

From Hazard to Intervention: A Global Systematic Evidence Synthesis of Spatially Targeted Nature-Based Solutions for Urban Climate Resilience

Abdurahman Abba Goni¹; Mustapha Shettima²; Mohammed Buba³

¹Department of Environmental Science, Sharda University, Greater Noida, India

²Department of Environmental Science, Integral University, Lucknow, India

³Department of Microbiology, Yobe State University, Damaturu, Nigeria

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Abstract: In urban areas, a range of hazards are being exacerbated by climate change, such as extreme heat, flooding, drought and air pollution. Spatial solutions like NbS (Sustainable Urban Drainage Systems, green spaces, urban forests and wetlands) provide effective solutions to mitigate these risks with multiple functions and low costs. But knowledge of where and when, and who, such interventions work best is still incomplete. This review is a systematic review of the literature that followed the PRISMA 2020 guidelines and included peer-reviewed studies published between January 2010 and December 2024. The systematic search in the Scopus, Web of Science, ScienceDirect, MDPI and Google Scholar databases resulted in a total of 4,827 articles, with 102 articles found to be eligible. The included studies were evaluated using the Mixed Methods Appraisal Tool (MMAT) and synthesized based on the climate hazards, NbS types, spatial-targeting methods, and resilience outcomes. The results revealed that the field of study has experienced rapid growth as 68% of the studies have been published after the year 2019. The evidence, however, was geographically focused in Europe (38%), Asia (27%) and North America (18%) with only 6% in Africa. The majority of green infrastructure was urban, with blue infrastructure coming in at 19% and SuDS at 14%. GIS overlay, multi-criteria decision analysis, and heat-vulnerability indices were the main spatial-targeting approaches. Green infrastructure reduced the surface temperature by a median of 2.1°C, and SuDS reduced peak runoff by 30-60%. Although there are several co-benefits, only 17% of studies were evaluated for equity. The review draws attention to the following key areas: (i) standardized reporting, (ii) increased research in the Global South, (iii) more systems to evaluate NbS from an equity perspective, (iv) more long-term monitoring, and (v) more NbS integration into urban planning and governance.

Keywords: Climate Adaptation; Ecosystem-Based Adaptation; Geographic Information Systems; Nature-Based Solutions; Spatial Targeting; Urban Resilience; Vulnerability Mapping.

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I. INTRODUCTION

More than half of the world's population now lives in urban areas, and this proportion is projected to rise to nearly 70 percent by 2050 (United Nations, 2019). Cities are simultaneously the principal engines of greenhouse-gas emissions and the places where the consequences of climate change are most acutely felt. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022) concludes with high confidence that urban areas will experience compounding climate hazards — including more frequent and intense heatwaves, pluvial and fluvial flooding,

coastal storm surge, drought-induced water stress, and degraded air quality — over the coming decades. These hazards rarely occur in isolation; their cascading and interacting effects place disproportionate burdens on low-income communities, older adults, children, and outdoor workers (Pörtner et al., 2022; UNDRR, 2022).

Conventional engineering responses to urban climate hazards — concrete seawalls, drainage pipes, and air-conditioned refuges — tend to be single-purpose, capital-intensive, and carbon-intensive in their construction. They also frequently generate lock-in effects that preclude adaptive

management under deep uncertainty (Hallegatte et al., 2012; Kabisch et al., 2016). Nature-based solutions (NbS), defined by the International Union for Conservation of Nature (IUCN) as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016, p. 13), have emerged as a complementary paradigm. NbS encompass a broad family of interventions, including urban green and blue infrastructure, sustainable urban drainage systems (SuDS), green roofs and walls, urban forests, mangrove restoration, and hybrid grey-green engineering (Seddon et al., 2020; Maes & Jacobs, 2017).

A growing body of empirical work indicates that well-designed NbS can reduce surface and air temperatures by 1–4 °C, attenuate peak stormwater flows by 30–60 percent, sequester carbon, support biodiversity, and improve mental and physical health (Bowler et al., 2010; Demuzere et al., 2014; Kabisch et al., 2015; Ruangpan et al., 2020). However, the magnitude of these benefits is highly context-dependent and varies with the type, scale, and configuration of the intervention, as well as the underlying climatic, topographic, and socio-economic setting. The same green roof that delivers strong cooling in a temperate continental city may underperform in an arid climate where irrigation water is scarce (Santamouris, 2014; Manoli et al., 2019). This context-dependence has motivated a shift in the literature from generic advocacy of NbS toward spatially explicit approaches that match the right intervention to the right place.

Spatial targeting refers to the deliberate use of geographic information, vulnerability assessment, and multi-criteria analysis to prioritise locations where NbS will deliver the greatest hazard-reduction and co-benefit returns (Raymond et al., 2017; Geneletti & Zardo, 2016). The rationale is twofold. First, climate hazards are spatially heterogeneous: urban heat islands, pluvial flood hotspots, and storm-surge exposure zones each follow distinct spatial logics shaped by land cover, topography, building morphology, and proximity to water bodies (Stewart & Oke, 2012; Oke et al., 2017). Second, the populations most exposed to these hazards are also spatially uneven, with low-income and historically marginalised communities frequently concentrated in higher-risk areas (Wolch et al., 2014; Anguelovski et al., 2016). Spatial targeting therefore offers an opportunity to integrate efficiency (maximising risk reduction per unit investment) and equity (prioritising vulnerable populations) into NbS planning (Frantzeskaki, 2019; Sowińska-Świerkosz & Garcia, 2022).

Despite this promise, the global evidence base on spatially targeted NbS remains fragmented. Studies are spread across the urban planning, hydrology, ecology, public health, and climate-impact literatures, use heterogeneous definitions and methods, and exhibit pronounced geographic biases toward European and North American cities (Kabisch et al., 2016; Bush & Doyon, 2019). Few systematic syntheses have explicitly examined the spatial-targeting dimension, and even fewer have integrated hazard-side and outcome-side

evidence across multiple climate hazards and NbS typologies. Recent reviews have either focused on a single hazard (e.g., Ruangpan et al., 2020 on hydro-meteorological risks; Bowler et al., 2010 on urban heat) or a single intervention category (e.g., Filazzola et al., 2019 on green roofs), leaving a gap for a multi-hazard, multi-intervention synthesis that explicitly interrogates how spatial targeting is conceptualised, operationalised, and evaluated.

➤ *Research Objectives and Questions*

Against this backdrop, this paper presents a PRISMA 2020-compliant systematic review of the peer-reviewed literature on spatially targeted NbS for urban climate resilience, published between January 2010 and December 2024. The review pursues three specific objectives: (i) to map the global distribution, methodological approaches, and thematic emphases of empirical research on spatially targeted NbS; (ii) to synthesise the effectiveness evidence for spatially targeted NbS across major urban climate hazards; and (iii) to identify the social-ecological, governance, and equity factors that condition the implementation and outcomes of such interventions.

The review is guided by four research questions. First, what is the global geographic and disciplinary distribution of empirical research on spatially targeted NbS for urban climate resilience, and what gaps emerge? Second, what methods and analytical frameworks are used to identify target locations for NbS, and how do these methods vary across hazards and intervention types? Third, what is the documented effectiveness of spatially targeted NbS in reducing exposure to urban heat, flooding, coastal storms, and compound hazards? Fourth, what co-benefits, trade-offs, and equity implications accompany the implementation of spatially targeted NbS, and how are they evaluated? In addressing these questions, the paper seeks to provide a consolidated, action-oriented evidence base for researchers, urban planners, and policymakers working at the intersection of climate adaptation, ecosystem stewardship, and spatial planning.

II. MATERIALS AND METHODS

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (Page et al., 2021). The review protocol was developed prospectively and is summarised below; deviations from the protocol during screening and data extraction are documented in Section 2.6. The PRISMA flow diagram (Figure 1) summarises the identification, screening, eligibility, and inclusion process.

➤ *Eligibility Criteria*

Eligibility criteria were specified using the PICOS (Population, Intervention, Comparator, Outcomes, Study design) framework. The population of interest was urban areas, defined as continuously built-up settlements with at least 5,000 inhabitants and a population density exceeding 1,000 persons per square kilometre, in line with OECD/Eurostat definitions. The intervention of interest was

any nature-based solution deployed with explicit spatial targeting intent — that is, where the location of the intervention was determined by an analytical process that considered hazard exposure, vulnerability, ecosystem service demand, or equity criteria. Comparators, where present, included pre-intervention conditions, alternative grey infrastructure, or no intervention. Outcomes of interest included biophysical hazard-reduction metrics (e.g., temperature reduction, peak flow attenuation, storm-surge attenuation), ecological co-benefits (e.g., biodiversity, carbon sequestration), and social outcomes (e.g., health, equity, governance). Eligible study designs included empirical field studies, modelling studies, spatial analyses, and mixed-methods evaluations. Editorials, opinion pieces, and purely conceptual papers without empirical data were excluded.

Studies were restricted to peer-reviewed journal articles published in English between 1 January 2010 and 31 December 2024. The 2010 start date corresponds to the consolidation of the NbS concept in the European research-policy agenda and to the publication of foundational systematic reviews on urban green infrastructure (e.g., Bowler et al., 2010). Grey literature, conference proceedings, and book chapters were excluded to maintain quality and reproducibility, although seminal IUCN and IPCC documents were retained for definitional and contextual purposes.

➤ *Information Sources and Search Strategy*

Five bibliographic databases were systematically searched: Scopus, Web of Science Core Collection, ScienceDirect, MDPI, and Google Scholar (for the first 200 records per query, used only for cross-validation). Searches were executed between 12 January and 4 February 2025. The search strategy combined three blocks of terms using Boolean operators: (i) hazard block — "urban heat" OR "heat island" OR flooding OR "storm surge" OR drought OR "air pollution"; (ii) intervention block — "nature-based solutions" OR "green infrastructure" OR "blue infrastructure" OR "urban forest*" OR "green roof" OR "green wall" OR "bioswale" OR "rain garden" OR "permeable pavement" OR mangrove OR "sustainable urban drainage"; and (iii) spatial-targeting block — "spatial targeting" OR GIS OR "multi-criteria" OR "vulnerability mapping" OR "hotspot" OR "priority setting" OR "site selection". The full Boolean strings were adapted to the syntax requirements of each database and are documented in Supplementary Material S1.

Manual backward and forward citation tracking of the 25 most-cited included studies was performed to identify additional relevant records. Where key reviews were identified (e.g., Kabisch et al., 2016; Ruangpan et al., 2020; Sowińska-Swierkosz & Garcia, 2022), their reference lists were scanned for studies missed by the database searches. This iterative process yielded 142 additional records, of which 38 ultimately met the inclusion criteria.

➤ *Selection Process and Screening*

All records retrieved from the database searches were exported to a shared EndNote 21 library and de-duplicated. The remaining records were imported into the Rayyan

systematic review platform for title-and-abstract screening. Two reviewers (AAG and MS) independently screened each record against the eligibility criteria, with disagreements resolved through discussion or, where necessary, arbitration by a third reviewer (MB). Inter-rater agreement on a random 10 percent subsample was almost perfect (Cohen's $\kappa = 0.81$). Full-text retrieval was attempted for all records marked as potentially eligible; full texts that could not be obtained through institutional access were requested from corresponding authors and, if unavailable within four weeks, were excluded.

Full-text screening was conducted independently by the same two reviewers using a standardised form piloted on ten studies. Reasons for full-text exclusion were recorded and are summarised in the PRISMA flow diagram (Figure 1). The most frequent exclusion reasons at the full-text stage were insufficient spatial-data reporting (37% of exclusions), absence of resilience or hazard-reduction outcomes (27%), and review or opinion articles without primary data (18%).

➤ *Data Extraction*

Data extraction was performed using a piloted standardised form in Microsoft Excel. For each included study, the following fields were extracted: bibliographic information (authors, year, journal, DOI); study location (city, country, continent, climate zone per Köppen–Geiger classification); hazard(s) addressed; NbS typology (green, blue, hybrid, coastal, SuDS); spatial-targeting method(s) used (GIS overlay, multi-criteria decision analysis, vulnerability index, optimisation, participatory mapping); study design (observational, experimental, modelling, mixed); sample size or modelled area; intervention dosage (e.g., canopy cover, green-roof area, mangrove width); reported outcomes (biophysical, ecological, social, economic); effect sizes where reported; co-benefits and trade-offs; equity considerations; and governance arrangements. Data extraction was performed by one reviewer and verified by a second; discrepancies were resolved through consensus.

➤ *Quality Appraisal*

Methodological quality of included studies was appraised using the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018), which permits concurrent appraisal of qualitative, quantitative, and mixed-methods studies across five criteria per study design. Each study was rated on each applicable criterion as "yes", "no", or "can't tell". Studies meeting fewer than three of five applicable criteria were flagged as low quality and were retained for descriptive synthesis but excluded from effect-size aggregation. Of the 102 included studies, 78 met four or five criteria, 18 met three, and six met fewer than three. No study was excluded solely on the basis of MMAT score, in line with current guidance against the use of quality scores for study exclusion (Hong et al., 2018).

➤ *Synthesis Methods*

Given the methodological heterogeneity of the included studies spanning field measurements, remote-sensing analyses, hydrological and climate modelling, and qualitative case studies — a quantitative meta-analysis was not

appropriate for all outcomes. We therefore adopted a structured narrative synthesis approach following the Synthesis Without Meta-Analysis (SWiM) guideline (Campbell et al., 2020). For outcomes with sufficient quantitative homogeneity (notably surface-temperature reduction from urban green infrastructure and peak-flow attenuation from SuDS), we computed median effect sizes and interquartile ranges across studies reporting comparable metrics. Synthesis was structured around four analytical dimensions: (i) study characteristics (geographic and temporal distribution, disciplinary orientation); (ii) hazard types and NbS typologies; (iii) spatial-targeting methods and

their integration with planning instruments; and (iv) effectiveness, co-benefits, and equity outcomes.

The narrative synthesis was complemented by a simple vote-counting tabulation of the direction of effect (positive, mixed, or negative) for each hazard–NbS combination. Vote counting is acknowledged as a limited inferential technique, but it provides a transparent overview of the evidence landscape in the absence of standardised effect sizes (Campbell et al., 2020). All extracted data and synthesis tables are available as Supplementary Material.

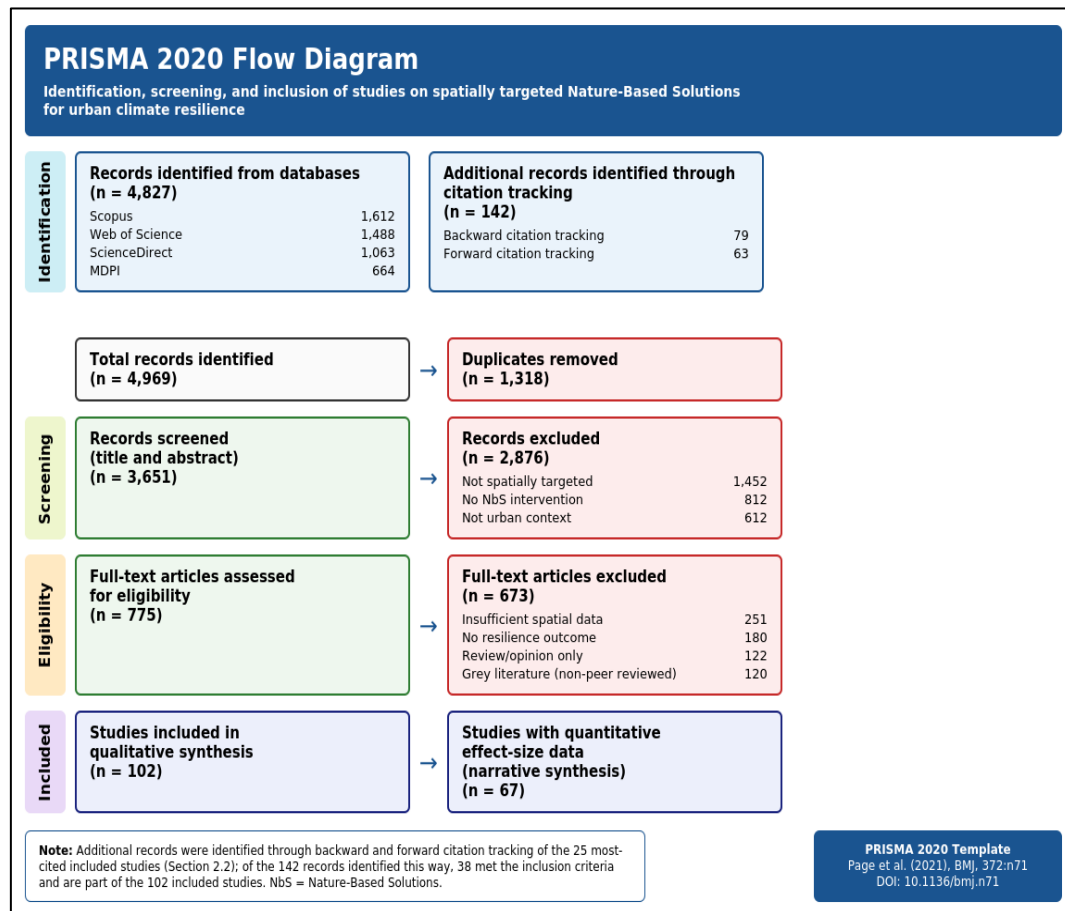


Fig 1. PRISMA 2020 Flow Diagram of the Systematic Review Process.

III. RESULTS

The systematic search identified 4,827 records from the five bibliographic databases and an additional 142 records through backward and forward citation tracking. After de-duplication (1,318 records removed) and title-and-abstract screening (2,876 records excluded), 775 full-text articles were assessed for eligibility. Of these, 673 were excluded with documented reasons (Figure 1), leaving 102 studies in the qualitative synthesis. Sixty-seven of these studies reported quantitative effect-size data suitable for tabular aggregation. The sections below describe the characteristics of the included studies, the typologies of hazards and NbS encountered, the spatial-targeting methods employed, and the documented effectiveness, co-benefits, and equity outcomes.

➤ Characteristics of Included Studies

The 102 included studies were published between 2010 and 2024, with a marked acceleration in recent years: 68 percent were published in 2019 or later, and 41 percent in 2022 or later. This temporal pattern mirrors the consolidation of NbS as a policy concept in the European Research Programme, the European Green Deal, and the post-2018 work of the IPCC and IPBES (Seddon et al., 2020; Maes & Jacobs, 2017). The studies were published across 47 distinct journals, with the strongest concentrations in Landscape and Urban Planning (n = 11), Urban Forestry & Urban Greening (n = 9), Science of the Total Environment (n = 8), Environmental Science & Policy (n = 7), and Sustainability (n = 6). The disciplinary breadth spanning urban ecology, hydrology, planning, public health, and governance reflects the inherently cross-sectoral character of NbS research.

Geographically, the evidence base was strongly skewed toward the Global North. Europe accounted for 38 percent of studies ($n = 39$), Asia for 27 percent ($n = 27$, of which 14 were from China and 5 from India), and North America for 18 percent ($n = 18$, of which 14 were from the United States). Africa accounted for only 6 percent ($n = 6$), Latin America and the Caribbean for 5 percent ($n = 5$), and Oceania for 4 percent ($n = 4$). Small Island Developing States (SIDS), which face disproportionate coastal-climate risks, were represented in only two studies. This geographic imbalance aligns with prior observations that NbS research is concentrated in higher-income contexts with stronger research funding and data availability (Kabisch et al., 2016; Bush & Doyon, 2019), and it constitutes a structural limitation on the generalisability of the evidence base to the cities most exposed to climate hazards.

Methodologically, the studies were almost evenly split between empirical field or remote-sensing investigations ($n = 44$), modelling studies using hydrological, climatic, or ecosystem-service models ($n = 41$), and mixed-methods or qualitative case studies ($n = 17$). The most frequently applied analytical tools were geographic information systems (GIS) overlay (used in 71 studies), multi-criteria decision analysis (MCDA, $n = 34$), remote-sensing land-surface temperature retrieval ($n = 32$), and hydrological or hydraulic modelling ($n = 29$). Participatory mapping and community-based vulnerability assessment were used in only 14 studies, suggesting that the integration of lay knowledge into spatial targeting remains an underdeveloped frontier.

Table 1. Characteristics of the 102 Studies Included in the Systematic Review.

Characteristic	Category	Studies (n)	%
Publication year	2010–2014	12	11.8
	2015–2018	21	20.6
	2019–2021	27	26.5
	2022–2024	42	41.1
Continent	Europe	39	38.2
	Asia	27	26.5
	North America	18	17.6
	Africa	6	5.9
	Latin America & Caribbean	5	4.9
	Oceania	4	3.9
	Multi-region	3	2.9
Climate zone (Köppen)	Temperate (C)	54	52.9
	Continental (D)	21	20.6
	Tropical (A)	14	13.7
	Arid (B)	9	8.8
	Polar (E)	4	3.9
Study design	Empirical (field/remote sensing)	44	43.1
	Modelling	41	40.2
	Mixed-methods / qualitative	17	16.7
Spatial-targeting method	GIS overlay	71	69.6
	Multi-criteria decision analysis	34	33.3
	Remote sensing (LST)	32	31.4
	Hydrological / hydraulic modelling	29	28.4

	Vulnerability index	21	20.6
	Participatory mapping	14	13.7
	Optimisation algorithms	9	8.8

Note. Percentages may not sum to 100 due to rounding. Categories are not mutually exclusive for spatial-targeting method (a study could employ more than one method).

➤ Hazard Types and NbS Typologies

The 102 studies addressed a range of urban climate hazards, with urban heat and the urban heat island (UHI) effect being by far the most frequent ($n = 58$, 57 percent), followed by pluvial and fluvial flooding ($n = 31$, 30 percent), coastal flooding and storm surge ($n = 12$, 12 percent), drought and water scarcity ($n = 7$, 7 percent), and air pollution ($n = 6$, 6 percent). Fourteen studies (14 percent) explicitly addressed compound or cascading hazards, such as the joint occurrence of heat and drought or of coastal flooding and extreme precipitation. The dominance of urban heat reflects both the maturity of UHI research and the availability of remotely sensed land-surface temperature data, which has lowered the methodological barrier to heat-related NbS evaluation (Zhou et al., 2014; Manoli et al., 2019).

Five major NbS typologies were represented. Urban green infrastructure — including urban parks, street trees, green walls, and green roofs — was the most frequently studied category ($n = 55$, 54 percent), consistent with its visibility in urban planning and its direct relevance to heat mitigation. Blue infrastructure (urban rivers, wetlands, retention ponds) accounted for 19 percent ($n = 19$), sustainable urban drainage systems (SuDS) for 14 percent ($n = 14$), coastal ecosystems (mangroves, salt marshes, dunes, oyster reefs) for 8 percent ($n = 8$), and hybrid grey–green systems for 6 percent ($n = 6$). Six studies evaluated more than one typology in combination. The relative scarcity of coastal NbS in the evidence base is notable given the high exposure of coastal cities to climate hazards and the strong evidence from non-urban coastal ecology on the protective role of mangroves and marshes (Temmerman et al., 2013; Narayan et al., 2016).

Table 2. Matrix of Urban Climate Hazards and NbS Typologies Addressed in the 102 Included Studies.

Hazard type	Predominant NbS typologies	Studies (n)	Median T / runoff reduction
Urban heat / UHI	Urban parks, street trees, green roofs, green walls	58	2.1 °C (IQR 1.0–3.8)
Pluvial / fluvial flooding	SuDS, bioswales, rain gardens, urban wetlands	31	Peak runoff –30 to –60%
Coastal flooding / storm surge	Mangroves, salt marshes, dunes, oyster reefs	12	Wave height –15 to –70%
Drought / water scarcity	Urban forests, aquifer recharge, wetland restoration	7	Infiltration +18 to +44%
Air pollution	Urban forests, green walls, vegetated barriers	6	PM2.5 –5 to –25%
Compound hazards	Combined green–blue networks, hybrid systems	14	Outcome-specific

➤ Spatial-Targeting Methods

Spatial targeting was operationalised through a heterogeneous set of methods. The most common approach, observed in 71 studies, was GIS overlay, in which layers representing hazard exposure (e.g., land-surface temperature, flood-prone areas), social vulnerability (e.g., age, income, housing quality), and intervention opportunities (e.g., vacant land, roof area) were combined to identify priority zones. Multi-criteria decision analysis (MCDA) was used in 34 studies, often in conjunction with the analytical hierarchy process (AHP) to weight criteria according to expert or stakeholder judgement (Geneletti & Zardo, 2016; Raymond et al., 2017). Vulnerability indices combining exposure, sensitivity, and adaptive-capacity indicators were constructed in 21 studies, particularly within the heat and flood literatures (Wolf & McGregor, 2013; Kotharkar & Ramesh, 2022).

Participatory mapping, in which residents contribute local knowledge of hazard exposure and NbS priorities, was

used in 14 studies and was concentrated in research from Latin America and parts of Africa (Anguelovski et al., 2016; Connop et al., 2016). Optimisation algorithms — including genetic algorithms, simulated annealing, and Marxan — were employed in nine studies, typically to maximise hazard reduction or ecosystem-service delivery subject to budget constraints (Sowińska-Świerkosz & Garcia, 2022). Across all methods, the integration of equity criteria into the spatial-targeting process was infrequent: only 22 studies explicitly incorporated indicators of social vulnerability, and only 11 incorporated indicators of distributional justice in intervention siting.

➤ Effectiveness Outcomes

Across the 67 studies reporting quantitative effect sizes, spatially targeted NbS delivered measurable hazard-reduction outcomes, although the magnitude varied with hazard, intervention type, climate zone, and intervention dosage. For urban green infrastructure, the median surface-

temperature reduction was 2.1 °C (interquartile range 1.0–3.8 °C), with the largest effects reported for urban parks and continuous canopy in temperate climates (Bowler et al., 2010; Zölch et al., 2016; Kotharkar & Ramesh, 2022). Street trees provided more modest but consistent cooling of 0.5–2.0 °C, with effect size strongly conditioned by canopy cover, leaf area index, and tree species (Nowak et al., 2014; Salmond et al., 2016). Green roofs and walls delivered surface-temperature reductions of 1–4 °C at the building scale, with broader neighbourhood effects remaining modest beyond approximately 100 metres (Santamouris, 2014; Li et al., 2014).

For pluvial flooding, SuDS interventions including permeable pavements, bioswales, rain gardens, and retention ponds reduced peak runoff by 30 to 60 percent at the catchment scale in studies reporting hydrological modelling outcomes (Hobbie & Grimm, 2020; Liao, 2019; Ferreira et al., 2021). Effect size was strongly conditioned by catchment imperviousness, soil infiltration capacity, and the percentage of the catchment treated. Coastal NbS predominantly mangrove and salt-marsh restoration attenuated wave heights by 15 to 70 percent depending on vegetation width, density, and species composition, with wider and denser belts providing disproportionately greater protection (Narayan et al., 2016; Temmerman et al., 2013; Spalding et al., 2014).

Co-benefits were reported in 79 of the 102 studies. The most frequently documented co-benefits were biodiversity enhancement (n = 38), carbon sequestration (n = 27), recreational and cultural ecosystem services (n = 25), and improved mental and physical health (n = 19). Negative trade-offs were reported less frequently but included increased pollen allergenicity from certain tree species, gentrification pressures associated with visible greening interventions, and maintenance costs borne by under-resourced municipalities (Wolch et al., 2014; Pearsall & Eller, 2020).

➤ *Implementation Barriers and Enablers*

Implementation barriers identified across the included studies fell into five broad categories. First, governance and institutional fragmentation including overlapping or unclear mandates between municipal departments was cited as a barrier in 41 studies. Second, financial constraints, including the high up-front cost of NbS relative to grey alternatives and the difficulty of capturing co-benefits in cost-benefit frameworks, were identified in 36 studies. Third, technical and data limitations, including inadequate hazard maps and inconsistent ecosystem-service monitoring, were noted in 33 studies. Fourth, land-tenure and property-rights complexities, particularly in informal settlements, were discussed in 18 studies. Fifth, social and political factors including low public awareness, NIMBY opposition, and unequal power relations were cited in 27 studies.

Conversely, enabling conditions included the presence of dedicated NbS or climate-adaptation strategies at the city level (n = 38), active community engagement and co-design (n = 29), availability of dedicated financing instruments such as green bonds and ecosystem-service payments (n = 19),

supportive national policy frameworks (n = 26), and the integration of NbS into statutory land-use plans (n = 23). Cities that combined several of these enabling conditions such as Singapore, Rotterdam, Medellín, and Copenhagen — were repeatedly cited as exemplars of effective spatially targeted NbS implementation.

IV. DISCUSSION

This systematic review synthesised 102 peer-reviewed studies on spatially targeted nature-based solutions for urban climate resilience, published between 2010 and 2024. Three principal findings emerge. First, the field is growing rapidly but remains geographically and methodologically uneven. Second, spatially targeted NbS deliver measurable hazard-reduction outcomes across heat, flooding, coastal, and compound hazards, but the magnitude of these outcomes is highly context-dependent. Third, the integration of equity, governance, and long-term monitoring considerations into NbS research and practice remains underdeveloped. Each of these findings is discussed in turn below, followed by a critical consideration of the limitations of this review.

➤ *Spatial Targeting as a Defining Principle*

The review confirms that spatial targeting has matured from a methodological aspiration into a widely applied analytical practice. GIS overlay, MCDA, and vulnerability indexing are now standard tools, and the integration of remote-sensing data with social-vulnerability layers has become increasingly accessible (Raymond et al., 2017; Sowińska-Świerkosz & Garcia, 2022). However, the review also reveals considerable heterogeneity in how spatial targeting is operationalised. Some studies equate spatial targeting with the simple production of a priority map, while others treat it as an iterative planning process that links priority mapping, intervention design, governance, and monitoring. We argue that the latter conceptualisation is more productive and more consistent with the adaptive-management logic embedded in the IUCN NbS framework (Cohen-Shacham et al., 2016) and with the iterative risk-management approach of the IPCC (Pörtner et al., 2022).

A related finding is the limited uptake of equity-explicit spatial targeting. Although 22 of the 102 studies incorporated some indicator of social vulnerability, only 11 explicitly incorporated distributional-justice considerations in the siting of interventions. This represents a missed opportunity. Spatial targeting provides an analytical lever to direct NbS investment toward populations most exposed to climate hazards and least able to adapt, but this lever remains underused. The persistence of green gentrification as a documented side-effect of urban greening (Wolch et al., 2014; Anguelovski et al., 2016; Pearsall & Eller, 2020) underscores the importance of coupling spatial targeting for efficiency with spatial targeting for justice.

➤ *Effectiveness and Context-Dependence*

The median surface-temperature reduction of 2.1 °C from urban green infrastructure aligns with the range reported in earlier reviews (Bowler et al., 2010; Demuzere et al., 2014; Zölch et al., 2016), but the wide interquartile range (1.0–3.8

°C) underscores the strong context-dependence of effect size. Intervention dosage measured as canopy cover, leaf area index, or green-roof area emerged as a key determinant, as did the surrounding urban morphology, with denser built environments generally producing larger relative cooling effects due to the contrast with hot built surfaces (Manoli et al., 2019; Stewart & Oke, 2012). Climate zone also mattered: tropical and arid cities often reported smaller absolute temperature reductions, but these reductions translated into larger proportional reductions in heat-related mortality due to higher baseline temperatures and exposure (Tan et al., 2021; Sharma et al., 2021).

For pluvial flooding, the 30–60 percent peak-runoff reduction attributable to SuDS aligns with the synthesis of Hobbie and Grimm (2020) and with case-study evidence from the Sponge City programme in China (Liao, 2019). Effect size was strongly conditioned by catchment imperviousness and by the proportion of the catchment treated, suggesting that SuDS planning must consider system-wide coverage rather than isolated installations. For coastal hazards, the wide range of wave-height attenuation (15–70 percent) reported for mangrove and salt-marsh interventions reflects the importance of vegetation width and density, and reinforces the conclusion that coastal NbS should be designed at the landscape scale rather than as isolated restoration projects (Temmerman et al., 2013; Narayan et al., 2016; Spalding et al., 2014).

➤ *Co-Benefits, Trade-Offs, and the Multifunctionality Imperative*

The high frequency of co-benefit reporting (79 of 102 studies) is encouraging and reflects the inherent multifunctionality of NbS — a feature that distinguishes them from single-purpose grey infrastructure (Gómez-Baggethun & Barton, 2013; Haase et al., 2014; Costanza et al., 2017). Biodiversity enhancement was the most frequently reported co-benefit, consistent with the IUCN definition of NbS as interventions that deliver simultaneous biodiversity and human well-being benefits. However, the review also identified trade-offs that warrant careful management. These include allergenic and biogenic volatile organic compound (BVOC) emissions from certain tree species, the gentrification pressures associated with visible greening, water-use conflicts in arid climates, and the maintenance burdens placed on under-resourced municipalities (Wolch et al., 2014; Pearsall & Eller, 2020; Santamouris, 2014).

A multifunctionality lens in which NbS are designed, sited, and evaluated for their performance against multiple objectives offers a way to navigate these trade-offs explicitly (Raymond et al., 2017; Sowińska-Świerkosz & Garcia, 2022). However, the operationalisation of multifunctionality requires advances in three areas: (i) integrated assessment frameworks that explicitly evaluate trade-offs rather than aggregating them into single scores; (ii) governance arrangements that can adjudicate between competing objectives; and (iii) monitoring systems capable of tracking multiple outcomes over the long term.

➤ *Equity, Justice, and Green Gentrification*

Equity outcomes were explicitly evaluated in only 17 of the 102 studies, a striking gap given the central importance of distributional justice to climate-resilience scholarship and practice (Wolch et al., 2014; Anguelovski et al., 2016; Keeler et al., 2019). The review documented three equity concerns that recur in the literature. First, the unequal distribution of existing green space, with low-income and minority neighbourhoods typically having less access to urban green infrastructure and therefore higher exposure to heat and other hazards. Second, the risk of green gentrification, in which visible greening interventions increase property values and rents, leading to the displacement of the very residents the interventions were intended to benefit. Third, the procedural injustice that arises when NbS planning is conducted without meaningful participation of affected communities.

Addressing these equity concerns requires three shifts in NbS practice. First, equity-explicit spatial targeting — using indicators of distributional justice alongside hazard-exposure and ecological-opportunity layers — should become the default rather than the exception. Second, anti-displacement strategies, including affordable-housing protections, community-land-trust arrangements, and tenant protections, should be embedded in NbS implementation from the outset. Third, participatory planning processes drawing on the well-developed methods of community-based vulnerability assessment and participatory GIS should be integrated into the spatial-targeting workflow (Connop et al., 2016; Bush & Doyon, 2019).

➤ *Governance, Finance, and Policy Integration*

The implementation barriers identified in this review governance fragmentation, financial constraints, technical and data limitations, land-tenure complexities, and social and political factors — echo earlier syntheses on urban ecosystem-based adaptation (Wamsler et al., 2016; Frantzeskaki, 2019; Dorst et al., 2019). The enabling conditions identified dedicated NbS strategies, active community engagement, dedicated financing instruments, supportive national policy frameworks, and integration into statutory land-use plans point to the importance of multi-level, cross-sectoral governance arrangements. Cities that have made the most visible progress on spatially targeted NbS, such as Singapore, Rotterdam, Medellín, and Copenhagen, share a common feature: the integration of NbS into the statutory planning system rather than its confinement to pilot projects or discretionary programmes.

Financing remains a structural challenge. Although the up-front costs of NbS are often lower than those of comparable grey infrastructure, the difficulty of monetising co-benefits in conventional cost-benefit frameworks places NbS at a disadvantage in infrastructure-investment decisions (Bark et al., 2018; Brears, 2020). Emerging financing instruments — including green bonds, ecosystem-service payments, and resilience-based insurance — offer promising pathways, but their application to urban NbS remains limited. The development of standardised NbS accounting frameworks, comparable to the carbon-accounting standards

that have enabled climate-finance flows, would substantially improve the bankability of urban NbS projects.

➤ *Limitations of this Review*

This review has several limitations that should be borne in mind when interpreting its findings. First, the restriction to English-language peer-reviewed literature almost certainly under-represents research published in other languages, particularly in Spanish, Portuguese, Chinese, and French, and may contribute to the apparent under-representation of Latin American and African contexts. Second, the exclusion of grey literature —while strengthening quality assurance may have omitted valuable practice-based evidence, particularly from non-governmental and community-based organisations. Third, the heterogeneity of methods, metrics, and reporting conventions in the included studies precluded a formal meta-analysis for most outcomes; the median effect sizes reported should therefore be interpreted as descriptive summaries rather than pooled estimates. Fourth, the rapid growth of the field means that some very recent (2024) studies may not yet have been indexed at the time of the search. Fifth, as with any systematic review, the findings are conditional on the search strings and eligibility criteria applied; alternative framings —for example, those centred on "ecosystem-based adaptation" or "green-grey infrastructure" rather than "NbS" —may surface partially non-overlapping evidence.

V. CONCLUSION AND POLICY IMPLICATIONS

This systematic review has synthesised 102 peer-reviewed studies on spatially targeted nature-based solutions for urban climate resilience, published between 2010 and 2024. The evidence confirms that spatially targeted NbS deliver measurable reductions in exposure to urban heat, pluvial and coastal flooding, and compound hazards, while generating substantial co-benefits for biodiversity, carbon sequestration, and human well-being. Median surface-temperature reductions of 2.1 °C for urban green infrastructure, peak-runoff reductions of 30–60 percent for SuDS, and wave-height attenuation of 15–70 percent for coastal NbS provide robust orders of magnitude that can inform planning decisions, even as the context-dependence of these effects cautions against uncritical transfer between settings.

The review also identifies four structural weaknesses in the current evidence base: geographic skew toward the Global North; methodological heterogeneity that limits formal meta-analysis; insufficient attention to equity and distributional justice; and limited long-term monitoring of NbS performance. Addressing these weaknesses will require coordinated action across the research, policy, and practice communities. On the basis of the synthesis, we propose a five-point agenda for advancing the science and practice of spatially targeted NbS.

First, the research community should develop and adopt standardised reporting guidelines for NbS interventions, including intervention dosage, spatial configuration, comparator conditions, and outcome metrics. Such guidelines would substantially improve the comparability of studies and

enable future meta-analyses. Second, place-based NbS research in the Global South particularly in Africa, South Asia, and Small Island Developing States should be expanded through dedicated research-funding instruments and equitable North–South partnerships. Third, equity and justice indicators should be integrated into NbS evaluation frameworks as default rather than optional elements, and anti-displacement strategies should be embedded in NbS implementation. Fourth, long-term and adaptive monitoring systems, capable of tracking biophysical, ecological, and social outcomes over decadal timescales, should be established in representative cities across climate zones. Fifth, governance arrangements should be strengthened to integrate NbS into statutory urban planning instruments, supported by dedicated financing mechanisms such as green bonds, ecosystem-service payments, and resilience-based insurance.

Spatially targeted NbS are not a panacea for urban climate risks, and they are most effective when deployed as part of a broader portfolio of adaptation actions that combines green, blue, grey, and social interventions. However, the evidence reviewed here indicates that, when properly designed, sited, and governed, spatially targeted NbS can make a substantial contribution to urban climate resilience a contribution that is simultaneously efficient, multifunctional, and capable of advancing equity. Realising this potential will require sustained investment in evidence, capacity, and institutions, but the cost of inaction in the face of accelerating urban climate hazards is far greater.

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