Urban intelligence for extreme heat mitigation and adaptation

Experience in Asian cities

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Abstract

As urbanization accelerates globally, cities play a pivotal role in addressing the environmental and socio-economic challenges associated with rapid population growth, particularly in the context of climate change. This research focuses on a critical concept of urban intelligence and relevant AI applications in mitigating and adapting to extreme heat conditions, a critical issue in densely populated Asian cities. Extreme heat exacerbates public health risks, infrastructure degradation, and socio-economic inequalities, particularly in informal settlements with inadequate cooling resources. Leveraging AI, cities such as Singapore, Seoul, and Kuala Lumpur are pioneering innovations in real-time heat monitoring, predictive analytics, and climate-adaptive urban design. These efforts include the integration of AI with digital twin technologies for simulating urban heat islands, optimizing green and blue infrastructure, and enhancing smart building operations. This paper also discusses the opportunities and challenges of implementing AI-driven urban intelligence in Asian cities, highlighting the need for equitable access to technology, preservation of local historic architecture, and integration of traditional knowledge with modern innovations. The findings suggest that while AI holds significant promise for enhancing urban resilience to extreme heat, successful implementation will require careful consideration of local contexts, regulatory frameworks, and the socio-economic dynamics of rapidly urbanizing regions.

Introduction

Cities are central to achieving the sustainable development goals outlined in UN Sustainable Development Goal 11. The UN estimates that by 2050, the global population will reach 10 billion, with 68% residing in urban areas (United Nations, 2018). Meanwhile, cities also intensify environmental pressures and socio-economic conflicts, consuming over two-thirds of the world's energy and producing more than 70% of global carbon emissions (Luqman et al., 2023). Among the challenges, extreme heat poses a significant threat to urban areas, worsening health issues such as heat-related illnesses and respiratory conditions, increasing energy demand that strains power grids, damaging infrastructure through thermal expansion and contraction, degrading air quality by elevating pollution levels, and threatening water supplies due to higher evaporation rates. Extreme heat events can further lead to substantial economic costs, especially the ones related to healthcare and infrastructure repairs while exacerbating social inequalities by disproportionately affecting lower-income neighborhoods with fewer green spaces and limited cooling resources.

Asian cities are particularly vulnerable to the challenges of extreme heat due to their rapid urbanization and dense populations. The Intergovernmental Panel on Climate Change (IPCC) projects that many parts of Asia will experience more frequent and severe heatwaves by 2050, with the number of days exceeding 35°C expected to rise significantly in cities like Karachi, Delhi, and Ho Chi Minh City. (World Resources Institute, 2021). Urban areas, such as Tokyo, Bangkok, and Manila, are already several degrees hotter than nearby rural regions due to the concentration of buildings, roads, and other heat-absorbing infrastructure. (Chapman et al., 2017). In densely populated cities like Dhaka, Mumbai, and Jakarta, the impact of extreme heat is further exacerbated, particularly in informal settlements that lack adequate infrastructure. (Rashid et al., 2013). These conditions pose significant public health risks, with studies indicating the percentage of heat-related deaths attributed to human-induced climate change in Southeast Asia is between 48% to 61%, which is the second highest after Central and South America. (Medicine, 2021). In response to these challenges, cities are actively exploring and implementing planning interventions, policies, and technological solutions to mitigate and adapt to the growing impacts of extreme heat.

AI and urban intelligence

With growing urban big data and smart city applications, Artificial intelligence (AI) is increasingly becoming integrated into our urban environments, giving rise to urban intelligence as a comprehensive capability that leverages big data computing and information technology to enhance urban systems

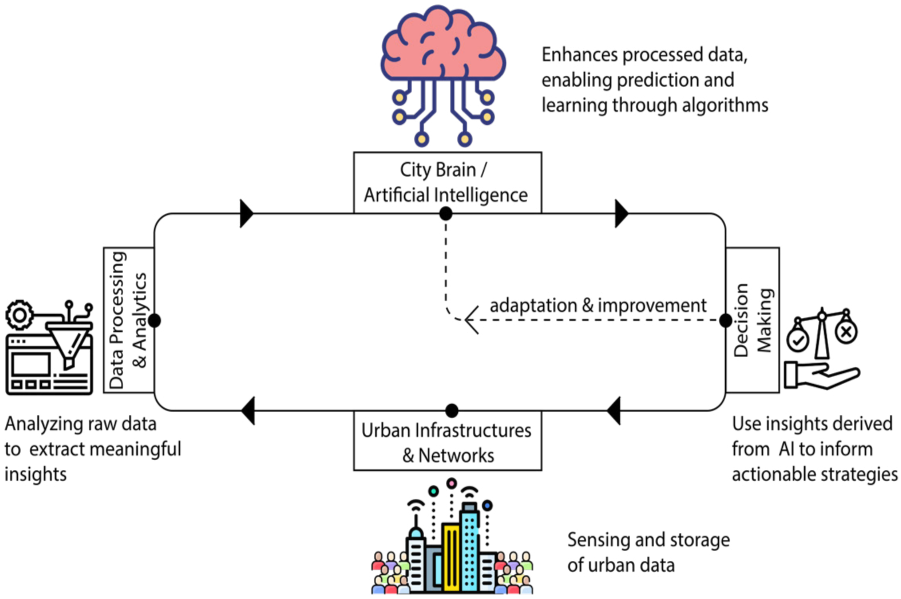

Figure 1: Anatomies and processes of urban intelligence (Source: Author)

Figure 2: Capacities of urban intelligence (Source: Author)

across various domains. AI enables computers to perform tasks traditionally associated with human cognition, such as perception, comprehension, and decision-making. These tasks rely on computing that involves data processing, analytical modeling, and outcome generation aligned with predefined objectives. AI's effectiveness largely depends on the quantity and quality of data and algorithms inspired by the human brain's decision-making processes with reasoning, learning, and problem-solving capabilities (Figure 1).

Urban intelligence plays a critical role in climate change resilience by providing real-time monitoring, predictive analytics, and automated responses that help cities anticipate and mitigate the impacts of extreme conditions (Lai, 2021, 2022). Urban infrastructure networks handle the sensing and storage of urban data. AI-powered infrastructures, such as intelligent transportation networks and waste management systems, can significantly improve urban operational efficiency. Then, data processing and analytics involving analyzing raw data to extract meaningful insights. Machine learning enhances the processed data, enabling prediction and learning through various algorithms. Ultimately, decision-making and adaptation use the insights derived from AI to inform actionable strategies. For instance, urban intelligence can advance urban health through everyday applications like personalized health monitoring and automated suggestions (Figure 2). These capabilities can greatly enhance climate resilience by utilizing predictive analytics and automated response systems to anticipate, mitigate, and adapt to extreme heat conditions.

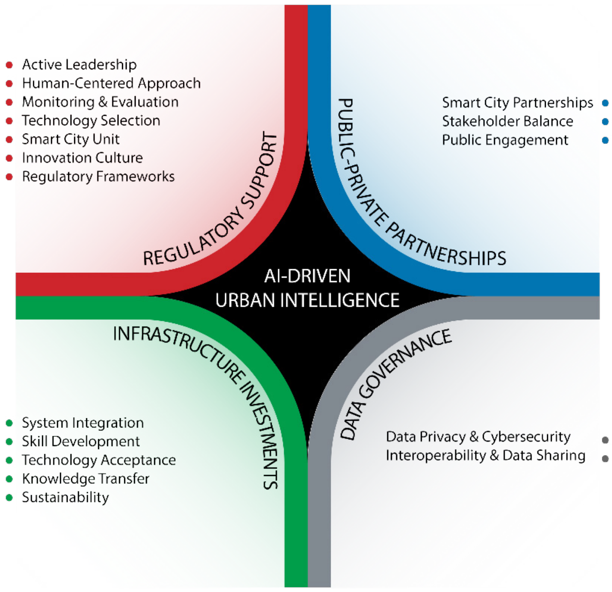

Figure 3: Government Roles in AI-driven Urban Intelligence (Source: Author)

As cities and companies are still experimenting with the capacity and use cases of urban intelligence due to the complexities of real-world urban scenarios and environment, there are already early-stage implementations across Asia for urban heat sensing, mitigation, and adaptation into the existing smart city ecosystems and frameworks. In Asia, researches have shown that responsibility and involvement in planning and implementation of smart city initiatives still largely falls on municipal governments. Hence, city governments and policymakers play significant roles in promoting and integrating the development of AI-driven urban intelligence (Figure 3). The key policy contributions are active regulatory support, inclusive public-private partnerships, sustainable infrastructure investments, and secure data governance. For example, AI for Urban Cooling, a joint grant call launched by AI Singapore and the Institute for Information and Communication Technology Planning and Evaluation, South Korea funds the research on AI-Assisted Multi-scale Microclimate Models. It is a scientific and technological cooperation between Singapore and South Korean researchers to develop AI-assisted models as a solution to satisfy the analytic, simulation and design recommendation needs to mitigate urban heat island effect and improve thermal comfort in urbanized areas. In addition, China aims to achieve global leadership in AI theory, technology, and applications, establishing itself as a key global innovation hub for AI by 2030, according to the comprehensive plan for the development of artificial intelligence (AI) by the State Council of China.

Urban heat sensing

Real-time heat monitoring and forecasting

Urban intelligence provides comprehensive sensing capacity that enables cities to monitor, measure, quantify, and analyze local heat-related factors. Cities like Tokyo and Singapore deploy IoT sensing networks to collect real-time temperature, humidity, and air quality data, which are essential for identifying heat hotspots and microclimatic variations within the city. (Nurmadiha Osman et al., 2021). AI models can leverage historical data, urban infrastructure, and satellite imagery to predict extreme heat events. For example, Seoul uses AI-driven models to forecast heatwaves and provide early warnings, helping authorities and citizens prepare in advance. (Asadollah et al., 2021). In Singapore, the local city agencies collaborated with ARUP on UHeat, a tool for identifying local urban heat effects. (ARUP, 2023). This tool leverages machine learning to analyze large volumes of satellite images by tagging building materials like glass, steel, tarmac, vehicles, air conditioning units, data centers, and other urban developments that may raise local temperatures (Figure 4).

Urban heat simulation

In large and densely built urban areas, AI can pair with digital twin technology to simulate extreme urban heat conditions at finer spatial resolution and nearly real-time frequency. Singapore has been utilizing various urban intelligence tools to improve building inspections with image processing and thermal sensing to monitor facade defects in buildings, identify types, and respond to repair costs (Figure 5). The city further invested in its R&D on a new technology that can simulate and assess building energy loss. By thermal scanning, it would be easier to locate the inefficiency of insulation in buildings and identify where action is needed. Real-time temperature sensing and heat distribution simulation across cities can help identify hotspots and implement targeted cooling strategies. By leveraging predictive analytics, AI models can forecast heatwaves, create real-time heat maps, guide proactive measures to protect vulnerable areas and the local population, and allow cities to prepare and respond proactively.

Figure 4: The UHeat tool analyzes the city's temperature between different locations in Singapore
(*Source*: https://www.arup.com/insights/from-urban-heat-to-biomimetic-design-how-digital-tools-can-support-greener-cities/)

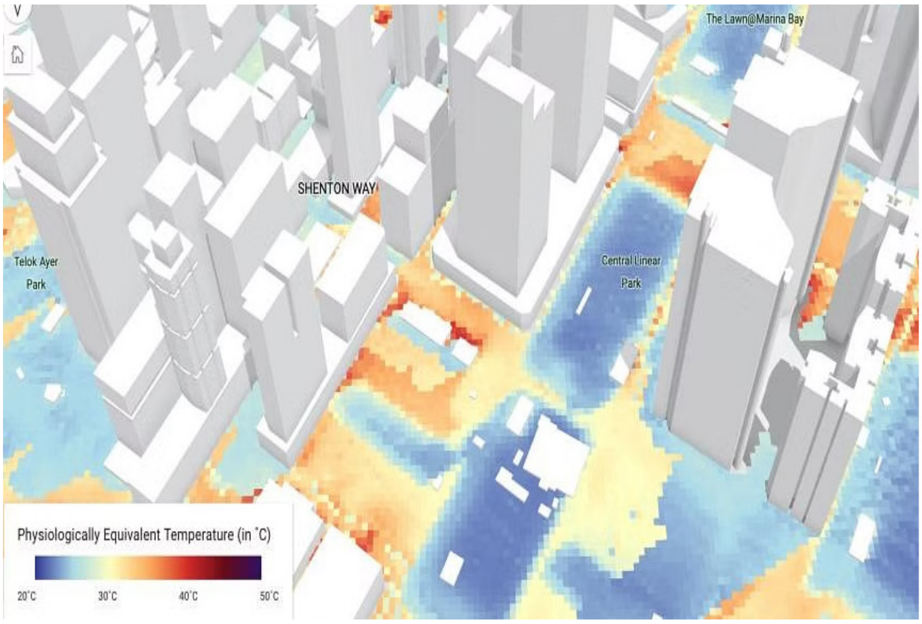

Figure 5: Digital twin of local temperature in the Central Business District, Singapore

(*Source*: ARUP)

Urban heat mitigation

Green & Blue infrastructure optimization

Urban heat mitigation refers to strategies and actions taken to reduce or counteract the extreme heat effects in cities. (Martilli et al., 2020). The goal is to lower urban temperature, improve thermal comfort for residents, reduce energy consumption for cooling, and enhance overall urban sustainability and livability. Urban heat mitigation can be done through various stages and processes in the optimization of urban green and blue infrastructures. Beginning with stakeholder engagement which ensures that local businesses, communities and residents have involvement in the early phases of co-designing and co-planning, this is followed by a feasibility study, which involves conducting cost-benefit analyses and identifying heat-vulnerable areas for targeted interventions. After examining both co-benefits and dis-benefits, the next step involves designing and integrating suitable measures into long-term urban planning and policies. The implementation phase ensures partnerships, proper resource allocation, and the use of progress tracking

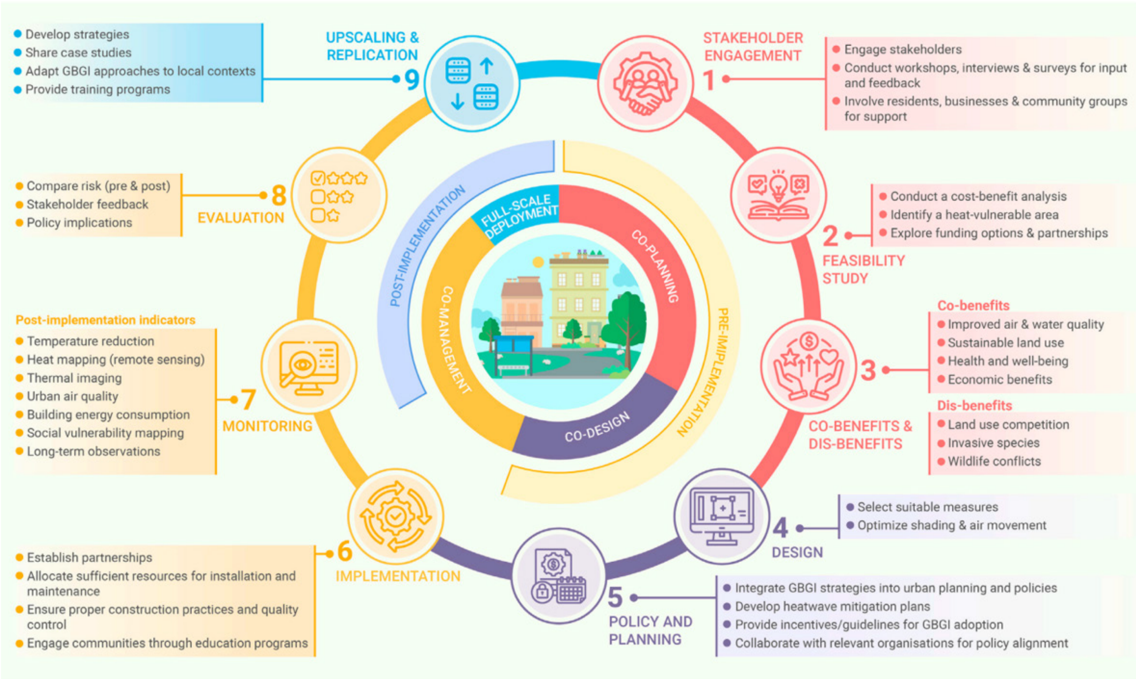

Figure 6: Urban green and blue infrastructure to mitigate extreme urban heat
(*Source*: Kumar, P., Debele, S. E., Khalili, S., Halios, C. H., Sahani, J., Aghamohammadi, N., ... & Jones, L. (2024). Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs. The Innovation, 5(2).)

tools; monitored by post-implementation indicators to provide insights into various urban metrics. Lastly, successful strategies are scaled and replicated to fit local contexts, spreading best practices through shared case studies and training programs.

Urban intelligence aids heat mitigation by leveraging data-driven decision-making, predictive analytics, and generative design to optimize spatial layout and infrastructure management. For instance, it can optimize the placement and maintenance of green and blue infrastructure, such as parks, green roofs, and water bodies, to maximize their cooling effects and reduce the urban heat island effect (Saaroni et al., 2018) (Figure 6).

Smart building operation

AI-empowered tools can enhance building energy efficiency through smart systems that adjust HVAC (heating, ventilation, and air conditioning) operations based on real-time data, further mitigating heat impacts and improving overall urban resilience. In China, cities are putting special emphasis on utilizing AI for optimizing building energy efficiency and carbon reduction. At the individual building level, intelligent analytical tools along with IoT networks can monitor, simulate, predict, and control HVAC systems, customize energy consumption strategies in real-time, and visualize energy efficiency improvement and cost reduction to support better decision-making. In Wuxi, China, the local city agency cooperated with Schneider Electric to launch SpaceLogic AI BOX, a comprehensive tool that combines AI technology with digital energy management, creating an AI application for building HVAC management (Electric, 2023). This intelligent solution relies on four functions that include digital twinning, modeling verification, system optimization, and energy-saving monitoring (Figure 7).

Urban heat adaptation

Climate-adaptive urban design

Urban heat adaptation involves making adjustments in the ecosystem, infrastructure, buildings, or public space to minimize the negative impacts of climate change and to protect residents, especially vulnerable groups, from health risks. (Chen & He, 2022). Common actions include establishing cooling facilities, enhancing electricity utility capacity, reducing solar radiation absorption with reflective materials, improving building thermal insulation, promoting green roofs, increasing air circulation in an urban environment, and providing more urban green space. Climate-adaptive urban design, particularly in the context of extreme heat, involves creating urban spaces that can effectively reduce and adapt to rising temperatures and the urban heat island effect. This approach integrates green infrastructure, such as parks, green roofs, and urban forests, alongside blue infrastructure (for example, water bodies) to cool urban areas, improve air quality, and create more comfortable living conditions. Appropriate building layout and land use planning will also help to improve urban ventilation and thermal environment.

Urban intelligence leverages AI and IT technology to enhance climate-adaptive design by optimizing cooling elements' placement (Eslamirad et al., 2020; Yoo et al., 2023), predicting heat-wave patterns (Mustafa et al., 2020),

Figure 7: SpaceLogic AI BOX solution for smart building management

(*Source*: Schneider Electric)

and enabling real-time adjustments in urban infrastructure (Qi et al., 2022). By leveraging climate data and smart technologies, cities can implement targeted heat mitigation strategies, monitor their effectiveness, and dynamically adapt to changing climate conditions, ensuring that urban environments remain resilient and livable (Cheong et al., 2022). Extreme heat-adaptive urban design integrated with urban intelligence has important value for cities in South and South-East Asia. In Kuala Lumpur, Malaysia, the city uses AI to analyze airflow patterns and optimize the placement of buildings, roads, and green spaces for better climate adaptation. In Thailand, the City of Bangkok has explored utilizing spatial analytics and AI to operate smart shading systems and reflective materials within certain neighborhoods, which potentially can scale up to citywide scale (Irvine et al., 2022). Singapore also developed AI-assisted multi-scale microclimate models at the district or neighborhood scale, based on data including weather and climate, urban shape and morphology, and anthropogenic activity. This model enables numerical simulations and AI-based design recommendations to mitigate the urban heat island effect and improve thermal comfort in high-density, urbanized areas. Furthermore, it can also evaluate the proposed AI design recommendations in terms of societal and economic impact, such as carbon savings or cost savings, to further guide urban design and implementations.

Climate-adaptive social resilience

Climate adaptation does not only involve the environmental and physical realm but also covers public health policies to protect residents from health risk exposures. From the societal aspect, cities need to raise public awareness and emergency response capacity through innovative policies and special programs for extreme heat events. Leveraging the rising generative AI and intelligent tools based on large language models (e.g., ChatGPT), cities can support dynamic policy-making and public engagement through AI-aided apps, educating citizens and enabling more flexible policy implementation based on real-time data. Through these capabilities, AI empowers cities to enhance their resilience to extreme heat and adapt to the challenges posed by climate change. In particular, AI-based urban intelligence tools can identify residents' heat risk exposure in real-time, and based on different scenarios, targeted public health policies can be formulated. In the Republic of Korea, Seoul has built an assessment system to track and map urban heat hazards, exposures, and vulnerability on a daily basis using real-time population data and machine learning (Yoo et al., 2023). This system can monitor urban heat hazards and guide site-specific adaptation and response plans for dynamic urban heat events (Figure 8).

Opportunities and challenges

Leveraging urban intelligence for extreme heat mitigation and adaptation in Asian cities presents unique opportunities and challenges shaped by the region's diverse climates, rapid urbanization, and varying levels of technological advancement. In the future, planners and architects may explore novel integration of urban intelligence with traditional knowledge and local building materials. For instance, lime, stone, and bamboo are common traditional South Asian building materials, which can be integrated with smart sensors to enhance cooling strategies. (Ebrahim, 2024). Developing climate-responsive urban infrastructure is another critical strategy for Asian cities regarding the rapid urbanization and demand for new infrastructure. Especially in new urban development, cities can plan and build

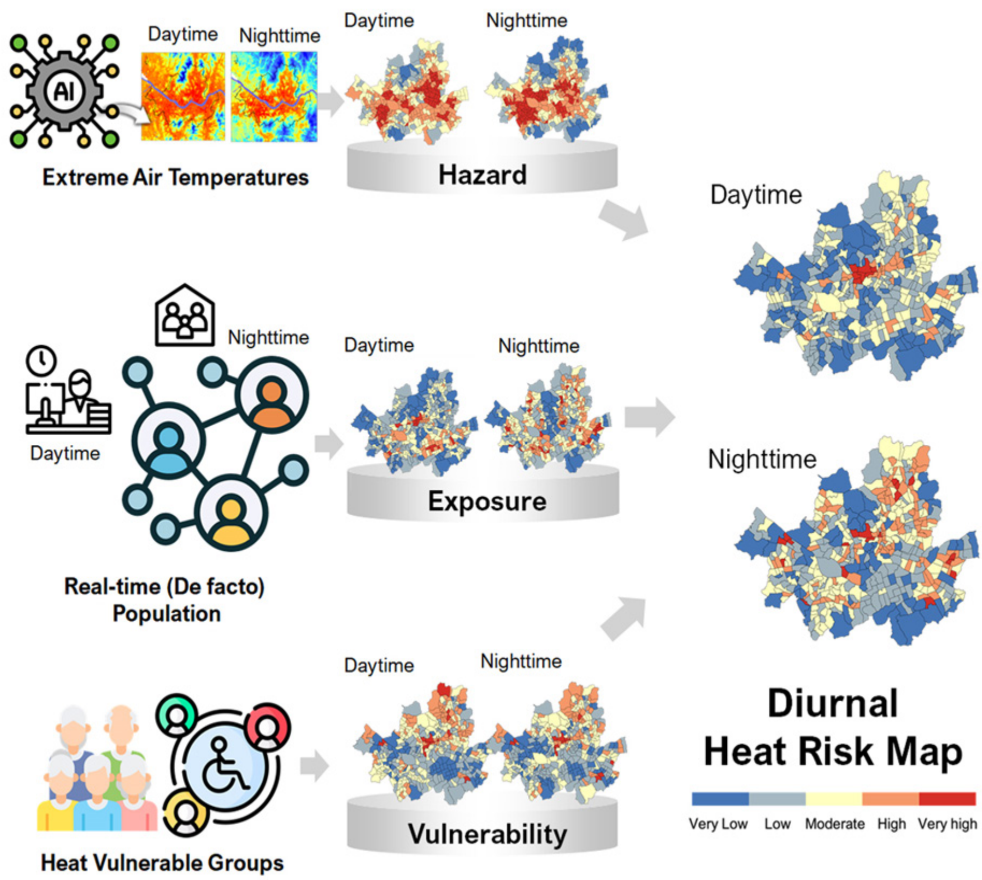

Figure 8: Framework for evaluating and mapping daily heat risk in Seoul, Republic of Korea.
(*Source*: Authors adapt from Yoo et al. 2023).

new areas using data-driven models that predict the impacts of heat islands and optimize the placement of green spaces, water bodies, and wind corridors to mitigate extreme heat. Finally, cities can leverage digital platforms to engage communities in heat mitigation efforts, such as heatwave alerts via mobile apps or participatory energy conservation management through digital tools.

Despite promising opportunities, some risks and challenges require careful assessment and further research. Data availability and quality are a first hurdle for many Asian cities. Limited open data, particularly on microclimates, energy use, and infrastructure resilience, can constrain leveraging urban intelligence to mitigate and adapt to extreme heat. Furthermore, the existing inequality in access to technology creates a digital divide and injustice in many Asian cities, where wealthier neighborhoods may benefit from advanced urban intelligence applications. At the same time, low-income areas often have more vulnerable populations without access to technology. Finally, the rich historic architectural heritage in many Asian cities may cause cultural resistance or regulatory hurdles to implementing urban intelligence solutions for heat mitigation. The preservation of historic architecture limits the extent to which modern, heat-resistant materials and technologies can be used in certain parts of the city, complicating efforts to mitigate heat in densely populated areas.

In summary, while urban intelligence for extreme heat mitigation and adaptation in Asian cities holds significant promise, it requires careful consideration of local contexts. Successful implementation will depend on integrating traditional knowledge with cutting-edge technology, ensuring equitable access to these solutions, and navigating the challenges posed by rapid urbanization and regulatory frameworks.

Conclusion

The rise of smart city development generates vast amounts of data, offering rich resources for advancing urban-related AI technologies but also necessitates automated data processing and analytical power that often exceeds the current capacities of cities. As AI continues to integrate into our urban spaces and environments, cities are blending their physical, social, and digital aspects more than ever, creating new user experiences and daily life scenarios while introducing new problems, risks, and challenges for future living. By combining various data sources with artificial intelligence, urban intelligence aims to improve coordination between different systems and support better, more precise, and forward-thinking planning decisions. Looking ahead, urban intelligence can help understand the complex relationships between ecological, economic, and social factors in the context of climate change, aiding in coordinated digital transformation and refined city management to be more heat-resilient.

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