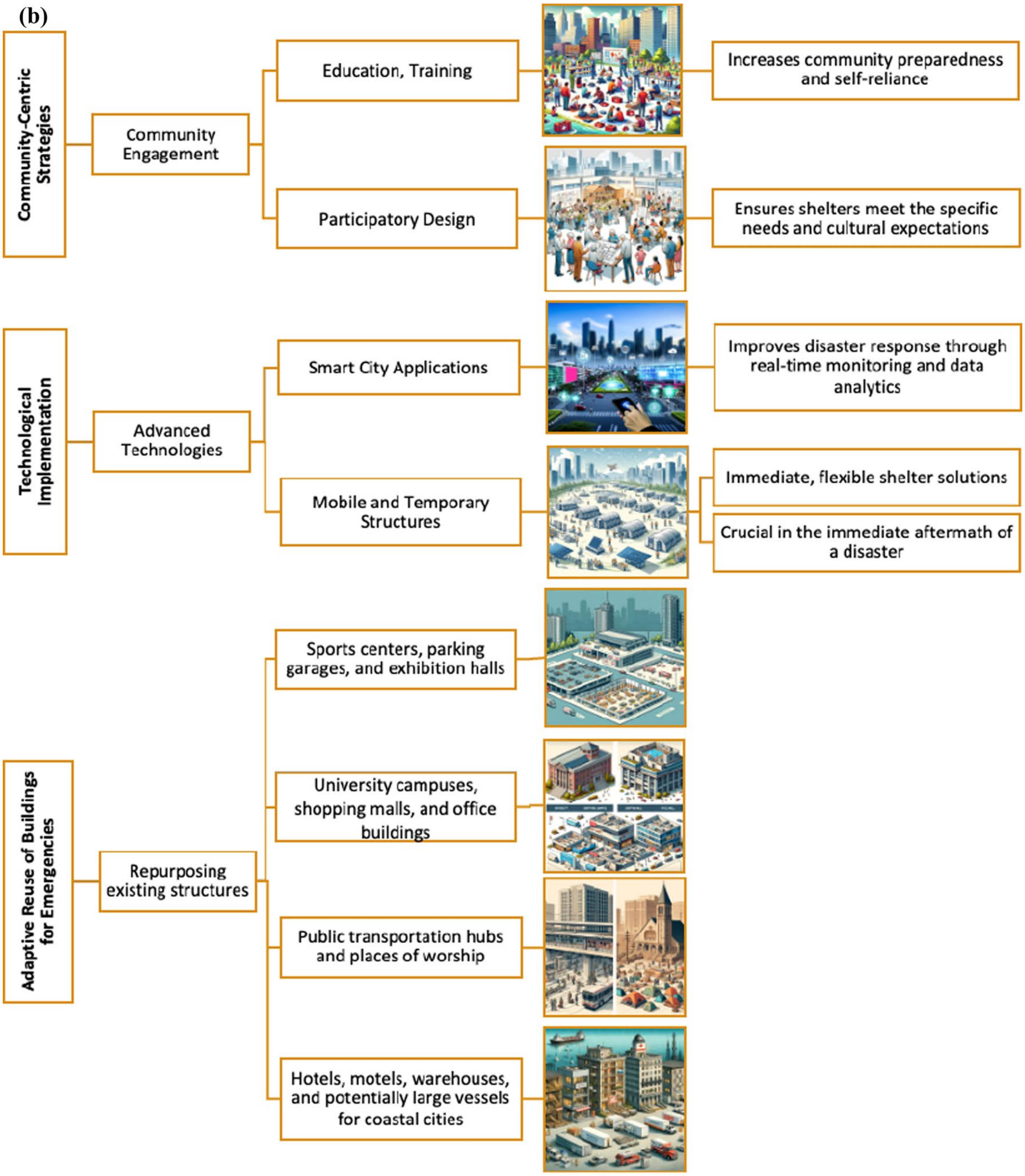


Fig. 4 (continued)

high cost ranking. Rain harvesting system and planting trees and forest, on the other hand have higher social acceptability and lower cost than other strategies.

4.1.3 Food

The food RS, discussed in Fig. 3 (Sect. 3.2) are evaluated below across the 6 criteria (Fig. 8). Strategies like community gardens, and edible landscaping are low cost, scalable, and of high community acceptance. Comparably, other strategies like green roofs, greenhouses and aquaponic have high cost, high infrastructure impact and high maintenance.

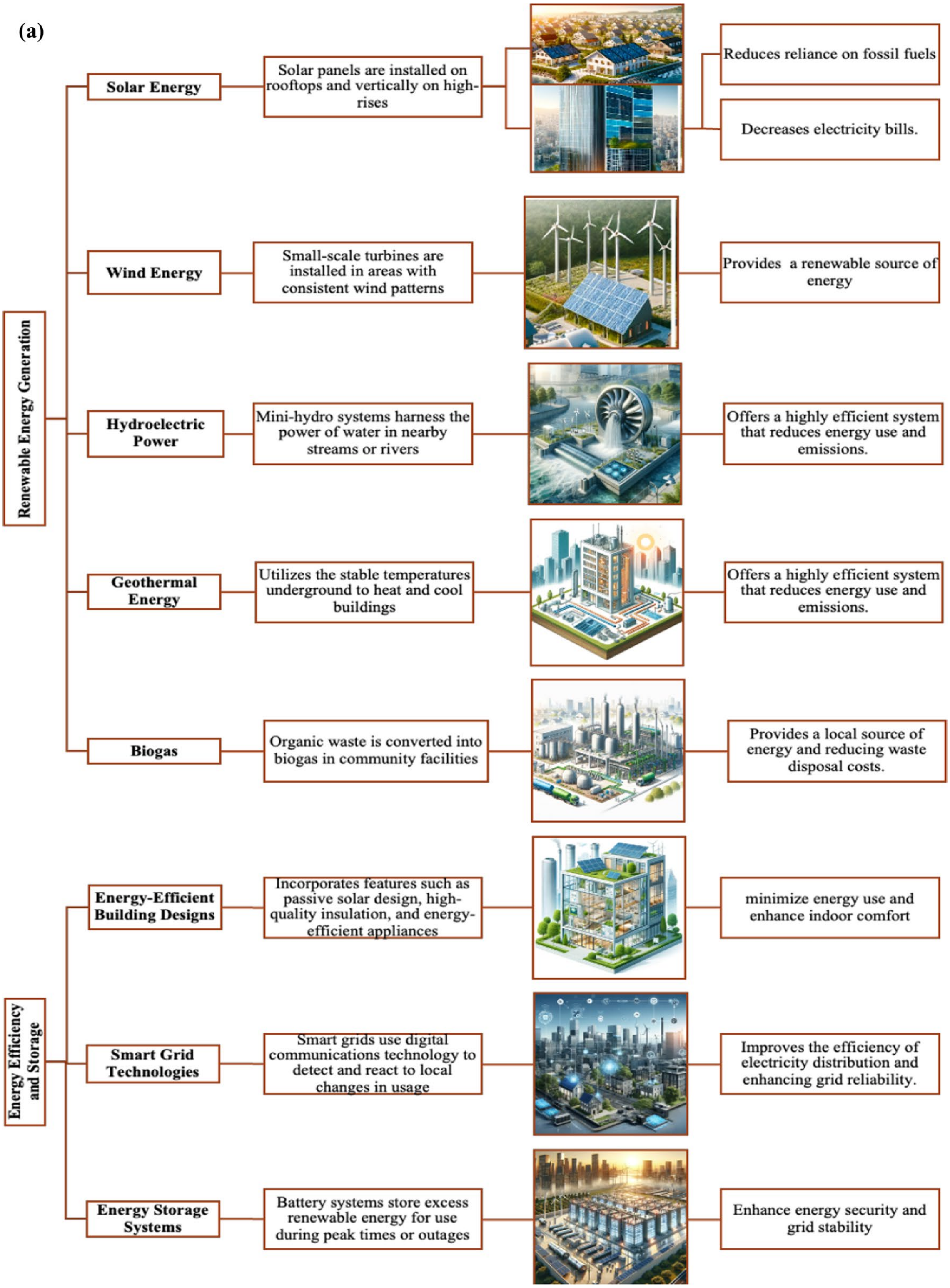


Fig. 5 **a** Energy strategies; Illustrations produced using AI tools. **b**, Energy strategies (ctd.)

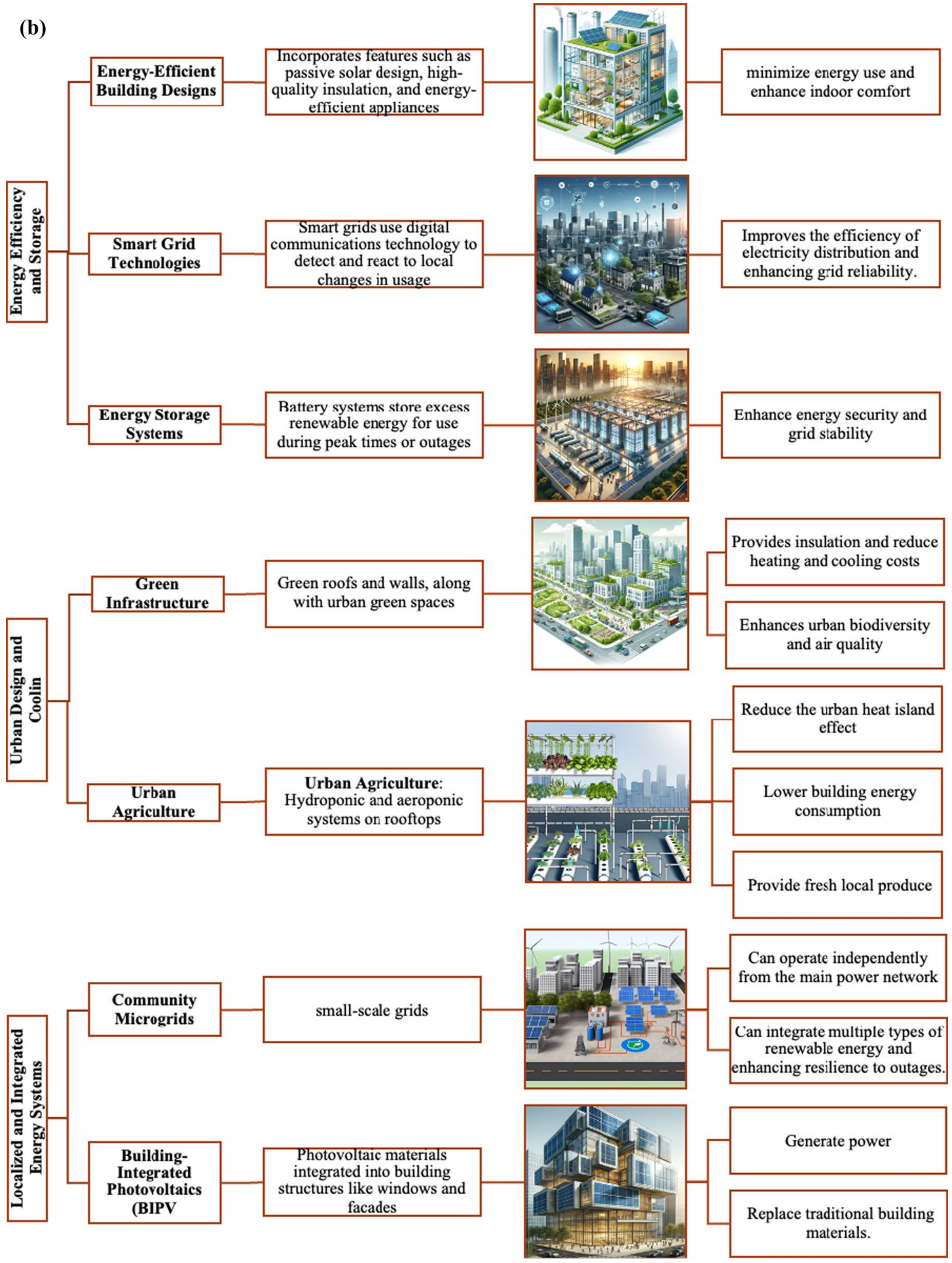


Fig. 5 (continued)

Figure 9 compares all food RS, with respect to each criterion. Strategies such as aquaponics, greenhouses, vertical farming, green roofs and urban farms, have comparatively higher cost, higher maintenance needs, and lower

Table 1 Resilience criteria and their ranking

Criterion	Definition	Ranking method
Cost	Initial and ongoing costs	Rated from low (1) to high (5)
Infrastructure Impact	The degree to which existing infrastructure needs to be modified	Rated from low (1) to high (5)
Scalability	How easily the strategy can be scaled up or adapted to different urban areas	Rated from difficult (1) to easy (5)
Regulatory and Zoning Challenges	Legal and administrative hurdles	Rated from few (1) to many (5)
Community Acceptance	How likely the community is to accept and support the strategy	Rated from low (1) to high (5)
Maintenance Needs	Ongoing maintenance requirements	Rated from low (1) to high (5)

Fig. 6 Ranking of each of water management strategy across the different criteria

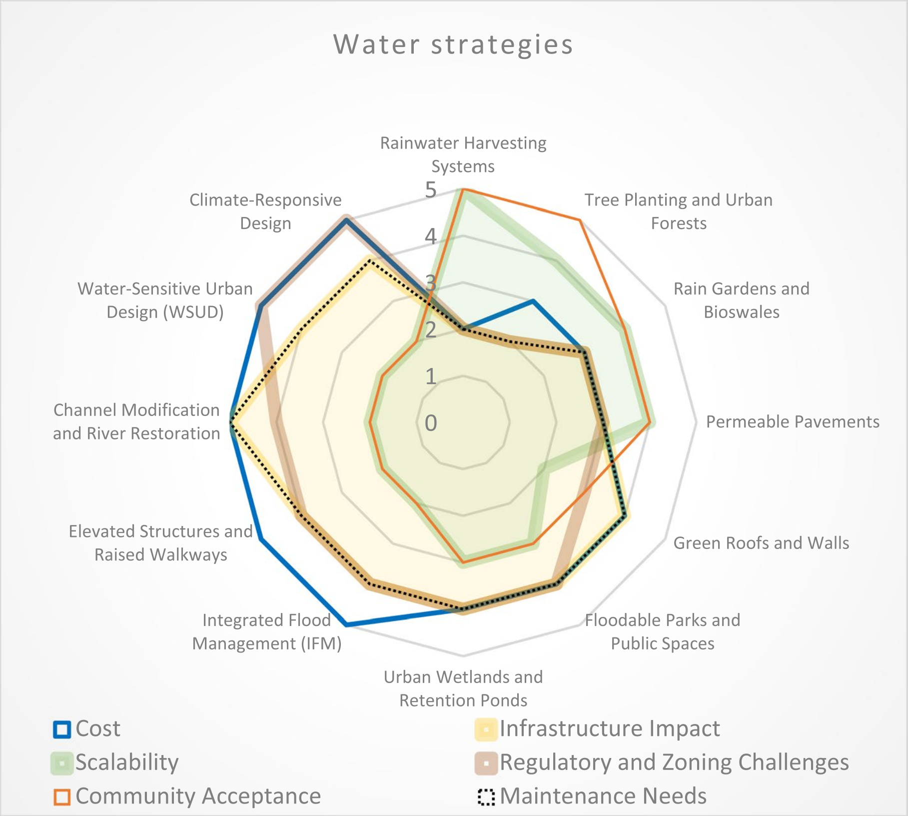


Fig. 7 Comparison of water RS with respect to evaluation criteria ranking

scalability. Other alternatives such beekeeping and chicken coops are associated with moderate to low cost, low infrastructure impact, moderate to higher regulatory and zoning challenges.

4.1.4 Shelter

The evaluation of shelter RS, presented in Fig. 4, are displayed in the graphs of Fig. 10. Repurposing existing structures has relatively low cost and infrastructure impact, moderate maintenance needs and regulatory challenges, and is highly scalable. Green space utilization and engaging the community in the sheltering process have the lowest cost, and high acceptability and scalability. Transforming community centers to resilience hubs have high community acceptance, moderate regulatory challenges, and scalability, while having relatively higher cost and higher infrastructure impact.

A comparison of various shelters strategies with respect to the six evaluation criteria is presented in Fig. 11. Community acceptance is the highest for repurposing existing structures, hazard-sensitive zoning, green space utilization, community engagement and community centers as resilience hubs. Cost is the highest for infrastructure resilience and lowest for repurposing existing structures and green space utilization.

4.1.5 Energy

The graphs in Fig. 12 present the ranking of each of the strategies across the evaluation criteria. For example, solar energy utilization and green infrastructure has relatively lower cost, higher acceptance and higher scalability. Community microgrids have higher cost, but also high acceptability and scalability.

A comparison of the evaluation of all strategies across the 6 criteria is presented in Fig. 13. Cost has the lowest ranking for solar energy, urban agriculture, energy efficient design and green infrastructure. These same strategies, together with microgrids have the higher acceptability. Maintenance needs is the lowest for green infrastructure, energy efficient design, geothermal energy, and solar energy.

Fig. 8 Ranking of each of food strategy across the different criteria

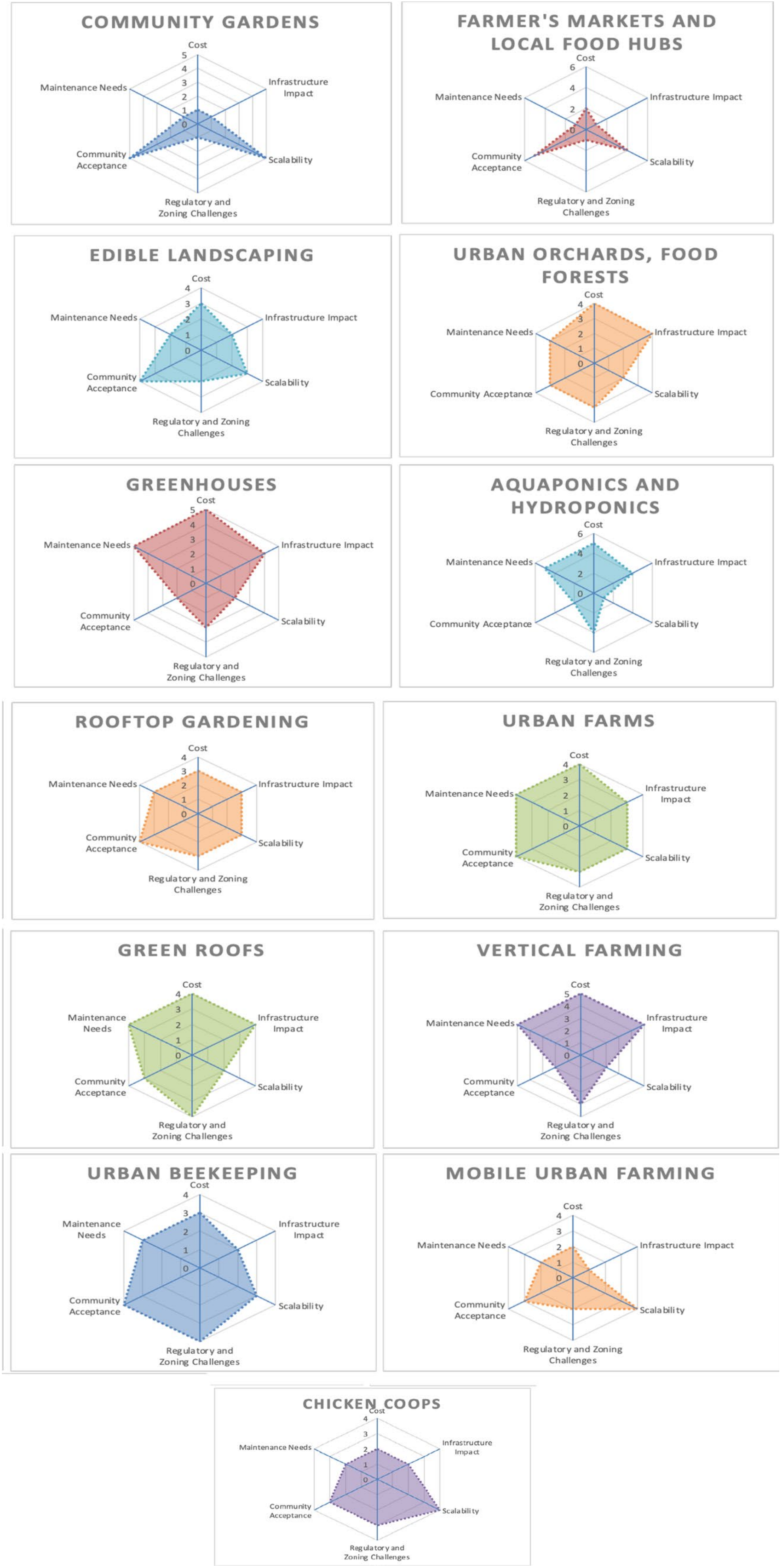
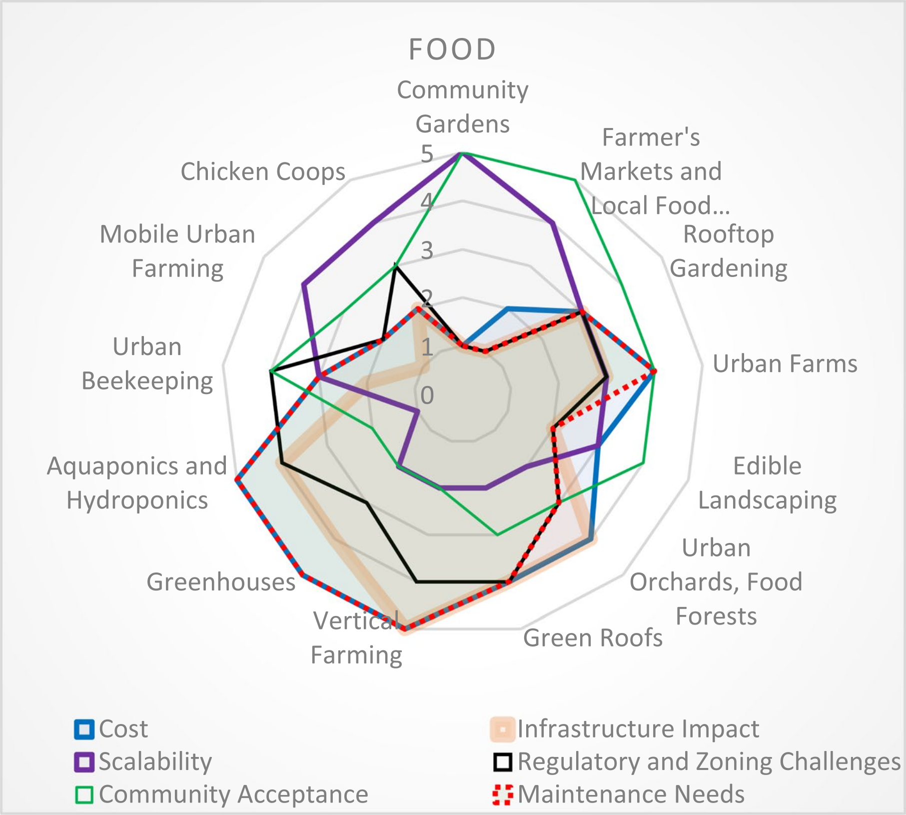


Fig. 9 Comparison of food RS with respect to evaluation criteria ranking



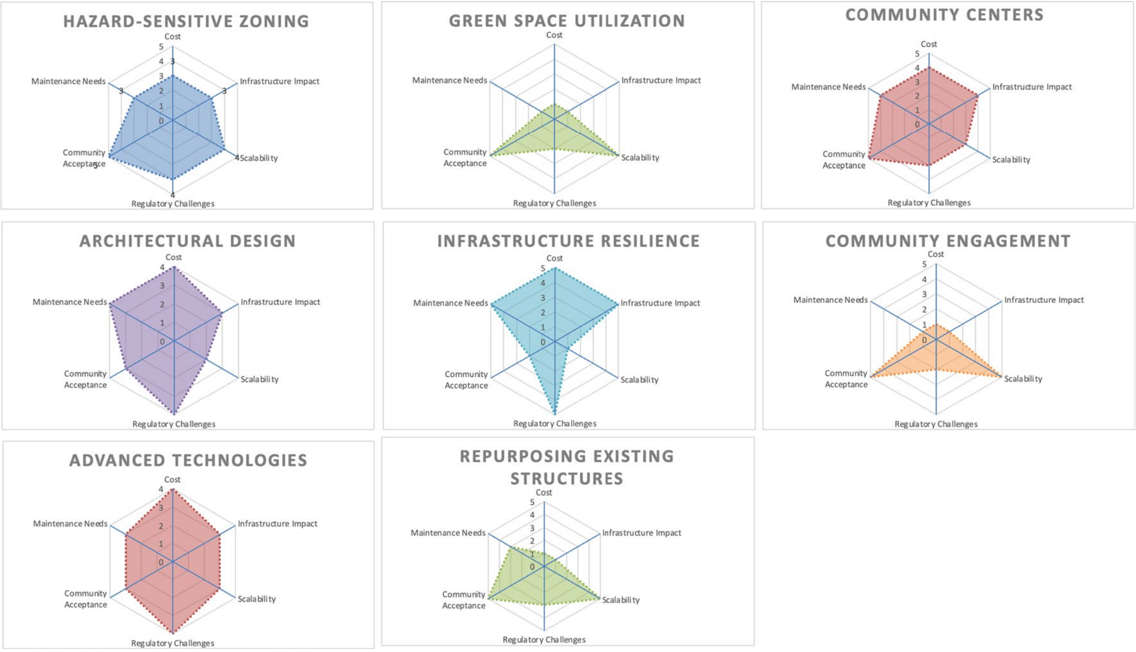


Fig. 10 Ranking of each of shelter strategy across the different criteria

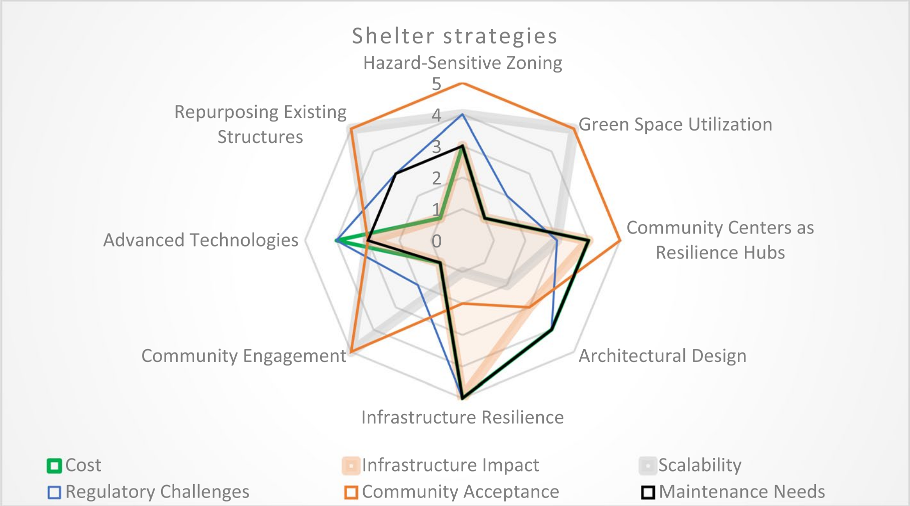


Fig. 11 Comparison of shelter RS with respect to the evaluation criteria ranking

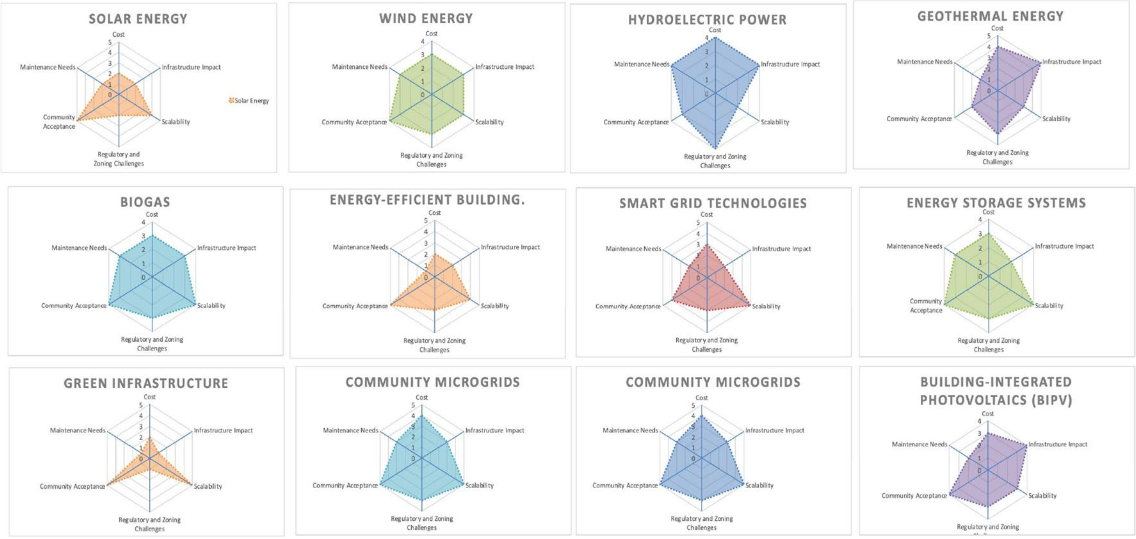


Fig. 12 Ranking of each of energy strategy across the different criteria

4.2 Comparing strategies across the various RDs

To conduct a comprehensive analysis across all listed strategies, each of the strategies in all resilience domains (RD) is systematically evaluated against the RSs of water management, food production, shelter, and energy resilience, employing a weighted scoring system, as explained in the following.

For each strategy, a *Resilience Score* is assigned based on how effectively this strategy contributes to enhance the resilience of each of the four RDs. Resilience implies in this work the ability to withstand and recover quickly from difficulties. It is assumed that a strategy that contributes to enhance resilience in multiple RDs will score high. The definition of the scores is presented in Table 2.

A weight can be then assigned to each of the RDs, based on the priority given in specific situation. For instance, if water management has the highest priority, due to flood prone zoning, then a relatively higher weight can be given to this RD. Three scenarios are presented as an example in this work, to highlight how weight can be assigned according to different priorities. These are summarized in Table 3.

For example, denoting the scores associated with the four RDs—Sw, Sf, Ss and Se—for water, food, shelter and energy, respectively, Green Roofs strategy can score high in water (Sw = 3) and moderate in the remaining 3 RDs (Sf-Ss = Se = 2). Rain Gardens and Bioswales can score high in water (Sw = 3), low in food (Sf = 1), low in shelter (Ss = 1),

Fig. 13 Comparison of energy RS with respect to the different criteria ranking

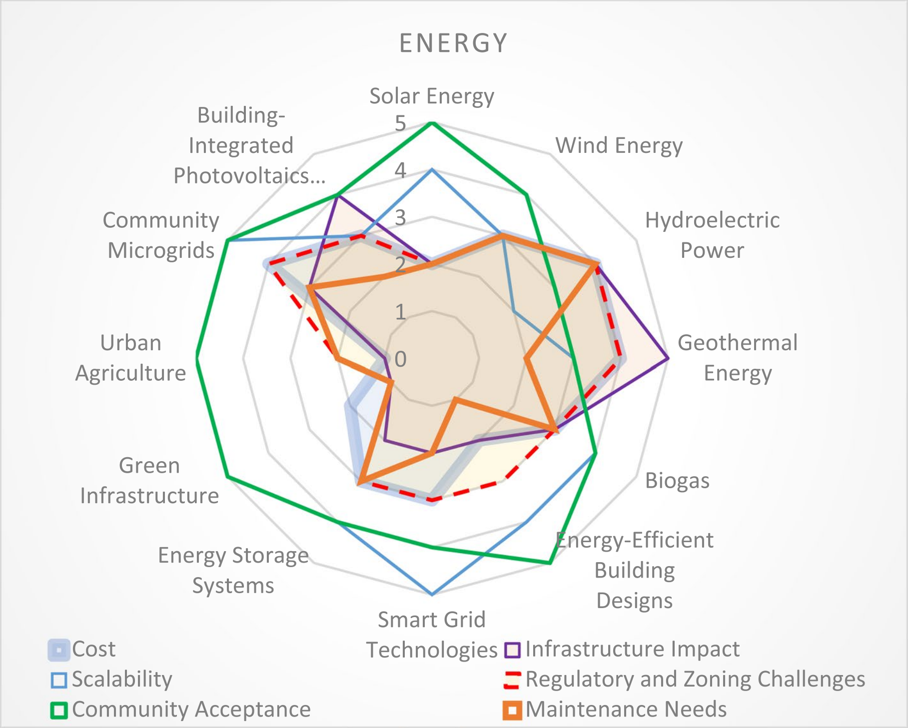


Table 2 Strategy resilience score assignments

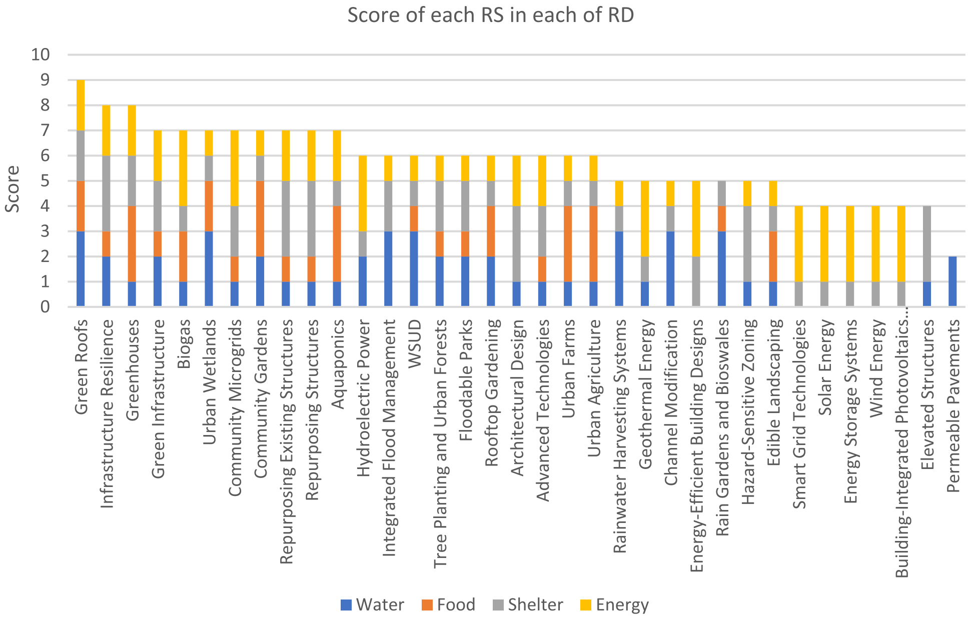
Score	Contribution
0	No impact
1	Low impact (provides some resilience but not significant or indirect)
2	Moderate impact (provides noticeable resilience benefits)
3	High impact (key strategy for resilience in this area)

Table 3 Scenarios of weight allocation according to different priorities

Scenario	Priority	Weights
1	Water and energy	Water management: 30% Food production: 20% Shelter: 20% Energy: 30%
2	Energy	Water: 20% Food: 20% Shelter: 20% Energy: 40%
3	Energy, electrification	Water: 15% Food: 15% Shelter: 20% Energy: 50%

and no impact in energy (Se = 0), while Energy-Efficient Building Designs can have no impact in water (Sw = 0), no impact in food (Sf = 0), moderate in shelter (Ss = 2), and high in energy (Se = 3). Such evaluation is conducted for all strategies assuming certain impacts based on general knowledge about these strategies. The scores of all RSs are presented in Fig. 14 for all RDs.

Fig. 14 Ranking of each strategy in each RD



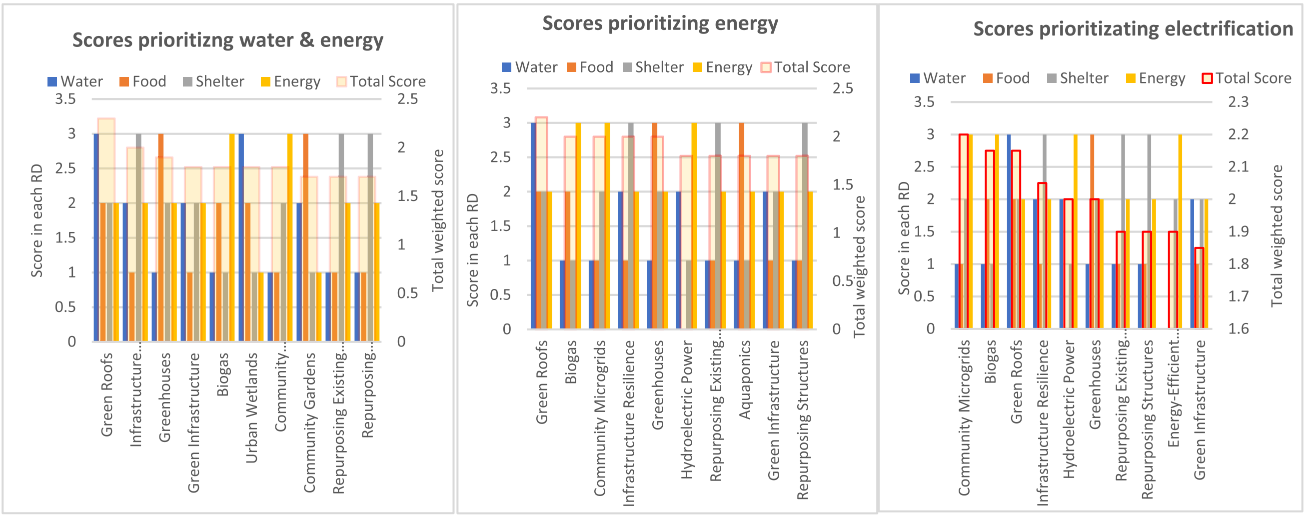


Fig. 15 Scores for the top 10 urban resilience strategies, classified according to the priorities of the 3 scenarios (Table 3)

The total resilience score of each RS is then calculated based on the weighted sum of their scores across the various RDs. The total score (see Fig. 15) is calculated by multiplying the score of each strategy, within a specific RD, by the respective weight of this RD (e.g. 30% for water and energy, 20% for food and shelter, in scenario 1), then summing these weighted scores, as expressed in Eq. 1:

$$St = Sw * Ww + Sf * Wf + Ss * Ws + Se * We \tag{1}$$

where *Ww, Wf, Ws, We, Sw, Sf, Ss, Se,* are the weights and the scores assigned for water, food, shelter and energy, respectively.

For example, the Energy Efficient Design has a total score St = 0*0.3 + 0*0.2 + 2*0.2 + 3*0.3 = 1.3. This ranking helps prioritize strategies based on their assumed comprehensive contributions to urban resilience. It can be particularly useful for planning and investment decisions in urban development and sustainability initiatives.

The graphs in Fig. 15 display the scores for the top 10 urban resilience strategies (presented in Fig. 14), according to the 3 scenarios presented in Table 3. The figure presents the strategies in order of reducing total weighted score (see Fig. 15). The relative contributions of each strategy to water management, food production, shelter, and energy, in line with the weighting system adopted in each of the scenarios, is included as well.

4.3 Ranking best strategies

This section employs scenario 3, discussed above, to illustrate the process of ranking best strategies. The top scoring strategies identified in platform 2 above (e.g. in scenario 3), are ranked again, against the 6 RCs (Table 1), discussed in Sect. 4.1 (see Fig. 16). The scoring is based on typical expectations for each strategy. Weights are then assigned to each criterion based on its importance. For simplicity in this section, equal weighting is assumed for all 6 criteria (i.e. 0.167). Adjustments can be made based on specific priorities such as achieving lower cost, lower maintenance, or others.

The next step is to determine a final score for each strategy in a given scenario. Since lower values are more desirable for Cost, Regulatory Challenges, Infrastructure Impact and Maintenance Needs, these scores are inverted. This was done by subtracting the actual score from 6 (since the scale is 1–5, the inverted score (S_{inv}) is equal to 6—actual score). The final score can then be calculated by multiplying each criterion score (or inverted score), by its weight and summing the results. Equation 2 is a variation of Eq. 1 allowing for inverted scores.

$$\mathit{Final\ Score} = (S_{inv-C}).\mathit{Wc} + \mathit{Scalability}.\mathit{Ws} + (S_{inv-r}).\mathit{Wr} + \mathit{Community\ Acceptance}.\mathit{Wa} + (S_{inv-a}).\mathit{Wm} + (S_{inv-i}).\mathit{Wi}. \tag{2}$$

The indices *c, s, r, a, m,,* are the weights assigned for cost, scalability, regulatory, acceptance, maintenance and infrastructure, respectively.

The results for the best 10 strategies for scenario 3 presented in Sect. 4.1, are shown in Fig. 17. This allows to determine the best strategy that can simultaneously contribute to a number of resilience domains (as discussed in 4.2), while fulfilling specific objectives (e.g. low cost, high scalability, etc.). For example, in this theoretical case- i.e. scenario 3, implementation of solar energy has the highest overall score, indicating that it can contribute to multiple RDs, while also best fulfilling the 6 criteria (cost, scalability, regulatory, acceptance, maintenance and infrastructure). This score is calculated as employing the scores for each criterion (see Fig. 16) and an equal weight of 0.167 to all criteria, as following:

$$S_{Tot-(solar\ energy)} = 2 * 0.167 + 5 * 0.167 + 2 * 0.167 + 5 * 0.167 + 1 * 0.167 + 1 * 0.167 = 4.76.$$

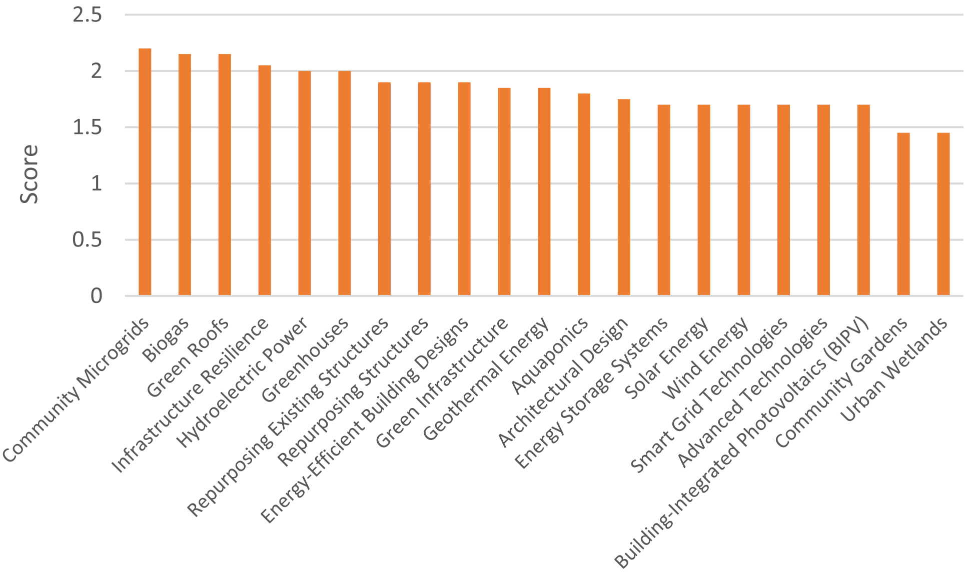


Fig. 16 The top scoring strategies for scenario 3—energy and electrification

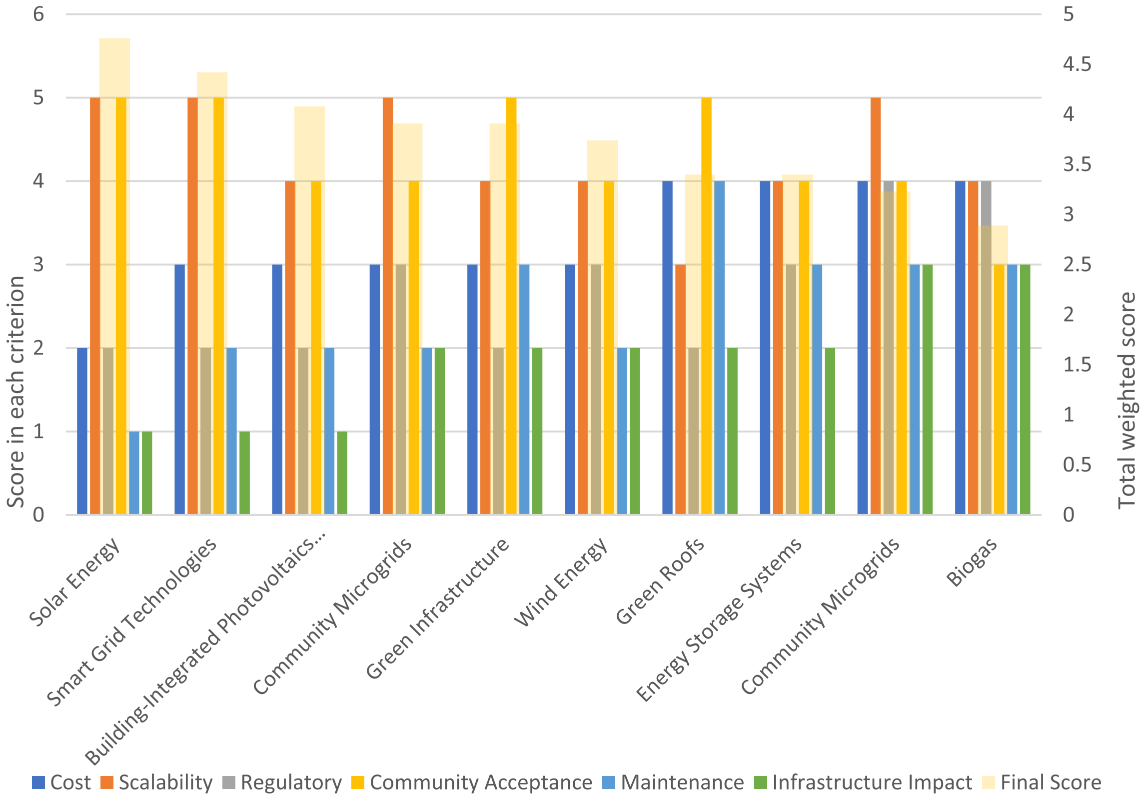


Fig. 17 Best 10 strategies, associated with Scenario 3, that simultaneously contribute to multiple criteria, and have best scores across the 6 RC

5 Discussion

This study presents a range of mitigation and adaptation strategies that enhance the resilience of urban areas in four domains, water, food, shelter and energy. These strategies encompass sustainable design and technological aspects, ensuring effective integration in urban planning. This dual focus on resilience and sustainability is essential for developing long-term solutions that address current and future environmental challenges. This work also proposes a framework to rank and prioritize the analysed strategies according to several practical criteria, and to select strategies that can contribute simultaneously to more than one resilience domain. Several key points can be deduced from this work, which can lead to further development and implementation of resilience strategies, as discussed in the following.

- A wide range of strategies are presented in this work, based on various initiatives implemented in different cities in the world. Many strategies are relatively simple and can be readily implemented with not much change and alteration to existing infrastructure, while others need more planning. Some of the strategies can contribute to more than one resilience domains, making them more efficient and beneficial to implement in an overall resilience program. An example is greenhouses, that can be employed not only to produce food, but can help in energy production by integrating for instance semi-transparent PV cells in their envelopes.
- The presented strategies could be scaled up to accommodate technological advances and diverse geographical and cultural environments. The database of potential design strategies can be continuously updated, thereby ensuring that all stakeholders have access to the information and informing authorities of the best solution possible. The assessment criteria—costs, maintenance, impacts, acceptability, regulatory aspects, and scalability are flexible and can be modified to align with changing needs of different contexts. This ensures that the strategies remain relevant and effective across different real-life situations and scenarios, promoting resilient and sustainable urban development.

- Despite the hypothetical nature of the scores assigned to strategies in their evaluation process, systematically applying weights that reflect the relevance and significance of various selection criteria and objectives allows to identify key strategies that meet these criteria. For instance, by prioritizing criteria such as cost-effectiveness and scalability, the framework can filter out the most viable strategies for implementation in different urban contexts, ensuring that chosen solutions align with the desired outcomes and resource availability. This approach supports a more targeted and effective selection process, tailored to specific urban resilience goals.
- The ranking system employed in the proposed framework is determined by applying common knowledge. To increase its rigor and credibility, it should incorporate recorded data on costs, impact, maintenance frequency and community experiences. Surveys are an effective way to gauge community acceptance and regulatory barriers. Ultimately, a robust methodology will involve collection of fine-grained cost data, life-cycle assessment of environmental and infrastructural impacts, and historical maintenance records. Community surveys will assess acceptance, and consulting with urban planners and legal experts will identify regulatory barriers. A data-driven ranking methodology employing these parameters is likely to yield an improved, context-specific ranking of best resilience strategies for urban environments and can help urban planners and policymakers to take informed decisions about what strategies are feasible in different urban contexts.
- While initial scores and weights are employed primarily to demonstrate the methodology, they can be adapted based on specific urban characteristics and needs through systematic studies. This adaptability is vital for accurately assessing and comparing resilience strategies across various cities or regions, given that each urban area possesses unique challenges and strengths. By adjusting the ranking criteria to reflect localized data and conditions, the assessment's relevance is enhanced, and strategies are better aligned with each area's distinct needs. This approach supports the development of targeted interventions that effectively enhance urban resilience.
- Adapting resilience assessment methodologies to different urban contexts is challenging due to unique city characteristics, data variability, and the requirement for a multidisciplinary approach. Simplification can be achieved by establishing a standardized yet customizable methods, employing advanced technologies such as GIS and AI for efficient data analysis, and encouraging collaboration among governments, academia, and industry. Beginning with pilot projects and incrementally expanding the methodology can further streamline the process, making resilience assessments more manageable and effective across diverse urban settings.
- The proposed framework offers flexibility, allowing for modification and expansion of evaluation criteria and strategies to accommodate diverse needs. Additionally, the framework can be partially applied for specific objectives. For instance, platform 1 of the framework can be applied simply to rank strategies in a specific resilience domain, according to a set of evaluation criteria such as low-cost or social acceptance, aiding in selecting the most feasible options. Alternatively, the framework can identify strategies that contribute to multiple domains while simultaneously ranking those with higher feasibility rate.

Moreover, in planning and implementing urban resilience strategies, adopting long-term visions and ensuring that short-term actions align with sustainable future goals, is crucial. Concepts and strategies, planned with a long-term perspective, reduce costs, enhance sustainability, and improve community acceptance. By focusing on enduring benefits, cities will be better prepared for the challenges ahead, of both increased urbanisation and ongoing effects of climate change.

Developing adequate regulations for the adoption of various resilience strategies is crucial for the effective and consistent implementation of urban resilience strategies. Regulations can provide safety and promote widespread acceptance [53]. For instance, setting standards for solar energy, energy-efficient buildings, community microgrids, green infrastructure, smart grids, and urban agriculture, will ensure fast and effective adoption, facilitating the integration of these strategies into urban development.

This paper compiles various urban resilience strategies and introduces an evaluation framework to prioritize them according to several criteria. The identified strategies aim at enhancing the climate resilience of urban areas across various domains such as water management, food production, shelter, and energy. Although some of these strategies require long-term planning and integration into the urban landscape they can be gradually implemented in existing neighborhoods. The evaluation framework systematically assesses various resilience strategies, focusing on key objectives and identifying the domains most critical for reinforcement within a region. It also pinpoints strategies that simultaneously strengthen resilience across multiple domains, thereby optimizing implementation costs. Although many of the presented strategies already exist in design, planning, or technological forms, effective implementation requires organized and determined actions by cities and municipalities. The framework presented is not only efficacious to analyze strategies suitable for urban settings but also flexible, allowing for the adjustment of criteria and the expansion of options. Overall, the study provides a scalable, adaptable and replicable tool that can be customized to meet diverse urban requirements, making it an invaluable resource for cities worldwide to systematically enhance their resilience across essential domains.

Author contributions As the sole author of the paper, Dr. Hachem-Vermette contribute to all the work in the article.

Data availability Data sets generated during the current study are available from the author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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