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Empirical insights into resilience-based strategies for addressing haze pollution: enhancing green infrastructure and urban resilience

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Amid growing concerns about haze pollution and its detrimental effects on ecological systems and public health, this study proposes a novel approach to addressing this pressing issue. Drawing on a cohort of 120 environmental academics, the research employs advanced second-generation statistical methodologies, including partial least squares structural equation modeling, to introduce an innovative strategy rooted in resilience theory. This approach emphasizes resilience as the foundation for advancing green infrastructure and urban sustainability in the context of haze pollution. The findings highlight resilience as a key driver in fostering green infrastructure and urban resilience through the integration of smart technology adoption, nature-based solutions, and environmental digital platforms. These factors collectively enable urban environments to effectively tackle the dual challenges of climate change and pollution. Recognizing haze pollution as a widespread concern, particularly in developing nations, the study provides actionable strategies with global relevance. By offering practical insights, this research contributes to the global pursuit of sustainable urban development and resilience.

KEYWORDS

urban resilience, haze pollution, green infrastructure, PLS-SEM, Pakistan

1 Introduction

Ecosystems worldwide are undergoing significant changes due to rapid social and economic growth (Li et al., 2023). Although the United Nations' 2030 Sustainable Development Goals aim to address various global challenges, they have also brought environmental issues into sharper focus, such as soil erosion, urban heat islands, depleting carbon stocks, and environmental degradation (Qiu et al., 2022; Hua et al., 2022; Aziz et al., 2021a; Oquendo Di Cosola et al., 2021). Among these, the adverse consequences of air pollution have been widely studied (Sarfraz, 2020; Kim et al., 2015). Aerosols, commonly observed as haze, are one of the most harmful pollutants due to their widespread impact on both the environment and human health. Haze pollution, largely resulting from energy production and consumption, severely affects human health, ecosystems, cultural heritage, and climate. It is estimated that haze pollution causes between 2.6 and 4.8 million premature deaths annually worldwide. Major cities such as Beijing, Delhi, Lahore, Mexico City, Los Angeles, and Tehran frequently experience haze pollution (Chen et al., 2013; Shabbir, 2019).

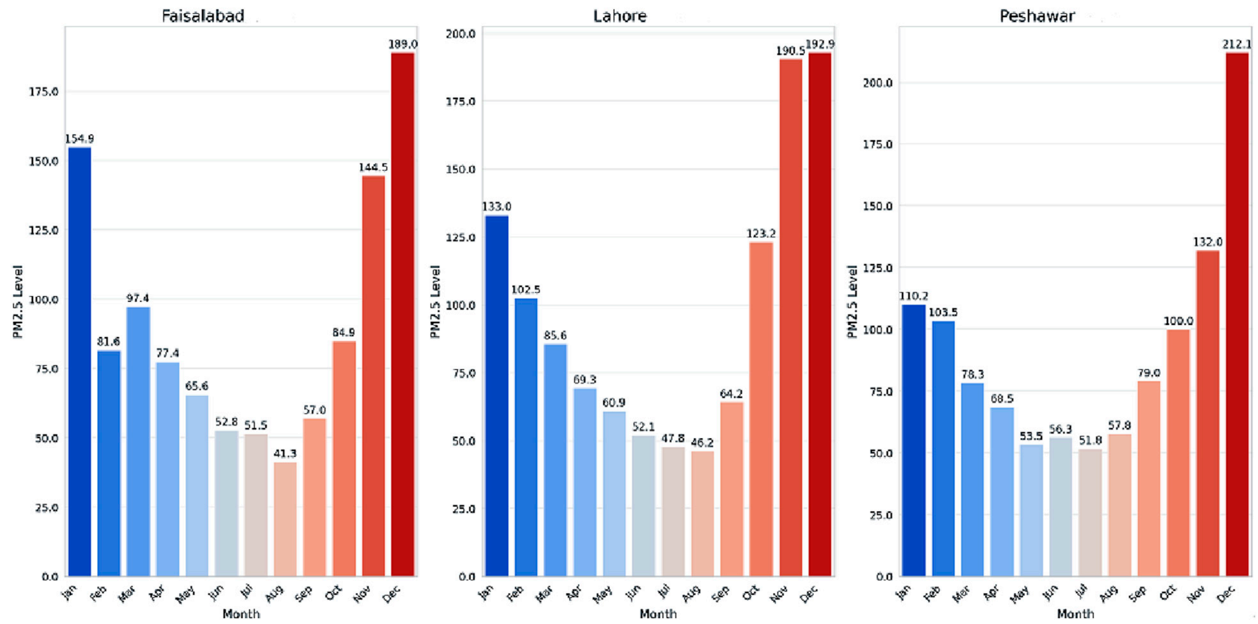

FIGURE 1
PM2.5 levels throughout the year 2022 Source: IQ Air 2022 World Air Quality Report.

In Pakistan, air pollution has become a pressing concern, particularly in its central regions. Lahore, once known as the "City of Gardens," is now engulfed by toxic smog. Despite being the country's second-largest city with an annual economic growth rate of 4% (Riaz and Hamid, 2018), Lahore ranked second for the worst air quality in 2022, according to the Air Quality Index (IQAir, 2022). During haze pollution episodes, the city's 11 million residents are enveloped in dense haze, obstructing the sun and blanketing the streets, especially at night. Similarly, Faisalabad and Peshawar rank among the top three cities in Pakistan with the worst air quality, as shown in Figure 1. This problem worsens in cooler months when temperature inversions trap pollutants near the ground. In 2019, the United Nations Children's Fund reported that 154,000 children under the age of five died globally due to outdoor air pollution, with haze pollution being one of the leading causes of mortality in young children in Pakistan. Due to weaker immune systems, children are more vulnerable to respiratory infections when exposed to prolonged haze pollution.

Air quality plays a crucial role in a nation's development, as it directly impacts economic growth. A healthy population, thriving businesses, a dynamic tourism industry, and abundant job opportunities are essential to economic progress. However, air pollution, particularly haze pollution, undermines these factors and hampers economic growth (Shahid et al., 2019; Rana, 2020). In 2016, global air pollution resulted in an annual financial loss of 5 trillion USD, with developing countries, particularly in South Asia, suffering the most. Labor income losses in these countries amounted to 1% of their GDP (World Bank, 2016). This issue is becoming even more pressing as the proportion of people living in urban areas is expected to rise from 55% to 68% by 2050 (World Health Organization, 2021). Lahore, specifically, is regularly ranked among the worst cities for air quality, with air pollution reducing Pakistan's average life expectancy by 3.9 years (Human Rights Watch, 2024; Ijaz, 2023). The impact is not limited to locals; tourists, such as the Sikh community visiting Kartarpur, are also affected. In 2023, haze pollution caused travel delays and led to the temporary closure of schools in Lahore. If haze pollution remains unchecked, Pakistan's GDP could decline by more than 5.88%. Enhancing urban resilience and addressing smog-related air pollution are critical for sustaining economic growth.

Urban resilience is key to addressing these challenges. Resilience enables cities to adapt to, respond to, and recover from natural hazards, including haze pollution (Yamagata and Maruyama, 2016; Gencer, 2017). The concept of urban resilience, introduced in the 1990s (Tobin, 1999), has become increasingly important as urbanization in Pakistan spurs economic growth but also exacerbates issues such as waste management, sanitation, employment, food security, housing, and health services (Tumini et al., 2017; Aziz et al., 2021b). Saja et al. (2018) emphasize that urban areas must be prepared to reduce disaster impacts and losses. While Pakistan's government has initiated efforts, integrating resilience into development strategies is crucial (Aziz et al., 2023; Aziz et al., 2024). This research aims to explore this integration by gaining insights from local environmental academics on the factors contributing to urban resilience in the context of haze pollution. These academics, with expertise in environmental science, urban planning, and sustainability, are well-equipped to provide research-based responses to complex environmental issues (Azzimonti et al., 2021). Their input will help shape practical and effective policies to address the growing threat of haze pollution. Their perspectives are essential in identifying sustainable, context-specific solutions for Pakistani cities, ensuring that urban resilience strategies are based on expert knowledge and are feasible for real-world application.

This research stands out from prior studies in several key ways. It uniquely applies the established resilience framework to the underexplored issue of haze pollution in Pakistan. Most research on urban resilience has been conducted in regions like the United States, Europe, and China, focusing on urban disasters such as hurricanes and floods (Cutter, 2016; Khazai et al., 2018; Deatrick, 2015; Klein et al., 2017; Leobons et al., 2019) or urban resources like water and energy (McPhearson et al., 2015; Raub et al., 2021; Buckley et al., 2021), and urban ecology (Menconi et al., 2020). While resilience theory has been widely applied in various contexts such as urban flood management (McFadden et al., 2009; Djordjević et al., 2011), environmental management (Coaffee, 2008), water management (Yazdani et al., 2011), and urban resilience assessment (Feldmeyer et al., 2019; Fu and Wang, 2018; Sharifi, 2020; Sharifi and Yamagata, 2018), there is a significant gap in its application to haze pollution, particularly in emerging countries. This research offers a novel approach by contextualizing the resilience framework within Pakistan's unique socio-environmental settings. It extends beyond theoretical analysis, integrating empirical data from three of Pakistan's most affected cities to provide practical, context-specific recommendations for enhancing urban resilience against haze pollution.

In addition, the recent study by Datola (2023) offers a comprehensive theoretical framework for assessing and implementing resilience in urban planning. This framework was chosen as the basis for this research because of its detailed definition of the essential elements of urban resilience and its practical recommendations for resilience design. The study emphasizes operational methods, which aligns with the objective of exploring the practical applications of resilience in urban environments. By building upon Datola's (2023) theoretical framework, this research incorporates empirical investigation to confirm and refine the theoretical model in real urban settings. The empirical approach enriches the theoretical model by assessing its relevance across different urban contexts, providing evidence-based guidance for urban planners and policymakers. This integration bridges the gap between theory and practice, ensuring that the proposed strategies are both conceptually valid and practically implementable.

Furthermore, this study distinguishes itself by not only identifying key characteristics of the resilience framework but also recognizing these attributes as transformative tools to enhance urban resilience in the face of haze pollution. The study employs Partial Least Squares Structural Equation Modeling (PLS-SEM), a second-generation multidimensional approach, to examine associations, test theories, and verify existing models. This method is particularly effective for handling complex models, small sample sizes, non-normally distributed data, and scenarios requiring flexibility and forecasting accuracy. The integration of these methods makes this study a significant contribution to the existing body of knowledge, emphasizing the resilient approach in fostering urban resilience amidst haze pollution. To sum, this paper contributes to both theoretical and practical knowledge by adapting resilience frameworks to the specific challenges posed by haze pollution in Pakistan and providing empirical evidence that can guide future urban resilience planning efforts in similar contexts.

The rest of the research is organized as follows: Section 2 establishes the theoretical framework with key concepts and explains the study's hypotheses. Sections 3, 4 present the research methodology and findings, respectively. Section 5 provides the study's conclusion and offers some possible policy recommendations.

2 Literature and theoretical framework

The concept of urban resilience has become central in urban studies, particularly as cities face increasing environmental, economic, and social challenges. The foundations of resilience theory were laid by Holling (1973) and later expanded by Folke (2006), who emphasized the adaptability of ecosystems and socio-ecological systems in the face of disturbances. Resilience is often defined as the capacity of a system to absorb shocks, adapt, and evolve while maintaining core functions. According to Hudson (2010), resilience is not a static attribute but a dynamic, long-term process that is critical for sustainable development. A resilient system is characterized by its ability to anticipate, absorb, accommodate, or recover from the effects of hazardous events (Rana, 2020; Cinner and Barnes, 2019; Convertino and Valverde, 2019; Bruce et al., 2020). This dynamic nature makes resilience particularly important in urban environments, where the complexity of socio-ecological interactions demands flexible and adaptive management strategies (Rana, 2020; Cinner and Barnes, 2019; Convertino and Valverde, 2019; Bruce et al., 2020).

Urban resilience, in particular, has been defined by scholars such as Cumming and Peterson (2017) and Sterk et al. (2017) as the capacity of urban systems to withstand and recover from various disturbances, including environmental, economic, and social shocks. In the context of cities, resilience extends beyond the ecological to include social, economic, and infrastructural dimensions, reflecting the complexity of urban systems. This ability to adapt and recover is especially important in the face of climate change and increasing environmental challenges, such as pollution (Raza et al., 2021). Urban resilience is not just about bouncing back from crises but also about transforming and evolving in response to new challenges. This transformative potential is particularly relevant as cities face ongoing threats from pollution, climate change, and rapid urbanization.

While several studies have explored resilience across various sectors such as transportation (Leobons et al., 2019), agriculture (Córdoba Vargas et al., 2020), the environment (Manyena et al., 2019), energy (Mutani et al., 2020), and climate change (Heinzlef et al., 2020; Keshavarz and Moqadas, 2021), psychology (Bonanno et al., 2008), ecology (Holling, 1973), engineering (Fiksel, 2003), socio-ecological systems (Folke et al., 2002; Walker et al., 2004), urban planning (Ahern, 2011; Wilkinson, 2012; de Luca et al., 2021), and disaster risk management (Coaffee, 2008; Cutter et al., 2008), the exploration of resilience in response to specific environmental challenges like haze pollution, particularly in Pakistan, remains limited.

Haze pollution represents a significant environmental challenge for urban areas across the globe, including Pakistan. Characterized by elevated levels of particulate matter and other contaminants in the atmosphere, this type of pollution presents significant health risks, has a detrimental impact on the environment, and results in considerable economic costs. The adverse effects of haze pollution underscore the urgent need for urban areas to develop resilience strategies that not only mitigate the immediate impacts of pollution but also enhance long-term adaptability to environmental changes. However, the academic literature on urban resilience in the context of haze pollution remains under-researched, particularly in the Global South. This study aims to address this gap by examining the influence of environmental professionals' viewpoints on urban resilience initiatives to mitigate haze pollution in Pakistan. The study seeks to enhance understanding of how cities can strengthen their resilience to environmental challenges by analyzing expert-driven solutions that incorporate sustainable practices, technological innovation, and nature-based strategies.

Urban resilience, as a strategy, is increasingly seen as transformative, enabling cities to address a wide range of environmental and socio-economic risks in the context of climate change, globalization, and urbanization (Masnavi et al., 2019; Córdoba Vargas et al., 2020). The primary goal of this transformative approach is to build cities that are not only capable of recovering from shocks but also adaptable enough to evolve in response to new challenges (Yamagata and Maruyama, 2016). Within the field of urban planning, resilience has emerged as a key principle that informs the design and development of cities, enabling them to manage diverse types of disturbances (Desouza and Flanery, 2013; Ilmola, 2016; Sharifi and Yamagata, 2016; Sharifi and Yamagata, 2018). According to Sharifi and Yamagata (2018), urban planning plays a crucial role in facilitating resilience by providing the frameworks and tools necessary for cities to adapt and thrive under uncertain conditions. Ahern (2011), Meerow and Newell (2015), Shivaprasad Sharma et al. (2018), and Wilkinson (2012) emphasize that the relationship between urban resilience and urban planning is one of the most pressing challenges in the current urban agenda. They argue that a deeper understanding of this relationship is essential for developing urban policies and designs that enhance resilience in the face of environmental threats.

Technological innovation constitutes a vital element of urban resilience, particularly in the context of pollution reduction and the enhancement of environmental sustainability. Liu et al. (2018) highlights the pivotal role of technological innovation in mitigating haze pollution in China. The author demonstrates that such advancements not only reduce local pollution but also generate advantageous spillover effects in neighboring regions. This conclusion is supported by Yu and Du (2019), who argues that innovation, even during economic downturns, can significantly reduce CO_2 emissions, thereby facilitating widespread environmental improvements. Carrión-Flores and Innes (2010), and Ahmad et al. (2020) have demonstrated that environmental innovation is a crucial factor in mitigating toxic gas emissions and enhancing air quality, particularly in developed nations such as the United States and OECD member countries. These findings emphasize the importance of integrating novel technologies into urban resilience measures, particularly in regions such as Pakistan, where haze pollution is increasingly endangering public health and urban sustainability.

In addition to technical alternatives, nature-based solutions have emerged as a promising strategy for enhancing urban resilience. Faivre et al. (2017) posit that the integration of nature-based solutions into urban planning is a means of enhancing ecosystem resilience and fostering sustainable urban growth. Nature-based solutions employ natural systems and processes to address environmental concerns, such as pollution, while simultaneously providing additional benefits, including enhanced biodiversity, improved public health, and greater social wellbeing. Recent case studies from cities such as Chania, Crete (Tsekeri et al., 2022), and Milan (Mahmoud et al., 2021) demonstrate the integration of nature-based solutions (NBS) with digital technology to enhance sustainability and livability. In China, Internet of Things (IoT), mixed reality, and information and communication technologies (ICT) are integrated with nature-based solutions to enhance citizen awareness and integration. The amalgamation of nature-based solutions with advanced technology not only bolsters environmental resilience but also generates novel economic prospects, especially in domains associated with green infrastructure and urban innovation (Bayulken et al., 2021; Barbarwar et al., 2023; Istrate and Hamel, 2023).

The importance of nature-based solutions is especially significant in Pakistan, where rapid urbanization and environmental degradation have exacerbated the challenges associated with haze pollution. The objective of this project is to examine how Pakistani cities can enhance their resilience to environmental risks by focusing on solutions driven by academics that integrate green infrastructure with technological innovations. It is of paramount importance to engage the expertise of environmental professionals in the formulation and implementation of policies that are technically viable and contextually appropriate. Insights from environmental specialists regarding urban resilience measures may provide a pragmatic framework for addressing current environmental challenges and establishing a foundation for future sustainability.

Furthermore, engaging the public and encouraging community involvement is crucial for fostering urban resilience. Studies by Mahmoud et al. (2021), Mahmoud et al. (2024) and Castelo et al. (2023) emphasize the necessity of involving local communities in the design and implementation of nature-based solutions to foster a sense of ownership and ensure the long-term efficacy of resilience programs. Digital platforms that facilitate environmental education and citizen interaction have the potential to significantly raise awareness of the hazards associated with haze pollution and promote the adoption of sustainable practices. Communities that are well-informed and engaged are better positioned to contribute to resilience-building initiatives, particularly in the context of disaster preparedness and sustainable urban development.

The aforementioned research indicates that the integration of technological innovation, nature-based solutions, and community engagement enables cities to enhance their capacity to adapt to environmental issues and foster long-term resilience. Moreover, environmental academics offer invaluable insights into the enhancement of urban resilience, particularly in regions such as Pakistan, where haze pollution poses significant risks to public health and sustainability. In light of the mounting environmental threats, it is imperative to implement prompt, comprehensive, and multidisciplinary strategies. Moreover, the National Infrastructure Commission (NIC) also emphasized the need for a framework that anticipates future shocks and stresses, values resilience, and drives adaptation. This aligns with the Ministry of Defence (MOD) and the National Resilience Strategy (NRS), which also called for evaluating socio-economic resilience to support decision-making (Medland et al., 2024).

So, this study develops four hypotheses (H1, H2, H3, H4) to investigate the influence of environmental academic's perspectives on urban resilience solutions in Pakistan. These hypotheses are (H1): the impact of scholar perspectives on resilience (H2), the role of smart technology in alleviating haze pollution (H3), the efficacy of nature-based solutions, and (H4) the significance of public awareness and community involvement in enhancing resilience. Collectively, these hypotheses align with a substantial body of literature that underscores the pivotal role of innovation, sustainable practices, and civic engagement in strengthening urban resilience to environmental challenges such as haze pollution.

H1: Environmental academics perceptions of the risk posed by haze pollution in Pakistan are likely influenced by various factors, including pollution levels, health impacts, and economic consequences. The study hypothesizes that the severity of academics concerns regarding haze pollution will shape their views on urban resilience in response to this environmental challenge.

H2: Given the critical role of sustainable green development practices in mitigating haze pollution and enhancing urban resilience in Pakistan, the study anticipates that environmental academics will advocate for the adoption of smart technologies as practical tools to combat haze pollution in Pakistani cities. Additionally, these technologies will contribute to strengthening urban resilience. In essence, we hypothesize that the adoption of smart technologies mediates the relationship between the severity of haze pollution and urban resilience.

H3: Nature-based solutions play a pivotal role in addressing haze pollution and fostering urban resilience in Pakistan. The study expects that environmental academics will recognize the necessity of implementing nature-based solutions in Pakistan to combat haze pollution and enhance urban resilience effectively.

H4: Public awareness, education, and community engagement are critical components in building urban resilience against pollution. The study anticipates that environmental academics will emphasize the role of digital environmental platforms in raising public awareness and providing education as key measures to enhance urban resilience against haze pollution in Pakistan. Well-informed and engaged communities can contribute to resilience by adopting sustainable practices and participating in disaster preparedness efforts.

3 Materials and methods

3.1 Study participants

The survey was conducted in three major cities in Pakistan—Lahore, Faisalabad, and Peshawar—which were selected due to their significant haze pollution, large populations, and substantial economic activity. These cities face critical environmental challenges, making them well-suited for examining urban resilience in response to pollution. Participants were drawn from a pool of environmental academics, including masters and doctoral researchers, senior researchers, and professors from leading institutions in these cities. The rationale for focusing on this group lies in their profound expertise and active involvement in research related to the environment and urban development. Understanding how urban resilience methods are influenced by expert advice, particularly during periods of elevated pollution, is critical to gaining insight into this phenomenon. While the opinions of environmental academics may not directly enhance urban resilience, they influence it indirectly by shaping public policy and altering planning procedures. Their knowledge in pollution control, urban ecosystems, and sustainable development enables them to provide evidence-based recommendations that policymakers can implement as effective resilience strategies. Furthermore, many researchers work across disciplinary boundaries, integrating insights from social sciences, public health, and urban planning, thereby enriching their contributions to resilience-building initiatives. A snowball sampling method was employed to select participants for the survey conducted in October 2023. A total of 132 questionnaires were distributed, of which 120 yielded valid results. The demographic composition of the sample is presented in Table 1.

3.2 Research instruments

This study examines the resilience framework by incorporating key constructs such as the perceived adversity of haze pollution (PAHP) and resilient approaches, including smart technology adoption (STA), nature-based solutions (NBS), and environmental digital platforms (EDP), which together contribute to green infrastructure and urban resilience (GIUR). Each variable is measured using a 5-point Likert scale, ranging from "strongly disagree" to "strongly agree." The measurement items are adapted from previous studies, with modifications made to suit the study's objectives, as presented in Table 2. Moreover, the questionnaire was pre-tested with a small group of academics, and their feedback led to further refinement of the questions. We also randomized the question order to reduce potential bias and ensured participants' anonymity and confidentiality, promoting honest and unbiased responses.

3.3 Statistical analysis

Using the PLS-SEM technique, a statistical model encompassing all dimensions is constructed. The PLS model consists of two phases: the measurement model and the structural model. The measurement model evaluates the relationships between observable variables (sub-factors) and latent variables (factors) while also assessing the reliability and validity of the constructs. The structural model, on the other hand, examines the path coefficients that connect the constructs (see Figure 3). The model's fitness is determined by analyzing the path coefficients. To validate the constructs' internal consistency, as well as the path coefficients and significance levels for hypothesis testing, the PLS algorithm and bootstrapping technique are applied. Using a sample size of 5,000, the bootstrapping method is employed to determine the significance of the paths. Additionally, this technique enables the analysis of variations in dependent variables. The indirect effect of mediation is assessed using bootstrapped confidence intervals.

TABLE 1 Demographic information of participants.

Age	Frequency	Percentage
25–35	69	57.5
36–45	23	19.2
46–55	17	14.2
56+	11	9.1
Level of competency		
M.Phil Scholars	38	31.7
Ph.D Scholars	51	42.5
Senior Researchers	13	10.8
Professors	18	15.0
Affiliations		
Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, Pakistan	54	45.0
College of Earth and Environmental Sciences, University of Punjab Lahore, Pakistan	41	34.2
Department of Environmental Sciences, University of Peshawar, Pakistan	25	20.8

Source: Field Survey (October 2023).

4 Results and discussion

4.1 Demographic characteristics

The sample of 120 academics in this study was carefully selected to ensure scientific rigor and representativeness in terms of age, research field, and institutional affiliation. The age distribution includes participants from four groups: 25–35 years (57.5%), 36–45 years (19.2%), 46–55 years (14.2%), and 56+ years (9.1%), ensuring a broad range of experience levels. The competency levels in the sample include M. Phil researchers (31.7%), Ph.D. scholars (42.5%), senior researchers (10.8%), and professors (15.0%), capturing a comprehensive spectrum of expertise. Academics were selected from three prominent institutions in Pakistan: The Institute of Soil and Environmental Sciences at the University of Agriculture Faisalabad (45.0%), the College of Earth and Environmental Sciences at the University of Punjab Lahore (34.2%), and the Department of Environmental Sciences at the University of Peshawar (20.8%). Table 1 below provides a comprehensive overview of the research sample's composition, ensuring diverse representation.

4.2 Measurement model assessment results

4.2.1 Convergent validity

Both discriminant and convergent validity are essential for evaluating the measurement model before hypothesis testing. Convergent validity assesses the correlation between multiple indicators of the same construct and is evaluated using metrics such as composite reliability (CR), average variance extracted (AVE), Cronbach's alpha, Rho-alpha, and the variance inflation factor (VIF). VIF specifically measures multicollinearity between variables, where higher values indicate greater multicollinearity. In factor analysis, loadings represent the strength of association between each indicator and its corresponding construct, with higher loadings indicating a more accurate representation of the underlying construct. Figure 2 illustrates the outer loadings, showcasing the presence of several latent variables, their observable indicators, and the interrelationships among them. The adoption of STA is evaluated using five indicators (STA1–STA5), all of which exhibit robust loadings (0.850–0.911), reflecting a strong correlation with the underlying construct. Similarly, the PAHP assessed with five indicators (PAHP1–PAHP5), demonstrates moderate to strong loadings ranging from 0.631 to 0.819. The EDP acts as a mediating variable, demonstrating a path from PAHP (loading of 0.378) and significantly influencing GIUR and NBS with path coefficients of 0.222 and 0.199, respectively. The construct validity of GIUR is supported by the strong loadings of its five indicators (GIUR1–GIUR5), which range from 0.734 to 0.900. Similarly, the assessment of NBS (through NBS1–NBS5) reveals significant loadings (0.819–0.883), indicating a strong correlation with the latent variable. The model highlights the influence of STA and PAHP on GIUR and NBS through the EDP, emphasizing the interdependence of these constructs in advancing urban resilience and environmental sustainability.

Internal consistency reliability is assessed using cronbach's alpha, which measures the degree of relatedness among a set of items. Higher alpha values indicate greater reliability. Rho-A serves as an alternative indicator of internal consistency, similar to Cronbach's alpha. AVE measures how closely a construct's items converge to represent the same underlying concept, with higher values indicating stronger convergent validity. CR is used within the framework of structural equation modeling to assess the dependability of a latent construct. According to Hair et al. (2021), acceptable thresholds for key metrics include loadings above 0.50, CR above 0.70, and AVE above 0.50.

Table 2 presents the metrics and outcomes for convergent validity among the constructs related to environmental sustainability and technology adoption. The EDP framework includes elements such as recommendations for energy-efficient appliances and advocacy for green initiatives. These elements demonstrate significant loadings (0.777–0.861) and satisfactory reliability (Alpha = 0.733, Rho-A = 0.748). The GIUR construct encompasses elements related to aesthetic improvements and pollution mitigation, exhibiting high loadings (0.821–0.900) and exceptional reliability (Alpha = 0.882, Rho-A = 0.893). The NBS framework, which includes the implementation of solar and wind energy, shows strong loadings (0.819–0.883) along with excellent reliability (Alpha = 0.909, Rho-A = 0.928).

The PAHP construct captures concerns about elevated CO_2 emissions and associated health hazards, with loadings ranging from 0.631 to 0.819. While its reliability is satisfactory (Alpha = 0.784, Rho-A = 0.799), the AVE (0.534) is slightly below the ideal threshold. Finally, the STA construct, which includes elements such as the Internet of Things (IoT) and electric vehicle

TABLE 2 Scales and convergent validity results.

Constructs	Items	VIF	Loadings	Alpha	Rho-A	CR	AVE
Environmental digital platform							
Prompts and reminders on adopting energy-efficient appliances	EDP1	1.341	0.777	0.733	0.748	0.848	0.652
Encourage digital platforms on green initiatives	EDP2	1.501	0.780				
Advocacy for sustainable green infrastructural development	EDP3	1.618	0.861				
Green infrastructure and urban resilience							
Aesthetic appeal of infrastructural development	GIUR1	1.991	0.821	0.882	0.893	0.914	0.681
Reduced pollution	GIUR2	3.311	0.900				
Purified air quality	GIUR3	2.525	0.826				
Healthy wellbeing	GIUR4	2.357	0.836				
Monetary savings	GIUR5	1.654	0.734				
Nature-based solutions							
Solar panels adoption	NBS1	3.392	0.867	0.909	0.928	0.931	0.731
Wind turbines adoption	NBS2	3.448	0.883				
Increase vegetation	NBS3	3.279	0.881				
Trees Plantation	NBS4	2.758	0.824				
Enhance green built-up areas	NBS5	2.246	0.819				
Perceived adversity of haze pollution							
Increased CO_2 emissions	PAHP1	1.384	0.631	0.784	0.799	0.850	0.534
Increased PM2.5	PAHP2	1.337	0.675				
Perceived health risks	PAHP3	1.345	0.737				
Perceived adverse effects on the ecosystem	PAHP4	1.874	0.777				
Perceived effects on daily errands	PAHP5	2.058	0.819				
Smart technologies adoption							
Use of IoT for energy efficiencies	STA1	3.860	0.902	0.930	0.941	0.947	0.781
Smart thermostat and lightening	STA2	3.744	0.897				
Adherence to sustainable architecture and urban planning	STA3	2.727	0.850				
Electric vehicle adoption	STA4	4.279	0.911				
Encouraging rider-sharing apps	STA5	3.480	0.858				

Source: Authors' estimations.

adoption, demonstrates substantial loadings (0.902–0.911) and exceptional reliability (Alpha = 0.930, Rho-A = 0.941). The results confirm robust convergent validity and reliability for most dimensions, validating their suitability for further investigation into environmental sustainability and technology adoption. All values fall within acceptable limits, reinforcing the validity of the constructs in this study.

4.2.2 Discriminant validity

The Heterotrait-Monotrait (HTMT) correlation ratios and the Fornell-Larcker approach are used to assess discriminant validity. Discriminant validity is a component of the measurement model that evaluates the distinction between overlapping constructs and ensures that the constructs are accurately separated from one another. The Fornell-Larcker criterion specifically examines the discriminant validity of multiple constructs within a research model. In essence, the Fornell-Larcker criterion evaluates the relationships between latent constructs by comparing the square root of the AVE for each construct with the correlations of that construct with others. The Fornell-Larcker criterion results, presented in Table 3, confirm the discriminant validity of the constructs. Each construct—EDP, GIUR, NBS, PAHP, and STA—exhibits stronger correlations with its own items (indicated by the square roots of AVE on the diagonal) than with items from other constructs (off-diagonal correlations). This pattern demonstrates that these constructs are distinct and can be

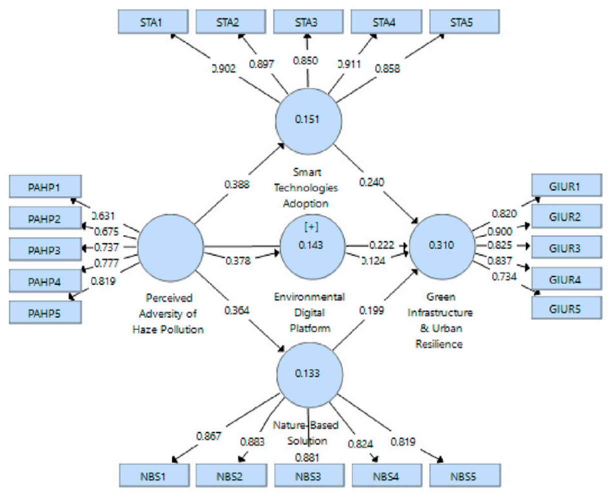

FIGURE 2
Measurement model.

reliably differentiated from one another, thereby supporting the validity of the measurement model for further analysis.

Moreover, the HTMT ratio is also used to assess discriminant validity. This method evaluates whether the constructs in a model are distinct from one another, ensuring they measure different underlying concepts rather than being highly correlated or overlapping. According to Gaskin and James (2019), the HTMT correlation coefficient should not exceed 0.90. The results in Table 4 confirm discriminant validity, as the correlations between different constructs remain below 0.90. This pattern indicates that the constructs—EDP, GIUR, NBS, PAHP, and STA—are distinct from one another, with their inter-construct correlations being weaker than their intra-construct correlations. These findings provide robust evidence of the discriminant validity of the measurement model, further supporting its reliability.

4.3 Structural model assessment

The PLS bootstrapping technique was employed in this study to evaluate the significance of correlations. This method facilitates the analysis of path coefficients and the R-squared (R^2) value, both of which contribute to assessing the explanatory power of the structural model. Figure 3 illustrates the structural model, which includes variables aligned with the resilience theory framework. These variables comprise perceived adversity, sustainable technology adoption, nature-based solutions, and environmental digital platforms. The dependent variable in focus is urban resilience. Through these constructs, the study seeks to identify the key characteristics essential for fostering resilient cities. It acknowledges that urban areas are particularly vulnerable to climate threats, building upon the work of Cutter (2016) and other researchers, including Jacobson (2020), Leykin et al. (2016), and Tilloy et al. (2019). Consequently, strengthening urban resilience is posited as a vital response to haze pollution and climate change.

Furthermore, the analysis by Liu and Wu (2022) underscores the importance of regional sustainability in enhancing people's living standards. Scholars across various fields have investigated different capacities for achieving system resilience, addressing aspects such as sustainability, ecology, economy, climate change, and engineering (Ribeiro and Goncalves, 2019; Chelleri and Baravikova, 2021; Semenza, 2021; Matthew et al., 2022). Monavvarian et al. (2018) have emphasized the need to address outdated and vulnerable infrastructure, which aligns with this study's focus on improving urban environmental resilience in the context of haze pollution.

Heyd (2021) and Horton and Horton (2020) highlight that metropolitan areas are highly vulnerable to the impacts of climate change creating socio-ecological challenges that threaten public health. This study's findings reveal a positive relationship between PAHP and GIUR ($\beta = 0.230$, $p = 0.000$). This indicates that heightened awareness of haze pollution motivates communities to advocate for greener and more resilient urban environments. In essence, communities' perception of haze pollution can act as a catalyst for the development of green infrastructure and urban resilience. These findings provide valuable insights into the current state of urban areas, shedding light on the status of urban resilience systems and identifying areas where resilience capacities need improvement. This aligns with the research conducted by Sharifi and Yamagata (2018), which also underscores the importance of exploring strategies to enhance urban resilience.

The study further examined the mediated effects of PAHP on GIUR through the pathways of EDP, NBS, and STA. It highlights that communities' perceptions of haze pollution not only directly motivate them but also drive their engagement with and adoption of smart technologies, nature-based solutions, and environmental digital platforms. Communities that recognize the adverse impact of haze pollution are more likely to take concrete actions through these pathways, ultimately enhancing their cities' ability to withstand environmental challenges. These findings indicate that while PAHP has a direct influence on GIUR, it also exerts an indirect impact through these mediating constructs. This underscores the importance of considering multiple pathways through which environmental perceptions can shape urban sustainability. These pathways represent potential conditions for future interventions. The study by Myeong and Shahzad (2021) proposed a technology-driven air quality management solution for smart cities, emphasizing energy-efficient and cleaner pollution control methods. It explored the integration of data-driven approaches and citizen involvement in public sector pollution management, a key component of smart city frameworks. Their analysis suggests that digital transitions in resource management can enhance public governance, reduce energy consumption, and improve environmental quality. The findings of Kolokotsa et al. (2024) underscore the economic and social benefits of data-driven smart city development, supported by community collaboration. In a similar vein, Chen (2023) found that smart city policies have been effective in mitigating NO_2 concentrations in pilot cities, particularly in large, densely populated cities with high administrative hierarchies, such as those in eastern China. The positive impact of such policies can be seen in cities like Shenzhen, where smart air quality monitoring and emission control technologies have led to a reduction in air pollution

TABLE 3 Fornell-Larcker criterion results.

Constructs	Environmental digital platform	Green infrastructure and urban resilience	Nature-based solutions	Perceived adversity of haze pollution	Smart technologies adoption
Environmental Digital Platform	0.807				
Green Infrastructure and Urban Resilience	0.341	0.825			
Nature-Based Solutions	0.334	0.371	0.855		
Perceived Adversity of Haze Pollution	0.378	0.435	0.364	0.731	
Smart Technologies Adoption	0.274	0.402	0.206	0.388	0.884

Source: Authors' estimations.

TABLE 4 Heterotrait-Monotrait ratio results.

Constructs	Environmental digital platform	Green infrastructure and urban resilience	Nature-based solutions	Perceived adversity of haze pollution	Smart technologies adoption
Environmental Digital Platform					
Green Infrastructure and Urban Resilience	0.423				
Nature-Based Solutions	0.406	0.404			
Perceived Adversity of Haze Pollution	0.477	0.491	0.407		
Smart Technologies Adoption	0.322	0.430	0.216	0.427	

Source: Authors' estimations.

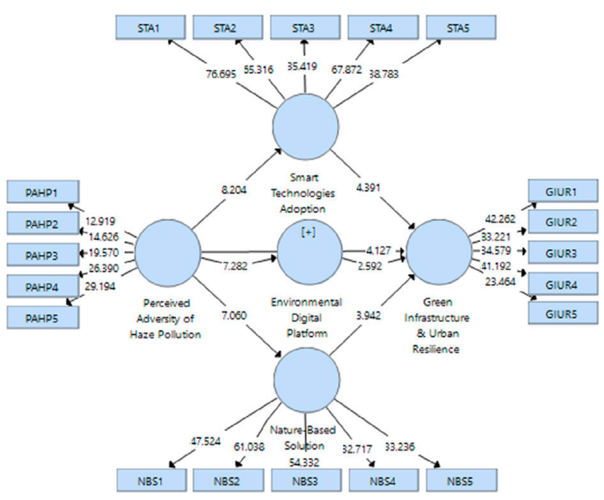

FIGURE 3
Structural model assessments.

levels. Additionally, Ben Othmen et al. (2024) highlighted the potential of nature-based solutions, such as green infrastructure, in addressing climate change threats. These solutions, including the management of green spaces, runoff containment, and the restoration of wetlands and riverbanks, have been successfully implemented in various regions. For example, Singapore has demonstrated how green infrastructure can help mitigate urban heat islands and improve air quality, with research showing up to a 15% reduction in PM2.5 levels in areas with increased urban greenery. These studies offer tangible examples of how smart city solutions and nature-based infrastructure can effectively address urban environmental challenges.

The results align with previous studies by Allan and Bryant (2011), Kim and Lim (2016), McLellan et al. (2012), Spaans and Waterhout (2017), and Wardekker et al. (2010), all of which emphasized the need for coordinated human, financial, and physical resources. Identifying these pathways is a significant contribution of this research. Incorporating them into urban resilience strategies can lead to actionable outcomes. Additionally, assessing cities' performance in relation to these pathways helps identify critical challenges and prioritize interventions. This approach resonates with earlier research on short-, medium-, and long-term interventions (Habitat, 2017; Napoli et al., 2020; Oppio et al., 2020; Datola and Bottero, 2021; Caprioli et al., 2023; Sikandar et al., 2024). Moreover, resilient approaches play a crucial role in urban settings, particularly as they support the diverse and robust infrastructure essential for critical city services. This infrastructure must be delivered efficiently and with careful planning. According to Kalani et al. (2019), timely detection and warning systems can significantly enhance relief and rehabilitation efforts, both before and after crises, thereby improving urban resilience.

In the context of smart technologies, it becomes evident that STA, driven by PAHP, empowers communities to proactively enhance urban resilience. STA is increasingly recognized as a pivotal strategy for sustainable urban management. Previous researchers, including Aziz et al. (2020a), Aziz et al. (2020b), Meerow and Newell (2017), Simić et al. (2017), and Fu et al. (2021), have emphasized the importance of green infrastructure. Numerous scholars have explored various factors critical to urban resource resilience, including governance, human and societal capacities (Bruce et al., 2020; Esfandi et al., 2022; Sharifi and Yamagata, 2016), promotion strategies (Li et al. 2022; Wang H. et al., 2021; Wang P. et al., 2021), water management (Boltz et al., 2019), energy policy (Shandiz et al., 2020), land management (Du et al., 2020; Si et al., 2021), and urban rail transit networks (Jin et al., 2014; Lu, 2018; Zhang et al., 2018). Serdar et al. (2022) also highlighted the role of improved transportation in fostering healthy urban development.

Urban ecological resilience is a multidisciplinary field that integrates insights from diverse domains. The strong positive relationship between NBS and GIUR highlights the significant benefits of incorporating natural elements into urban planning. NBS improves air quality, reduces flood risks, and enhances overall urban livability. Cities that prioritize NBS are better equipped to withstand environmental shocks and stresses, thereby bolstering their resilience. This finding aligns with the growing recognition of the advantages of integrating natural elements into urban environments, such as green spaces, urban forests, and sustainable water management systems. It also resonates with studies by Feng et al. (2022) and Li et al. (2018a), Li et al. (2018b), which emphasize the role of natural resources in carbon sequestration and mitigating urban heat islands. Additionally, MacLaren et al. (2022) highlighted the importance of eco-friendly practices in reducing the negative environmental impacts of cereal production. NBS also serve as effective measures to address urban climate and biodiversity risks while mitigating social inequalities (Dorst et al., 2019; Wang et al., 2022; Fang et al., 2023). This underscores their vital role in creating sustainable, resilient urban ecosystems that meet environmental and social challenges head-on.

Table 5 presents the path analysis results, which reveal a positive relationship between EDP and GIUR. This finding suggests that leveraging digital platforms for environmental initiatives can significantly contribute to the development of sustainable urban infrastructure and resilience. Digital platforms facilitate the dissemination of information on sustainable practices, encourage community engagement, and enable data-driven decision-making in urban planning. Consequently, cities that harness the potential of these platforms are more likely to adopt environmentally friendly policies and enhance their resilience to environmental challenges. When individuals perceive the adverse effects of haze pollution on their wellbeing, they are more inclined to use digital platforms to access information on air quality, health recommendations, and sustainable practices. This aligns with the growing emphasis on technology-driven solutions in urban planning and sustainability. Digital platforms play a crucial role in disseminating information and mobilizing communities to support cohesive decision-making processes with a shared objective (Ribeiro and Gonçalves, 2019). The integration of information across various subsystems fosters coordinated operations and rapid responses throughout the city. This principle of integration is fundamental to urban resilience, enabling systems to work in unison during crises (Godschalk, 2003; Spaans and Waterhout, 2017). By sharing information effectively, digital platforms strengthen urban resilience by supporting unified and informed decision-making processes that address environmental and social challenges.

Figure 3 illustrates a structural equation model that elucidates the interconnections among key components related to environmental technology and urban resilience. The role of STA is to act as a critical mediator, indicating the extent of technology utilization through multiple indicators (STA1 to STA5). The EDP has a significant impact on the adoption of both smart technologies and nature-based solutions, as evidenced by a strong path coefficient of 4.391. This underscores its role in promoting the convergence of technological and nature-based approaches. Moreover, GIUR is linked to both STA and the EDP, suggesting that technological advancements reinforce urban resilience initiatives. This relationship is supported by a notable path coefficient of 4.127. The model also incorporates the PAHP, which directly influences the EDP. The substantial path coefficient of 7.060 indicates that concerns about air quality significantly affect the adoption of digital solutions. Each construct is measured by distinct indicators, including PAHP1 to PAHP5 for perceived adversity and NBS1 to NBS5 for nature-based solutions, reflecting their different dimensions. The model emphasizes the complex interrelationship between the uptake of smart technology, the use of environmental platforms, and the advancement of urban resilience. It demonstrates that the integration of smart technologies is essential for promoting sustainable urban practices and mitigating environmental concerns, particularly those related to haze pollution.

Table 6 shows that 31% of the variance in urban resilience can be attributed to exogenous components. Furthermore, a thorough collinearity test should be conducted in PLS-SEM to address mutual dependence and assess common method bias. VIFs are used to determine CMB, according to Kock (2015). The results confirm that the latent constructs' VIF values do not exceed 5 (Hair et al., 2011), suggesting no CMB in the data. Table 6 presents a detailed summary of the key constructs in the structural equation model, evaluating their impact on urban resilience using the following metrics: R^2, F^2, and VIF. The EDP accounts for 14.3% of the variance in urban resilience ($R^2 = 0.143$, adjusted $R^2 = 0.140$), exhibiting a moderate effect size ($F^2 = 0.228$) and low multicollinearity (VIF = 1.254). This suggests that the EDP plays a significant role in enhancing urban resilience. The GIUR construct accounts for the greatest variance, explaining 31.0% ($R^2 = 0.310$, adjusted $R^2 = 0.300$). However, its individual effect size is minimal ($F^2 = 0.071$), indicating that although GIUR exhibits a strong correlation with urban resilience, its influence is comparatively less substantial when evaluated alongside other predictors. Conversely, NBS accounts for 13.3% of the variance ($R^2 = 0.133$, adjusted $R^2 = 0.130$) but exhibits a trivial effect size ($F^2 = 0.003$), indicating that NBS has a limited impact on urban resilience. Similarly, the PAHP demonstrates a minimal effect size ($F^2 = 0.001$) and low multicollinearity (VIF = 1.384), suggesting that

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TABLE 5 Path analysis results.

Relationships	Beta	T-value	Confidence intervals		P-value
			0.025	0.975	
EDP > GIUR	0.124	2.551	0.024	0.215	0.011
NBS > GIUR	0.199	3.857	0.099	0.298	0.000
PAHP > EDP	0.378	7.151	0.272	0.484	0.000
PAHP > GIUR	0.223	3.879	0.111	0.336	0.000
PAHP > NBS	0.364	6.518	0.247	0.458	0.000
PAHP > STA	0.388	8.617	0.304	0.479	0.000
PAHP > EDP > GIUR	0.047	2.325	0.012	0.090	0.020
PAHP > NBS > GIUR	0.072	3.531	0.035	0.116	0.000
PAHP > STA>GIUR	0.093	3.711	0.049	0.147	0.000

Source: Authors' estimations.

TABLE 6 R2, F2 and VIF.

Constructs	R2	Adj R2	F2	VIF
Environmental Digital Platform	0.143	0.140	0.228	1.254
Green Infrastructure and Urban Resilience	0.310	0.300	0.071	
Nature-Based Solutions	0.133	0.130	0.003	1.218
Perceived Adversity of Haze Pollution			0.001	1.384
Smart Technologies Adoption	0.151	0.148	0.038	1.207

Source: Authors' estimations.

concerns about haze pollution exert a modest direct influence on the resilience model. Finally, the variable representing the adoption of smart technologies accounts for 15.1% of the variance in the model (R^2 = 0.151, adjusted R^2 = 0.148), with a minimal effect size (F^2 = 0.038) and low multicollinearity (VIF = 1.207), indicating a limited impact on urban resilience. The results demonstrate that GIUR and EDP exert a significant influence on urban resilience, while constructs such as NBS and PAHP have a negligible impact, suggesting that the predictors exert differing levels of influence.

5 Conclusion and policy implications

High levels of haze pollution in major Pakistani cities and their surroundings pose significant threats to public health and the environment. Urgent measures are needed to control harmful emissions in this key urban center of Pakistan. The primary goal of this study is to predict urban resilience in the context of haze pollution in Pakistan. Through an in-depth analysis of data gathered from 120 environmental academics, this research offers valuable insights and implications, advancing the understanding of urban resilience, particularly in the face of haze pollution. The findings emphasize the need for a comprehensive approach to urban planning, integrating digital platforms, nature-based solutions, and smart technologies to enhance urban resilience. Furthermore, the study highlights the crucial role of environmental perception, exemplified by Perceived Adverse Haze Pollution, underscoring the importance of robust awareness campaigns and community engagement for sustainable urban development.

This research serves as a foundational resource for future investigations and policy development related to urban resilience in the context of haze pollution. It highlights the interconnected nature of various factors within the research model and emphasizes the importance of considering diverse pathways for sustainability. The path analysis results carry significant implications: (1) Holistic approaches to urban planning and sustainability are essential, involving the integration of digital platforms, nature-based solutions, and technology adoption, alongside community perceptions of environmental challenges. (2) The strong influence of perceived adversity regarding haze pollution underscores the critical role of environmental awareness and education in urban settings, fostering initiatives such as public campaigns, community engagement, and educational programs. (3) Policymakers can use these findings to design and implement policies that promote the adoption of digital platforms for environmental initiatives, nature-based solutions, and innovative technologies in urban planning and development. In conclusion, this research makes a significant contribution to the global discourse on resilient and sustainable urbanization in the face of environmental challenges, offering an innovative framework for understanding the multifaceted nature of urban resilience and providing actionable recommendations for policymakers and urban planners.

Although the model includes essential constructs such as EDP, GIUR, NBS, and PAHP, it is important to acknowledge the potential presence of hidden variables or complex interactions that were not considered in the current analysis. These latent factors may influence urban resilience in the context of haze pollution but have not been explored here. Future research could employ advanced statistical techniques or qualitative methods to uncover and incorporate these hidden variables, providing a more nuanced understanding of the factors contributing to urban resilience amidst haze pollution in Pakistan. Additionally, future research could encompass variables such as economic indicators, infrastructure quality, public health metrics, community engagement measures, government policies, and social capital indicators. Integrating these variables would offer a holistic perspective on the diverse dynamics shaping urban resilience, enriching the analysis of urban sustainability in the face of haze pollution in Pakistan. This limitation underscores the evolving and complex nature of urban sustainability research, highlighting the need for continued exploration and refinement of the research model.

The limitation of this study is its reliance on survey for data collection. While academics provide valuable insights, their perspectives are inherently subjective and may not always reflect the broader, real-world circumstances. This subjectivity can limit the generalizability of the findings, as they are based on expert opinions rather than empirical data. To improve the reliability of future studies, it is crucial to incorporate data from a wider range of locations, which would offer a more accurate and comprehensive understanding of urban resilience. Such data would serve to validate expert views and ensure that policy recommendations are grounded in the actual experiences of people across Pakistan. Additionally, the study's focus on environmental professionals and stakeholders involved in urban and environmental issues may have introduced a potential bias. This emphasis might have overlooked perspectives from policymakers, the general public, and corporate leaders, narrowing the scope of the conclusions. Therefore, future research should incorporate a more diverse range of participants to provide a broader, more balanced perspective on urban resilience solutions. As urban resilience is a complex, multi-dimensional concept that extends beyond environmental concerns, such as air pollution, to include broader socio-economic and infrastructural elements (Kadaverugu et al., 2022). According to Cutter et al. (2008), resilience involves not only the ability of urban systems to recover from environmental shocks but also their capacity to adapt to long-term stressors. This includes governance strategies, economic resilience, and the robustness of infrastructure, all of which play crucial roles in ensuring that cities can thrive despite environmental and socio-economic challenges. Integrating these dimensions allows for a more holistic approach to smog governance, where strategies for pollution control intersect with policies for social equity, sustainable economic development, and adaptive infrastructure (Ahern, 2011). By considering urban resilience in this broader context, the study can provide avenue for better understanding the multi-faceted strategies necessary to manage environmental stressors like smog.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AR: Writing – original draft. JZ: Writing – review and editing. MI: Data curation, Writing – review and editing. HS: Validation, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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