

## ORIGINAL CONTRIBUTION

## Climate-Resilient Technologies for Infrastructure, Energy, and Water Systems: A Review and Future Outlook

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**Abstract**— The design, operation, and governance of engineered and natural systems are already being influenced by climate risks. The term “climate-resilient technologies” is increasingly being used across applied sciences to refer to both physical innovations (materials, devices, infrastructure configurations) and cyber-physical capabilities (monitoring, data assimilation, control, and decision support) that enable systems to anticipate climate stressors, maintain critical services during disruptions, recover quickly, and adapt over time. This review summarizes research in the built environment, water and energy systems, food production, coastal protection, and digital analytics. The literature is emphasized through a systems framework that connects hazards (e.g., heat, floods, droughts, storms, sea-level rise, wildfire) to exposure and vulnerability, technological intervention mechanisms, and measurable resilience outcomes. Recent trends promise a shift in the single asset hardening approach to portfolios that combine advanced materials (e.g., self-healing and ultra-durable concretes), passive and nature-based cooling (cool roofs, green roofs, urban greening), distributed and islandable energy architectures (microgrids and storage), next generation membrane-based water supply augmentation (desalination and reuse), and data-driven early warning and operational optimization. Despite rapid innovation, gaps in evidence remain, including performance under compound extremes, long-term maintenance and governance requirements, equity outcomes, and standardized metrics for cross-context comparability. The study concludes by proposing a research agenda focused on stress testing under deep uncertainty, harmonized resilience metrics, lifecycle and embodied carbon accounting, and the scaling of hybrid grey-green-digital solutions. Accordingly, future research priorities include stress-testing technologies under deep uncertainty, harmonization of resilience performance metrics, life-cycle and embodied-carbon integration, and scaling of hybrid grey-green-digital solutions through relevant governance, funding, and institutional frameworks.

**Index Terms**— Climate resilience, Adaptation technologies, Infrastructure, Water systems, Energy systems, Decision-making under uncertainty

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## I. INTRODUCTION

Climate change is altering the frequency, intensity, and spatial patterns of hazards that matter to engineered systems: hotter heatwaves, more intense precipitation extremes, longer droughts, storm surge and sea-level rise, and wildfire conditions. In applied sciences, “resilience” has evolved from an ecological framing to a broadly used engineering and policy concept: the capacity of a system to withstand shocks, limit losses, and continue delivering essential functions while learning and adapting over time [1, 2].

Resilience has been associated with, but is not synonymous with, reliability or robustness. Reliability stresses performance under expected disturbances, whereas resilience explicitly includes High-Impact/Low-Probability

(HILP) events, cascading failures across interdependent systems, and post-event recovery trajectories [3, 4, 5]. In the case of climate risks, deep uncertainty is the additional obstacle: Hazards are non-stationary, and the tails of distributions are often the drivers of the largest losses [6, 7].

The practical subset of adaptation considered in this review comprises climate-resilient technologies: innovations that can be designed, validated, deployed, and maintained to reduce climate-driven disruptions in applied systems. Technology is broadly defined here as encompassing materials and components (e.g., advanced concretes, membranes), infrastructural configurations (e.g., microgrids, blue green drainage), and digital capabilities (e.g., remote sensing, machine learning forecasting) that enable resilient operation [8, 9, 10].

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A consistent theme across the literature is that resilience rarely emerges from a single intervention. Instead, it depends on portfolios that combine structural measures (hardening), operational flexibility, redundant path-

ways, and social and institutional enablers [11, 12]. In the climate context, robust strategies often involve staged investments and trigger based pathways that can be adjusted as new information becomes available [13, 14].

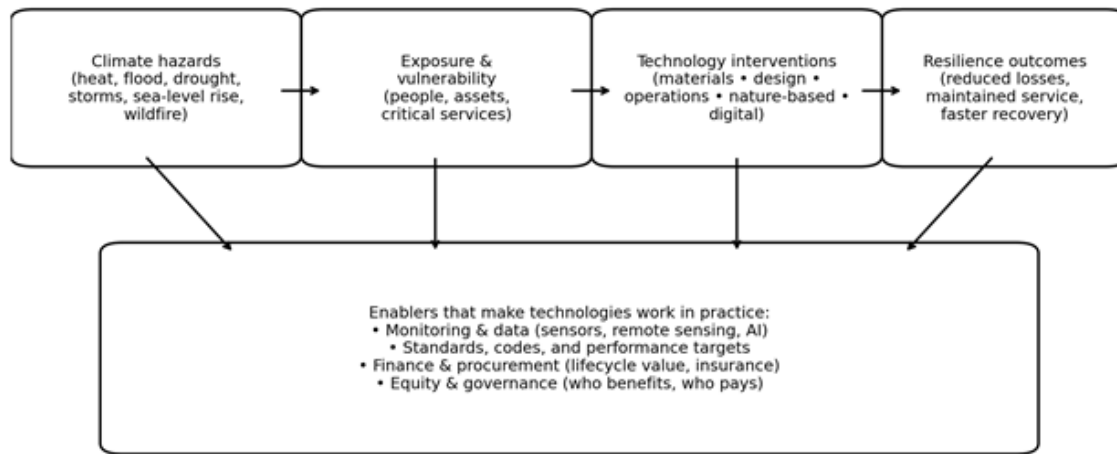


Fig. 1. Systems framing of climate-resilient technologies in applied sciences (author-generated)

## II. REVIEW APPROACH AND SCOPE

The evidence base of climate-resilient technologies remains fragmented across disciplines, sectors, and space despite the rapid growth of research on climate adaptation and resilience. There is a large body of literature in individual technologies or individual sectors, such as buildings, energy systems, water infrastructure, or coastal protection, but no systematic study of cross-sector interactions, cascading risk, or relative performance in the face of common climate stressors. Consequently, decision makers are usually not provided with integrative advice on how the technology portfolio in terms of combinations of technologies has to work in an interdependent energy-water-food-infrastructure nexus [15].

Another challenge is the lack of consistent and standardized measures of resilience. Although many studies have documented indicators (e.g., a decrease in cooling demand, a decrease in outage time) that are technology-specific, they are not harmonized across sectors and are not explicitly related to service-level performance and recovery curves. This constrains the ability to compare adaptation options, access trade-offs, equity implications, lifecycle effects, and scalability over the long run, issues that have gained greater prominence in recent resilience and sustainability literature [10, 9].

Also, much of the extant evidence is obtained from lab experiments, short-term pilots, or past climate, with very little checking of under-compound and extreme events or under non-stationary climate futures [16]. Recent surveys emphasize the necessity of stress-testing technology under conditions of deep uncertainty and the interplay among physical performance, governance, institutional capacity, and operational constraints [14, 17].

It is in this context that this review aims to provide a systems-based synthesis of climate-resilient technologies in applied domains. In particular, the review (i) groups technologies based on climate hazards/exposure/vul-

nerability pathways, (ii) compares how resilience mechanisms and maturity vary across diverse sectors, such as the built environment, energy, water, coastal systems, food production and digital analytics, (iii) and identifies research gaps, implementation constraints and research priorities that are needed to promote robust, equitable and scalable climate adaptation.

### A. Ethical considerations

The present review is based solely on publicly accessible and peer-reviewed literature, does not involve human participants or personal data, or proprietary datasets. The issue of ethics is thus considered by being transparent in reporting sources, citing them properly, and critically synthesizing published evidence based on the accepted review article standards.

### B. Conceptual foundations: From hazards to technology portfolios

A useful way to connect disparate technologies is to anchor them in the hazard–exposure–vulnerability framing used across risk science. Hazards describe the physical climate stressor; exposure describes what is in harm’s way; vulnerability describes how sensitive exposed assets and people are and how quickly they can recover [11, 18]. In engineered systems, resilience is often described through a performance trajectory. An initial drop after the event, followed by recovery and adaptation, which reduces future loss. Quantitative frameworks vary, but most share the idea that resilience metrics should capture magnitude and duration of service loss, not only failure probability [3, 4].

Because climate change induces non stationarity, resilience planning benefits from methods that do not rely on a single forecast. Dynamic Adaptive Policy Pathways (DAPP) and other deep uncertainty approaches help build strategies that are robust across plausible futures and can be adjusted when signposts are observed [13, 14].

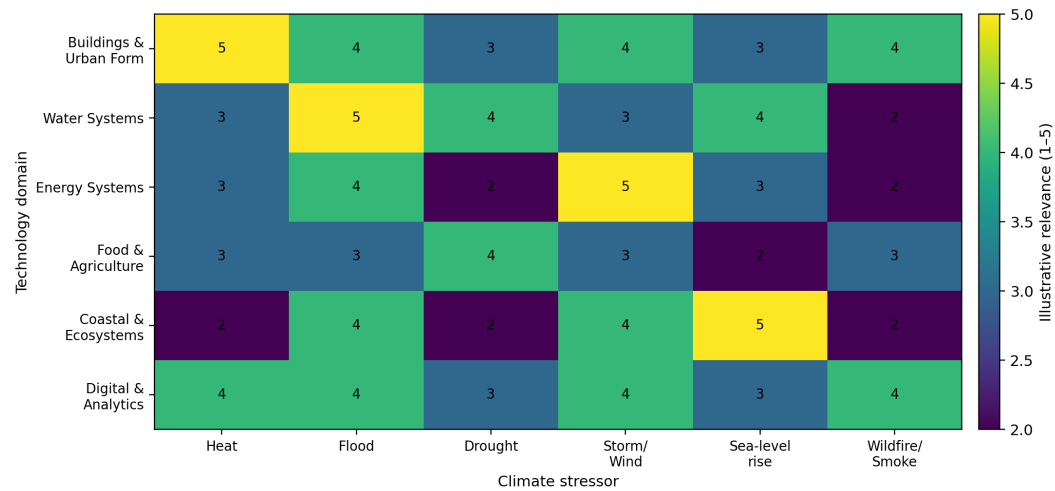


Fig. 2. Conceptual relevance matrix linking technology domains to major climate stressors (author-generated; illustrative)

TABLE I  
CLIMATE-RESILIENT TECHNOLOGY FAMILIES, MECHANISMS, AND TYPICAL EVIDENCE BASE (SELECTED EXAMPLES)

Domain	Technology family	Primary stressors	Resilience mechanism	Typical maturity	Representative studies
Built environment	Cool roofs & cool materials	Heat	Reduce heat gains; improve thermal comfort; lower peak demand	Commercially mature; performance context-dependent	[19, 16]
Built environment	Thermal energy storage (PCMs)	Heat, peak demand	Shift/limit indoor temperature peaks; demand flexibility	Piloted; performance depends on design	[20]
Built environment	Green roofs / urban greening	Heat, pluvial floods, air quality	Evapotranspiration cooling; stormwater retention; co-benefits	Mature with design uncertainties	[21, 22, 23]
Urban water	Permeable pavements / SuDS	Intense rainfall, flooding	Increase infiltration/storage; reduce runoff peaks; water quality benefits	Mature but sensitive to clogging/maintenance	[24, 25]
Materials & structures	Self-healing cementitious materials	Flooding, corrosion, aging	Autonomous crack sealing; extend service life; reduce maintenance disruptions	Emerging-to-piloted	[26, 27]
Materials & structures	Ultra-high perform. concrete	Floods, storms, aging	Higher durability; improved fatigue and chloride resistance	Commercially available; needs design guidance	[28, 29]
Energy	Microgrids & distributed storage	Storms, heat, wildfire (outages)	Islanded operation; redundancy; flexible control; faster restoration	Scaling rapidly; regulatory dependence	[8, 9]
Water supply	Desalination & advanced membranes	Drought, saltwater intrusion	Augment supply; improve selectivity/efficiency; energy-water co-optimization	Mature (RO) + rapid material innovation	[30, 31, 32]
Coastal	Nature-based & hybrid defences	Storm surge, waves, sea-level rise	Wave attenuation; surge friction; risk reduction + ecosystem services	Context-specific; requires monitoring	[33, 15]
Digital	Forecasting, digital twins & decision support	Multiple hazards	Early warning; resource allocation; dynamic control; adaptive pathways	Fast-moving; validation needed	[34, 10, 35]

### C. Built environment and infrastructure

Another passive approach to enhancing resilience, thermal energy storage offers to mitigate the temperature of indoor spaces, as well as shift cooling loads away from peak demand periods. Phase Change Material (PCM) has been extensively reviewed in building applications and may offer benefits in leveling the swings in indoor temperature, as well as reduce peak loads, but the extant benefits in real life are highly dependent on PCM selection, placement and charge-discharge cycle [36, 37, 38, 20].

Another strategy is provided by vegetated systems, green roofs, green walls, and urban greening: evaporative cooling and shading, as well as stormwater retention. It has been recorded that there are energy impacts and ecological services, although different outcomes of surface depth and irrigation have been observed, as well as the choice of plants and immediate weather [21, 22, 23]. In addition to heat, green roofs have the ability to limit exposure to particulate pollution in the street level as well as create an environment where biodiversity can thrive, but at the trade-off of maintenance and water demand during drought periods [39].

Flood resilience in the built environments takes the shape of both structural protections and the “wet-side” strategies that admit inundation but minimize the damage. The example of amphibious architecture is based on borrowing strategies of buoyancy and putting the structures on top during the flood and being connected to services [40, 41]. These methods are most likely to work in periods of floods with no constant deep floods; they also need to be particularly critical of utility connections, access, and community acceptance.

At the materials level, one of the fundamental challenges to resilience is that climate stress (heat, moisture, salinity) may lead to a decrease in safety margins. The self-healing cementitious materials are created to increase the durability of service by sealing cracks independently, thus minimizing water and aggressive ions intrusion, hence, decreasing maintenance requirements [26]. Under special conditions, a bacteria-based tool has demonstrated crack healing and permeability reduction [42, 43, 27].

In addition to self-healing solutions, Ultra-High-Performance Concrete (UHPC) has emerged as a preferred critical asset, due to its high strength and enhanced durability; a review study has found promise and has highlighted the importance of careful and well-influenced mixtures and standard tests to ensure foreseeable field behavior [28, 29].

For critical infrastructure, stormwater management is also a necessary requirement for resilience. Run-off peaks, improved infiltration, and better quality of water can be achieved by permeable pavements and larger sustainable drainage systems (SuDS), and it has been demonstrated to have beneficial impacts but also identifies clogging and maintenance as crucial factors determining performance [25]. The world operates differently with terminology and design philosophies, SuDS, LID, WSUD, yet the purpose of the physical is alike; it is distributed retention and infiltration to prevent flooding of sewer networks [24].

### D. Water Systems: Supply augmentation, reuse, and climate-resilient storages

The central concern regarding climate impacts lies in water systems since droughts decrease supply, floods destroy treatment facilities, and changes in water quality relations due to warming. Several resilience technologies in water are designed to diversify the sources and enhance selectiveness of treatment, and provide greater flexibility to storage and conveyance.

A critical drought resilience alternative in water-depleted areas has been desalination, which is energy-consuming and may present environmental issues. One of the main research directions relates to enhancing membrane materials and process design to make them less energy-consuming and more specific [30, 44]. [31] review in which next generation materials, including thin film nanocomposites through to the biomimetic

structure, would address constraints of existing membranes, and [32] posit that even a small improvement in selectivity can be of more importance than improved permeability to real system operation. Membrane distillation provides the opportunity to deploy low-grade heat or waste heat at the water-energy nexus, although it is prone to scaling and fouling [45].

Beyond supply augmentation, water reuse and well-developed treatment could augment the supply of water and thus increase resilience, although decrease reliance on susceptible surface water sources. The general technological focus of the water purification roadmaps is the multi-barrier methods of treatment with less chemical requirement and intensity of energy [46]. To be resilient to climate, the crucial question is whether a strategic technology can achieve water quality goals, or whether it is capable of achieving the goals under changing influent conditions, power outages, and broken chemical supply chains.

Managed Aquifer Recharge (MAR) increases the storage possibilities by treating aquifers as reservoirs and treating environments. According to [47], MAR is a state-of-the-art technology that is capable of underpinning stormwater harvesting, recycling water storage, and drought buffering. These benefits of resilience, however, rely on the hydrogeological aptness, regulatory governing, and monitoring to deal with risks like intrusion of pathogens, trace organics, and salinity. A cross-cutting challenge is that the interventions aimed at water resilience can displace the risk, such as by raising the energy demand used in the process of desalination, or by raising the dependence on digital control. Therefore, the combination of energy system resilience with evaluation is considered to be even more significant [48, 5].

### E. Energy systems: Resilient architectures and operational intelligence

The problem of energy resilience has emerged as a focal point of climate resilience as disruptions in power systems ripple through water, health, transportation, and communications sectors. Extreme weather may also pose a risk to the integrity of generation and transmission infrastructure, and heatwaves may impact demand and equipment efficiency at the same time [8].

The concept of resilience continues to be differentiated in the literature from traditional reliability measures, with a primary focus on performance during and post-cataclysmic occurrences and the worth of both hardening and smart operation procedures [49]. Distributed energy resources and microgrids are also notable technologies since they can work in islanded conditions and can also serve critical loads during system-wide power interruptions. Reviews on microgrid modeling and operations as a strategy to improve resilience are presented by [9], where [50] provide a holistic approach that clearly connects threats, vulnerabilities, and mitigation strategies, including cyber-physical aspects.

The critical point is that microgrids do not necessarily need to be resilient by default: The control systems, the fuel supply chains, and the protection schemes should be tailored to operate under the most extreme of conditions. In terms of applied science, resilience is based on (i) component robustness (inverter behavior in abnormal conditions), (ii) operational policy (load shedding, black start, crew dispatch), and (iii) institutional policy that would allow islanding and cost recovery. It is a socio-technical rather than purely technical challenge because of these requirements.

High penetrations of variable renewables can both reduce emissions and increase vulnerability to certain hazards unless paired with storage, flexible demand, and robust grid-forming capabilities. Decarbonization and resilience are increasingly intertwined. The emerging research focuses on co-optimizing reliability, resilience, and decarbonization, rather than treating them as separate objectives [8, 49].

#### F. Coastal and ecosystem protection through a hybrid grey-green approach

Coastal systems concentrate exposure and are subject to compound hazards: Storm surge, waves, sea-level rise, and river flooding. Ecosystem-based approaches have transitioned from “soft” alternatives to recognized engineering options when properly designed and monitored [51]. A key strength of nature-based and hybrid defenses is their multi-functionality. Mangroves, salt marshes, and reefs can reduce wave energy and attenuate surge while also providing habitat and carbon sequestration. [52] synthesize field measurements and project costs, finding that certain habitat restorations can be cost-effective relative to grey structures for comparable wave attenuation within limits. [33] quantify avoided flood damages by coastal wetlands during Hurricane Sandy, providing a concrete example of risk reduction value that is meaningful for insurers and planners. Empirically, wetlands have been shown to be capable of reducing property loss by a measurable amount during a tropical cyclone at the property level [15].

People and property can also be protected by coastal ecosystems due to the sea-level rise and storms, but these advantages are subject to local geomorphology and ecosystem state [53]. Scaling must hence entail governance and stewardship systems that ensure that the ecosystems remain healthy with time.

Notably, climate change does not ensure the protection performance of ecosystems. Rise in the sea level, changes in sediment supply, and degradation of the ecosystem are a few ways in which it can be compromised. As a consequence, one of the current research break-even points in the applied-science research is the integration of ecological dynamics, in particular, with engineering performance models that create so-called hybrid solutions, living shoreline, reefs with breakwaters, or marsh restorations with setback levees that can sustain sustainability as conditions change [52, 51].

#### G. Food and agriculture: Climate-smart, data-enabled, and controlled environments

The anthropogenic issue of climatic effects on food systems manifests in the form of yield variability, heat stress, water scarcity, pests, and supply networks discontinuity. The Climate-Smart Agriculture (CSA) framing directly focuses on a threefold agenda, namely productivity, adaptation/resilience, and mitigation [54]. Although CSA represents a broad conceptual framework, numerous tangible technologies fall under its scope, including precision irrigation, enhanced water retention in soil, breeding of drought-resistant organisms, and data-oriented decision support.

Regarding resilience, a consistent conclusion across global assessments is that food systems must increase production while simultaneously reducing environmental pressure. This has been an incentive to study the closing of yield gaps, resource-efficient production, and sustainable intensification [55, 56]. Meanwhile, climate change effects on food security do not exist solely on the biophysical plane; they have an interaction with the markets

and livelihoods [57].

Climate change impacts on crops have already been observed in global production patterns, understanding the importance of adaptive management strategies [58]. The core technology directions of breeding and genomics apply in the area of drought tolerance; combined strategies involve connecting performance within water stress and physiological characteristics with molecular technologies [59].

With digital technology, agricultural resilience is rapidly evolving. Yield prediction, stress detection, and targeted management are more actively being performed with the help of machine learning and deep learning with references to remote sensing and on-farm measurements [60, 61]. Such tools have the potential to enhance situational awareness in case of a drought or heatwave, but they also lead to a new set of issues: what is the quality of data, what is the bias, and what is the possibility of increasing inequities in places where there is limited connectivity and data access.

Another approach to climate resilience through vertical farming and controlled-environment agriculture is that these systems decouple food production from climatic variability. [62] claim that efficient water use and urban food security can be achieved by controlled environments, although the strategy is limited by energy requirements and carbon intensity of electricity, once again bringing up the necessity to consider adaptation and mitigation together.

#### H. Digital technology: Forecasting, monitoring, and digital twins for resilient operation

Digital technologies are cross-cutting enablers across domains: They do not substitute physical interventions, but they can render portfolios more effective by providing an opportunity to anticipate and exercise more adaptive control. The rapid developments around remote sensing, inexpensive sensors, and machine learning have enlarged the set of tools to be able to make early warning and operational decisions.

Deep learning models have demonstrated good performance in rainfall runoff modeling in hydrology, which provides a chance to enhance flood forecasting given proper validation and characterization of uncertainty [10]. Likewise, machine learning surveys demonstrate that there is an increasing body of evidence about the flood prediction problem, although there are also problems of overfitting, non-stationarity, and even trans-basin and cross-climate transferability [35].

Digital twins are an emerging concept in infrastructure and cities: a continuously updated digital representation of an asset or system that can support monitoring, scenario analysis, and control. Urban analytics has used the term to describe the coupling of models, data, and decision-making at the city scale [63]. In construction and infrastructure, research suggests value in integrating sensor data, physics-based models, and decision support in one framework [34, 64]. For climate resilience, the key future challenge is linking digital twins with climate-hazard projections and stress-testing workflows, so they remain useful under changing climatic baselines.

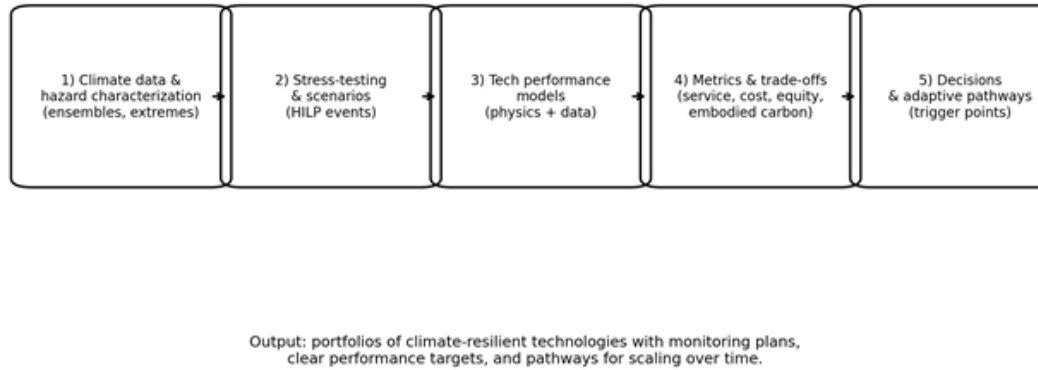


Fig. 3. Practical evaluation workflow for choosing and scaling climate-resilient technologies under deep uncertainty (author-generated)

### 1) Measuring performance: Metrics, trade-offs, and implementation constraints

One significant obstacle to scaling based on evidence is the absence of harmonized measures. Various studies show technology-specific performance (e.g., lower roof temperature, lower wave height, lower outage duration), but the decision makers require similar indicators that are used to decide on the portfolios. Measures of resilience must be clear in what service is being covered, and within what time scope, and what stressor is defining it [3, 4].

To adapt, cost-effectiveness alone is not sufficient. Technologies can have co-benefits (air quality, biodiversity, health) and trade-offs (water use, energy use, embodied carbon). One of the critical trends is therefore the in-

tegration of lifecycle thinking and resilience objectives - such as self-healing materials, which may reduce maintenance and embodied carbon over time despite incurring higher costs upfront, and nature-based solutions, which may provide broad co-benefits but require land and long-term stewardship [21, 52, 26].

Real-world performance can often be constrained by factors that belong to the realm of implementation. Permeable pavements and SuDS must be maintained to prevent clogging; microgrids must be granted regulatory permission and consider cybersecurity; desalination and reuse must be accepted by the population, and brine must be managed. These considerations indicate that technological maturity alone is not sufficient to determine readiness for climate resilience [12, 50].

TABLE II  
EXAMPLES OF MEASURABLE RESILIENCE PERFORMANCE INDICATORS ACROSS APPLIED DOMAINS (ILLUSTRATIVE)

Domain	Service-level metric	Typical data sources	Notes for interpretation
Buildings	Indoor heat index exceedance hours; peak cooling demand	Building sensors; weather stations; energy meters	Report baseline, occupancy, and outage conditions [65, 16].
Stormwater	Peak runoff reduction; time-to-drain; pollutant removal	Rain gauges; flow meters; water quality sampling	Maintenance status is a key confounder [25].
Energy	Outage duration for critical loads; unserved energy; recovery time	Utility outage logs; microgrid SCADA; asset condition data	Include cyber and fuel constraints [49, 9].
Coastal	Wave height reduction; avoided damages; overtopping frequency	Wave gauges; LiDAR/imagery; catastrophe models	Performance can degrade with ecosystem loss [52, 33].
Water	Specific energy consumption; treatment robustness under variable influent	Plant operating data; lab pilots; water quality monitoring	Consider energy-water coupling [30, 32]
Agriculture	Yield stability; water productivity; drought early-warning accuracy	Remote sensing; farm records; IoT sensors	Watch for data bias and access gaps [61].

### I. Future outlook and research agenda

Three near-term directions stand out across domains.

First, hybridization is becoming the default. Climate resilience rarely comes from purely grey or purely green solutions; rather, the most promising portfolios combine engineered components, nature-based processes, and digital monitoring/control. The coastal literature already frames this hybridization explicitly [52, 51], and analogous patterns are emerging in urban water (SuDS + sensors) and energy (microgrids + analytics).

Second, technologies are becoming increasingly adaptive rather than fixed in design. These comprise trigger-based investment decision paths [13], self-controlling and islanding in the energy system [49, 9], and smart data-driven operation optimization in water treatment and agriculture [45, 61].

Third, standards of evidence are increasing. With the growing influence of climate change, there is a rising demand among stakeholders for transparent performance indicators, open information, and reproducible assessments. For machine learning and digital twins, this implies robust validation under non-stationarity and careful treatment of uncertainty and bias [63, 10, 35]. For materials and nature-based systems, it implies long-duration monitoring and clarity about failure modes and maintenance requirements [52, 26].

Research priorities that would substantially advance the field include: (i) standardized stress-testing protocols for compound events (e.g., heat + outage + wildfire smoke), (ii) lifecycle assessment that jointly reports both resilience benefits and embodied carbon, (iii) methods to quantify distributional equity impacts of technology portfolios, and (iv) design guidance for hybrid systems that maintain performance as climate baselines shift.

TABLE III  
A PRAGMATIC RESEARCH AND DEPLOYMENT AGENDA FOR CLIMATE-RESILIENT TECHNOLOGIES (SYNTHESIS)

Need	Why it matters	Example directions
Stress-testing under deep uncertainty	Climate hazards are non-stationary; tails drive losses	DAPP and robust methods in sector toolkits [13, 14].
Long-term field evidence	Lab performance often differs from real-world aging and maintenance	Monitoring programs for SuDS, self-healing materials, PCMs and NBS [36, 25, 52, 26].
Harmonized metrics	Decision makers need comparable outcomes across options	Service-loss curves and recovery metrics [3, 4].
Energy–water–food nexus evaluation	Interdependencies create cascading failures	Coupled models of co-located systems [48, 5].
Equity and governance integration	Benefits and burdens are unevenly distributed	Metrics and participatory design aligned with urban resilience scholarship [11, 12].

### III. CONCLUSION

The technical domain of climate-resilient technologies is rapidly expanding within applied sciences; however, the field is most well established when it considers resilience to be a system property, but not a product feature. The most significant evidence is in favor of portfolios combining passive physical solutions (cool and green materials, thermal storage), distributed and flexible infrastructures (microgrids, diversified water supplies), nature-based or hybrid protections (wetlands and living shoreline), and digital capabilities (forecasting, monitoring, and decision support). Further development relies on the ability to establish comparable metrics, experimenting with technologies under the extremes of the compounds, and scaling solutions in a way that is maintainable, financeable, and equitable.

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