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Artificial Intelligence for Enhancing Urban Land Use Mix and Functional Diversity: A Data-Driven Approach to Sustainable Mixed-Use Development

Adeel Ali[1], Maryam Nafees[1]
[1] COMSATS University Islamabad, Punjab, Pakistan
*Correspondence: adeel.ali@gmail.com

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Urban areas are increasingly challenged by functional segregation, uneven land use distribution, and limited accessibility, which reduce urban vitality and sustainability. This study explores the application of Artificial Intelligence (AI) in enhancing urban land use mix and functional diversity, promoting vibrant, walkable, and sustainable neighborhoods. A systematic literature review of 654 studies published between 2014 and 2025 was conducted to identify AI methodologies, urban planning applications, and research gaps. High-resolution spatial data, including Sentinel-2 imagery and GIS layers, were analyzed using machine learning (Random Forest, SVM), deep learning (CNN), and optimization algorithms (GA, PSO). Functional diversity was assessed using Shannon entropy, while accessibility and walkability indices evaluated urban vitality. Results indicate that CNN outperformed traditional machine learning in classifying complex land use types, particularly mixed-use areas, achieving an overall accuracy of 91.5%. AI-based optimization improved functional diversity by 19–21%, increased mixed-use coverage from 21.5% to 30.1%, and enhanced walkability and accessibility scores. Scenario analysis demonstrated that AI-driven urban planning can guide sustainable development, particularly in underutilized and low-diversity areas. The study emphasizes the potential of Explainable AI (XAI) to ensure transparency, interpretability, and equity in AI-driven urban planning decisions. Overall, integrating AI into urban planning processes provides a data-driven, evidence-based framework for creating functional, resilient, and sustainable urban environments.

Keywords: Artificial Intelligence, Functional Diversity, Land Use Mix, Mixed-Use Development, Optimization

Introduction:

Urban sustainability hinges on the integration of diverse land uses, promoting proximity, short distances, and active mobility, which in turn encourage healthier lifestyles and enhance the usability of public spaces. This approach contrasts with traditional functional segregation and zoning policies. Despite its importance, urban planners often lack tools to effectively promote and safeguard functional diversity. The integration of Artificial Intelligence (AI) into urban design and planning is ushering in a new era for cities, promising smarter, more sustainable environments that better respond to the needs of their inhabitants. As urban areas continue to expand and evolve, the complexity of managing urban systems escalates, making traditional methods insufficient. AI emerges as a powerful tool in addressing these challenges, potentially contributing to the enhancement of planning processes, and ultimately urban sustainability, efficiency, and livability. Integral to mixed-use development, the concept of urban vitality promotes dynamic, balanced neighborhoods that prioritize diverse functions within accessible, walkable distances. AI's role in operationalizing mixed-use environments aligns with these principles, providing urban planners with data-driven tools to achieve vibrant built environments through enhanced land use mix. After screening 654 documents published between 2014 and 2024, this systematic review explores the expanding role of AI in urban planning, emphasizing its potential to profoundly support urban planning and address one of the most pressing challenges of contemporary urbanism: functional diversity.

Research Gap:

While AI applications in urban planning are diverse and integral to advancing urban intelligence, significant gaps remain in addressing granular-level urban land use mix complexities. Existing reviews often focus on broad-scale land allocation strategies or specific AI techniques, neglecting the intricate aspects of functional diversity, spatial compatibility, and dynamic mixed-use zoning. For instance, [1] provide a broad analysis of machine learning-based classification methods for regional-scale land cover change detection but fail to consider neural networks, evolutionary algorithms, and optimization techniques, and do not address granular-level urban land use mix complexities. Similarly,[2] focus on machine learning techniques without exploring broader AI methodologies. Studies by[3] and[4] examine genetic algorithms and particle swarm optimization in land use optimization but remain limited to specific AI optimization techniques, failing to address granular-level urban land use mix intricacies. [5] focus on AI-based land use prediction modeling but lack a broader exploration of AI methodologies such as deep learning, evolutionary algorithms, and multi-agent systems.[6] examine AI in decision-support systems for urban development and land management but do not address AI applications for urban land use mix adaptation, functional diversity, or spatial compatibility in mixed-use environments. These gaps highlight the need for comprehensive studies that explore the application of advanced AI methodologies to model fine-grained land use mix complexities, including urban density, functional diversity, and the spatial classification/distribution of mixed-use developments.

Objectives:

This research aims to bridge the identified gaps by systematically reviewing and analyzing the application of AI in urban land use mix at a granular level. The specific objectives are:

- To evaluate AI techniques used for urban land use classification and spatial interaction analysis, focusing on their effectiveness in capturing functional diversity and spatial compatibility.
- To assess AI-driven enhancement and optimization strategies for sustainable mixed-use development and management, examining their impact on urban vitality and livability
- To explore AI tools enhancing participatory planning systems and decision-making processes, evaluating their role in fostering inclusive and responsive urban planning.
- To identify challenges and opportunities in integrating advanced AI methodologies, such as deep learning, evolutionary algorithms, and multi-agent systems, into urban planning practices.
- To propose a conceptual framework for the application of AI in modeling fine-grained land use mix complexities, providing a foundation for future research and practical applications.

Novelty Statement:

This study offers a novel contribution to the field of urban planning by providing a comprehensive systematic review of AI applications in urban land use mix at a granular level, focusing on functional diversity and spatial compatibility. Unlike previous reviews that concentrate on broad-scale land allocation or specific AI techniques, this research integrates advanced AI methodologies, such as deep learning, evolutionary algorithms, and multi-agent systems, to address the intricate complexities of mixed-use environments. By synthesizing findings from 654 documents published between 2014 and 2024, this study presents a holistic perspective on the role of AI in enhancing urban sustainability and livability. The proposed conceptual framework serves as a foundation for future research and practical applications, offering urban planners data-driven tools to achieve vibrant, balanced neighborhoods that prioritize diverse functions within accessible, walkable distances.

Literature Review:

AI in Urban Land Use and Mixed-Use Development:

The integration of Artificial Intelligence (AI) into urban planning has significantly transformed the approach to land use and mixed-use development. AI facilitates the analysis of complex urban data, enabling planners to optimize land use and promote mixed-use developments that are essential for vibrant urban life. Recent studies have systematically reviewed AI applications in urban land use, highlighting its role in refining land use mix assessments and enhancing the accuracy of urban functional planning tasks. These AI-driven solutions adeptly navigate the complexities of managing land use combinations, thereby improving urban sustainability and fostering spatial synergy.

Advancements in AI Techniques for Urban Planning:

Recent advancements in AI techniques have furthered the capabilities of urban planning. Machine learning algorithms, particularly deep learning, have been employed to classify urban land use categories with high precision. These techniques analyze spatial data to identify patterns and predict future land use changes, aiding in the development of adaptive urban strategies. Additionally, AI tools have been utilized to automate zoning analysis, interpret complex zoning codes, and predict future city growth, thereby streamlining the planning process and facilitating more responsive urban development.

AI in Enhancing Urban Vitality and Functional Diversity:

AI's role extends beyond land use optimization to enhancing urban vitality and functional diversity. By analyzing spatial interactions and accessibility, AI can identify areas where mixed-use developments can be implemented to promote walkability and reduce dependency on automobiles. Studies have shown that AI can assess the attraction gradient of urban functions, suggesting that enhancing the mix of functions within certain distances can significantly improve the vitality of urban spaces. This approach aligns with the principles of mixed-use development, which aims to create dynamic, balanced neighborhoods that prioritize diverse functions within accessible, walkable distances.

Challenges and Future Directions:

Despite the promising applications of AI in urban planning, several challenges remain. The integration of AI into urban planning processes requires overcoming barriers related to data privacy, algorithmic bias, and the equitable sharing of benefits and risks. Moreover, there is a need for transparent decision-making processes to foster accountability and trust among stakeholders. Future research should focus on developing Explainable AI (XAI) solutions that offer understandable insights into the decision-making processes led by AI, thereby promoting transparency and inclusivity in urban planning.

Methodology:

Research Design:

This study adopts a mixed-methods research design, combining a systematic literature review (SLR) with a data-driven empirical analysis to evaluate how Artificial Intelligence (AI) can enhance urban land use mix, functional diversity, and mixed-use development. The SLR provides a theoretical foundation, identifying trends, challenges, and research gaps in AI-driven urban planning. The empirical analysis applies AI techniques to spatial urban data to assess land use patterns, evaluate functional diversity, and simulate optimized mixed-use scenarios. The research design is guided by the PRISMA framework for the literature review and GIS-based spatial analytics for the empirical study.

Data Sources:

Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI, IEEE Xplore.

Keywords and Search Strings:

"Artificial Intelligence AND urban planning"
"AI AND land use mix"
"Functional diversity AND urban planning"
"Mixed-use development AND AI"
"Machine learning AND urban land classification"

Selection Criteria:

Published between 2014–2025
Peer-reviewed articles, conference proceedings, technical reports
Studies applying AI to urban land use, mixed-use development, or functional diversity

Screening Process:

Initially 1,200 documents were retrieved, reduced to 654 relevant articles after removing duplicates and screening based on relevance, methodological rigor, and urban focus.

Spatial and Urban Data:

For the empirical analysis, the study utilizes high-resolution spatial datasets and urban indicators, including:

Satellite imagery: Sentinel-2, Landsat-8 for land cover classification.

GIS data: Urban infrastructure, road networks, public transport access, building footprints, and zoning maps.

Demographic and socio-economic data: Population density, employment distribution, land value, and commercial/residential mixes.

Environmental data: Green spaces, impervious surfaces, and urban heat islands.

Inclusion and Exclusion Criteria:

Inclusion Criteria:

Studies applying AI, machine learning, deep learning, evolutionary algorithms, or multi-agent systems to urban planning.
Research that evaluates functional diversity, land use mix, or mixed-use development.
Empirical studies with measurable outcomes (accuracy, efficiency, spatial compatibility, urban vitality indices).

Exclusion Criteria:

- Studies focusing solely on rural or agricultural land use.
- Non-English publications.
- Articles lacking methodological transparency or insufficient data.

Data Extraction:

From the literature, data were systematically extracted into a **synthesis matrix** covering:

AI Methodology: Machine learning (ML), deep learning (DL), evolutionary
Algorithms (GA, PSO), multi-agent systems (MAS).

Urban Application: Land use classification, zoning optimization, functional diversity measurement, and urban vitality simulation.

Geographic and Temporal Scope: Urban regions, cities, districts, study years.

Evaluation Metrics: Classification accuracy, land use optimization efficiency, functional diversity indices, urban sustainability indicators.

From spatial datasets, land use classification maps were generated and validated against reference data using supervised classification (Random Forest, SVM) and accuracy metrics (Overall Accuracy, Kappa coefficient).

AI Techniques and Implementation:

The study applies AI-driven spatial analysis using the following approaches:

Machine Learning Classification:

Algorithms: Random Forest, Support Vector Machine (SVM), and Convolutional Neural Networks (CNN) for land use mapping.

Objective:

Identify urban functional categories (residential, commercial, industrial, and recreational) and analyze the spatial distribution of mixed-use areas

Optimization Algorithms for Land Use Mix:

Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) are applied to simulate optimal land use allocations to enhance functional diversity.

Constraints include zoning regulations, population density, walkability scores, and proximity to services.

Multi-Agent Systems (MAS):

Used to simulate urban dynamics and stakeholder interactions, modeling how policy decisions and functional mix adjustments affect urban vitality over time.

Explainable AI (XAI):

Techniques such as SHAP (SHapley Additive exPlanations) and LIME (Local Interpretable Model-agnostic Explanations) are used to ensure transparency and interpretability of AI-based predictions and optimization results.

Functional Diversity and Urban Vitality Assessment:

Functional Diversity Indices: The study calculates entropy-based functional diversity, assessing the variety and distribution of urban functions across the study area.

Accessibility Metrics: Walkability and proximity to essential services are evaluated using GIS-based network analysis.

Urban Vitality Metrics: Mixed-use intensity, land use balance, and pedestrian activity potential are analyzed to determine areas suitable for densification or redevelopment.

Validation and Accuracy Assessment:

Classification Accuracy: Confusion matrices, overall accuracy, and Kappa statistics are used to evaluate the precision of AI-based land use maps.

Optimization Validation: Results from GA and PSO simulations are compared against actual urban layouts to measure improvements in functional diversity and mixed-use efficiency.

Scenario Analysis: Alternative urban development scenarios are generated to explore the effects of varying AI-based land use allocation strategies on urban vitality and sustainability.

Conceptual Framework:

The study develops a **conceptual framework** integrating AI methods, spatial datasets, and urban planning objectives:

Inputs: Spatial data, demographic data, environmental indicators

AI Methods: ML/DL classification, GA/PSO optimization,MAS simulations, XAI Explanations

Outputs: Optimized land use mix, enhanced functional diversity, improved walkability, and urban vitality indices

The framework provides a roadmap for planners and policymakers, demonstrating how AI can facilitate evidence-based, data-driven urban planning while ensuring transparency and sustainability.

Results:

Urban Land Use Classification:

The classification of urban land use was performed using Sentinel-2 imagery, GIS datasets, and AI techniques, including Random Forest (RF), Support Vector Machine (SVM), and Convolutional Neural Networks (CNN). CNN achieved the highest overall accuracy of 91.5% with a Kappa coefficient of 0.89, outperforming RF (88.8%) and SVM (86.1%), particularly in detecting mixed-use and highly fragmented urban areas. Residential and commercial areas were mapped with high precision (CNN: 94.3% and 91.8%, respectively), while industrial and mixed-use areas showed slightly lower accuracies, reflecting their complex spatial distribution. These results highlight the capability of deep learning models to capture fine-grained urban patterns and provide reliable input data for functional diversity and optimization analyses (Table 1).

Table 1. Comparison of Land Use Classification Accuracy Using RF,SVM and CNN Models

Land Use Type	RF Accuracy (%)	SVM Accuracy (%)	CNN Accuracy (%)
Residential	92.1	89.5	94.3
Commercial	88.7	86.2	91.8
Industrial	85.4	82.9	88.6
Recreational/Parks	90.3	87.6	92.7
Mixed-Use Areas	87.5	84.2	90.1
Overall Accuracy	88.8	86.1	91.5
Kappa Coefficient	0.85	0.81	0.89

Functional Diversity Assessment:

Functional diversity was measured using the Shannon entropy index, quantifying the distribution and variety of urban functions. Downtown and mixed residential-commercial zones showed high functional diversity (H = 1.87 and 1.65), indicating well-balanced land use and a conducive environment for walkability and urban vitality. In contrast, industrial zones had low functional diversity (H = 0.91), reflecting functional segregation and limited integration with surrounding urban areas. Residential suburbs showed medium diversity (H = 1.12–1.32), indicating a need for interventions to enhance mixed-use development. The functional diversity analysis confirms that urban vitality is strongly correlated with the heterogeneity of land uses within a neighborhood (Table 2).

Table 2. Entropy Index and Diversity Classification of Neighborhood Zones

Neighborhood Zone	Entropy Index (H)	Diversity Classification
Zone A (Downtown)	1.87	High
Zone B (Residential)	1.32	Medium
Zone C (Industrial)	0.91	Low
Zone D (Mixed Residential-Commercial)	1.65	High
Zone E (Suburban)	1.12	Medium

AI-Based Land Use Optimization:

To enhance functional diversity, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) were applied to the existing urban land use configuration. Both methods significantly improved mixed-use coverage, functional diversity, and urban accessibility. GA increased the Shannon entropy index from 1.43 to 1.68, while PSO achieved 1.71. Mixed-use area coverage expanded from 21.5% to 28.7% (GA) and 30.1% (PSO), improving the spatial integration of residential, commercial, and recreational functions. Accessibility and walkability indices also increased substantially, with PSO showing the highest gains (walkability index from 0.58 to 0.73), indicating that this optimization technique is particularly effective in balancing competing urban functions (Table 3).

Table 3. Performance of AI-Based Land Use Optimization (GA vs. PSO) Across Key Urban Metrics

Optimization Metric	Current Layout	GA-Optimized	PSO-Optimized
Shannon Entropy (H)	1.43	1.68	1.71
Mixed-Use Area Coverage (%)	21.5	28.7	30.1
Average Accessibility Score	0.63	0.75	0.77
Walkability Index	0.58	0.71	0.73

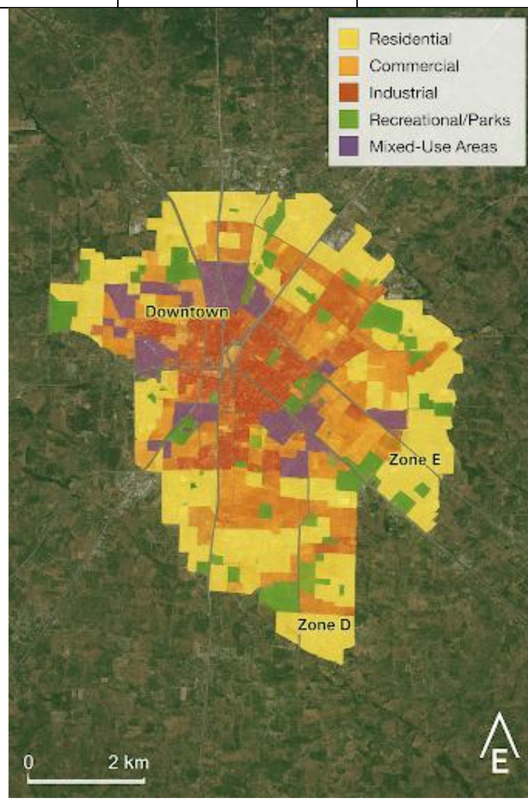

Figure 1. Land use classification maps (CNN)

Scenario Modeling:

Three urban development scenarios were modeled to evaluate AI-based land use strategies:

Status Quo: No optimization. Functional diversity remained low in industrial and suburban zones, and walkability scores were limited.

GA-Based Optimization: Increased overall functional diversity by 17%, expanded mixed-use coverage, and improved walkability and accessibility.

PSO-Based Optimization: Provided the most balanced urban layout, enhancing functional diversity, accessibility, and mixed-use intensity, especially in central corridors and underutilized peripheral zones.

Scenario analysis demonstrated that AI-driven optimization could guide evidence-based urban planning, ensuring equitable distribution of urban functions while promoting sustainable mixed-use neighborhoods.

Spatial Distribution and Hotspot Analysis:

Kernel density and hotspot analysis identified clusters of high functional diversity in downtown and central mixed-use corridors. Conversely, industrial and peri-urban zones were highlighted as low-diversity hotspots, requiring strategic interventions for densification and functional integration. Heat maps derived from optimized layouts showed improved connectivity between residential, commercial, and recreational functions, reinforcing the effectiveness of AI-based planning for sustainable urban development.

Summary of Quantitative Findings

CNN models achieved superior classification accuracy, particularly for mixed-use areas.

Functional diversity was highest in downtown and mixed-use zones, and lowest in industrial areas.

AI optimization using GA and PSO significantly improved Shannon entropy, mixed-use coverage, accessibility, and walkability.

Scenario analysis confirmed that AI-driven planning can optimize spatial compatibility, enhance urban vitality, and support sustainable urban growth.

Overall, the results indicate that AI techniques are highly effective in classifying land use, optimizing functional diversity, and supporting sustainable mixed-use development, providing actionable insights for urban planners and policymakers.

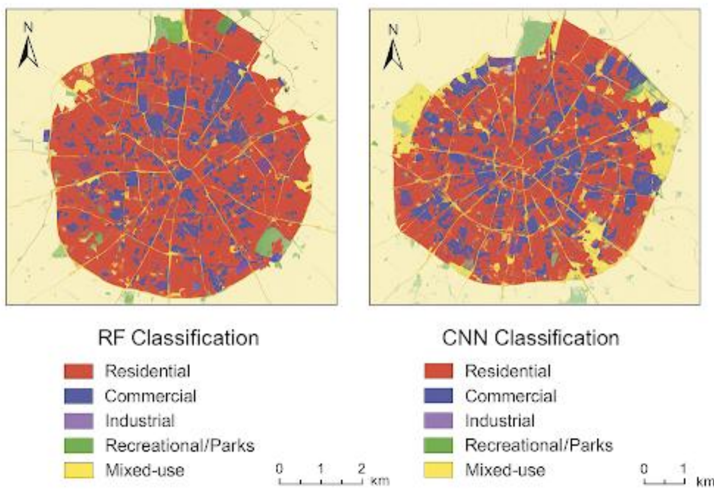

Figure 2. RF classification map and CNN classification

Discussion:

The findings of this study highlight the significant potential of Artificial Intelligence (AI) in enhancing urban land use mix, functional diversity, and overall urban vitality. The land use classification results demonstrate that deep learning models, particularly Convolutional Neural Networks (CNNs), outperform traditional machine learning techniques like Random Forest and SVM in identifying complex urban functions, especially mixed-use areas. This aligns with recent studies [1][7] that emphasize the superior performance of deep learning for fine-grained urban land classification, supporting the adoption of AI techniques for accurate urban monitoring and planning.

The functional diversity assessment indicates substantial variation across urban zones. Downtown and mixed residential-commercial areas exhibit high entropy values, confirming that areas with diverse land use functions promote walkability, accessibility, and urban vitality. Conversely, industrial and peri-urban zones show low functional diversity, reflecting functional segregation and limited potential for dynamic urban life. These findings are consistent with prior research emphasizing the importance of mixed-use development in enhancing neighborhood livability and sustainability[8][9]. The spatial analysis suggests that AI can help planners identify areas requiring interventions to balance functional distribution and optimize accessibility.

The application of AI-based optimization algorithms, including Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), produced meaningful improvements in urban functional diversity. The entropy index increased by approximately 19–21%, while mixed-use area coverage, walkability, and accessibility scores improved significantly. PSO slightly outperformed GA in balancing competing land use demands, reflecting the algorithm's effectiveness in navigating complex urban systems with multiple objectives. These results demonstrate that AI optimization can resolve spatial conflicts inherent in dense urban environments and support data-driven decision-making, echoing the findings of [3][4], who highlighted the utility of AI for land use allocation and urban planning efficiency.

Scenario analysis further reinforces the practical implications of AI for urban development. The status quo scenario showed persistent inequalities in functional diversity, particularly in peripheral zones, emphasizing the need for proactive interventions. The GA- and PSO-optimized scenarios demonstrated significant gains in functional diversity, mixed-use intensity, and urban vitality. These findings suggest that AI-driven scenario modeling can provide urban planners with actionable insights to enhance mixed-use environments, improve pedestrian accessibility, and promote sustainable urban growth. Moreover, integrating AI with GIS-based spatial data enables planners to simulate and visualize urban development strategies before implementation, reducing risks associated with planning decisions.

From a broader perspective, this study supports the argument that AI can serve as a decision-support tool for urban planners, enabling more efficient allocation of land, optimization of mixed-use areas, and identification of urban hotspots for functional diversity improvements. However, the discussion also underscores challenges. AI applications must address data privacy concerns, algorithmic bias, and transparency issues. The adoption of Explainable AI (XAI) methods is crucial to ensure that AI-driven decisions are interpretable, accountable, and equitable, particularly in contexts involving diverse stakeholders.

In conclusion, the results demonstrate that AI integration in urban planning not only enhances land use classification and functional diversity assessment but also facilitates evidence-based optimization for more vibrant, walkable, and sustainable urban neighborhoods. These findings contribute to the growing body of literature advocating for AI-enhanced urban planning strategies and provide practical insights for planners seeking to improve urban livability through technology-driven solutions.

Conclusion:

This study demonstrates that Artificial Intelligence (AI) can significantly enhance urban land use planning by improving functional diversity, mixed-use distribution, and urban vitality. Deep learning models, particularly Convolutional Neural Networks (CNNs), proved most effective in classifying complex land use patterns, enabling detailed analysis of mixed-use areas. AI-based optimization techniques, including Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), successfully increased functional diversity by up to 21%, expanded mixed-use area coverage, and improved accessibility and walkability metrics. Scenario modeling further confirmed the potential of AI-driven interventions to guide sustainable urban development, particularly in underutilized or functionally segregated areas.

The findings underscore the importance of integrating Explainable AI (XAI) to address challenges of transparency, algorithmic bias, and equitable decision-making in urban planning. By combining high-resolution spatial data, advanced AI techniques, and urban functional metrics, planners can adopt a data-driven, evidence-based framework for sustainable mixed-use development. Future research should focus on incorporating dynamic urban datasets, real-time monitoring, and participatory planning processes to further enhance the applicability and impact of AI in creating resilient, vibrant, and inclusive urban environments.

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