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Research article

Post-anthropocentric sustainable urban resilience: Reframing cities as human-nonhuman-artificial co-resilient systems

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Abstract: Background: Urban resilience scholarship is undergoing a fundamental paradigm shift, moving beyond anthropocentric frameworks that position human welfare as the sole measure of success and technology as a neutral instrument. Conventional resilience models remain anchored in anthropocentric assumptions that treat non-human ecological agents and artificial intelligence (AI) as passive instruments rather than co-constitutive participants in urban adaptive capacity. In this conceptual paper, I advance the theoretical understanding of post-anthropocentric co-resilience by reconceptualizing cities as hybrid assemblages where humans, non-human species, ecological processes, and AI function as interconnected agents within a unified system. Drawing on a synthesis of Social-Ecological-Technological Systems (SETS) theory, complexity science, posthumanist philosophy, and emerging scholarship on algorithmic governance, I developed a novel Triadic Co-Resilience Framework that identifies three mutually constitutive dimensions of urban adaptive capacity: biophysical, sociotechnical, and cybernetic. Methods: A thematic literature synthesis was conducted across Web of Science, Scopus, and Google Scholar, covering publications from 2015 to 2024. Sources were selected through systematic searching and citation tracking, with inclusion criteria requiring direct engagement with at least two of the three framework dimensions. Thirty-seven sources were retained for detailed coding and thematic analysis, organized around four analytic themes: Paradigm shifts, distributed agency, ethics and governance, and systemic fragility. Results: The analysis revealed that conventional resilience approaches systematically underestimate the contributions and vulnerabilities introduced by non-human actors, particularly as AI systems assume increasingly autonomous roles in urban sensing, decision-making, and resource allocation. Rather than enhancing resilience uniformly, AI integration can amplify systemic fragility when divorced from ecological and ethical co-resilience principles. I identified a paradox of artificial resilience, in which AI integration can simultaneously enhance and undermine urban adaptive capacity depending on whether ecological and ethical co-resilience principles are maintained. Conclusions: In this paper, I articulate a prioritized research agenda focused on operationalizing distributed agency, developing systemic accountability mechanisms for hybrid systems, and integrating multispecies justice into urban governance. Key priorities include empirical case studies in diverse urban contexts (including cities in the Global South with limited technological infrastructure), experimental governance pilots, and the development of measurable co-resilience indicators. This work contributes to sustainability science by providing conceptual tools for designing urban systems that can adapt, transform, and thrive as genuinely collaborative human-nonhuman-artificial endeavors.

Keywords: urban resilience; post-anthropocentrism; artificial intelligence; co-resilience; distributed agency; socio-ecological-technological systems; multispecies justice; smart cities; algorithmic governance; sustainability

1. Introduction

The concept of urban resilience has undergone considerable evolution since its initial borrowing from ecological systems theory in the 1970s [1–3]. Early formulations emphasized the capacity of urban systems to absorb disturbance and return to a prior equilibrium state, framing resilience primarily as a defensive property against external shocks [2,4]. This engineering-oriented perspective gradually gave way to more dynamic interpretations that recognized resilience as encompassing not only persistence but also adaptability and transformability [3,5–7]. Yet, even as these conceptualizations became more sophisticated, they remained anchored in a fundamentally anthropocentric worldview that positions human welfare as the objective, human institutions as the primary agents of change, and technology as a neutral tool subordinate to human intention [1,8,9].

The limitations of this anthropocentric framing have become increasingly apparent as cities confront the intertwined crises of climate change, biodiversity loss, and technological disruption [4,8,10,11]. Urban areas now account for over seventy percent of global carbon emissions and are simultaneously among the most vulnerable sites for climate impacts, including heat waves, flooding, and resource scarcity [10,12,13]. These challenges cannot be adequately addressed through human agency alone; they emerge from and are shaped by complex interactions among human populations, built environments, ecological systems, and increasingly autonomous technological networks [1,3,14]. The rapid proliferation of artificial intelligence (AI), digital twins, Internet of Things sensors, and algorithmic governance systems has introduced a new category of actors whose influence on urban dynamics rivals that of human decision-makers in scope and consequence [8,9,15,16].

In this paper, I develop a post-anthropocentric conceptualization of sustainable urban resilience that reframes cities as co-resilient assemblages of human, non-human, and artificial agents. The central thesis is that resilience in contemporary cities is not a property that humans possess or create but rather an emergent phenomenon arising from the dynamic interactions among diverse entities with varying degrees of agency, intentionality, and adaptive capacity [1,4,17]. This reconceptualization carries profound implications for urban planning, governance, ethics, and sustainability. If resilience is genuinely distributed across human and non-human actors, then conventional governance models predicated on human control and accountability require fundamental revision [9,14,18]. Similarly, justice frameworks that recognize only human interests must expand to accommodate the legitimate claims of ecological systems and, perhaps more controversially, AI whose actions affect urban welfare [19,20].

The paper proceeds as follows: In Section 2, I establish the theoretical foundations by tracing the evolution of resilience thinking and introducing the key conceptual resources for a post-anthropocentric approach. In Section 3, I describe the methodology employed in synthesizing the literature. In Section 4, I present a novel Triadic Co-Resilience Framework that organizes the key dimensions of distributed urban resilience. In Section 5, I report the findings from the literature review, organized thematically around distributed agency, ethics and governance, and systemic fragility. In Section 6, I discuss the implications of these findings and develop original insights regarding the paradoxes and possibilities of co-resilient urban futures. In Section 7, I articulate practical implications for urban planning. In Section 8, I: conclude the paper by identifying research gaps and proposing a prioritized agenda for future inquiry. Throughout, I attend to the political-economic dimensions of co-resilience, the limitations of the framework's applicability to diverse urban contexts, including cities in the Global South, and the technical limitations of AI systems that condition their contributions to urban resilience.

2. Theoretical background

2.1. The evolution of urban resilience thinking

The trajectory of urban resilience scholarship can be understood as a progressive broadening of ontological scope and epistemic ambition [5,21]. The first generation of resilience thinking, heavily influenced by engineering disciplines, conceptualized resilience as the ability of a system to return to equilibrium following disturbance [2]. This approach privileged stability, predictability, and rapid recovery as the hallmarks of a resilient system. Applied to cities, it manifested in efforts to harden infrastructure against known hazards and to develop response protocols that minimize disruption to normal functioning [22,23].

The second generation drew more explicitly on ecological systems theory, particularly the work of C.S. Holling and colleagues on adaptive cycles and panarchy [21,24]. This ecological resilience perspective emphasized that systems may have multiple stable states and that disturbances can trigger transitions between these states [3,24]. Rather than viewing change as inherently negative, this approach recognized that disturbance and reorganization are integral to long-term system persistence [5,24]. The implication for cities was a shift from protecting a single desired state to cultivating adaptive capacity that enables navigation through change [4,21,25].

The third and current generation extends this ecological framing to encompass social and technological dimensions, giving rise to the Social-Ecological-Technological Systems (SETS) paradigm [1,3,4]. SETS approaches recognize that contemporary cities are irreducibly hybrid entities where social dynamics, ecological processes, and technological infrastructures co-evolve in complex, often unpredictable ways [1,17]. This framework foregrounds the need for multi-level, polycentric governance structures that can respond to cross-scale interactions and emergent challenges [1,4]. Resilience, in this view, is neither a static property nor a purely human achievement but an emergent characteristic of the socio-ecological-technological assemblage [1,5].

2.2. Post-anthropocentric thought and distributed agency

The theoretical resources for a genuinely post-anthropocentric urban resilience take from several intellectual traditions that challenge the privileged position of human agency in accounts of social and material change [9,19]. Actor-network theory, as developed by Bruno Latour and others, proposes that agency is not an inherent property of humans but is instead distributed across networks of human and non-human actants [9,17]. In this view, technologies, natural phenomena, and material artifacts all exercise forms of agency by shaping the conditions of possibility for action and mediating the effects of other agents [9,17,18].

Posthumanist philosophy extends this critique by questioning the ontological boundaries separating humans from other entities [9,20]. Scholars in this tradition argue that the human subject is constituted through relations with non-human others, including animals, ecosystems, and, increasingly, AI [9,17]. Applied to urban contexts, posthumanism suggests that cities should be understood not as human creations that happen to contain non-human elements but as genuine multispecies and multi-agent assemblages in which human agency is one force among many [4,9,17].

The emergence of increasingly autonomous AI has added new urgency to these theoretical debates [8–10]. Contemporary AI systems do not merely execute human instructions; they learn, adapt, and make decisions that can deviate from and even contradict the intentions of their human designers [8,9,14]. In urban contexts, AI systems manage traffic flows, allocate emergency services, predict infrastructure failures, and optimize energy consumption with varying degrees of human oversight [14,15,26]. The question of whether and how to attribute agency, responsibility, and perhaps even moral status to these systems has moved from philosophical speculation to practical governance challenge [9,17].

2.3. Co-resilience as emergent property

The concept of co-resilience synthesizes insights from SETS theory, distributed agency, and complexity science to propose that resilience in hybrid systems is fundamentally relational and emergent [1,17]. Rather than residing in any single component or being produced through hierarchical control, co-resilience arises from the patterns of interaction, feedback, and mutual adjustment among diverse system elements [3,5]. This perspective draws on the complex adaptive systems theory, which emphasizes that system-level properties like resilience emerge from local interactions among heterogeneous agents following relatively simple rules [18,24].

For urban systems, co-resilience implies that the adaptive capacity of the city depends critically on the health and functioning of its non-human components, from urban forests and green infrastructure to water cycles and soil microbiomes [13,27]. It also depends on the reliability, interpretability, and ethical alignment of artificial systems that increasingly mediate urban functions [8,9]. Crucially, co-resilience is not simply additive; the interactions among human, ecological, and artificial components can produce synergies that enhance resilience beyond what any component could achieve alone, but they can also produce vulnerabilities and cascading failures that none of the individual components would exhibit in isolation [1,9,15]. To ground the analysis that follows, several key concepts require operational definition. Cybernetic agency, as used in this paper, refers to the capacity of artificial systems (including AI, algorithmic platforms, and sensor networks) to autonomously sense environmental conditions, process information, generate predictions, and initiate actions that materially alter urban dynamics, even when those actions were not explicitly programmed by human designers [8,14,28]. This definition acknowledges functional agency without making ontological claims about machine consciousness. Relational resilience refers to the adaptive capacity that emerges from the quality, diversity, and redundancy of relationships among heterogeneous urban actors (human, ecological, and artificial) rather than from the properties of any individual component [1,17]. In operational terms, relational resilience can be assessed through indicators such as network connectivity, feedback loop integrity, cross-dimensional coordination capacity, and the diversity of adaptive pathways available to the system. Systemic accountability denotes a governance approach in which responsibility for outcomes in hybrid systems is distributed across nodes of decision-making authority, with mechanisms for tracing the contributions of human, algorithmic, and ecological factors to specific outcomes and for identifying intervention points where corrective action is possible [9,14]. Unlike individual responsibility models, systemic accountability does not require identification of a single culpable agent but instead focuses on the structural conditions that enable or fail to prevent harmful outcomes.

3. Methodology

In this conceptual paper, I employed a literature synthesis designed to integrate scholarships across urban resilience, sustainability science, AI, posthumanist theory, and urban governance [23,29]. The synthesis was guided by three organizing questions: (1) How is the role of non-human and artificial actors conceptualized in current urban resilience frameworks? (2) What theoretical resources exist for developing post-anthropocentric approaches to urban resilience? (3) What are the key tensions, gaps, and unresolved challenges in integrating distributed agency into resilience thinking and practice?

Literature was identified through systematic searches of interdisciplinary databases, including Web of Science, Scopus, and Google Scholar, using search terms combining "urban resilience" with "artificial intelligence", "posthumanism", "multispecies", "distributed agency", "SETS", "socio-ecological-technological", and related concepts. To facilitate reproducibility, the principal search strings were: "urban resilience" AND "artificial intelligence"; "urban resilience" AND "posthumanism"; "urban resilience" AND "distributed agency"; "urban resilience" AND "socio-ecological-technological systems"; "urban resilience" AND "multispecies"; and "urban resilience" AND "smart city governance." Boolean AND operators were used to combine terms, and searches were run across title, abstract, and keyword fields in each database. The search was limited to publications from 2015 to 2024 to capture the most current theoretical developments while including foundational works identified through backward citation tracking. Searches were conducted iteratively across three rounds: An initial systematic search, a targeted search to fill conceptual gaps identified during preliminary reading, and a final round of citation tracking (forward and backward) to identify additional relevant sources. Explicit inclusion and exclusion criteria guided source selection. Sources were included if they: (a) Addressed urban resilience or urban sustainability as a primary topic; (b) engaged substantively with at least two of the three framework dimensions (biophysical, sociotechnical, or cybernetic); and (c) were published in peer-reviewed journals, edited volumes, or as institutional reports with demonstrated scholarly influence. Sources were excluded if they: (a) Addressed resilience only in non-urban contexts without transferable theoretical content; (b) were purely technical or engineering-focused without engaging governance, ethical, or ecological dimensions; or (c) were editorials, commentaries, or opinion pieces without substantive theoretical development. The quality and influence of each source was assessed using a combination of citation frequency (via Google Scholar), journal impact metrics, and expert judgment regarding theoretical contribution. Priority was given to sources that advanced novel theoretical frameworks, proposed integrative models, or identified critical tensions in the literature. A total of thirty-seven sources were retained for detailed analysis. While this number may appear modest, the selection reflects the intentional focus of a conceptual synthesis on depth of engagement rather than exhaustive coverage. Each source was analyzed in full rather than summarized from abstracts alone, enabling identification of nuanced arguments, implicit assumptions, and points of disagreement that a broader but shallower review might overlook.

For the analysis, I employed a thematic synthesis approach adapted for conceptual integration rather than empirical aggregation [23,29]. Initial coding identified key concepts, claims, and arguments within each source. These codes were then grouped into higher-order themes corresponding to the major sections of the results: Theoretical foundations, distributed agency, ethics and governance, and systemic fragility. Throughout this process, attention was given to points of agreement and disagreement among sources to identify emerging consensus and productive tensions that could inform original theoretical contributions. Particular care was taken to note where sources challenged or contradicted one another, as these disagreements often signaled conceptual boundaries requiring further theorization. To guard against selection bias, the coding scheme was reviewed after the first pass and refined to ensure adequate representation of critical and dissenting perspectives, including philosophical objections to extending agency or moral consideration to non-human entities. It should be acknowledged that this synthesis drew predominantly on English-language, Western-published scholarship, which constituted a limitation. Urban resilience in the Global South frequently depends on informal governance arrangements, community-driven strategies, and low-technology adaptation practices that are underrepresented in the databases searched. Where possible, sources addressing diverse geographical and socioeconomic contexts were included, but the analysis could not claim comprehensive global coverage. This limitation is discussed further in Section 6. The Triadic Co-Resilience Framework presented in Section 4 emerged from this synthetic analysis as a novel integrative structure not present in any single source but supported by convergent evidence across the literature.

4. Conceptual framework: The triadic co-resilience model

Based on the theoretical synthesis, I propose a novel Triadic Co-Resilience Framework for understanding and assessing urban adaptive capacity in post-anthropocentric terms. The framework identifies three interdependent dimensions of co-resilience: Biophysical, sociotechnical, and cybernetic. Each dimension encompasses distinct types of agents, processes, and vulnerabilities, but the framework emphasizes that resilience emerges from the interactions among dimensions rather than from any dimension in isolation.

4.1. Biophysical dimension

The biophysical dimension encompasses the non-human living systems and ecological processes that constitute the metabolic foundation of urban life [13,27]. This includes urban vegetation, wildlife populations, soil communities, hydrological cycles, atmospheric dynamics, and the countless microbial and invertebrate species that perform essential functions from decomposition to pollination [13,30]. These entities are not passive backdrop to human activity but active participants in urban resilience, providing ecosystem services such as stormwater management, air purification, urban heat mitigation, and food production [13,31].

From a co-resilience perspective, biophysical agents possess their own forms of adaptive capacity that can either complement or conflict with human resilience objectives [13,19]. Urban wildlife, for example, may thrive in conditions that humans find undesirable, while human interventions designed to enhance resilience (such as sea walls or channelized waterways) may degrade ecological functions that provide long-term adaptive benefits [10,27]. Recognizing the agency of biophysical systems requires acknowledging that their contributions to resilience are not fully controllable and that effective co-resilience strategies must work with rather than against ecological dynamics [13,19,32].

4.2. Sociotechnical dimension

The sociotechnical dimension encompasses the human social systems and their material-technological extensions that organize urban life [1,3]. This includes formal institutions of governance, economic markets, social networks, cultural practices, and the built infrastructures through which these social arrangements are enacted and reproduced [4,18]. In the SETS framework, the sociotechnical dimension is understood as irreducibly hybrid: Social relationships are always mediated by material and technological artifacts, while technologies are always embedded in social contexts that shape their development and use [1,3,4].

Human agency remains central to the sociotechnical dimension but is reconceptualized in relational terms [4,9,33]. Rather than autonomous individuals making free choices, humans are understood as embedded in networks of relationships with other humans, with material infrastructures, and increasingly, with artificial systems [9,17]. Sociotechnical resilience depends not only on the capacities of individual humans but on the quality of these relational networks, including their diversity, connectivity, and capacity for collective learning [4,18,34]. Community empowerment, social cohesion, and participatory governance emerge as key determinants of sociotechnical adaptive capacity [18,33].

4.3. Cybernetic dimension

The cybernetic dimension, a novel contribution of this framework, encompasses the AI, digital infrastructures, and algorithmic systems that increasingly mediate urban functions [14,35,36]. This includes smart city platforms, digital twins, Internet of Things sensor networks, predictive analytics, autonomous vehicles, and the machine learning algorithms that enable these systems to learn and adapt [8,15]. The term “cybernetic” is chosen deliberately to evoke the feedback-oriented, self-regulating character of these systems while acknowledging their integration with human and ecological components [28,37]. While the SETS paradigm recognizes technology as one of three interacting domains, it generally treats technological systems as infrastructure or tools serving human objectives [1,3]. The cybernetic dimension, by contrast, foregrounds the autonomous, adaptive, and feedback-driven behavior of AI and algorithmic systems, treating them as agents capable of independent learning and decision-making rather than as passive instruments. This distinction is consequential: It shifts analytical attention from what technologies do for human users to how algorithmic actors reshape urban dynamics on their own terms, introducing forms of agency, fragility, and ethical complexity that the standard SETS framing does not fully capture.

The cybernetic dimension introduces distinctive forms of agency, learning, and vulnerability into urban systems [8,28]. AI systems can process information at scales and speeds far exceeding human cognitive capacity, potentially enabling more rapid and precise responses to disturbance [15,28]. However, these systems also introduce new failure modes, including algorithmic bias, adversarial attacks, cascading infrastructure failures, and the brittleness that can result from optimization for narrow objectives [38]. Cybernetic co-resilience requires attention to interpretability (can humans understand system behavior?), redundancy (can functions be maintained when systems fail?), and reversibility (can harmful actions be corrected?) [14,28].

4.4. Interdimensional dynamics

The distinctive contribution of the Triadic Framework lies in its emphasis on the interactions among dimensions [17]. Biophysical-sociotechnical interactions include the ways human communities depend on and shape ecological systems, as studied in urban ecology and political ecology [13,27]. Sociotechnical-cybernetic interactions encompass the complex relationships between human institutions and AI systems, including questions of governance, accountability, and algorithmic justice [9,14,20]. Biophysical-cybernetic interactions, perhaps the least studied, involve the ways AI systems monitor, model, and intervene in ecological processes, from precision agriculture to wildlife tracking to climate modeling [8,15,39].

Co-resilience emerges from the overall configuration of these interdimensional relationships [1,5,17]. Positive configurations feature complementary adaptive capacities, effective feedback loops, and governance structures that enable coordination across dimensions [1,4,17]. Negative configurations feature misaligned objectives, broken feedbacks, and power asymmetries that enable one dimension to degrade the resilience of others [5,9,14]. The framework thus provides an analytical tool for assessing urban co-resilience and a normative orientation for designing governance arrangements that promote positive interdimensional dynamics. Critically, the framework also anticipates practical conflicts among dimensions that require active management. Biophysical and sociotechnical objectives may clash when, for example, wetland restoration for flood resilience conflicts with demands for developable land or when wildlife corridors intersect planned transportation routes [10,13,27]. Sociotechnical and cybernetic tensions arise when algorithmic optimization of resource allocation overrides community preferences or when automated decision-making erodes participatory governance norms [9,14]. Biophysical and cybernetic conflicts emerge when AI-driven monitoring systems prioritize quantifiable ecological metrics at the expense of harder-to-measure dimensions such as biodiversity or soil health [8,15]. Managing these conflicts requires explicit governance protocols that include: (a) Deliberative forums where representatives of each dimension (including proxies for ecological interests and AI system auditors) negotiate trade-offs transparently; (b) predefined thresholds and red lines that prevent any single dimension from being systematically subordinated; and (c) adaptive review mechanisms that reassess interdimensional priorities as conditions change [1,4,18].

5. Results

5.1. Theoretical foundations and paradigm shifts

The literature reveals a significant and accelerating shift from anthropocentric to post-anthropocentric frameworks in urban resilience scholarship. Foundational theories, including SETS and complex adaptive systems approaches, dominate the field, emphasizing the intertwined nature of social, ecological, and technological domains. These frameworks highlight adaptability, transformability, and distributed agency as core principles that supersede earlier emphases on stability and control. The SETS approach, in particular, foregrounds the need for multi-level, polycentric governance and explicitly recognizes resilience as an emergent property arising from interactions among diverse agents rather than a characteristic that can be engineered through top-down intervention.

However, the literature also reveals persistent tensions between post-anthropocentric theoretical commitments and anthropocentric analytical practices. Many studies that invoke SETS or distributed agency frameworks nonetheless default to human-centered metrics, governance models, and policy recommendations. The gap between theoretical acknowledgment of non-human and artificial agency and the practical integration of these actors into resilience assessment and planning represents a significant challenge for the field.

5.2. Distributed agency: Human, non-human, and artificial actors

Research documents the growing role of AI, digital twins, IoT networks, and autonomous systems as active agents in urban sensing, decision-making, and adaptation. These artificial actors do not merely implement human decisions; they interpret environmental signals, generate predictions, and, in some cases, take autonomous actions that shape urban dynamics in ways that may deviate from human intentions. Digital twin technologies now enable real-time monitoring and simulation of urban systems at unprecedented scales, creating new possibilities for anticipatory governance but also new questions about the relationship between model and reality.

This distributed agency challenges traditional governance models predicated on clear chains of human command and accountability. When an AI system makes a decision that affects thousands of residents, who bears responsibility if the decision proves harmful? The literature identifies this as a critical unresolved question, with few governance frameworks adequate to the challenge. The research also emphasizes the need for interpretability, redundancy, and reversibility in intelligent systems as safeguards against the risks of distributed artificial agency.

Regarding non-human biological actors, the literature increasingly recognizes that ecological agents from urban forests to microbial communities contribute actively to urban resilience rather than merely providing passive services. This recognition supports calls for multispecies approaches to urban planning that consider the needs and contributions of non-human species as legitimate factors in governance decisions. However, operationalizing multispecies agency in planning practice remains largely unexplored territory.

5.3. Ethics, justice, and governance beyond humans

A critical and contested theme in the literature concerns the extension of ethical and justice frameworks to include non-human and artificial entities. Some scholars argue for a graduated moral status for AI, robots, and ecological agents, moving beyond the binary of rights versus no rights toward a nuanced approach calibrated to the specific capacities and vulnerabilities of different entities. Others caution against too-rapid extension of moral consideration, warning that attributing agency or interests to artificial systems may obscure human responsibility and enable new forms of exploitation.

The automation of resilience decision-making raises pointed questions about participation, accountability, and the redistribution of power in smart cities. Algorithmic governance can enhance efficiency and consistency but may also entrench inequalities, exclude marginalized voices from decision processes, and create new forms of technocratic dominance. The literature identifies a need for governance models that preserve meaningful human participation while accommodating the distinctive contributions and risks of artificial agents.

Environmental and multispecies justice frameworks provide resources for extending ethical consideration to non-human biological actors. These frameworks argue that ecological systems and non-human species have legitimate claims to consideration in governance decisions, whether understood through intrinsic value, relational value, or instrumental value to long-term human and planetary flourishing. Nature-based solutions for urban resilience represent one practical manifestation of these principles, though implementation often remains anthropocentrically framed.

5.4. Fragility, failure, and co-resilience

While AI and smart technologies can enhance urban resilience in specific domains, the literature sounds significant warnings about increased systemic fragility if ethical and ecological co-resilience principles are not integrated. Algorithmic failures, whether due to biased training data, adversarial manipulation, or unforeseen edge cases, can cascade through interconnected urban systems with consequences that exceed the impact of failures in more isolated systems. Ecological degradation that undermines the biophysical foundations of urban life may proceed undetected when monitoring systems are optimized for narrow metrics. Infrastructure dependencies, particularly on digital and energy systems, create single points of failure that can disable resilience capacities precisely when they are most needed.

The literature emphasizes the need for redundancy, diversity, and adaptive capacity as counterweights to the fragility risks of tightly coupled socio-technical-ecological systems. Resilient systems maintain multiple pathways for critical functions so that failure in one pathway does not disable the system. They preserve diversity of agents, strategies, and resources that can be mobilized in response to novel challenges. Additionally, they cultivate adaptive capacity through learning, experimentation, and the capacity to reorganize in response to changing conditions.

Moreover, the question of moral and political responsibility in hybrid systems remains substantially underexplored. When failures occur in systems where agency is distributed across human, ecological, and artificial components, assigning responsibility becomes deeply challenging. The literature calls for new models of shared accountability that acknowledge the genuine contributions of non-human actors while preserving human capacity for meaningful oversight and correction. Several AI limitations warrant deeper analysis than the literature has provided to date. First, transparency and interpretability remain fundamental obstacles: Many high-performing AI systems operate as opaque decision-making processes whose internal logic cannot be meaningfully audited by the communities they affect [14,28]. This opacity is particularly problematic in resilience contexts, where understanding why a system recommended a particular course of action is essential for learning from successes and failures. Second, algorithmic bias poses systemic risks for urban equity. AI systems trained on historical data inevitably encode the structural inequalities in those data, potentially directing resources away from marginalized communities or underestimating the vulnerability of populations that are poorly represented in training datasets [9,14]. Third, cybersecurity vulnerabilities in interconnected urban AI platforms create single points of catastrophic failure. A compromised traffic management or emergency response system could disable critical resilience functions precisely during the crises when they are most needed [15,35]. Fourth, the dependence on high-quality, continuously updated data creates fragility in data-poor environments. Many cities, particularly in the Global South, lack the sensor infrastructure and data governance capacity required to support the AI systems envisioned in smart city frameworks [18,35]. These limitations suggest that cybernetic co-resilience strategies must incorporate robust fallback mechanisms, regular bias auditing, cybersecurity protocols, and realistic assessments of local data infrastructure before deploying AI-dependent resilience systems.

5.5. Claims and evidence summary

Table 1 summarizes the key claims identified in the literature review, the strength and nature of supporting evidence, and the primary sources for each claim.

Table 1. Key claims, supporting evidence, evidence strength, and identified research gaps from the literature review.

Claim	Type of evidence	Sources
Urban resilience is a distributed property of socio-ecological-artificial assemblages	Strong theoretical and conceptual support from SETS and complex adaptive systems literature	[1–5,8,17,18,24]
AI and digital twins are emerging as active agents in urban resilience	Multiple reviews and case studies document integration of AI and digital twins in urban systems	[8,9,14,15,28,35,38,39]
Ethical frameworks must expand to include non-human and artificial entities	Growing consensus in critical urban theory and posthumanist literature	[5,9,14,17,19,20]
Overreliance on AI can increase systemic fragility	Documented cases of algorithmic failure and theoretical warnings in resilience literature	[1,5,9,14,15,17]
Responsibility in hybrid systems is under-theorized	Few empirical studies address accountability in distributed agency contexts	[5,9,14,17,18,20]
Empirical research on co-resilience is limited	Most literature is conceptual or theoretical with few applied case studies	[1,3–5,17,24]

6. Discussion

As Table 1 indicates, the evidence base for post-anthropocentric urban resilience is predominantly theoretical and conceptual, with empirical validation remaining a critical gap across all major claims. The strongest evidential support exists for the foundational claim that resilience is a distributed property of socio-ecological-artificial assemblages, where converging theoretical frameworks from SETS, complexity science, and actor-network theory reinforce one another. By contrast, claims regarding accountability in hybrid systems and the practical governance of distributed agency rest on comparatively thin foundations, with few empirical studies testing proposed governance models. The absence of empirical research on co-resilience is particularly notable: While theoretical arguments for integrating biophysical, sociotechnical, and cybernetic dimensions are compelling, no researcher has attempted to measure co-resilience across all three dimensions in a real urban setting. The literature synthesis reveals a field in significant transition, moving from anthropocentric frameworks that position humans as the sole agents of resilience toward post-anthropocentric approaches that recognize cities as hybrid assemblages of human, non-human, and artificial actors [1,2,4]. This transition carries profound implications for theory, governance, and practice. In this section, I develop several original insights that emerge from bringing the reviewed literature into dialogue.

6.1. The paradox of artificial resilience

A central paradox emerges from the literature on AI and urban resilience: The same technologies that promise to enhance resilience can also undermine it [8,9,15]. AI systems can process vast amounts of information, detect patterns invisible to human observers, and respond to disturbances with speed and precision that human institutions cannot match [8,14]; yet, these capabilities come bundled with vulnerabilities that are qualitatively different from those of human or ecological systems [15]. AI systems are brittle in ways that natural systems are not; they can fail suddenly and completely when encountering conditions outside their training distribution, whereas ecological systems typically degrade more gracefully [9,14].

This paradox suggests that the relationship between AI integration and urban resilience is non-linear and context dependent. Modest AI integration that augments human decision-making while preserving redundant human and ecological capacities may enhance overall resilience. Aggressive AI integration that displaces human judgment, homogenizes responses, and creates dependencies on systems with hidden failure modes may reduce resilience even as it increases efficiency and apparent predictability [9]. The key variable may be not how much AI is integrated but how: Whether integration preserves diversity, redundancy, and reversibility or whether it creates brittle monocultures of algorithmic governance [9,28]. A concrete illustration is Barcelona's Superblocks program, which uses AI-driven traffic modeling to reroute vehicle flows around designated residential clusters. In this case, algorithmic optimization of traffic patterns has delivered measurable reductions in air pollution and noise while freeing street space for pedestrian and ecological use; yet, the same system has drawn criticism for redirecting congestion into lower-income peripheral neighborhoods whose residents have little input into the model's design parameters, illustrating precisely how AI integration can simultaneously enhance one dimension of urban resilience while undermining equity and sociotechnical co-resilience in another.

6.2. The accountability gap in distributed agency

The literature identifies a significant accountability gap arising from the distribution of agency across human and non-human actors [9,17]. Traditional governance and legal frameworks presuppose identifiable human agents who can be held responsible for decisions and their consequences [9,14]. When decisions emerge from complex interactions among humans, algorithms, and ecological processes, these frameworks struggle to assign responsibility in ways that enable learning and correction [9].

I propose that addressing this accountability gap requires moving from individual responsibility models to systemic accountability frameworks. Rather than seeking to identify the single agent responsible for an outcome, systemic accountability would assess the contributions of multiple agents, examine the interaction patterns that produced the outcome, and identify intervention points where human oversight could prevent similar outcomes in the future. This approach acknowledges the reality of distributed agency while preserving meaningful human capacity for governance and correction [9,17,40].

6.3. Multispecies justice and the limits of inclusion

The emerging literature on multispecies justice raises fundamental questions about the scope and limits of ethical inclusion in urban governance [9,19]. Extending moral consideration to non-human biological actors requires grappling with the incommensurability of interests across species and the impossibility of genuine consent or participation from non-human agents [19]. Unlike human justice frameworks that can at least aspire to include all affected parties in deliberation, multispecies frameworks must operate through human proxies whose interpretations of non-human interests are inevitably partial and potentially self-serving [13,19].

These challenges are amplified when considering artificial entities [9,20]. The question of whether AI systems can have interests that warrant moral consideration remains deeply contested [9]. Even setting aside metaphysical questions about machine consciousness, there are practical questions about whose interests AI systems represent and advance [9,14]. An AI system trained on historical data may encode and perpetuate the interests of past human agents, including their biases and blind spots [9,14]. Treating such systems as having independent interests worthy of consideration risks laundering human preferences through a technological veneer [14]. Thus, a significant philosophical objection to the framework advanced here must be acknowledged directly. Critics argue that extending the concept of agency to artificial systems conflates functional behavior (responding to inputs according to programmed or learned rules) with genuine agency (acting from intentions, interests, or purposes) [9,20]. From this perspective, attributing agency to AI naturalizes human design choices and obscures the human power structures that determine how algorithms operate, whose interests they serve, and whose welfare they may compromise. In this paper, I adopt a pragmatic rather than metaphysical position: Regardless of whether AI systems possess agency in a philosophically robust sense, they exercise functional influence over urban outcomes that governance frameworks must account for. The framework treats cybernetic agency as a descriptive category for planning and governance purposes, not an ontological claim about machine consciousness or moral status. This distinction is important because it enables the framework to address the practical governance challenges posed by autonomous algorithmic systems without committing to contested metaphysical positions about artificial minds.

6.4. Toward relational resilience

Synthesizing the reviewed literature, I propose relational resilience as a conceptual orientation for post-anthropocentric urban sustainability. Relational resilience shifts focus from the adaptive capacities of individual components (whether human, ecological, or artificial) to the quality of relationships among components [1,17]. A relationally resilient urban system is characterized by diverse and redundant connections among actors, effective feedback mechanisms that enable mutual adjustment, governance structures that facilitate coordination without imposing brittle centralization, and ethical frameworks that recognize interdependence while preserving accountability [1,4].

This relational orientation aligns with the Triadic Co-Resilience Framework presented in Section 4 by emphasizing interdimensional dynamics as the locus of resilience. Additionally, this suggests practical priorities for urban planning and governance: Investing in the interfaces and feedback mechanisms that connect biophysical, sociotechnical, and cybernetic dimensions; preserving diversity of actors and approaches rather than optimizing for single best solutions; and cultivating adaptive governance capacities that can respond to emergent challenges without requiring predictions of their specific form [1,17].

6.5. Political-economic dimensions of co-resilience

The Triadic Co-Resilience Framework, as developed above, must be within the political-economic structures that shape urban resilience in practice. Power asymmetries, economic inequality, and competing stakeholder interests fundamentally condition which dimensions of co-resilience receive investment and attention, and which are neglected [4,18]. Corporate interests in smart city technologies may drive cybernetic integration at the expense of biophysical investments that lack comparable profit potential [14,35]. Land development pressures may systematically subordinate ecological resilience to sociotechnical expansion [10,13]. Low-income communities and informal settlements, which often bear disproportionate exposure to climate risks, may be excluded from the governance processes that determine resilience priorities [18,33].

Recognizing these dynamics requires the framework to incorporate explicit attention to who benefits and who bears risk in co-resilience configurations. Moreover, the distribution of algorithmic authority, access to green infrastructure, and participation in governance processes are not merely technical questions; they are deeply political ones shaped by existing structures of economic and social power [4,9]. Effective co-resilience governance must therefore include mechanisms for redistributive justice, meaningful inclusion of marginalized stakeholders, and accountability structures that prevent resilience investments from reinforcing existing inequalities [18,20,33,41].

6.6. Generalizability and the global south

A significant limitation of this analysis and the broader literature it synthesizes concerns generalizability across urban contexts. The Triadic Co-Resilience Framework was developed primarily from scholarships rooted in high-income, technologically advanced urban settings where sophisticated AI platforms, extensive sensor networks, and robust digital infrastructure are present or plausible [8,15,35]. Cities in the Global South, however, frequently operate under conditions of limited financial resources, constrained technological infrastructure, weak institutional capacity, and different cultural-political traditions [42] that may render parts of the cybernetic dimension less immediately relevant [18,30,33].

This does not invalidate the framework, but it does require careful contextual adaptation. In many cities across sub-Saharan Africa, South Asia, and Latin America, urban resilience depends heavily on informal governance networks, community-based mutual aid systems, indigenous ecological knowledge, and low-technology adaptive strategies [33,43]. These practices embody principles of distributed agency and relational resilience that the framework endorses, even though they operate through social and ecological channels rather than digital ones. For example, Dhaka, Bangladesh, illustrates how co-resilience can operate through predominantly non-digital channels: Community-managed drainage committees in informal settlements coordinate flood response through mobile phone messaging networks and local ecological knowledge of monsoon water flows, effectively distributing agencies across human social networks and biophysical systems without relying on advanced AI infrastructure. Such cases demonstrate that the relational logic of the Triadic Framework applies even where the cybernetic dimension takes the low-technology form [27,30]. Future applications of the Triadic Framework should therefore treat the cybernetic dimension as scalable, ranging from advanced AI integration in well-resourced contexts to simpler digital tools, community information systems, or non-digital collective decision-making processes that fulfill analogous coordination functions. The framework's core insight, that resilience is relational and emergent across multiple dimensions of agency, holds across contexts even when the technologies involved differ substantially.

7. Implications for urban planning practice

The post-anthropocentric reconceptualization of urban resilience carries significant implications for planning practice [4,25]. While theoretical frameworks have advanced considerably, the translation of these frameworks into operational tools and governance arrangements remains nascent [4,17]. In this section, I identify priority areas where theory can inform practice.

7.1. Assessment and monitoring

In urban resilience assessments, researchers typically focus on human assets and capabilities, with ecological and technological factors treated as contexts or resources [23,44,45]. A co-resilience approach would expand the assessment to explicitly include the adaptive capacities of biophysical and cybernetic dimensions, using indicators that capture the health and functioning of urban ecosystems and the reliability and interpretability of AI systems [1,28,46]. Assessments would also attend to interdimensional dynamics, evaluating the quality of feedbacks and coordination mechanisms that enable mutual adjustment among components [1,5].

Furthermore, digital twin technologies offer promising platforms for integrated monitoring across dimensions [8,39]. However, their implementation must attend to the risks of creating additional dependencies on AI systems and of privileging quantifiable metrics over qualitative dimensions of resilience that resist measurement [35,39,47]. Participatory approaches that incorporate forms of knowledge, including traditional ecological knowledge and community-based monitoring, can complement technological monitoring while preserving the diversity of perspectives [4,33]. Concretely, a co-resilience assessment protocol should incorporate measurable indicators across all three dimensions and their interactions. Biophysical indicators might include urban canopy coverage ratios, permeable surface area percentages, biodiversity indices for key indicator species, and ecosystem service delivery rates for functions such as stormwater absorption and air quality regulation [10,13,27]. Sociotechnical indicators could encompass community participation rates in resilience planning, social network density in vulnerable neighborhoods, institutional response times to disturbance events, and equity metrics measuring the distribution of resilience investments across income groups [4,18,33]. Cybernetic indicators should track AI system uptime and reliability, algorithmic bias audit results, data quality and coverage metrics, cybersecurity incident rates, and the availability of manual override and fallback procedures [14,15,28]. Interdimensional indicators, perhaps the most novel contribution, would assess the functionality of feedback loops connecting dimensions, the frequency and quality of cross-dimensional governance deliberations, and the speed of coordinated response when disturbances affect multiple dimensions simultaneously.

7.2. Governance design

The SETS literature consistently emphasizes the need for polycentric, adaptive governance structures that can respond to cross-scale interactions and emergent challenges [1,24]. Polycentricity involves multiple, overlapping centers of decision-making authority rather than a single hierarchical structure [4,24]. This arrangement enables experimentation and learning while providing redundancy against failures in any single governance node [18,24].

Incorporating AI into polycentric governance requires careful attention to the distribution of algorithmic authority and the preservation of human oversight [9,28]. AI systems should augment rather than replace human decision-makers, with clear mechanisms for human review and override of algorithmic recommendations [9,14]. Transparency requirements should ensure that AI decision processes are interpretable to affected parties, enabling meaningful participation and accountability [28]. Governance arrangements should also attend to the representation of non-human interests, whether through designated advocates, environmental impact requirements, or other mechanisms that bring ecological considerations into deliberation [13,19]. An actionable implementation pathway for co-resilience governance would proceed through three phases. In the first phase (institutional foundation), cities would establish cross-departmental co-resilience task forces that bring together urban planning, environmental management, IT and data governance, and community engagement functions under a shared mandate. In the second phase (pilot integration), cities would select two or three defined urban zones for experimental co-resilience governance, deploying integrated monitoring across biophysical, sociotechnical, and cybernetic dimensions while establishing deliberative forums for interdimensional conflict resolution. In the third phase (scaling and adaptation), successful governance models would be refined based on pilot outcomes and extended across the city, with built-in review cycles that enable periodic reassessment of interdimensional priorities as urban conditions evolve [1,4,24].

7.3. Infrastructure investment

Infrastructure investment decisions have shaped urban resilience for decades, making them critical leverage points for implementing co-resilience principles [22,44]. A co-resilience approach would prioritize investments that enhance interdimensional synergies, such as a green infrastructure that provides ecological and human benefits, or smart systems that enhance monitoring while preserving redundant manual capacities [10,30]. Investment decisions would also attend to fragility risks, avoiding over-reliance on single technologies or centralized systems that create catastrophic failure modes [9,14].

Nature-based solutions represent particularly promising investments from a co-resilience perspective [27,30]. Green roofs, urban forests, permeable pavements, and restored wetlands can provide multiple resilience functions simultaneously while enhancing, rather than degrading, biophysical adaptive capacities [10,30]. These investments also tend to be more robust to failure than engineered alternatives, degrading gradually rather than failing catastrophically [10,27]. Integrating nature-based solutions with smart monitoring can combine the robustness of ecological systems with the precision of digital technologies [8,27,39].

8. Conclusion and future directions

This paper has advanced a post-anthropocentric reconceptualization of sustainable urban resilience, positioning cities as co-resilient assemblages of human, non-human, and artificial agents. The Triadic Co-Resilience Framework identifies biophysical, sociotechnical, and cybernetic dimensions of urban adaptive capacity while emphasizing that resilience emerges from the interactions among these dimensions rather than from any dimension in isolation. The literature synthesis reveals significant theoretical progress toward post-anthropocentric approaches but also persistent gaps between conceptual innovation and practical implementation.

Several contributions emerge from this analysis. First, the identification of the paradox of artificial resilience highlights the non-linear relationship between AI integration and urban adaptive capacity, cautioning against uncritical enthusiasm for smart city solutions while identifying conditions under which AI can genuinely enhance co-resilience. Second, the concept of systemic accountability offers a path forward for governance in contexts of distributed agency, preserving meaningful human oversight without requiring identification of single responsible agents. Third, the relational resilience orientation provides a unifying conceptual framework that directs attention to the quality of relationships among urban components as the primary determinant of adaptive capacity.

8.1. Research gaps and future agenda

In the literature review, I identify several critical gaps that researchers must address. Moreover, empirical research on the practical implementation of post-anthropocentric resilience frameworks remains limited; most scholarships operate at theoretical or conceptual levels [1,17]. Case studies that document how distributed agencies oeprate in urban contexts, including the interactions among human institutions, ecological systems, and AI platforms, are urgently needed. Research on accountability mechanisms for hybrid systems is particularly limited [9,14]. Moreover, experimental governance arrangements that test different approaches to systemic accountability could help in the development of practical tools (Table 2).

Furthermore, the integration of multispecies justice into urban governance presents conceptual and practical challenges that remain largely unaddressed [13,48]. In future studies, researchers should explore mechanisms for representing non-human interests in planning processes, methods for assessing trade-offs among human and non-human welfare, and approaches for resolving conflicts when human and non-human resilience objectives diverge. Similarly, the ethical status and appropriate treatment of increasingly autonomous AI systems require sustained interdisciplinary inquiries that bring computer scientists, ethicists, urban planners, and affected communities together [9,49,50] (Table 3).

Table 2. Research coverage and gaps across key topics.

Topic	Empirical studies	Theoretical work	AI/Artificial agency	Multispecies justice	Governance models
Distributed agency	2	8	6	1	4
Co-resilience	3	7	4	2	3
AI/Tech fragility	1	5	7	GAP	2
Ethics/Justice	1	6	2	5	3
Accountability	GAP	3	1	GAP	2

Table 3. Priority research questions for advancing post-anthropocentric urban resilience.

Research question	Rationale
How can distributed agency among human, non-human, and artificial actors be operationalized in urban resilience planning?	Operationalizing distributed agency is essential for moving from theory to practice and ensuring effective co-resilience in real-world cities.
What governance models best ensure accountability and ethical decision-making in AI-mediated urban systems?	New governance models are needed to address power, participation, and responsibility in hybrid socio-ecological-artificial assemblages.
How can multispecies and artificial justice frameworks be integrated into urban sustainability policies?	Integrating justice for non-human and artificial entities is crucial for equitable and sustainable urban futures.
What conditions determine whether AI integration enhances or undermines urban co-resilience?	Understanding the paradox of artificial resilience is essential for avoiding fragility while capturing benefits of smart city technologies.
How can systemic accountability frameworks be designed and implemented for hybrid urban systems?	Addressing the accountability gap is essential for maintaining meaningful human oversight while acknowledging distributed agency.

8.2. Closing reflection

The post-anthropocentric reframing of urban resilience represents more than an academic exercise; it reflects the material realities of cities in the Anthropocene. Urban areas are hybrid assemblages where human intentions interact with ecological dynamics and algorithmic processes in ways that no single actor controls or fully comprehends. Recognizing this reality is the first step toward governance arrangements that can navigate the complexity of contemporary urban challenges.

The path toward co-resilient urban futures requires humility about human capacities for prediction and control, respect for the contributions of non-human actors, vigilance about the risks introduced by artificial systems, and commitment to governance structures that preserve accountability while acknowledging interdependence. Three innovations distinguish this paper's contribution to the field. First, the identification and analysis of the paradox of artificial resilience moves beyond binary framings of AI as either savior or threat, instead specifying the conditions (preservation of diversity, redundancy, and reversibility) under which AI integration enhances rather than undermines adaptive capacity. Second, the concept of systemic accountability provides a governance mechanism suited to conditions of genuinely distributed agency, moving past the conceptual impasse created by trying to force hybrid systems into individual-responsibility frameworks. Third, the operationalized definitions of cybernetic agencies, relational resilience, and systemic accountability offered here provide testable constructs that can anchor future empirical research, bridging the persistent gap between conceptual sophistication and measurement practice in the field. Looking ahead, the most pressing need is for collaborative research programs that bring together urban planners, ecologists, computer scientists, ethicists, and community stakeholders to co-design and test co-resilience governance arrangements in real urban settings. Such programs should deliberately include cities across economic, technological, and cultural contexts to ensure that the resulting frameworks serve genuine global needs. By reframing resilience as a distributed, emergent property of human-nonhuman-artificial assemblages, this paper provides conceptual foundations for scholarships and practices oriented toward genuinely sustainable urban futures.

Use of AI tools declaration

The author declares he has not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The author declares there is no conflict of interest.

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