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# Global evidence linking local development-oriented urban actions to climate change mitigation and adaptation

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# *Global evidence linking local development-oriented urban actions to climate change mitigation and adaptation*

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## Abstract:

Cities' action is essential to achieving the global climate target, but it is invariably anchored in the real-world constraints and motivations, and indirectly contributes to climate co-benefits. However, much of literature organizes from a climate-first perspective, offering limited insight into how local development topics, urban actions, and climate impacts intersect across cities. This critical gap fails to capture how most development-oriented urban actions subtly affect emissions or climate resilience, which ultimately may result in less effective outcomes. In this study, we systematically evaluate 5,610 studies across over 750 cities, linking city types, local development topics, urban actions, and associated climate impacts, based on an AI-assisted knowledge extraction pipeline. Our findings show disparities in the evidence of urban action worldwide, which are rooted in local development topics associated with their profiles and constrained by their own capacity. The evidence is uneven, with nature-based (19%), energy (19%), and transport (16%) related actions accounting for roughly 53%. Evidence on blue–green infrastructure covering more than 150 cities globally, while some actions (such as shared automated electric transportation) are city-specific. Even the same actions (e.g., waste prevention, minimization and management) are associated with different climate co-benefits across cities. More effort is needed to close remaining gaps and capture lessons from specific urban cases. Analyzing urban action with a development-oriented perspective helps explain climate impacts of local action, and supports urban practitioners in leveraging their strengths to respond to diverse development topics while delivering climate co-benefits.

# 1 Introduction

Urban areas are home to about 55% of the global population, account for the majority of global economic output, and contributed roughly 67–72% of global carbon dioxide and methane emissions in 2020[1], while facing increasing exposure to climate extremes[2-4]. As a result, cities are widely recognized as playing a central role in global climate governance. Over the past two decades, thousands of cities worldwide have made climate-related commitments, including targets and action plans[5-7]. Understanding how urban actions, particularly under urban typology[8], affect climate mitigation and adaptation is critical not only for achieving global climate goals, but also for supporting effective and equitable urban development. In recent years, a growing body of studies has examined urban climate actions across specific domains, including transport[9], health[10], land use and nature-based solutions[11], urban adaptation[12,13], and governance arrangements and policy instruments [14-16]. Large-scale assessments, including those by the IPCC, have further strengthened the evidence on synergies and trade-offs associated with climate options [1,17]. Most of this literature is framed through a climate-first lens, treating climate impact as the entry point and treating development-related outcomes as co-benefits.

This is in contrast to how decisions about cities are actually made, the political legitimacy and budgetary priorities of local decision-makers are invariably anchored in the immediate development challenges[18-20], such as poverty alleviation, economic development, and service provision. As a result, many urban actions that ultimately affect emissions or climate resilience are not designed for climate. Crucially, local geography and institutional settings differ across cities, which influence their choice of actions and how they result in climate outcomes[13,21,22]. Analyzing development-oriented urban actions is crucial, as it places climate-relevant evidence within the real constraints and motivations of cities, revealing climate mitigation and adaptation synergies and trade-offs in contexts where explicit climate strategies are constrained by institutional capacity, fiscal space, or political incentives. However, due to systematic evidence remains fragmented, it is still difficult to identify which

development-oriented actions are most likely to deliver robust and scalable climate co-benefits across cities. This gap fails to capture how most urban actions, and limits the ability of urban practitioners to leverage development agendas as effective entry points for accelerating climate mitigation and adaptation, which may lead to less effective urban actions[23].

We used a methodological framework that included a large language model-assisted knowledge extraction pipeline, which produced global evidence connecting urban profiles, urban actions, local development topics, and their impacts on climate mitigation and adaptation. Specifically, our research began with a series of Boolean queries, and we conducted a systematic literature search of the Scopus and Web of Science databases, ultimately retrieving 58,047 peer-reviewed research papers after deduplication. These papers report actions、 policies, or solutions driven by cities' own development and explore trade-offs and synergies related to climate mitigation and adaptation. We then employed a methodological framework comprising a large language model–assisted knowledge extraction pipeline, from which we screened 5,610 eligible peer-reviewed urban studies, of which 2,398 could be directly linked to a specific city, the remaining are not city-specific studies on cities or urban areas. Then, We used a two-stage pipeline to extract key knowledge from each urban study. First, we use three LLMs (Gemini-2.5 Pro, Qwen-3, and DeepSeek-V3.2) to extract key phrases from studies. Each LLM ran independently for three rounds for each study. Local development topics were then identified by expert review after phrases were clustered using BERTopic. Urban actions were classified into 48 sub-actions, then aggregated into 10 major action categories. Second, we re-applied the same procedure and identified studies to our above urban action categories and development topics, to analyze urban actions and corresponding development topics within a consistent boundary. The same process was used to extract city names, country names, and related climate impacts of urban actions simultaneously. Finally, we mapped the cities and countries in each study to the GHS Urban Centre Database (GHS-UCDB) to obtain other city attributes, which covering over 750 cities (see Methods for details).

Our study aims to reveal the heterogeneity of climate impacts of local actions across cities and their confidence of evidence, and identify associated underlying local development topics shaped by distinct urban profiles. We identify action categories with cross-city evidence of climate co-benefits (such as blue–green infrastructure, land-use planning, and water management), as well as systematic biases in the existing evidence across city types and action categories. We also observe an underreported imbalance in failure cases. Together, these findings clarify how existing evidence is distributed across spatial and action dimensions, and point to the need for more targeted reporting of specific urban actions and stronger cross-city comparative research to better support urban practitioners in advancing actions that address local development topics while delivering climate benefits.

# 2 Results

## 2.1 Distinctive urban profiles reflected in their actions for local development

Our study indicates that there is a growing diversity of evidence showing urban actions across multiple domains with implications for climate. Across action categories, the global evidence base is concentrated in three domains: Nature-based & Ecosystem (1,059 cases, 19%), Energy Solutions (1,047 cases, 19%), and Transport & Mobility (872 cases, 16%), which account for approximately 53% of all literature (Figure 1a). However, the degree of concentration varies by region. Cities in Africa, South America, and Oceania typically report fewer than 20 cases for each action type. In Africa, actions related to Nature-based & Ecosystem and Energy solutions account for 45% of all. In small islands, individual action categories rarely exceed four cases, with Resilience Enablers accounting for the largest share. In addition, Asian cities more frequently report actions related to Integrated Knowledge or Governance. For development topics, evidence of urban actions from cities in China and North Africa more strongly reflects efforts to meet "Green Energy and Economy Transition". In contrast, cities in Australia, North America, South Africa, and Brazil are more strongly oriented toward "Water Safety and

Reliability". In Southeast Asia and Japan, characterized by high exposure to natural hazards and strong attention to urban resilience, reported cases more often focus on “Urban Resilience and Risk Reduction". Evidence from urban projects in India, Türkiye, and Colombia highlights the importance of "Transport Accessibility and Efficiency" and "Sustainable Infrastructure and Urbanization"（Figure 1c）.

Over time, global evidence of actions reflecting development topics related to Energy Solutions and Transport & Mobility has increased markedly, alongside rapid growth in Resilience Enablers（Figure 1b&d）. By contrast, actions related to the development topics such as “Food Security and Sustainable Agriculture", " Social Equity and Inclusive Services", and " Coastal and Marine Development” are sparsely represented. Evidence is disproportionately concentrated in megacities, where greater resources support more published cases, such as in Beijing, New York City, and Shanghai（see figure S1). The distribution of action categories indicates gaps in the global evidence base on urban actions, particularly for action under Agriculture & Food Systems sector, with few documented cases in Africa and Australia, and for Construction & Building and Land Use & Spatial Planning in South America.

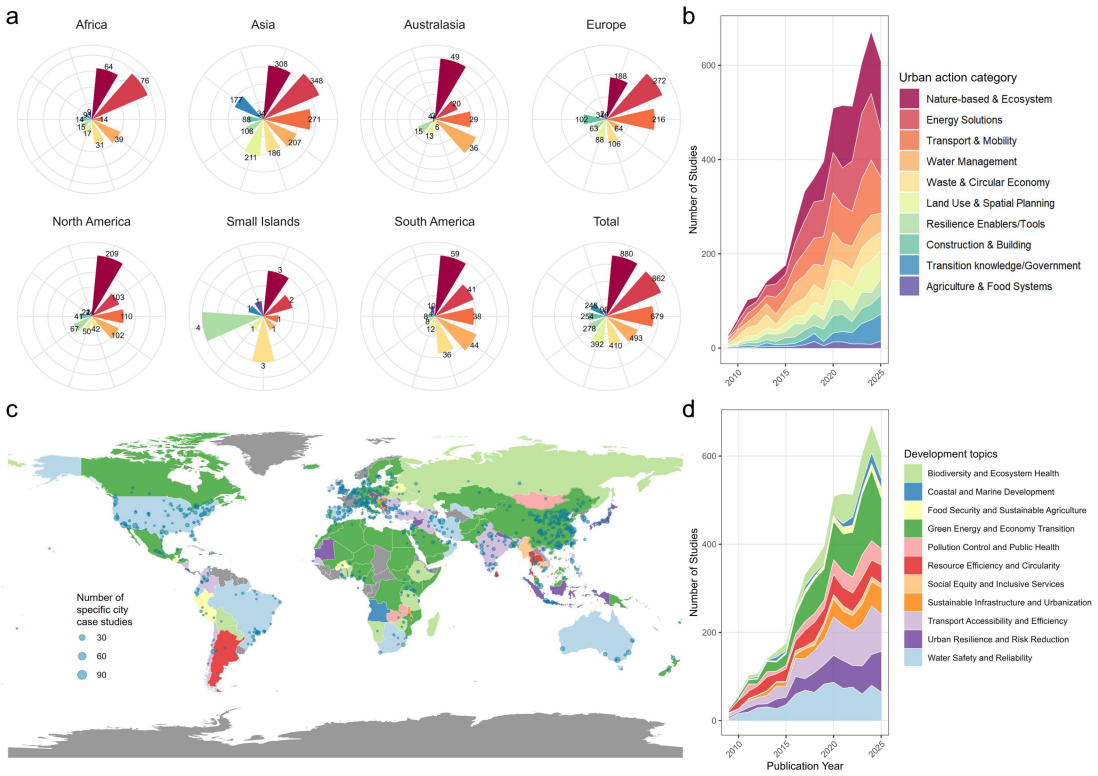



*Figure 1 Spatio-temporal patterns of studies on urban development-oriented actions with climate change mitigation or adaptation evidence. (c) Distribution of evidence across urban action categories by eight regions. For each region, the number of cases within each major action category is aggregated and displayed. Bar height represents the number of documented cases in each category. (b) Growth trend of the literature by urban action categories. (a) Geographic distribution of studies and their underlying development topics across countries. Countries are colored by the development topic with the highest number of studies. Specific city cases are overlaid as point symbols, with size indicating the number of cases in each urban area. (d) Growth trend of the literature by local development topics.*

There is a geographical imbalance in the distribution of literature evidence across different domain, as shown in Figure 1. Given the complexity of urban areas, namely, each city is shaped by a distinct set of attributes, each outcome individual[24]. To allow explored the differences in city profiles under this distribution, we therefore use three common attributes based on GHS-UCDB[25], i.e., population size, per capita carbon emissions, and the Sub-national Human Development Index (SHDI)[26], try to explore the typical profiles of cities in the evidence base, which are most often associated with particular urban actions and development topics(see method).

The mean urban attribution of cities across action categories displays regular patterns (Figure 2a). Urban actions categorized on “transport and mobility”, “resilience enablers and tools”, and “nature-based solutions (NbS)” corresponds to cities with mean SHDI > 0.8, indicating that developed cities are more likely to implement complex, resilience-oriented governance actions. Urban actions related to “agriculture and food systems” and “waste and circular economy” are associated with cities characterized by lower average population size and emission levels. “Policy and transition governance” actions are highly concentrated in Asian cities (as also shown in Figure 1b), these cities are typically densely populated, emission-intensive, and rapid economic growth.

In contrast, the Figure 2b shows the mean city attributes represented in the evidence for each development topic or action category, illustrating the bias in the characteristics of the cities covered. For local development topics, studies about urban action for addressing “Social Equity and Inclusive Services” mainly cover cities with per capita emissions below 4 t $CO_2$e per capita (lower than global average, i.e., 6 t CO2e per capita in 2019[27]), and an average SHDI < 0.8. Cities actions reflected by “Food Security and Sustainable Agriculture” and “Coastal and Marine Development” exhibit the lowest average SHDI (~0.75), and smaller populations, with per capita emissions of approximately 7 t $CO_2$e per capita, indicating that such actions are more frequently applied and reported by resource-constrained cities. "Urban Resilience and Risk Reduction" covers cities with larger average populations. By contrast, actions reflected by “Green Energy and Economy Transition” cover cities have higher average per capita emissions (>7 t $CO_2$e per capita), while those linked to “Sustainable Infrastructure and Urbanization” and “Transport Accessibility and Efficiency” have both high average SHDI (~0.83), suggesting their reliance on stronger institutional capacity and technological foundations.

Our results indicate that the concentration of transportation, NbS, risk resilience-oriented, and governance-related activities in large population, high-SHDI, high-emission cities is mainly because of their increased ability to

carry out activities with coordination costs. Conversely, waste management and agricultural-related activities are more often linked to cities with lower SHDI, indicating that resource security and the provision of essential services dominate their development demands. This indicates that the differences in the distribution of actions are related to their investment capabilities and implementation conditions than following best practices alone. Expanding the scope of viable urban initiatives could be achieved by bolstering foreign assistance and capacity-building for less developed urban areas[28].




*Figure 2 Characteristics of cities across categories of (a) urban action categories and (b) development topics in urban development-oriented studies collected in this study. Each point represents one development topic or urban action category. The x-axis shows the average per-capita greenhouse gas emissions, while the y-axis indicates the average Subnational Human Development Index (SHDI). Point size corresponds to the population, in 2020. All indicators are computed as averages across cities associated with each category.*

## 2.2 Differentiated climate co-benefits of local development-oriented urban actions worldwide

We then delved into 48 action subcategories to identify which "local development-oriented" actions have broader evidence of climate co-benefits

across urban contexts. Our results show that urban actions vary widely in their coverage and degree of their evidence across cities, Figure 3a shows the relationship between the total number of studies and their cross-city richness (that is, the number of individual cities covered), providing an evidence-based ranking. Among all action subcategories, green and blue infrastructure, urban land-use and spatial planning, and Integrated Water Management, stand out for having both the largest evidence and the richest city coverage, with evidence spanning over 100 cities. While some measures, such as Shared automated electric mobility and High-performance new building, exhibit a relatively high average number of cases per city (larger “bubble” size), their cross-city richness is limited, suggesting that their implementation is more context-specific.

Then, we introduce urban typology based on the work of Felix et al. [8], who categorized cities into four types: Emerging, Rapid Growing, Established, and Megacities, to better support practical decision-making across cities under a consistent framework. After selecting urban action cases with evidence with both climate mitigation and adaptation co-benefits (Figure 3b), we found that actions under the categories of Nature-based & Ecosystem and urban land-use and spatial planning demonstrate strong evidence of cross-city-type applicability, as well as strong evidence of meeting local needs related to “Biodiversity and Ecosystem Health” and “Urban Resilience and Risk Reduction”. In contrast, cross-city evidence for actions in water management, waste management, and agriculture remains largely limited to their core functions (such as meeting local needs related to “Water Safety and Reliability”, “Resource Efficiency and Circularity”, and “Food Security and Sustainable Agriculture”, respectively). Notably, the literature on action about Resilience Enablers reporting both climate mitigation and adaptation co-benefits is primarily concentrated in Established Cities and Megacities.

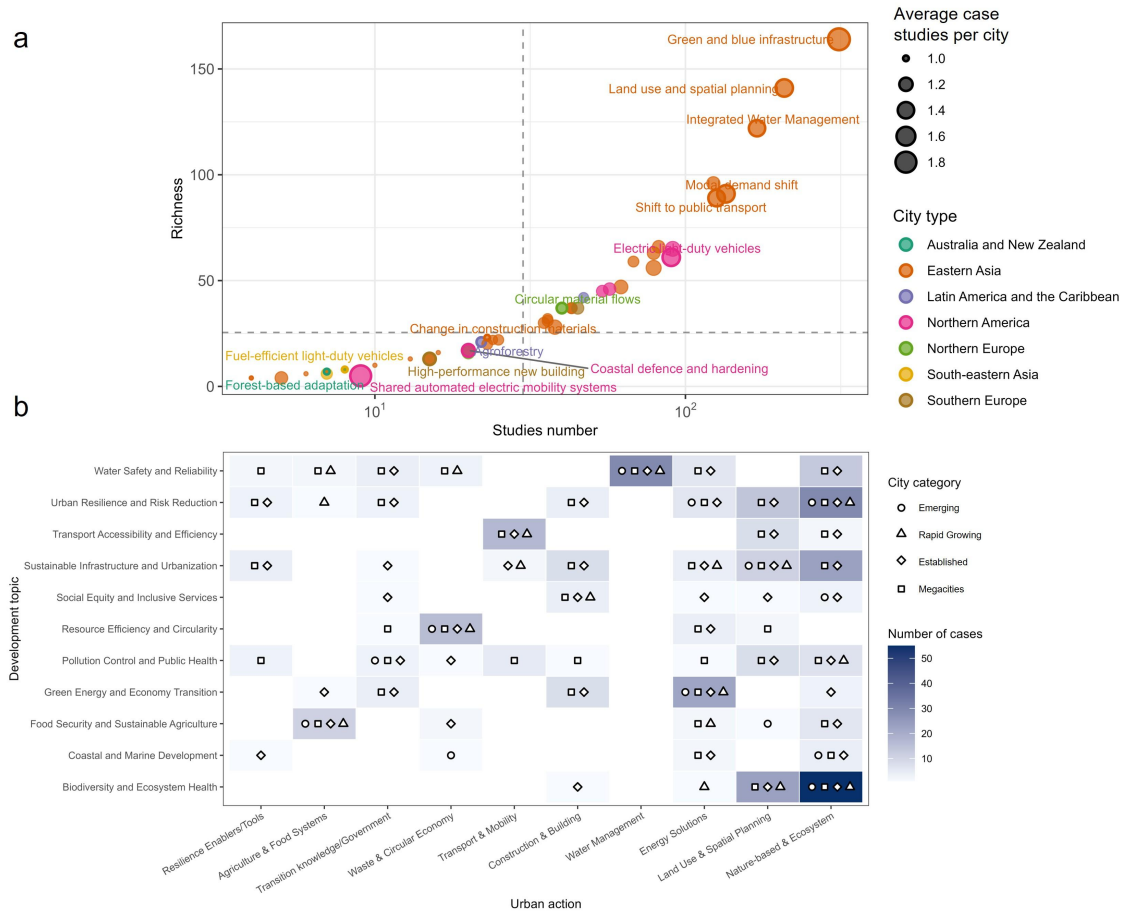
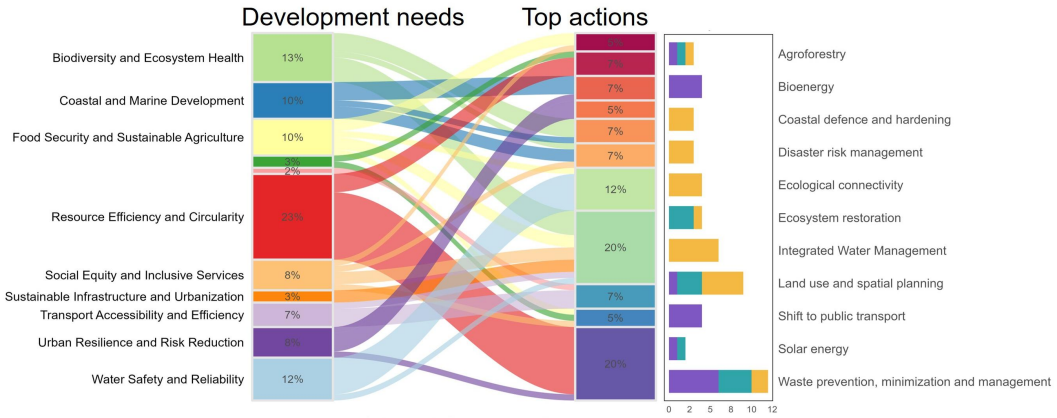



*Figure 3 Cross-city-type synergies and evidence richness of development-oriented urban action studies. (a) Sub-actions with their richness, where greater richness indicates broader coverage across individual cities. Each point represents a subcategory of local development-oriented urban action, with size indicating the average number of cases per city and color representing the region where the cities have the most cases of this action. Dashed lines represent the mean values for total cases and richness. (b)Distribution of urban actions with both mitigation and adaptation synergies across local development topics. The color of each tile represents the total number of cases, with darker colors indicating stronger evidence. The shapes on the heatmap show the city types covered.*

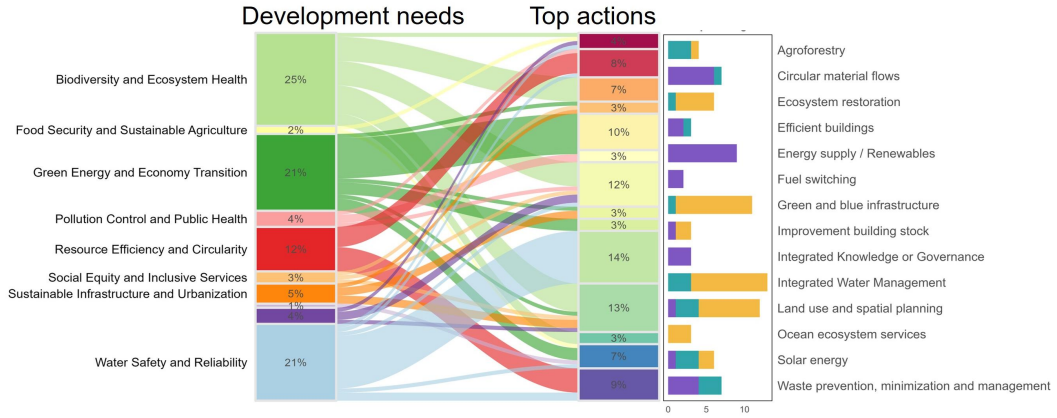
These interacts become clearer when local development topics, urban actions, and climate co-benefits are link together. We then filtered the top 10 action sub-categories with the strongest (most abundant) evidence across four city types. Figure 4 shows how these urban actions correspond to distinct underlying development topics and their differentiated patterns of climate co-benefits.

In emerging and rapid-growing cities, the studies are relatively limited, but shows a clear development-demand orientation. Emerging cities mainly focus on action under sub-categories of Land use and spatial planning (20%), Waste prevention, minimization and management (20%), and Integrated Water Management (12%), with their top actions underlying local development topics primarily related to “Resource Efficiency and Circularity” (23%), “Biodiversity and Ecosystem Health” (13%), and “Water Safety and Reliability” (12%). Evidence from rapidly-growing cities is more dispersed, with Integrated Water Management (14%), Land use and spatial planning (13%), and Green and blue infrastructure (12%) being the most prevalent. The local development topics associated with these top actions including “Biodiversity and Ecosystem Health” (25%), “Green Energy and Economy Transition” (21%), “Water Safety and Reliability” (21%). In these two city types, most action categories are supported by fewer than 10 cases, indicating insufficient coverage of research. In established and mega-cities, studies are more concentrated on Green and blue infrastructure (24% and 19%, respectively) and Land use and spatial planning (11% and 15%, respectively). The top actions in these cities underlying the local development topics of “Transport Accessibility and Efficiency” (27 and 29%, respectively) and “Water Safety and Reliability” (23 and 17%, respectively). Megacities show higher contribution of local need associated with “Pollution Control and Public Health” (13%) compared to established cities (6%). Furthermore, the number of studies in these two city types is substantial, e.g., evidence on blue–green infrastructure alone over 100 cases.

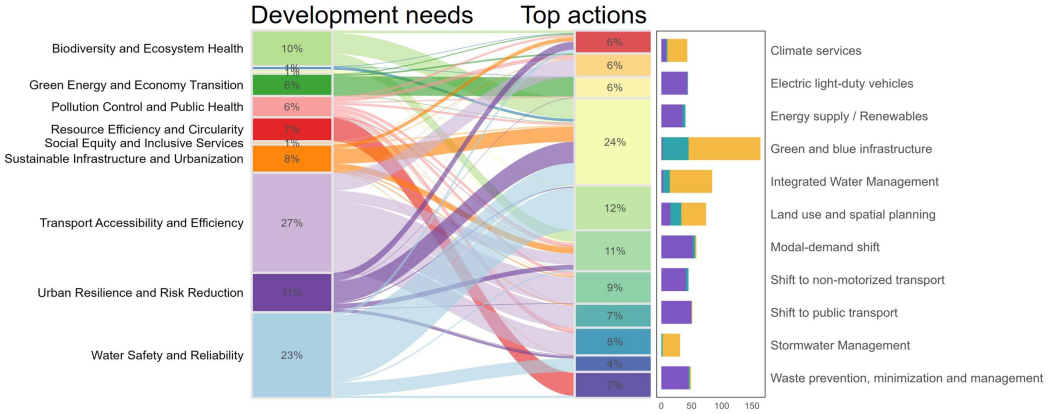
## Emerging



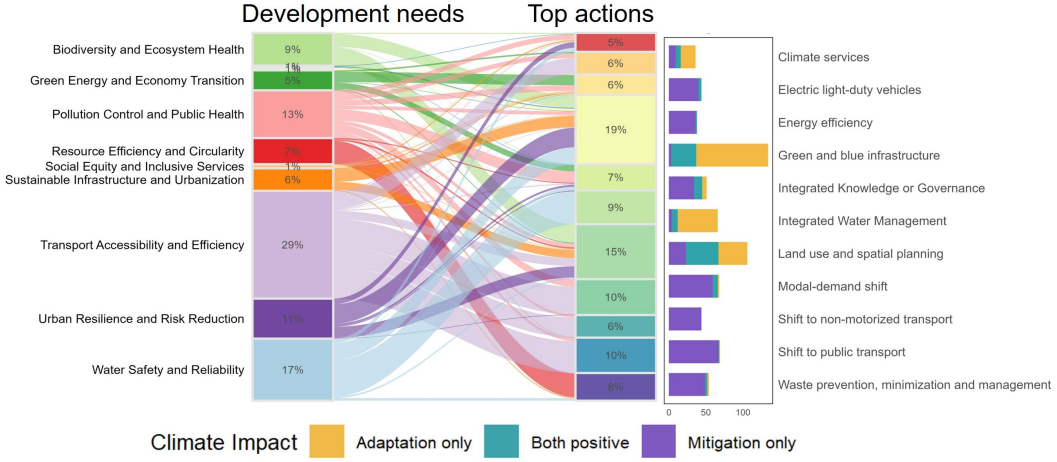

## Rapid growing




## Established




## Megacities




Climate Impact — Adaptation only — Both positive — Mitigation only

*Figure 4 Evidence of development-oriented urban actions and their climate change mitigation and adaptation co-benefits across four city types. Each panel represents a city type. Flows indicate how different sub-actions is linked to specific climate impacts and their confidence of evidence; The width of flow represents the proportion of studies reporting that specific action– climate impact linkage. The figure only shows the top ten actions with the largest evidence base for each city type, and tied actions are retained.*

Right-hand side of Figure 4，the urban actions are shown together with the confidence of evidence of their climate co-benefits. Nature-based action (i.e., green and blue infrastructure and Ecosystem services) and Integrated water management are more align with adaptation co-benefits, whereas Energy solutions (i.e., Bioenergy and Solar energy) and Transport and Mobility actions (i.e., Modal-demand shift or Electric vehicles) tend to align with mitigation co-benefits. Blue–green infrastructure and Land use and spatial planning actions show a predominance of adaptation co-benefits and some mitigation co-benefits, with strong confidence of evidence. Notably, even for the same action, the climate co-benefits vary across city types. For example, waste management in emerging cities are more reported with both adaptation-mitigation synergies, while in other cities it is predominantly linked to only mitigation benefits. Similarly, water management show strong evidence on adaptation benefits in both emerging and rapid-growing cities, while in megacities there is strong evidence for both adaptation and mitigation co-benefits. In general, these patterns suggest that how similar actions translate into differentiated climate outcomes across cities under the reflected of development topics under difference urban context.

### 2.3 Insights from under-reported failure cases

In our evidence base, studies are biased towards reported positive outcomes, climate mitigation benefits accounting for approximately half of specific city studies, while failure is reported very little (~3%)（see figure S2）. Simply looking at success stories (Section 2.2) limits our ability to truly understand the structural barriers faced by cities during action implementation. Therefore, include actions associated with negative outcomes is essential. Here, “failure” refers to a project that did not achieve its stated objectives, or

that produced unintended negative impacts during implementation.

Improving based on previous studies[29,30], the causes of failure cover six dimensions: People, Action, Information, Technology, Economic and Political conditions, and Funding, which ensured that the analysis of failure causes was comprehensive and traceable. Drawing on these studies that explicitly report negative lessons from urban actions, we find that failure is concentrated in three aspects: action (mentioned in 57% of reports), economic and political (53%), and technology (39%) (see table 6). Within the action factor, implementation obstacles (inability to implement plans, weak institutional tools, accounting for 48%) and management problems (insufficient execution, difficulty in project sustainability, accounting for 35%) are the most prominent. Among economic and political factors, prioritizing economic growth over environmental goals (62%) and policy backlashes (30%) often lead to deviations from action objectives. In terms of technology, trade-offs between competing objectives account for 54% of proportion. Actions that attract the greatest attention are also more likely to report adverse effects, particularly in these large and complex megacities. Taken together, the success of sustainable urban action depends on strengthening institutional execution and cross-sectoral coordination, the integration of environment into economic policymaking, and optimizing technology selection, to reduce unintended negative impacts.

*Table 1 Failure reasons for urban actions with negative climate impacts, expressed as the percentage of cases mentioning each reason.*

| Primary theme | Coverage (%) | Secondary theme | Proportion (%) |
|---|---|---|---|
| **People** | 21% | Stakeholder conflict | 73% |
| | | Psychological reactions (fear, blame, mistrust, risk aversion) | 27% |
| **Action** | 57% | Management problems (lack of enforcement, failure to sustain project) | 35% |
| | | Implementation barriers (plans not realized, weak institutional tools) | 48% |
| | | Lack of capacity | 10% |

| | | | |
|---|---|---|---|
| | | Avoidance of difficult decisions | 8% |
| **Information** | 29% | Communication failures | 30% |
| | | Lack of feedback or reflection | 45% |
| | | Data collection problems | 25% |
| **Funding** | 9% | Lack of funding | 78% |
| | | Misallocation or corruption | 22% |
| **Economic and political** | 53% | Economic growth overriding environmental goals | 62% |
| | | Lack of political support or unstable policy | 8% |
| | | Counterproductive government policy | 30% |
| **Technology** | 39% | Inappropriate technology choice (e.g., Mismatch with local, or requires excessive maintenance, cost, or expertise.) | 26% |
| | | Low efficiency or performance gap (e.g., Technology performs worse than expected) | 22% |
| | | Trade-offs with other objectives (e.g., Higher-than-expected environmental impacts) | 52% |

# 3 Discussion

We analyze how certain urban actions reflect the local development topics of cities as formed by their urban profiles and how these actions are related to climate consequences by evaluating 5,610 peer-reviewed urban studies. By offering a development-oriented viewpoint for evaluating urban actions that reflects the concerns of urban practitioners, this work supplements the climate-first narrative. This is crucial for local policymakers who want to take advantage of local assets while addressing a variety of development agendas.

Our findings demonstrate a significant discrepancy in the evidence relating to urban actions, their effects on the climate, and the underlying needs for local development. Cities in China and North Africa more frequently

report actions related to green energy and economic transition, whereas cities in Australia and North America are more likely to disclose actions about green energy and economic change. In Southeast Asia and Japan, reported actions are oriented toward urban resilience and risk reduction. Compared with other city types, emerging cities show a greater percentage of actions that subtly address resource efficiency (about 23% of the evidence) and food security and sustainable agriculture (almost 10% of the evidence), which reflects their needs related to the provision of basic resources. On the other hand, established cities and megacities concentrate more on improving their water security and transportation efficiency (which account for 40–50% of the evidence), as well as greater input in pollution control and urban resilience. Even the same action categories are linked to distinct patterns of climate co-benefit evidence across city types, according to our cross-city analyses. For instance, evidence of both adaptation and mitigation benefits is more frequently associated with waste management action initiatives in emerging cities, while evidence of mitigation benefits alone is more prevalent in other city types. Certain actions have substantial evidence, but their evidence for scalability is still restricted, and show spatial specialization (Figure 3a). In general, study numbers and city coverage for emerging and rapidly growing cities are limited. To help local practitioners adapt external solutions to local conditions and increase the likelihood of achieving climate co-benefits, it is therefore necessary to pay more attention to differences in development stage, socio-economic structure, and governance capacity, as well as to the conditions under which actions achieve their outcomes.

It is crucial to clarify that the action categories and underlying local development topics analyzed in this study are taken from the worldwide peer-reviewed literature and represent the evidence of climate impacts presented in scientific studies. The study is intended to support urban practitioners in capturing the issues that they face when responding to complex local challenges. The development priorities expressed in top-down local policy agendas do not exactly correlate with the distribution of evidence strength. Furthermore, heterogeneity in variables and methods across studies

constrains quantitative comparison across studies, making it difficult to directly estimate the degree of mitigation or adaptation performance of actions by cities. However, in our study, the proportions of climate impact topics align with the evidence base developed by Montfort, et al. [17], suggesting the robustness of our observed patterns.

To provide a more practice and solution-based knowledge foundation for local decision-making, future work might focus on enhancing the ability of evidence to reflect the complexity of real-world challenges. This includes clarifying the potential synergies among actions and the boundary conditions under which they apply, as well as identifying priority areas for further investigation. More focus on recording and contrasting failure cases is necessary because the evidence that is now available is concentrated in certain action categories and city types, most tends to disclose their good outcomes. Increased awareness and better decision-making would result from systematic reporting and process tracing of failure, lock-in mechanisms, and related costs and benefits. Furthermore, the cumulative worth of the evidence base would be increased by improving transparency and standardization in urban case studies[31]: through consistent reporting of city features, development topics, implementation conditions, and cost-benefits. Lastly, the use of multidisciplinary approaches, especially cutting-edge technologies like artificial intelligence, can improve the interpretation of evidence and assist local practitioners in finding solutions that align with local development agendas and maximize climate co-benefits.

# 4 Method

## 4.1 Evidence base construction framework

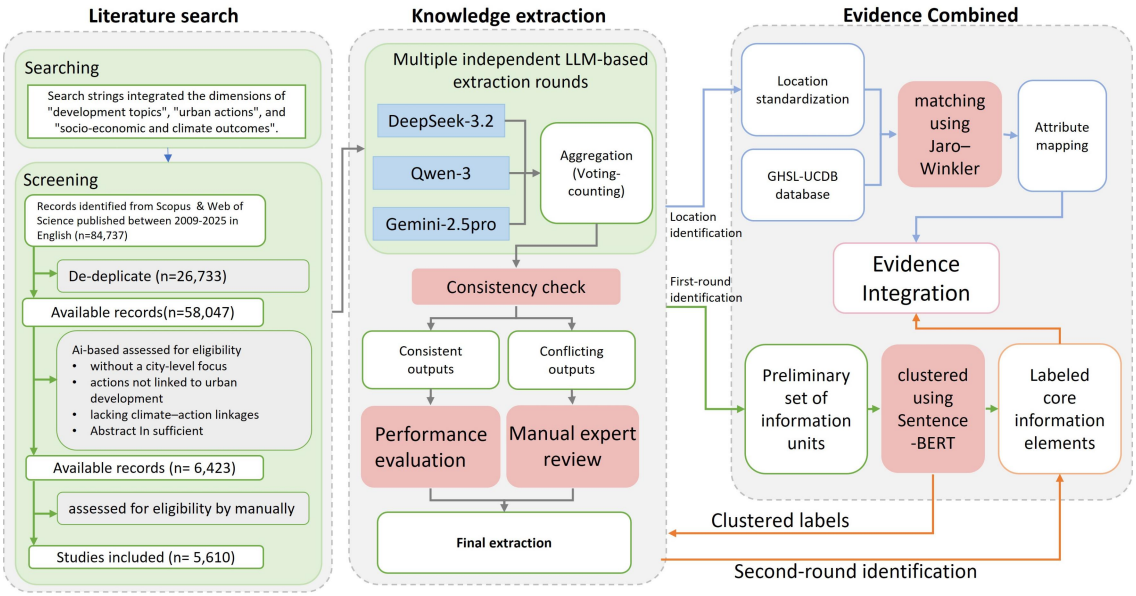



*Figure S 1 LLM-driven evidence extraction workflow.*

We employed an AI-assisted and human-in-the-loop information extraction pipeline to ensure both efficiency and reliability. First, we conducted a systematic literature search. To capture dimensions related to urban development, action types, and climate synergies or trade-offs, we constructed a series of Boolean search strings. Specifically, we reviewed titles, abstracts, and keywords from existing review articles and highly cited studies to identify synonymous and closely related terms. Employing these composite Boolean search strings, we executed searches via the Scopus and Web of Science. After deduplication, the initial literature base comprised 58,047 papers.

Second, we employed an AI-assisted and human-in-the-loop information extraction pipeline to ensure both efficiency and reliability. This rigorous filtering and validation process ultimately yielded 5,610 urban-related studies, of which 2,398 provided enough information to be directly connected to specific urban centers. We used a two-stage framework to analyze the screened and eligible literature. In the first stage, we used LLMs to extract raw information phrases from each study that described urban actions and associated development topics. We extracted key information from the titles and abstracts of each study using three different Large Language Models

(LLMs): Gemini-2.5 Pro, Qwen-3, and DeepSeek-V3.2. Each model was executed independently for three rounds. We encoded each phrase into semantic representations for urban development topics using BERTopic model. The output is then subjected to agglomerative hierarchical clustering. The preliminary clustering outputs were subsequently reviewed and aggregated by the research team, resulting in 11 local development topics. In order to identify 48 distinct urban actions, we used the IPCC AR6 framework and multi-source knowledge. These actions were then divided into ten major action categories. In the second stage, we systematically mapped each study to the 48 urban action categories and 11 local development topics identified in the first stage by applying the same methodology to each study. This guaranteed a systematic and comparable categorization, enabling the analysis of urban actions and the development requirements that go along with them within a uniform framework.

Finally, we used a combination of exact matching and fuzzy matching based on the Jaro-Winkler distance to extract city and country names simultaneously. These were then harmonized across data sources by mapping to the GHS Urban Centre Database (GHS-UCDB) and ISO3C country code. The final database was then created by combining corresponding urban action types, local development topics, and climate impacts.

### 4.2 **Literature search**

We first created a series of search strings to capture important dimensions to find literature pertinent to the research topic. These dimensions included study objects (urban actions and underlying urban development topics), climate impacts (synergy or trade-off), and outcomes (socio-economic performance or cost-benefits). We created the search strings iteratively to guarantee sufficient coverage across development topics. Specifically, we reviewed authoritative review articles and studies to compile commonly used keywords. The keyword list was refined through multiple rounds of manual checking based on expert judgement. Using these keywords, we constructed Boolean search strings for systematic literature retrieval. Terms from different

dimensions were combined using the “AND” operator, while related terms within the same dimension were linked using the “OR” operator, in order to maximize recall while maintaining relevance. The final search covered 18 urban development related topics and was limited to the period from January 2009 to September 2025, documenting the advancement of research pertinent to the IPCC AR6 assessment cycle.

The initial search was carried out in September 2025 by two authors (ZH and SJJ) using the title and abstract fields in Web of Science and Scopus. Applying the 18 query strings returned 84,725 abstracts, which were reduced to 58,047 records after deduplication. The analysis was limited to peer-reviewed journal articles. While journal publication is not inherently indicative of case success, the peer-review process provides a verified threshold that maintains a superior standard for documented evidence[32]. Future systematic studies could address this limitation by incorporating grey literature, such as official reports and government documents, to capture a broader spectrum of outcomes. Detailed search strategies are provided in the Appendix.

### 4.3 AI-assisted screening

#### 4.3.1 Inclusion and exclusion

To screen the 58,047 records, we used an LLM-assisted inclusion and exclusion procedure that has been used in previous studies[33]. First, the LLM was used to quickly screen titles and abstracts to remove clearly irrelevant records. This step was a fast but low-precision way to narrow down the sample. To make the results more reliable, the LLM ran three times for each record. The final inclusion or exclusion decision was made by vote counting rule. Then, this resulted in 5,610 studies, of which 2,398 were linked to specific cities, while the remainder were non-city-specific literature on cities or urban areas. In addition, 77 were retrospective studies with failure outcomes reported.

The prompts are detailed below.

| *Instruction:* |
| --- |
| *Please summarize the abstract of a full research article and determine whether to include, exclude, or mark as unclear based on the following criteria. Focus on studies that report actions or policies or solutions driven by cities' own needs and explore* |

*trade-offs and costs related to climate mitigation and adaptation, including real-world urban actions not primarily targeting climate goals.*

*Inclusion Criteria:*
*- The paper includes specific urban case studies and analyzes actions or policies or solutions or technologies driven by needs or priorities (e.g., economic growth, social equity, infrastructure，investment, social programs，health).*
*- Papers that considers synergies, trade-offs, co-benefits, or conflicts between urban actions and climate mitigation and/or adaptation efforts should be included.*
*- Papers that considers economic, social, or environmental costs related to these actions should be included.*
*- or paper compares different urban types (e.g., developed/developing) or stages of development.*

*Exclusion Criteria:*
*- Studies that only discuss urban actions without linking them to specific urban development topics or climate outcomes.*
*- Theoretical or modeling-only papers without empirical case studies.*
*- Book chapters or conference proceedings collections (individual conference papers can be included).*
*- Abstract/title insufficient to determine relevance.*
*- National or global scale studies without city-level focus.*

*Output format:*
*answer=[included/excluded/unclear]*
*\\nreason=A brief explanation*

### 4.3.2 Knowledge Extraction

1) Evidence processing and merging

Following the approach of Wu, et al. [32] , the extraction was driven by structured prompts to get key knowledge from the urban studies. The knowledge extraction process is executed auto via Python and R scripts interacting with LLM APIs.

In the first stage, we took raw phrases from each study that described the urban actions and corresponding local development topics based on multiple LLMs. Only the most prominent and illuminating development topic was kept when an abstract mentioned several. Next, we used the BERTopic model to create semantic vectors for every phrase pertaining to local development topics. Agglomerative hierarchical clustering was then used to analyze these vectors. The author team examined the resulting 20 development topic clusters and aggregated them into 11 local development topics. For urban actions, due to the wide range of technical approaches, implementation scales, and application contexts, we did not rely solely on LLM. We first we

created specific urban action descriptions based on established literature, led by IPCC AR6. To find overlapping or closely related actions, action statements taken from the first 1,000 studies were encoded and analyzed using the same techniques used for development topics. To avoid incorrectly grouping actions with different scales, two researchers examined the automated initial clustering results. Newly discovered actions that were not sufficiently covered by preexisting categories were added as the literature sample grew. A final list of 48 urban actions was created following several rounds of correction. These actions were subsequently aggregated into 10 major urban action categories for further analysis.

In the second stage, we applied the same procedure to each study and mapped to the aggregated urban action categories and local development topics established in the first stage, to analyze urban actions and their corresponding development topics for each study within a consistent boundary. To minimize illusions and randomness, the two stages of the knowledge extraction process are carried out independently for each article's title and abstract using three distinct large language models (LLMs), each of which is carried out independently three times. To ensure intra-model and inter-model consistency and stability, the results from various models were combined using a vote-counting rule (i.e., a final label was assigned when at least two LLMs converged on the same category; instances in which all three LLMs produced different labels or in which no category achieved two or more votes were classified as inconclusive and resolved through expert manual adjudication). The same process was used to simultaneously extract city names, country names, and related climate impacts of urban actions. We looked at climate mitigation and adaptation as two types of climate impacts, and the outputs were either positive impact, negative impact, or no evidence. To ensure overall robustness and reliability, cross-model validation and manual verification were applied to all critical stages.

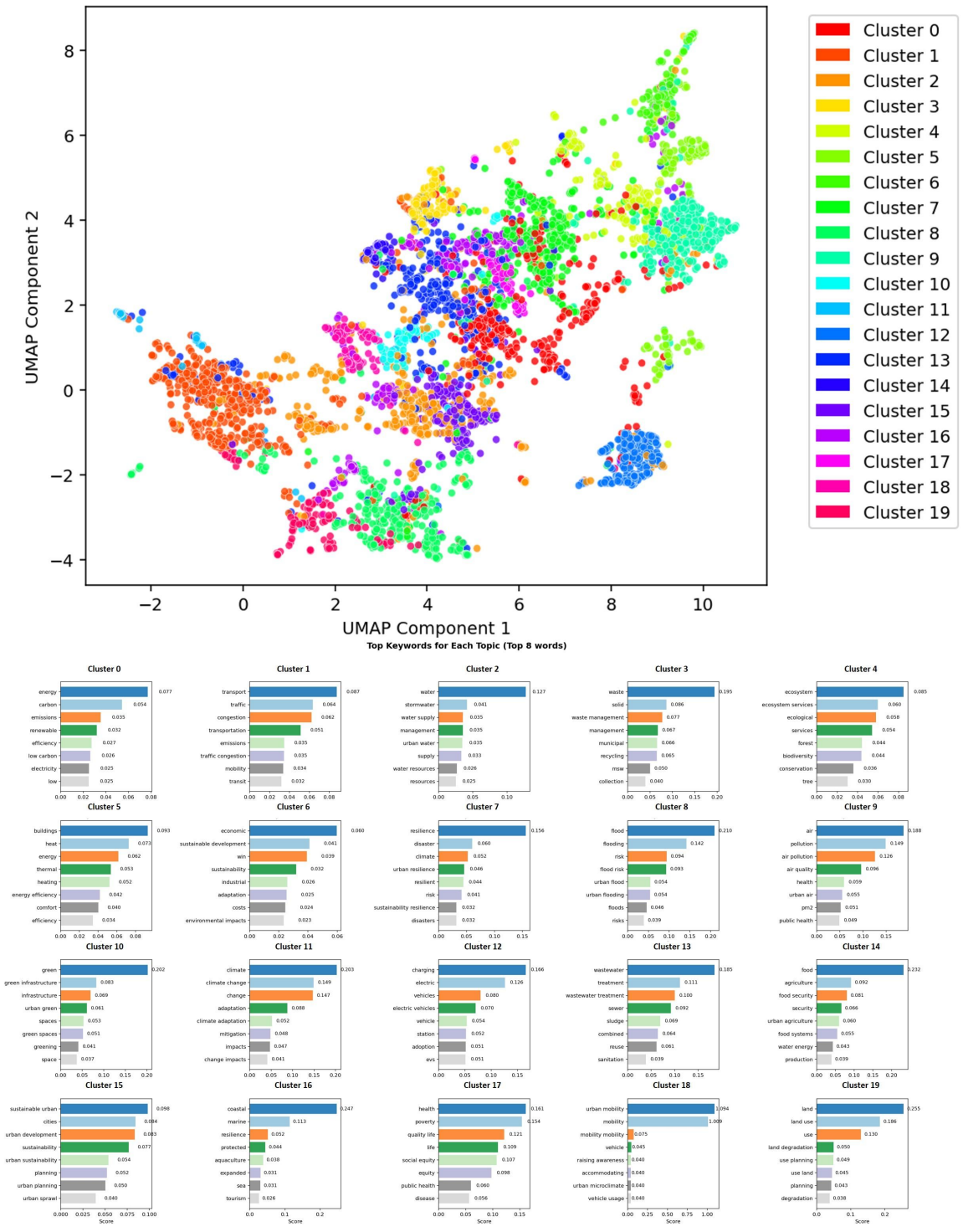



*Figure S 2 Clustering of local development topics. (a) Distribution of the initial local development topic topics identified by the BERTopic model. The axes represent the first two dimensions derived from UMAP dimensionality reduction. Data points are color-coded using a rainbow gradient according to their topic index. (b) Keywords associated with each topic.*

2) Geographic Information

Every study was mapped to the GHS-UCDB. The city names of each city-specific study were first cleaned and normalized to eliminate formatting noise to guarantee consistency and comparability of geographic information across data sources. Then, cities were matched using exact string matching. For cities that could not be matched exactly, we applied fuzzy matching, based on the Jaro–Winkler distance, to assess the similarity between cities reported in the literature and those listed in the GHSL-UCDB. In this database, cities are defined as urban centers with a population exceeding 50,000. Countries were standardized using ISO3C country codes.

After that, each study was given a geographic location that could be connected to its socioeconomic, environmental, and other characteristics. Finally, each study was assigned a geographical location, which could be linked to its socioeconomic, environmental, and other attributes. As a result, we linked each study to the relevant city profiles, development requirements, urban initiatives, and climate impacts.

#### 4.3.3 Validation

We employed confusion matrices to compare model outputs with manual reference labels to assess extraction performance. The results of the sampled data (n=307) were independently examined by three researchers (ZH, SJJ, and LYH) in five dimensions: City names, Development topics, Urban actions, Climate mitigation impact, and Climate adaptation impact. We categorized the results into four types, in which true negatives (TN) occurred when both the AI and manual review identified information as missing (NA). true positives (TP) represented cases where the AI's extracted category exactly matched the manual label. false negatives (FN) were cases where the AI missed a category identified manually, and false positives (FP) were defined as mismatches between AI and manual classifications. These results are summarized in Table S1 and Fig. 4.

Overall, the AI-assisted extraction framework showed high agreement with full manual extraction. For the city info extraction part, accuracy reached

96.81% (n = 282), with a false-positive rate of 1.46% (95% CI: 0.40%–5.17%). Accuracies for the information of local development topics, urban Action, climate mitigation outcomes, and climate adaptation outcomes were 88.85%, 89.51%, 92.18%, and 90.88%, respectively, with false-positive rates between 7.82% and 11.15%. Precision stayed consistent with accuracy, and recall reached or approached 100% in all stages, indicating the AI captured nearly all manually identified information.

*Table S 1 Performance metrics of information extraction*

| ***Stage*** | ***Data points*** | ***Accuracy (%)*** | ***False-positive rate (%)*** | ***95% CI of false positive rate (%)*** | ***Precision (%)*** | ***Recall (%)*** | ***F1 score (%)*** | ***Consistency (%)*** |
|---|---|---|---|---|---|---|---|---|
| *City names* | 282 | 96.81 | 1.46 | [0.40, 5.17] | 98.54 | 95.07 | 96.77 | 96.81 |
| *Development topics* | 269 | 88.85 | 11.15 | [7.92, 15.47] | 88.85 | 100.00 | 94.09 | 88.85 |
| *Urban actions* | 267 | 89.51 | 10.49 | [7.36, 14.74] | 89.51 | 100.00 | 94.47 | 89.51 |
| *Climate mitigation impact* | 307 | 92.18 | 7.82 | [5.31, 11.37] | 92.18 | 100.00 | 95.93 | 92.18 |
| *Climate adaptation impact* | 307 | 90.88 | 9.12 | [6.39, 12.87] | 90.88 | 100.00 | 95.22 | 90.88 |

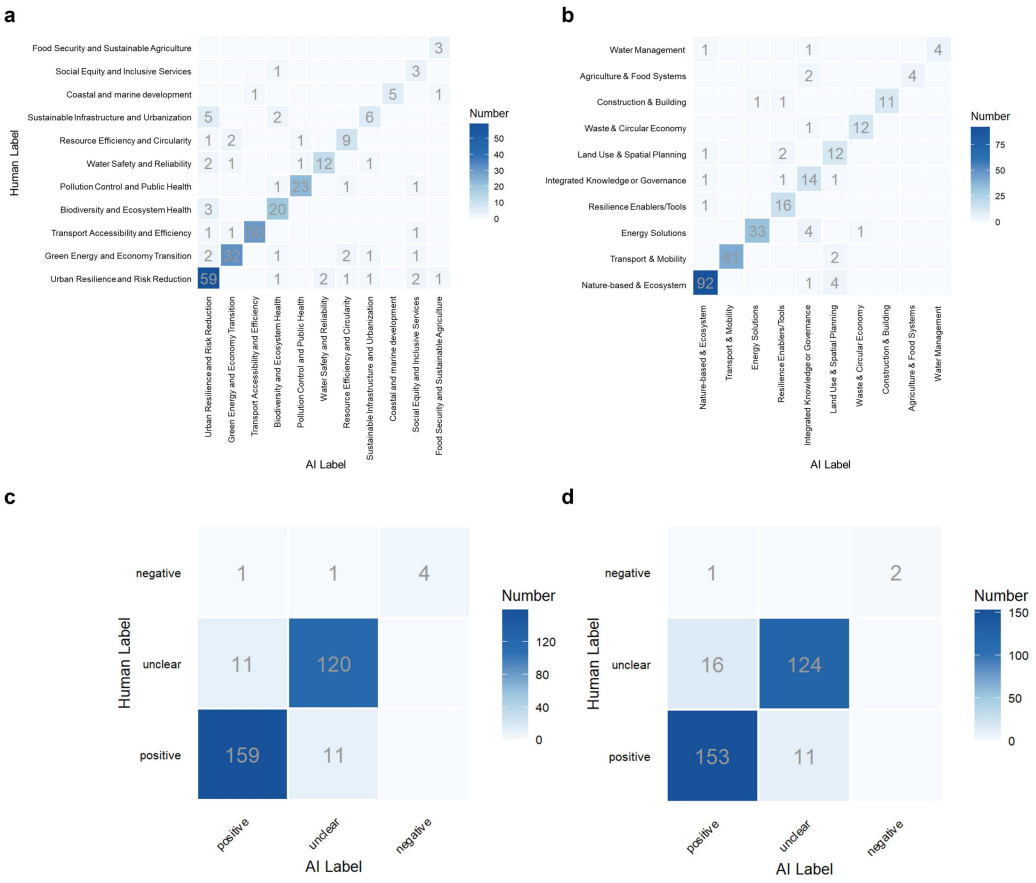



*Figure S 5 Confusion matrix comparing LLM labels with manual labels across evidence categories. Panels represent the results for (a) local development topics, (b) Urban action type, (c) Climate mitigation, and (d) Climate adaptation. The distribution shows high-frequency categories and their classification consistency.*

3) Failure Case Analysis

We then selected and analyzed failure cases. First, the study had to be based on empirical research. Second, it had to describe the logic linking actions to outcomes. Third, it had to report negative outcomes or failure cases. Here, “failure” refers to a project that did not achieve its stated socio-economic or environmental objectives, or that produced unintended negative impacts during implementation. Improving based on the previous study[29,30], the causes of failure cover six dimensions: People, Action, Information, Technology, Economic and Political conditions, and Funding, which ensured that the analysis of failure causes was comprehensive and traceable.

## Declarations

## Data Availability

The code and data required will be made publicly available upon acceptance of this manuscript.

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## Competing Interests statement

The authors declare no competing interests.

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Supplementary information:

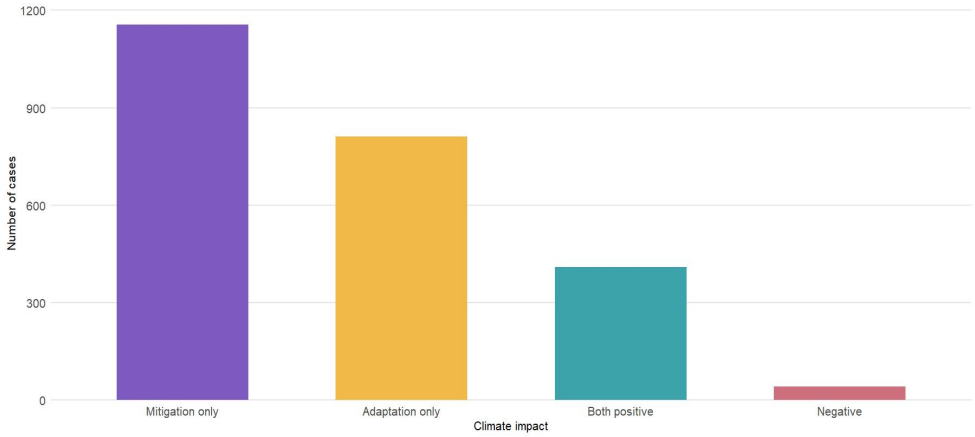



Figure S 1 The number of studies on climate impacts

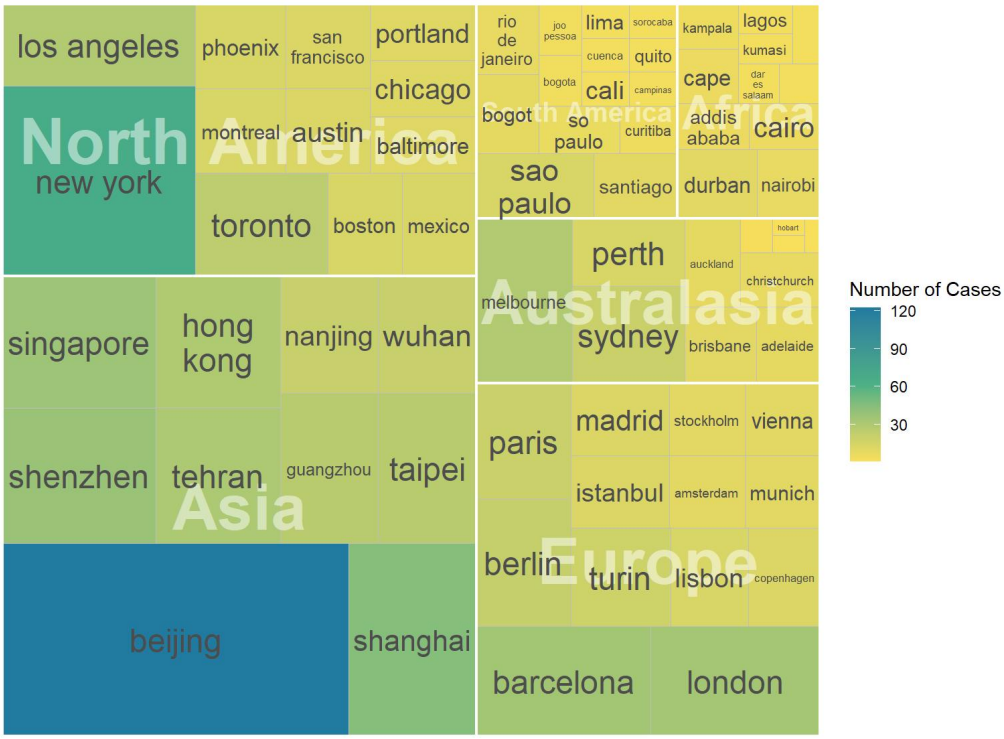


Figure S 2  Top 10 cities by number of cases by region

Table S 2 Mapping of clusters to local development topics

| Local Development topics | BERTopic clusters |
|---|---|
| Transport Accessibility and Efficiency | 1,12,18 |
| Coastal and marine development | 16 |
| Biodiversity and Ecosystem Health | 4 |
| Green Energy and Economy Transition | 0,11 |
| Social Equity and Inclusive Services | 17 |
| Sustainable Infrastructure and Urbanization | 6,10,15,19 |
| Pollution Control and Public Health | 9 |
| Urban Resilience and Risk Reduction | 5,7,8,11 |
| Resource Efficiency and Circularity | 3 |
| Food Security and Sustainable Agriculture | 14 |
| Water Safety and Reliability | 2,13 |

Table S 3 Hierarchy of major action categories and subcategories

| *Major action categories* | *Sub-action categories* |
|---|---|
| **Agriculture & Food Systems** | Agroforestry |
| | Dietary shifts |
| | Improved cropland management |
| | Reduce food loss and food waste |
| | Soil health management |
| **Construction & Building** | Change in construction materials |
| | Efficient buildings |
| | Energy-demand avoidance |
| | High-performance new building |
| | Improvement building stock |
| **Energy Solutions** | Bioenergy |
| | District heating & cooling networks |

| | |
|---|---|
| | Energy efficiency |
| | Energy supply / Renewables |
| | Fuel switching |
| | Geothermal energy |
| | Hydropower |
| | Resilient power systems |
| | Solar energy |
| | Wind energy |
| **Integrated Knowledge or Governance** | Integrated Knowledge or Governance |
| **Land Use & Spatial Planning** | Coastal zone management |
| | Land use and spatial planning |
| **Nature-based & Ecosystem** | Coastal defense and hardening |
| | Ecological connectivity |
| | Ecosystem restoration |
| | Forest-based adaptation |
| | Green and blue infrastructure |
| | Green infrastructure |
| | Ocean ecosystem services |
| | Urban afforestation |
| **Resilience Enablers/Tools** | Climate services |
| | Coastal defense and hardening |
| | Disaster risk management |
| | Social safety nets |
| **Transport & Mobility** | Electric light-duty vehicles |
| | Fuel-efficient light-duty vehicles |
| | Modal-demand shift |
| | Shared automated electric mobility systems |
| | Shift to non-motorized transport |
| | Shift to public transport |
| | Transport fuel switching |

| | |
|---|---|
| **Waste & Circular Economy** | Circular material flows |
| | Enhanced recycling |
| | Solid waste management |
| | Waste prevention, minimization and management |
| **Water Management** | Integrated Water Management |
| | Stormwater Management |
| | Water use efficiency |