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Posted Date: 3 March 2026

doi: 10.20944/preprints202603.0189.v1

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Review

Ten Questions on Innovative Urban Design Strategies for Sustainable Noise Management

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Abstract

This review paper examines innovative urban design strategies for sustainable noise management through a structured analysis framed by ten guiding questions. It begins with an overview of conventional noise assessment technologies and progresses to advanced mitigation approaches. Core principles of sustainable urban design are explored, alongside evaluations of urban and transportation planning, traffic-reduction measures, green infrastructure, and resilient architectural s trategies. Material innovations and modern noise-control technologies are presented as complementary solutions. Community-based methods, including citizen science and participatory planning, are highlighted for fostering inclusive governance. The discussion concludes by addressing key challenges and future directions, underscoring interdisciplinary collaboration to transform urban noise pollution into opportunities for healthier, more livable cities.

Keywords: urban noise; noise pollution; noise assessment; measurement techniques; urban planning; noise modeling; environmental health; city acoustics

1. Introduction

Urban noise pollution has emerged as one of the most pressing environmental concerns in modern cities, driven by the rapid expansion and development of urban areas worldwide. It disrupts acoustic harmony and affects human health, ecological balance, and overall well-being. Key contributors include traffic from roads, railways, and aviation, along with industrial and construction activities often located near residential zones [1]. Vibrant urban activities such as nightlife further intensify the acoustic load in metropolitan areas [2]. Together, these sources create a complex auditory environment that demands targeted and adaptive management strategies.

The consequences of prolonged exposure to urban noise pollution extend beyond mere annoyance, exerting profound physical and psychological impacts on individuals and communities [3,4]. Studies have consistently linked noise exposure to a range of health issues, including cardiovascular diseases, sleep disturbances, and hearing loss [5,6]. On the psychological front, chronic noise exposure has been shown to increase stress levels, hinder cognitive performance, and contribute to conditions like anxiety and depression, especially among vulnerable groups such as children and the elderly [7]. Table 1 presents common sources of urban noise pollution along with their associated impacts.

Additionally, urban noise pollution poses a significant threat to wildlife, affecting communication, behavior, biophysiology, reproduction, and ecosystem dynamics [8–11]. Chronic exposure to anthropogenic noise disrupts essential behaviors such as foraging, predator avoidance, and mating rituals by masking acoustic signals and increasing stress levels [12]. This interference can alter species interactions and ecological relationships. Migratory fish, for example, are particularly at risk as underwater noise from boats and industrial activities interferes with their communication and navigation, which can alter their migratory routes [13]. Birds, which depend on vocalizations for

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mating and territory defense, also suffer from decreased reproductive success because noise masks their calls [14]. In urban environments, the frequency of birdsong is often higher than that in rural and peri-urban areas, with habitat structure and anthropogenic noise shaping the acoustic space of urban birds. A study by Hao *et al*. ([15]) reported that bird dominance frequency increases with urbanization and low-frequency noise, as urban birds adjust their vocalization patterns to compete with the pervasive noise . These disturbances not only affect individual species but can lead to shifts in species composition and population dynamics, ultimately reducing overall biodiversity [16,17]. These findings emphasize the necessity of addressing noise pollution as both an environmental and public health concern, encouraging interdisciplinary efforts to better understand and mitigate its broad impacts.

Significant progress has been made in urban noise management over recent decades, with advancements in policy frameworks, engineering solutions, and public awareness campaigns. However, traditional approaches often fall short in addressing the dynamic nature of noise sources and their fluctuating intensities. Real-time assessment of noise levels and their origins remains a critical gap, as policymakers require actionable, data-driven insights to implement timely and effective interventions. In response, the integration of smart technologies and artificial intelligence has revolutionized noise management practices. From sensor networks that monitor soundscapes in real time to predictive models that inform urban planning, these innovations offer a proactive means of tackling noise pollution at its source.

In recent years, researchers have explored a variety of noise assessment techniques to identify major urban noise sources and develop effective mitigation strategies. Several review articles have documented progress in this field, highlighting tools and approaches used to quantify, monitor, and manage urban noise pollution [18–22]. Some of the "ten-question" review articles have specifically addressed urban noise issues. For example, Kang *et al*. ([23]) presented ten key questions on soundscapes in the built environment, identifying research gaps and setting a future agenda. Hornikx *et al*. ([24]) focused on computational modeling in urban acoustics, while Lam *et al*. ([25]) examined the feasibility and implementation of active noise control in various architectural contexts, including noise barriers and building façades, and explored its synergy with soundscape approaches. Heylighen *et al*. ([26]) addressed inclusive design in the built environment, and Kumar *et al*. ([27]) discussed the potential of smart buildings and cities to optimize energy use, enhance occupant comfort, and improve overall quality of life. While these contributions provide valuable insights into traditional and emerging noise management methods, they often lack a holistic discussion on the integration of advanced smart technologies and their transformative potential in urban noise mitigation.

The literature reviewed in this article, including journal papers, book chapters, and major review works, was selected primarily from the past decade, focusing on studies directly related to urban noise assessment, management, and mitigation. This selection emphasizes interdisciplinary research at the intersection of environmental science, engineering, urban planning, and public health, ensuring a current and relevant foundation for analysis.

Building on this foundation, the article explores how smart assessment and mitigation systems contribute to sustainable urban noise management. The discussion is structured around ten guiding questions that collectively frame a comprehensive analysis of urban noise challenges and solutions. It begins with an overview of conventional technologies for noise assessment (Q1) and advanced and emerging strategies for effectively managing urban noise pollution (Q2). The discussion then turns to the core principles of sustainable urban design that underpin effective noise mitigation (Q3), followed by an evaluation of urban and transportation planning, and traffic-reduction measures, that promote acoustically sustainable city design and reduce noise levels (Q4). Subsequent sections examine the role of green infrastructure in noise mitigation (Q5), and how sustainable architectural and building design strategies enhance urban noise resilience (Q6). The article then explores material innovation (Q7) and modern noise-control technologies (Q8) as complementary pathways for sustainable noise management in urban environments. Further, it explores community-based approaches, including

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citizen science, participatory planning, and public awareness initiatives, which support inclusive and adaptive noise governance (Q9). The final section identifies key challenges and outlines future directions, emphasizing the potential of innovation and interdisciplinary collaboration to reshape urban soundscapes (Q10). Collectively, these ten questions provide a narrative framework for understanding how design, technology, and community engagement can transform noise pollution into an opportunity for creating healthier, more livable cities.

Table 1. Common sources of urban noise pollution and their impacts.

Noise Sources	Average Sound Level	Health Impacts	Psychological Impacts	Environmental Impacts	References
Traffic Noise	Light traffic: 50–60 dB; Heavy traffic: 70–85 dB; Congested roads: 85–90 dB+	Increased blood pressure, heart disease, hearing damage, sleep disturbances	Stress, anxiety, irritability, decreased quality of life	Disturbance to wildlife, especially near roads	[28–30]
Construction Noise	Heavy machinery: 80–100 dB; Jackhammers: 90–110 dB	Hearing loss, sleep disturbance, stress, fatigue	Anxiety, irritability, chronic stress	Disturbance to ecosystems, displacement of wildlife	[31]
Air Traffic	Takeoff/landing: 80–100 dB; Up to 120 dB near airports	Cardiovascular issues, sleep disorders, hearing damage	Chronic stress, decreased quality of life	Impact on bird species and wildlife near airports	[32]
Public Transportation (Trains/Buses)	Trains: 85–95 dB; Buses: 70–80 dB	Hearing damage, hypertension, sleep disturbances	Irritation, anxiety, stress from commuting	Wildlife disturbance, particularly in urban parks	[33,34]
Industrial Noise	General machinery: 85–110 dB; Factory equipment: 90–100 dB	Hearing loss, hypertension, sleep disturbances	Anxiety, decreased productivity, chronic stress	Habitat disruption, displacement of animals	[35]
Street Performers/Music	Concerts/Clubs: 90–110 dB; Street performers: 70–85 dB	Hearing loss, sleep disturbance	Annoyance, stress, irritation	Minimal impact, except for wildlife disturbance	[36,37]
Domestic Noise (Households)	Vacuum cleaner: 70–75 dB; Lawn mower: 85–90 dB; Leaf blower: 80–90 dB	Hearing damage, sleep disturbances, stress	Frustration, irritation from noisy neighbors	Minimal environmental impact	[38]
Retail/Commercial Areas	Shopping centers: 60–75 dB; Fast food joints: 70–85 dB	Cognitive impairment, stress, disruption in social interactions	Irritation, stress, decreased social interaction	Minimal environmental impact	[39,40]

2. Ten Questions (and Answers) Driving Sustainable Urban Noise Management

2.1. Question 1: What Are the Traditional Approaches for Assessing and Managing Urban Noise Pollution?

Answer: Traditionally, urban noise assessment has been based on various methodologies, such as field measurements, predictive modeling, statistical analysis, and social assessments. These foundational approaches have been helpful for understanding and managing noise pollution in urban settings.

2.1.1. Field Measurements of Noise Levels

Field measurements remain one of the most prevalent and dependable techniques for evaluating urban noise levels. They provide critical empirical data that accurately reflect the actual acoustic environment in specific locations. By capturing real-time noise intensity, field measurements offer valuable insights into the noise climate, accounting for variations throughout different times of the day and night. Sound Level Meters (SLMs) are the primary instruments used for such measurements. These devices measure sound pressure levels in decibels (dB) and produce direct readings of the noise intensity in a given area. The results are typically expressed in various forms, such as L_{Aeq} (equivalent continuous sound level), L_{max} (maximum sound level), and L10, L50, L90 (background noise levels). These metrics are useful for assessing average, peak, and background noise levels, respectively, and for understanding temporal fluctuations over time. Beyond traditional SLMs, several other advanced measurement tools have become indispensable in modern urban noise assessments. Noise dosimeters, for instance, are wearable devices that measure an individual's exposure to noise over a specified period. Essentially, a dosimeter is a compact SLM with integrated data storage and computational capabilities, enabling it to calculate various metrics such as noise dose and time-weighted average (TWA). This tool is particularly beneficial for evaluating the noise exposure of specific populations,

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such as workers in industrial settings or residents living near high-traffic corridors. Another important component of field measurement is the use of permanent noise monitoring stations. These stations are installed at fixed locations and are designed for continuous, long-term monitoring of noise levels. Equipped with automated data collection systems, permanent stations gather noise data around the clock, often on a 24/7 basis. Such installations play a crucial role in applications including environmental noise assessment, compliance monitoring, strategic noise mapping, trend analysis, and evaluation of noise exposure in construction, industrial, or residential settings. In contrast to fixed monitoring stations, mobile noise monitoring offers greater flexibility in data collection. Using portable SLMs or specialized equipment, mobile monitoring enables noise measurement in areas where permanent stations may not be feasible or in rapidly changing urban environments. This approach is particularly useful for gathering data across diverse neighborhoods, assessing noise in transient locations, or tracking short-term events such as construction projects or temporary traffic patterns. Table 2 presents a selection of commonly used sound level meters, noise loggers, and monitoring stations for urban noise assessment, highlighting their key features, capabilities, and suitability for long-term environmental sound monitoring in city environments.

Table 2. Notable sound level meters and noise dosimeters for urban and occupational noise monitoring applications.

Model Name	Manufacturer	Key Features	Typical Use Case
High-End Class 1 Sound Level Meters			
SVAN 979	Svantek (Poland)	Advanced sound and vibration analyzer with wide dynamic range and simultaneous measurement	Precision environmental noise and building acoustics assessments
NL-63	Rion (Japan)	Low-frequency optimized Class 1 SLM; designed for tonal noise analysis	Specialized environmental noise studies
HBK 2255	Brüel & Kjær (Denmark)	Premium, single-channel Class 1 SLM; app-based workflows	Precision environmental assessments
NOR 145 / NOR 150	Norsonic (Norway)	High-performance SLMs with NorCloud integration	Citywide and airport noise monitoring
Mid-Range Class 1 Sound Level Meters			
SV 977D	Svantek	Dual-channel analyzer for building acoustics and environmental noise	Occupational and building noise surveys
HBK 2245	Brüel & Kjær	App-compatible Class 1 meter with Wi-Fi, GPS, and noise source identification	Urban and occupational environments
Spartan 821IH	Larson Davis (USA)	Durable personal noise dosimeter with Class 1 accuracy	Industrial worker noise exposure
831C	Larson Davis	Environmental noise analyzer; Class 1, multi-measurement capabilities	Road traffic and construction site monitoring
XL3 Acoustic Analyzer	NTi Audio (Liechtenstein)	Real-time spectral analysis, audio recording	Urban surveys, building diagnostics
Entry-Level Class 1 Sound Level Meters			
SV 971A	Svantek	Compact, general-purpose Class 1 SLM with logging	Basic urban noise mapping
XL2	NTi Audio	Portable, Class 1 SLM with FFT and octave band analysis	Mobile and indoor measurements
PCE-432 / PCE-432-ICA / PCE-432-EKIT	PCE Instruments (Germany)	GPS-enabled, IEC/ANSI compliant, Class 1 sound level meters	Indoor and outdoor environmental noise monitoring
Noise Dosimeters			
SV 102A+	Svantek	Dual-channel Class 1 noise dosimeter with octave analysis	Worker exposure in complex environments
SV 104 / SV 104A	Svantek	Compact, wearable dosimeters with Bluetooth	Personal noise exposure logging
CEL dBadge2	Casella (UK)	Wireless dosimeter with motion sensing and Bluetooth	Occupational health and safety audits
EG7 / EG8	TSI Quest (USA)	Real-time personal noise dosimeters with DMS software	Industrial noise compliance and analysis
PCE-NDL 10	PCE Instruments	USB-downloadable, compact dosimeter with Class 2 accuracy	Basic occupational exposure assessment
Noise Monitoring Station			
SV 307A	Svantek (Poland)	Class 1 SLM with built-in microphone verification, LTE/IoT connectivity	Optimized for all-weather outdoor noise monitoring at construction sites, transport corridors, industrial areas, and airports
SV 200A	Svantek (Poland)	Class 1 outdoor noise monitoring station with 3D acoustic beamforming, 4 MEMS microphones, weatherproof, and real-time source localization	Urban noise enforcement, construction site diagnostics, complex source identification
Optimus+ GPS	Cirrus Research (UK)	Class 1 sound level meter with GPS and voice tagging	Urban and occupational noise mapping

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2.1.2. Predictive Modeling

Predictive modeling is another key component of traditional urban noise assessments. This approach uses computational models to estimate the noise levels in urban areas based on input data about noise sources, environmental conditions, and geographical features. Specialized software, such as SoundPLAN, CadnaA, and IMMI, integrates noise emission models, acoustic dispersion models, geospatial data, and traffic data to create detailed noise maps, predicting noise levels across urban areas. These tools account for variables like traffic type (e.g., road, rail), traffic volume, and urban acoustics (e.g., buildings and barriers).

Empirical and semi-empirical models have traditionally formed the basis of urban noise assessment, relying on simplified mathematical formulations derived from experimental data and standardized measurements. These models are computationally efficient and suitable for large-scale noise mapping. Examples include ISO 9613-2, commonly used for outdoor sound propagation accounting for geometrical divergence, atmospheric absorption, and ground effects [41]; the FHWA Traffic Noise Model (TNM) in the U.S. for highway noise [42–46]; CNOSSOS-EU for European road traffic noise [47]; CoRTN in the UK for road traffic [48]; and RLS-90 in Germany [49,50], adapted to local traffic and infrastructure conditions.

Deterministic models simulate sound propagation using principles of physical acoustics, such as ray tracing, finite element methods (FEM), and boundary element methods (BEM). While these models provide high-detail simulations, they are computationally demanding. Stochastic models, in contrast, capture variability in noise sources and environmental conditions through statistical techniques, such as Monte Carlo simulations and geostatistical methods like Empirical Bayesian Kriging (EBK) and Inverse Distance Weighting (IDW) [51–53]. Although interpolation methods inherently introduce some level of uncertainty, they allow for a more continuous and realistic representation of urban noise patterns, helping researchers account for the complexities of the urban sound environment [54–56].

Land use regression (LUR) modeling is another statistical method for predicting spatial variations in urban noise. LUR models use GIS to integrate land use, traffic, and socioeconomic data, correlating these variables with noise measurements to predict noise levels across different areas. Notable applications include the LUNOS model in Dalian, China [57], and studies in Tel Aviv [58], São Paulo [59],Shiraz [60], Taiwan [61], Shanghai [62], and Guangzhou [63], which successfully employed LUR techniques for high-resolution noise mapping. LUR models have shown strong performance in capturing spatial noise patterns, though models like Random Forest have demonstrated superior accuracy in some cases [64]. However, LUR models also have notable limitations. Their predictive accuracy can be constrained by the quality and spatial resolution of input variables, and they often assume linear relationships between predictors and noise levels, which may oversimplify complex urban dynamics. Moreover, LUR models may struggle to account for temporal variability or rapidly changing urban conditions, reducing their generalizability across different time periods or cities.

2.1.3. Noise Mapping

Noise mapping is an essential tool in urban noise management, allowing planners, Noise mapping is a fundamental component of urban noise management, enabling the quantification and spatial visualization of environmental noise across urban areas [65,66]. By integrating field measurements, acoustic modeling, and geographic information, noise maps provide a thorough representation of noise pollution within a defined spatial scope. The mapping process typically begins with the formulation of study objectives and delineation of the study area, followed by data collection, which includes both in situ measurements and contextual inputs required for acoustic simulation models. These models estimate sound propagation to generate noise maps, which are then calibrated and validated using statistical methods to ensure accuracy and compliance with regulatory standards.

Widely adopted under frameworks such as the EU Environmental Noise Directive (END 2002/49/EC) and ISO 1996-1:2016, noise mapping serves as a robust, policy-relevant methodology for long-term environmental noise assessment [67]. It is instrumental in identifying high-exposure zones

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and quiet areas, evaluating population exposure, and supporting public health research, given the well-established links between chronic noise exposure and adverse health outcomes such as stress, hearing impairment, and cardiovascular disease. Additionally, noise maps inform urban planning and regulatory compliance by pinpointing areas where sound levels exceed permissible thresholds, facilitating enforcement and mitigation. Their temporal dimension allows for monitoring trends over time and assessing the acoustic impact of urban development. As part of Environmental Impact Assessments (EIAs), noise mapping offers a science-based framework to predict and manage noise impacts from proposed projects, enhancing evidence-based decision-making.

2.1.4. Social Assessments

Social assessments are essential for evaluating the subjective impacts of noise on urban populations, complementing objective measurements by capturing residents' perceptions and lived experiences. Methods such as surveys, questionnaires, interviews, and focus groups provide a more holistic understanding of noise effects on well-being, particularly where physical indicators fail to capture community distress.

Surveys and questionnaires are widely applied to assess noise perception and annoyance [68–71]. Standardized instruments, such as the ISO/TS 15666:2021 annoyance scale [72] or the ICBEN 11-point verbal or numerical rating scales [73], are frequently used to measure how often and how strongly residents feel disturbed by specific noise sources (e.g., road traffic, construction, nightlife). These questionnaires typically include questions on exposure duration, disturbance frequency, and perceived control over noise, allowing for statistical correlation with measured sound levels. Supplementary items may assess contextual factors, such as time of day, activity interference, or attitudes toward the noise source, to improve interpretability. Health-focused surveys often integrate modules from validated tools like the WHO Quality of Life (WHOQOL) or Perceived Stress Scale (PSS) to explore associations between self-reported well-being, sleep disturbance, or cardiovascular symptoms and prolonged noise exposure [74]. When combined with field data, such standardized and validated instruments provide strong evidence for designing targeted mitigation policies.

Qualitative methods such as interviews and focus groups capture deeper insights into coping strategies, cultural factors, and the broader social consequences of noise [75]. Unlike surveys, which rely on predefined responses, these approaches allow participants to articulate nuanced impacts on well-being, social interaction, and sense of place. Focus groups are particularly effective for identifying shared concerns and fostering dialogue, making them valuable tools in participatory urban planning. Together, these social assessment methods support behavioral and psychoacoustic studies by providing subjective data on how individuals perceive and emotionally respond to different sound environments, from traffic to industrial activity to music.

2.2. Question 2: What Advanced Methods and Emerging Technologies Are Transforming Urban Noise Management?

Answer: Urban noise management has become increasingly critical due to the expansion of transportation networks, industrial activities, and densely populated areas. Traditional noise mapping, often static or periodically updated, struggles to capture the dynamic spatiotemporal complexity of urban soundscapes. Advanced strategies now leverage Geographic Information Systems (GIS), IoT-based sensor networks, acoustic cameras, radar systems, and crowdsourcing to improve monitoring. Innovations in dynamic data acquisition, three-dimensional (3D) noise mapping, and AI-assisted approaches enhance assessment accuracy. The integration of big data analytics, cloud computing, machine learning, and artificial intelligence has further strengthened noise prediction and management. Emerging tools, including autonomous vehicles, UAVs, and immersive technologies such as AR and VR, provide new avenues for refined assessment and more responsive urban noise control.

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2.2.1. Innovative Technologies

Geographic Information Systems (GIS) for Urban Noise Modeling

Geographic Information Systems (GIS) offer a robust framework for integrating spatial and acoustic data to analyze urban soundscapes [76]. By combining topographic, land use, transport, and building data with acoustic metrics (e.g., L_{eq}, L_{10}, L_{night}, SEL), GIS supports spatial noise assessments across complex urban environments.

A key feature of GIS is spatial interpolation, used to estimate noise levels in unmeasured areas via methods like IDW, kriging, natural neighbor, radial basis functions, and trend surface analysis. These techniques address variability in dense, heterogeneous cityscapes. GIS supports 3D noise modeling through inputs like digital elevation models (DEMs), digital surface models (DSMs), and city models (e.g., CityGML, LoD2+), enabling simulations of reflections, diffractions, and absorptions. Coupled with ray tracing or image-source methods, GIS platforms can also integrate meteorological variables (e.g., wind, temperature, humidity) to refine noise dispersion estimates.

Noise modeling tools such as QGIS (with NoiseModelling) and ArcGIS interface with simulation software like SoundPLAN and CadnaA, allowing ISO-compliant, multi-source contour mapping. Python libraries (e.g., PyQGIS, ArcPy, scikit-learn) enable automation, spatial ML modeling, and web-GIS deployment. Tools like ArcGIS Online and mobile apps (e.g., NoiseCapture) support collaborative, crowdsourced data collection. Recent urban informatics initiatives like SONYC and UrbanSound combine edge acoustic sensors, cloud GIS, and AI to classify sound events in real time. These systems facilitate high-resolution, spatiotemporal noise analysis and support planning linked to human activity and equity indicators.

IoT-Based Sensor Networks

The Internet of Things (IoT) represents a network of interconnected devices equipped with sensors and communication technologies that autonomously collect and exchange environmental data [77]. In urban noise management, IoT provides infrastructure for real-time monitoring, automated data handling, and analytical assessment of urban soundscapes to guide evidence-based interventions.

Typically structured across several functional layers, from data collection to application delivery, IoT-based noise monitoring networks integrate acoustic sensors, wireless communication systems, and cloud or edge processing platforms [78,79]. These systems continuously measure acoustic parameters such as sound pressure levels and event durations, transmitting data securely for further analysis [80–85]. Machine learning and data analytics tools then support noise pattern recognition, source identification, and anomaly detection. Finally, the application layer visualizes results through dashboards, mobile applications, or real-time noise maps to support evidence-based decision-making for city planners and regulators.

Despite their advantages, IoT-based systems raise important concerns related to data protection, privacy, cybersecurity, and long-term system reliability. Addressing these issues is essential to ensure public trust, regulatory compliance, and the sustainable integration of IoT technologies into urban noise management frameworks.

Acoustic Camera

An acoustic camera is an advanced sensor system that visualizes sound sources in real time, combining high-sensitivity microphones with optical imaging and signal processing algorithms [86,87]. This integration produces spatial sound intensity maps overlaid on video, enabling the identification of noise sources in complex urban environments. Urban planners, researchers, and policymakers use these visualizations to assess and mitigate noise more effectively.

The system uses microphone arrays arranged in linear, circular, or 2D patterns to capture sound waves, and beamforming techniques analyze time differences in sound arrival to pinpoint sources. Intensity is displayed on heatmaps, while video imaging overlays sound data on real-world scenes. Modern systems also localize noise by frequency, duration, and decibel level, distinguishing between

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different sound types, such as low-frequency vehicle noise and high-pitched construction sounds. Some cameras offer 3D localization, identifying sound sources across multiple vertical levels in dense urban areas. Real-time sound propagation visualizations also assist in evaluating noise mitigation strategies, such as acoustic barriers [88]. Integration with machine learning and AI enables automated sound classification and continuous monitoring, reducing the need for manual input [89–91]. Deployed in smart city pilots across Europe and Asia, AI-powered acoustic cameras support real-time decision-making and public engagement through interactive sound visualizations.

Noise Radar Systems

Capturing sound from multiple directions in urban settings is challenging. Noise radar systems, which integrate acoustic detection with radar tracking, provide a robust solution for monitoring traffic-related noise. By combining an Acoustic Traffic Detector (ATD) with autonomous recognition algorithms, these systems detect and localize excessive noise events once thresholds are exceeded, filtering background noise to focus on dominant sources. Some implementations incorporate cameras for license plate recognition, digital displays for real-time warnings, and automated enforcement for fines, creating an integrated monitoring framework.

For road traffic surveillance, noise radar systems complement acoustic cameras by enhancing localization accuracy and source identification. This integration supports urban noise management through targeted mitigation, regulatory enforcement, and public awareness, while reducing the need for manual fieldwork. In the UK, rising concerns about modified vehicles prompted deployment of these systems under EU Regulation No. 540/2014, which limits vehicle noise to 72 dB(A), with a reduction to 68 dB by 2026. Trials launched by the Department for Transport in 2022 across cities such as Bradford and Birmingham used combined microphone arrays, radar, video, ANPR, and acoustic analysis [92]. While high-traffic conditions introduced challenges like false positives, results in controlled settings were promising. Public support and established enforcement infrastructure suggest strong potential for broader adoption of this technology.

Crowdsourcing

Crowdsourcing for urban noise management leverages citizen participation to collectively monitor and assess noise pollution through smartphones, apps, web portals, and social media [93–96]. Residents contribute real-time data by reporting disturbances, tagging locations, or uploading sound measurements, which are then aggregated into interactive noise maps. This participatory approach enables systematic identification of noise hotspots, facilitates targeted interventions, and supports evidence-based policymaking. Ethical considerations, including privacy, informed consent, and responsible data usage, are essential to ensure citizen participation is voluntary and data collection does not compromise personal information or public trust.

The proliferation of smartphones with built-in microphones, GPS, and connectivity has enabled large-scale noise monitoring at relatively low cost compared to traditional stationary equipment. A variety of mobile applications (e.g., NIOSH, NoiseCapture, Decibel X, and Decibel Pro) now support environmental and occupational noise assessments by estimating sound levels and enabling data sharing, collaborative mapping, and visualization [97–102]. Platform availability and calibration standards remain important considerations, as some apps are restricted to iOS or Android to ensure measurement reliability. These factors influence accessibility, consistency, and comparability across studies.

2.2.2. Advanced Noise Mapping Techniques

Dynamic Noise Mapping

Dynamic noise mapping is an emerging approach that integrates real-time or near-real-time data, advanced simulations, and multi-source inputs to capture the spatial and temporal variability of urban noise [103–105]. Unlike conventional static models, which provide long-term averages, dynamic models incorporate live noise measurements, meteorological data, and traffic information from sources

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like Noise Monitoring Terminals (NMTs), IoT sensors, and platforms such as OpenStreetMap [106,107]. These inputs are used in conjunction with GIS, interpolation methods (e.g., EBK, IDW), and statistical models (e.g., mixed-effects models) to generate high-resolution noise maps [108]. Tools like MATSim and NoiseModelling enable microscopic simulation of dynamic traffic behaviors, while machine learning techniques, including neural networks and random forests, further enhance predictive accuracy. Recent studies in cities like Taipei, Tartu, and Patiala have demonstrated the effectiveness of these methods, achieving hourly prediction errors within ±6 dBA or better and highlighting the benefits of real-time responsiveness and fine-scale traffic simulation [109–112].

Three-Dimensional (3D) Noise Mapping

Three-dimensional (3D) noise mapping extends conventional two-dimensional approaches by incorporating vertical data, including building height, volume, terrain, and elevated infrastructure [113–115]. Unlike horizontal maps that mainly show spatial dispersion, 3D models enable richer visualizations of acoustic propagation across complex cityscapes, allowing façade-level exposure assessment and estimation of indoor intrusion at multiple building elevations [116]. Modern approaches leverage GIS, building information modeling (BIM), and advanced acoustic simulations such as ray tracing and finite-difference time-domain (FDTD) methods [117,118], supporting detailed analyses in urban canyons, near high-rises, and along multi-level transport corridors.

High-resolution 3D mapping relies on diverse remote sensing datasets. Building volumes and heights are derived from SAR (e.g., Sentinel-1 C-band, ALOS L-band) and Landsat 8 optical imagery [119], while ancillary layers such as nighttime lights (VIIRS), digital surface models (ALOS World 3D), NDVI, and urban land cover products improve spatial resolution and predictive accuracy. LiDAR has become a central tool, producing dense, georeferenced point clouds of terrain, structures, and vegetation that are critical for accurate sound propagation modeling [120,121]. Mobile and airborne platforms further extend coverage to large or hard-to-access areas. Trajectory-level traffic data derived from LiDAR or other sensors can improve temporal modeling, supporting assessments that capture both spatial and temporal variations in noise exposure. Validation of 3D noise maps is typically performed by comparing modeled noise levels with in situ measurements across multiple building elevations or representative urban locations.

2.2.3. Computational Intelligence and Analytical Techniques

Machine Learning and Artificial Intelligence

Machine learning (ML) and artificial intelligence (AI) are increasingly applied in urban noise management to process complex acoustic datasets, extract patterns, and support decision-making [122–125]. Key applications include noise source classification, level prediction, traffic modeling, high-resolution spatial mapping, and anomaly detection. Supervised ML algorithms, such as K-Nearest Neighbors, Random Forests, and Support Vector Machines, are used to identify sources like road traffic, construction activity, human voices, and industrial operations using spectral, temporal, and perceptual features [126–128], while deep learning approaches enable finer distinctions within complex audio datasets [129–133], achieving high accuracy when trained on labeled datasets such as UrbanSound8K or city-specific recordings [134]. Regression-based ML models and artificial neural networks predict noise metrics like hourly equivalent levels using inputs such as traffic volume, vehicle speed, weather conditions, and land use patterns [135,136], often outperforming conventional deterministic models under nonlinear environmental interactions. In traffic noise management, ML integrates real-time sensor data with geospatial information to anticipate noise hotspots, evaluate the impact of traffic changes, and recommend interventions such as road surface modifications or traffic rerouting, while anomaly detection identifies sudden noise events [137]. Ensemble learning and hybrid frameworks combining ANFIS, FFNN, and SVR further enhance predictive performance across diverse urban settings [137]. Spatial ML models contribute to mapping noise exposure and perceptual responses, aiding urban planners in designing healthier soundscapes [138], and AI enables integration with traffic, land use, and meteorological data to support scenario-based simulations and policy evaluations [139].

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Coupled with real-time monitoring and cloud-based processing, these systems allow automated and proactive noise management in dense urban and developing peri-urban environments [140], though practical deployment must address data storage, security, and computational constraints.

Big Data Analytics and Cloud Computing

The rapid growth of sensor networks, acoustic simulation data, and crowdsourcing platforms has led to the generation of massive datasets that require advanced computational infrastructure for effective analysis. Cloud computing plays a critical role in addressing this need by offering scalable resources for the storage, processing, and sharing of large volumes of noise data [141]. With their flexible and on-demand capabilities, cloud platforms enable the handling of extensive datasets that are otherwise difficult to manage with traditional systems [142,143]. This scalability ensures that noise data from a wide range of sources, including sensor networks, social media platforms, and acoustic simulations, can be efficiently processed in real time or near-real time.

When combined with big data analytics, these cloud-based platforms unlock powerful capabilities for urban noise assessment [144–146]. The integration of big data techniques allows for the extraction of meaningful insights from vast datasets, such as identifying temporal and spatial noise distribution patterns across urban environments [147]. Big data analytics also facilitates the detection of correlations between noise exposure and public health outcomes, offering valuable insights into how noise affects residents' well-being [148,149].

2.2.4. Emerging Techniques

Autonomous Vehicles and UAVs in Noise Measurement

In recent years, several innovative technologies and methodologies have emerged for urban noise mapping, aimed at improving spatial resolution, accessibility, and data accuracy. One such approach is dynamic noise monitoring at the pedestrian level using autonomous vehicles. Ajdari *et al*. ([150]) introduced a system in which autonomous vehicles, already navigating city streets for delivery or transit purposes, are equipped with noise sensors to collect data at human ear level. This method provides continuous, high-density noise measurements across wide areas, capturing variations in the soundscape throughout the day and across different urban zones, and significantly enhancing the temporal and spatial granularity of noise maps compared to traditional static monitoring stations.

Another promising avenue involves drones equipped with microphones to monitor noise in difficult-to-access urban areas, such as around high-rise buildings, under bridges, and within industrial zones [151]. Multi-rotor drones, already used in environmental and bioacoustic monitoring, offer a flexible and rapid-deployment option for noise data acquisition. A major limitation of this approach is the self-generated noise from the drone's propellers, which can interfere with acoustic data. To mitigate this issue, researchers have developed combined hardware and software strategies. For example, Wang *et al*. ([152]) proposed suspending a shotgun microphone 2 meters below the drone using a steel fishing line, reducing drone-generated noise and capturing ground-level sounds more effectively, with additional post-processing filters removing residual ego-noise. Despite these technical solutions, the deployment of UAV-based noise monitoring faces legal and regulatory obstacles in many urban areas, which are often overlooked in current studies.

Immersive Technologies

Immersive technologies, including augmented reality (AR), virtual reality (VR), and extended reality (XR), are emerging tools for urban noise management by enhancing visualization, simulation, and stakeholder engagement [153]. AR overlays digital information, such as noise data or 3D models, onto real environments via devices like smartphones and smart glasses [154]. Utilizing platforms such as ARKit and ARCore, noise metrics can be spatially anchored in real time to support on-site assessments and participatory planning [155,156]. AR also allows visualization of mitigation measures (e.g., barriers, vegetation), facilitating collaborative decision-making [157].

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VR employs headsets and spatial audio system (e.g., Ambisonics) to recreate soundscapes, enabling users to explore existing or planned urban noise environments [158,159]. A key feature is *auralization*, which models sound propagation, reverberation, and occlusions for high ecological validity [160–163]. Combined with motion tracking and 3D visualization, VR allows intuitive assessment of traffic, construction, or quiet areas [164,165].

XR combines AR, VR, and mixed reality (MR), integrating physical and virtual elements with multisensory feedback [166,167]. In noise management, XR facilitates live monitoring, immersive simulations, and contextual visualization of interventions like traffic rerouting and urban design modifications [168–170]. Platforms like Snapdragon XR and Autodesk Workshop XR are being adopted in urban planning [171], while advances in spatial audio, motion tracking, haptics, and AI-enhanced 5G connectivity are expanding XR into participatory design, education, and healthcare.

2.3. Question 3: What Are the Core Principles and Defining Features of Sustainable Urban Design?

Answer: Sustainable urban design is a comprehensive approach to planning and developing urban areas that seeks to fulfill the needs of the present without jeopardizing the ability of future generations to meet their own. This design philosophy integrates environmental, social, and economic considerations to create urban spaces that are resilient, efficient, and livable. Sustainable urban design aims to establish a harmonious relationship between the built environment and natural ecosystems, prioritizing the well-being of communities while addressing global challenges such as climate change and resource depletion.

The goals of sustainable urban design encompass several key areas, all of which are deeply relevant to effective urban noise management. Environmental protection remains paramount, as minimizing pollution (noise, in our case) directly contributes to reducing the overall ecological footprint of cities by mitigating its impact on both human health and urban biodiversity [172]. Resource efficiency also plays a vital role, emphasizing the use of sustainable materials and technologies, such as use of recyclable materials, green infrastructure, and multifunctional noise barriers, that promote material efficiency and cost-effectiveness while enhancing acoustic comfort. Social equity is a core consideration, ensuring that noise mitigation strategies benefit all residents equally, particularly vulnerable groups disproportionately affected by excessive noise exposure, including low-income communities and age-sensitive groups [173,174]. From an economic perspective, effective noise management enhances property values, supports local businesses, and reduces healthcare costs associated with noise-related stress and illness, thereby contributing to the community's economic sustainability [175–179]. Finally, resilience is integral to sustainable urban noise management, focusing on adaptive planning and design approaches that enable cities to respond dynamically to changing noise sources, urban growth, and climate-related challenges.

Effective sustainable urban design for noise management is built on key characteristics such as integration, adaptability, and a focus on the community. Integration involves harmonizing transportation systems, housing, green spaces, and commercial areas to form acoustically balanced and livable environments. Mixed-use development exemplifies this principle by combining residential, commercial, and recreational spaces in ways that reduce traffic volumes and, consequently, noise emissions [180]. Compact, well-connected developments shorten commuting distances and encourage walking, cycling, and public transit use—activities that collectively reduce vehicular noise. Incorporating green infrastructure, such as vegetated barriers, parks, green roofs, and urban forests, enhances urban aesthetics while serving as natural sound absorbers. These features not only mitigate ambient noise levels but also support biodiversity, improve air quality, and manage stormwater sustainably [181,182]. By integrating these multifunctional systems, cities can progress toward multiple sustainable development goals (SDGs), including those related to health, climate action, and sustainable communities [183].

Adaptability is equally vital in the context of urban noise management, referring to the capacity of urban environments to respond to changing acoustic conditions, technologies, and social behaviors [184,185]. Flexible urban spaces, such as modular streetscapes or reconfigurable community zones,

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can accommodate evolving traffic patterns and new modes of mobility, helping to maintain acceptable noise levels over time [186]. The use of resilient materials and adaptive building designs, such as sound-reflective facades, dynamic noise barriers, and smart monitoring systems, ensures durability and continuous noise control performance under varying environmental conditions. These adaptive approaches also reduce long-term maintenance and retrofitting costs, supporting both acoustic and economic sustainability.

Lastly, community-centric design plays a pivotal role in managing urban noise sustainably. Involving residents in planning and decision-making processes can ensures that noise reduction strategies align with local needs, emotions, perceptions, and cultural contexts [187]. Public participation enhances transparency and fosters a sense of ownership, leading to better compliance with noise regulations and stronger support for mitigation measures. Designing inclusive social spaces, such as community gardens, quiet zones, and plazas shielded from major noise sources, promotes mental well-being and strengthens social cohesion. Moreover, integrating local culture and identity into acoustic design, such as through soundscapes that reflect community character—cultivates a sense of belonging and pride among residents. Figure 1 illustrates these core principles, highlighting how integrated, adaptive, and community-centered design contribute to sustainable and acoustically balanced urban environments.

Figure 1. Principles and Key Characteristics of Sustainable Urban Design: A schematic representation illustrating the core principles of sustainable urban design, including environmental protection, resource efficiency, social equity, economic viability, and resilience. It also highlights key characteristics such as integration, adaptability, and a community-focused approach.

2.4. Question 4: How Can Urban and Transportation Planning Strategies Work Together to Promote Acoustically Sustainable City Design and Reduce Urban Noise Levels?

Answer:

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2.4.1. Urban Planning Strategies

Urban planning strategies can play a crucial role in promoting acoustically sustainable city design by integrating noise mitigation principles across multiple spatial scales. Effective noise management begins at the site level, where careful planning and design can significantly reduce exposure for noise-sensitive functions. Strategic site selection involves placing residential buildings, schools, hospitals, and public institutions away from dominant noise sources such as highways, airports, railways, or industrial zones. When complete separation is not feasible, localized design interventions, such as building orientation, elevation, façade treatments, natural topography, vegetation belts, or water features, can mitigate noise impacts. These interventions operate at a tactical, site-specific scale, ensuring that immediate environments support comfort and well-being without relying solely on city-wide regulations.

At a broader scale, noise-resilient urban zoning provides an essential framework for city-wide noise management. By regulating the spatial arrangement of land uses, planners can designate areas for high-noise activities (e.g., industrial zones, major transport corridors) and separate them from low-noise areas (e.g., residential neighborhoods, parks, schools). Zoning policies may also include acoustic transition zones, such as green belts, buffer districts, or noise-limiting corridors, to reduce propagation between incompatible land uses. This strategic, regulatory approach ensures that urban growth balances economic activity with the acoustic quality of sensitive areas [188,189].

Furthermore, mixed-use developments contribute to acoustic sustainability by integrating residential, commercial, and recreational spaces within compact neighborhoods, thereby reducing urban sprawl, commuting distances, and traffic-related noise [190,191]. By localizing daily activities, these developments minimize reliance on vehicles, creating quieter and more livable urban environments. Walkability, cycling infrastructure, and green streetscapes further reduce transportation noise while improving overall quality of life. Pedestrian-friendly streets, safe crossings, and dedicated cycling lanes promote walking and biking as preferable modes of transportation over driving [192]. Research also highlights the importance of greening strategies in fostering cycling adoption [193,194]. Green streetscapes enhance aesthetics, safety, and comfort, while improving air quality and acoustic conditions. Parks and recreational areas within mixed-use developments provide tranquil environments that help reduce ambient noise, supporting community health and alleviating acoustic stress.

2.4.2. Transportation Planning and Mobility Management

Transportation systems are widely recognized as the leading contributors to environmental noise in dense urban areas [36,195]. Contemporary urban planning strategies therefore aim not only to reduce vehicle numbers but also to reorganize travel behavior, promote cleaner energy sources, and optimize traffic flow. The following subsections categorize the primary strategic approaches adopted by cities to mitigate urban traffic noise.

Traffic Flow or Volume Management

Vehicle volume and traffic dynamics directly influence urban noise emissions, as frequent acceleration, braking, and idling are major sources of peak sound levels. Traffic calming measures, including speed humps, roundabouts, chicanes, raised crossings, and pedestrian-priority "living streets", effectively reduce propulsion noise by enforcing lower and more stable speeds. For instance, the Barcelona Superblock model reduced local noise levels by 3–7 dB(A) by restricting through-traffic and implementing modal filtering [196–198]. Similarly, interventions in Ghent, Belgium, led to a significant reduction in car entries, prioritizing walking and cycling while improving the acoustic quality of residential districts.

Intelligent traffic management systems further enhance urban acoustic environments by optimizing vehicular flow in real time [199]. Singapore's Intelligent Transport System (ITS), for example, integrates AI-driven traffic predictions with real-time data from sensors, GPS devices, and surveillance cameras to minimize congestion and improve network efficiency [200]. The SURTRAC adaptive

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signal-control system in Pittsburgh reduced average vehicle delays by approximately 40%, decreasing stop-and-go driving and yielding measurable reductions in environmental noise of 2–3 dB(A) [201].

Public transportation infrastructure also mitigates traffic noise by offering alternatives to private vehicles. Transit hubs and transit-oriented development (TOD) encourage the use of buses, trains, and trams by situating residential and commercial areas near transit points [202]. For example, Bogotás TransMilenio BRT system achieved a 29% decrease in private car trips, contributing to quieter and cleaner urban corridors.

Electrification and Quiet Vehicle Integration

The electrification of transportation has emerged as a promising approach for reducing propulsion-related noise, particularly in lower-speed urban areas. Electric vehicles (EVs) are inherently quieter than internal combustion engine (ICE) vehicles, due to the absence of engine and exhaust sounds, leading to noticeable reductions in traffic noise [203,204]. Iverson *et al*. ([205]) reported that EVs are 4–5 dB quieter than comparable ICE vehicles at low speeds (~30 km/h). However, above moderate speeds, tire–road interaction dominates, limiting acoustic benefits on high-speed arterials [206].

Public electric fleets, particularly municipal buses, provide measurable urban-scale benefits. In Stuttgart, Germany, electric buses reduced average noise levels in quiet residential areas by up to 5 dB(A) [207], with the greatest benefits observed on routes with a high bus share, low average speeds, and minimal other heavy traffic. In Hong Kong, the deployment of electric light-duty vehicles and buses yielded maximum daytime noise reductions of 4.4 dB(A) in urban cores; with a fully electrified bus fleet, approximately 60% of the population experienced a 1 dB(A) reduction at street level, 15.3% experienced 1–2 dB(A), and 4.3% experienced more than 2 dB(A) reduction [208]. In San Francisco, a study on electric shared autonomous vehicles (SAVs) projected that if 6.6% of vehicles were electric SAVs by 2033, noise-polluting vehicle trips could decrease by 61%, alongside a 40% reduction in fine particulate matter concentrations.

While EVs improve acoustic quality, their reduced sound levels raise pedestrian safety concerns [209], prompting regulations for artificial vehicle alert systems (AVAS) [210,211]. The effectiveness of AVAS in maintaining both safety and acoustic sustainability is still under debate, as current standards may not fully account for contextual soundscape considerations [212].

Policy and Behavioral Interventions

Behavior-oriented regulatory tools have proven effective in reducing peak-period traffic and associated noise levels. Congestion pricing (CP) schemes remain a key area of research in sustainable urban transportation [213]. By charging vehicles to enter city centers during peak hours, CP discourages non-essential trips while promoting public transit and carpooling. London observed a 30% drop in traffic volumes under CP, and Stockholm achieved a 20% reduction in traffic along with a peak noise reduction exceeding 3 dB(A). Complementary low-emission zones further restrict high-noise, high-emission vehicles.

Temporal redistribution of traffic through flexible working hours and remote-work incentives also reduces rush-hour congestion [214]. During COVID-19 lockdowns, European cities such as Milan and Paris recorded over 50% declines in peak noise levels, demonstrating the effectiveness of temporal traffic management [215]. Demand-responsive curb pricing, as implemented in San Francisco's SFPark initiative, additionally prevents cruising behavior, a major source of unnecessary engine revving and horn use near commercial areas [216].

2.5. Question 5: How Does the Integration of Green Infrastructure Contribute to Noise Mitigation in Sustainable Cities?

Answer: Green infrastructure (GI) integrates natural elements into urban planning to enhance aesthetics, biodiversity, and air quality while mitigating noise pollution [217–219]. It reduces noise through absorption, reflection, diffraction, and masking effects. Vegetation such as leaves, branches, and soil absorb high-frequency noise, dense plantings scatter and reflect sound, and strategic layouts

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diffract noise away from sensitive areas. GI also enriches urban soundscapes with natural sounds like rustling leaves or bird calls, improving residents' psychological well-being.

Biophilic design, a key component of GI, incorporates natural elements into buildings to enhance comfort and address urban challenges. Green walls and vertical gardens, vegetated surfaces applied to building exteriors or interiors, can reduce noise by 5 to 10 dB in the mid-to-high frequency range, [220–222]. Their performance depends on plant density, substrate type, and wall thickness, though high installation costs and irrigation needs require careful evaluation.

Green façades, using climbing plants or modular panels, provide moderate attenuation (3–8 dB) and are lighter and more affordable alternative to green walls, though maintenance remains a challenge [223]. Their multilayered structure, including vegetation, substrate, support frames, and canopy—scatters and absorbs acoustic energy, particularly in the mid-to-high-frequency range. In addition to acoustic benefits, green façades contribute to thermal regulation, air purification, and aesthetic enhancement, supporting broader sustainability goals.

Green roofs, composed of vegetation, growing media, drainage, and waterproofing layers, reduce airborne noise, especially useful for multi-story buildings near elevated transport corridors such as highways, railways, or flight paths. Depending on design, sound reductions range from 1 to 10 dB, with intensive systems (deeper soil and denser vegetation) outperforming extensive ones [224]. Green roofs also shield rooftop mechanical equipment, thereby further reducing ambient noise pollution.

Innovative systems, such as microalgae bio-reactive façades, embed living algae in bioreactors or transparent panels, offering noise reduction alongside thermal control, CO_2 sequestration, biofuel production, and improved air quality [225–229]. These systems enhance the multifunctionality of GI in urban settings.

At the urban scale, green spaces, including parks, gardens, forests, and green belts, serve as large-scale noise buffers. Vegetation in these areas absorbs, deflects, and refracts sound, achieving reductions of up to 10 dBA Lden [230]. Dense tree lines can reduce traffic noise by 5 to 10 dB [231], while urban forests and green belts of 100 meters or more achieve reductions of 10 to 15 dB [232]. Even individual trees can reduce sound levels by 2–3 dBA, with clustered plantings achieving 6 to 8 dBA [233]. Parks enhance these effects by incorporating vegetation with landforms like berms or ponds that disrupt sound propagation [234].

Beyond acoustics, GI delivers co-benefits such as cleaner air, urban heat mitigation, stormwater management, and improved mental health. Neighborhood green spaces also enhance social well-being by providing spaces for recreation, relaxation, and community interaction [235–237]. A notable example is the *Parkroyal Collection Pickering* in Singapore, featuring a 15,000 m^2 high-rise tropical garden with walls, sky gardens, and terraces [238]. Hosting over fifty plant species adapted to various microclimates, it combines biodiversity conservation with noise mitigation, thermal comfort, and carbon reduction. Features such as rainwater harvesting and automated fertigation exemplify the integration of ecological function and architectural design, showcasing the potential of GI to enhance resilience in dense urban environments.

2.6. Question 6: How Can Sustainable Architectural and Building Design Strategies Enhance Urban Noise Resilience?

Answer:

Sustainable architectural and building design strategies can significantly enhance urban noise resilience by integrating spatial planning, material selection, and computational design approaches. Building orientation and massing play a crucial role in mediating the interaction between structures and environmental noise [239]. Strategic placement of less noise-sensitive areas, such as corridors, storage rooms, and stairwells, toward major noise sources, while orienting quiet-use spaces, including bedrooms, classrooms, and patient rooms, away from high-noise interfaces, reduces reliance on mechanical insulation and enhances occupant comfort. Geometric interventions, such as angled façades, staggered building blocks, and internal courtyards, disrupt sound propagation paths, attenuating intensity and creating acoustically comfortable microenvironments.

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Urban street canyons, the spaces between parallel rows of buildings along streets, further influence noise exposure in dense areas [240]. Acting as waveguides, street canyons channel and reflect sound, which can amplify traffic noise and elevate exposure for pedestrians and occupants [241]. A key determinant of canyon acoustics is the canyon aspect ratio (building height to street width). High ratios (tall buildings bordering narrow streets) tend to trap sound, whereas lower ratios promote dispersion and mitigate pedestrian and residential exposure [242–244]. Optimizing building height-to-width ratios, clustering structures to create internal buffer zones, and aligning massing with topography leverages natural sound barriers and shields courtyards or public spaces.

Architectural integration of acoustic materials and passive design elements complements these spatial strategies by enhancing building envelope performance. Integrating green infrastructure with acoustically responsive façades addresses both sustainability and noise mitigation [245,246]. Louvers, when constructed from high-insulation materials and combined with vegetation or perforated linings, deflect or absorb sound while maintaining shading and ventilation functions. Similarly, façades with absorptive or diffusive surfaces, textured panels, vegetated walls, laminated glass, resilient assemblies, or double-skin systems, reduce reverberation and energy buildup, whereas reflective surfaces intensify noise [247,248]. Innovative solutions, including anti-noise windows, active noise control and masking to reduce perceived annoyance [249].

Computational approaches further advance sustainable acoustic design. AI and generative algorithms enable real-time optimization of building orientation, spatial layout, and materials to reduce noise exposure [250]. When integrated with biophilic design principles, these tools support restorative spaces that buffer acoustic disturbances and enhance occupant well-being [251]. Parametric modeling and predictive analytics identify noise hotspots and propose interventions, such as green buffers or noise-dampening façades, while VR and BIM facilitate immersive testing of design strategies [252]. Such performance-based approaches ensure sustainable urban development that optimizes both environmental and acoustic comfort from the conceptual stage.

2.7. Question 7: How Can Sustainable and Innovative Materials Contribute to Reduce Urban Noise and Enhance Acoustic Comfort?

Answer:

2.7.1. Recycled Acoustic Materials

Sound insulation and acoustic barriers are vital for mitigating outdoor noise, especially along traffic corridors, construction sites, and industrial zones. Traditional high-performance materials, such as concrete walls, soundproof fences, acoustic panels, mass-loaded vinyl, and earth berms, effectively block or dissipate sound in noisy urban areas.

With growing emphasis on sustainability, Recycled materials are increasingly used to enhance acoustic environments while reducing environmental impact. These include repurposed plastics, rubber, denim, metals, construction waste, and bio-based materials like cork, hemp, and bamboo. Their ability to absorb, reflect, and diffuse sound helps mitigate noise while lowering carbon footprints and aligning with sustainable urban design goals.

Recycled materials are increasingly used in outdoor acoustic applications due to their resource efficiency and waste reduction potential. Among them, crumb rubber derived from end-of-life tires demonstrates excellent sound insulation properties, making it suitable for pavements and noise barriers [253,254]. Similarly, recycled plastics such as PET and polystyrene can be processed into porous acoustic panels that provide effective soundproofing. Caniato *et al*. ([255]) reported that foamed materials fabricated from microplastic waste and bio-based matrices exhibited strong acoustic absorption, particularly in the 2000–3000 Hz frequency range.

Construction and demolition waste (CDW) has also been successfully repurposed for noise barrier applications, offering a durable and environmentally friendly alternative to conventional materials [256,257]. Amarilla *et al*. ([258]) demonstrated that simple CDW-based barriers can achieve significant noise attenuation, thereby supporting circular economy principles by extending the lifecycle

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of construction materials [259,260]. A more recent innovation involves the reuse of decommissioned wind turbine blades as structural elements in roadside noise barriers [261]. The aerodynamic geometry (e.g., trailing edge serrations), composite composition, and high material strength of these blades make them particularly well-suited for such applications, combining acoustic performance, mechanical resilience, and environmental sustainability.

Moreover, bio-based materials like cork, hemp, flax, kenaf, coir, palm, corn, bamboo, and rice husk-derived composites, etc. are increasingly valued for both acoustic performance and sustainability [262–264]. Cork is lightweight, renewable, and effective for sound absorption. Hemp and flax fibers reduce sound transmission while being biodegradable. Bamboo, due to its fast growth and renewability, is used in functional and aesthetic acoustic panels. These materials also aid carbon sequestration. Kolya and Kang ([265]) explored the use of herbal waste (stems and leaves) in sound-absorbing wall panels, achieving effective absorption at 2.5 kHz and presenting a novel approach to waste reuse and sustainable acoustics. Bio-based materials also reduce greenhouse gas emissions through lower production energy demands.

Real-world projects illustrate these materials' efficacy. In Melbourne's Mordialloc Freeway project, noise barriers made from 75% recycled plastic, equivalent to 57 tons of soft plastic or 30 million water bottles, reduced noise while diverting waste from landfills [266,267]. The project also featured an 8 km shared path, integrating acoustic design with active mobility infrastructure. In Colombia, researchers tested façade materials and balcony designs in street canyons [268]. Materials like pumice stone and refractory brick achieved up to 5.1 dB and 3.6 dB insertion losses, while cork wood and metal wool reduced noise by up to 3.9 dB and 3.7 dB. However, balconies increased walkway noise by up to 4.7 dB, emphasizing the need to integrate material and architectural design in acoustic planning.

Despite their benefits, these acoustic materials face challenges, including higher initial costs, limited availability, and a lack of standardized performance testing. Future innovations in hybrid composites and bioengineered materials may enhance scalability and effectiveness. Policies promoting sustainable material use in urban planning can accelerate adoption. Prioritizing these solutions allows cities to improve acoustic comfort while supporting environmental and livability goals.

2.7.2. Acoustic Metamaterials for Enhanced Sound Attenuation

Acoustic metamaterials are an innovative class of engineered materials that enable precise manipulation of sound waves through subwavelength-scale structures, offering promising alternatives to conventional noise control methods [269,270]. Unlike traditional porous foams or fibrous composites, whose effectiveness is constrained by the mass law and limited to mid-to-high frequencies, metamaterials achieve compact and efficient sound attenuation even at low frequencies, thanks to unique properties such as negative effective mass density and bulk modulus [271].

Various design strategies target specific frequency ranges using locally resonant mechanisms, including Helmholtz, Fabry–Perot, and Mie-type resonances [272–274]. Structures such as micro-perforated plates (MPPs) [275] and coiling metastructures, like labyrinthine, spider-web, or helical channels [276–279], enable advanced functionalities such as low-frequency attenuation [280], broadband absorption [281], impedance matching [282,283], negative acoustic refraction [284,285], active noise control [286–288], and even acoustic energy harvesting [289].

To enhance acoustic performance, recent research explores hybrid systems that integrate metamaterials with natural or recycled porous media. These combinations improve broadband absorption and tunability while aligning with ecological design goals [290–293], making them suitable for applications in architecture, transportation, and industry.

Despite their potential, real-world applications of acoustic metamaterials remain limited. Most implementations are confined to controlled indoor environments, such as soundproof booths, acoustic panels, and partition walls, due to high fabrication costs, complex manufacturing processes, and scaling challenges. Outdoor uses, including traffic or construction noise mitigation, are still in early experimental phases and face additional barriers such as material durability and environmental variability [294]. Realizing the full urban potential of metamaterials will require advancements in cost-

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effective, scalable production and robust, weather-resistant designs tailored for long-term performance in diverse settings.

2.7.3. Pavement Surface Modifications for Reducing Traffic Noise

Pavement and road surface modifications represent one of the most effective strategies for mitigating traffic noise in urban environments. These interventions primarily address the tire–road interaction, a dominant source of rolling noise, by optimizing surface texture, material composition, and structural design. Through reductions in friction, air compression, and vibration, such modifications improve the acoustic environment along roads and highways while maintaining safety and durability standards.

Surface and structural modifications can either alter the pavement's internal composition or modify its surface characteristics to reduce noise generation at the source. Designed for durability, skid resistance, and weather resilience, these treatments are particularly suitable for urban retrofitting and noise-sensitive areas near residential or institutional zones. A widely adopted approach is the use of low-noise porous asphalt, also referred to as open-graded asphalt [295]. Its permeable structure allows air and water to pass through the surface, reducing the air compression that typically amplifies tire–road noise. Compared to dense-graded surfaces, porous asphalt can achieve noise reductions of approximately 3–4 dB(A) [296]. Another effective solution is rubberized asphalt, which incorporates recycled crumb rubber into conventional concrete or bitumen mixes. The addition of rubber enhances material elasticity, thereby attenuating vibration-induced noise and improving ride comfort [297]. Moreover, it supports sustainability by repurposing end-of-life tires [298].

Recent innovations in quiet concrete focus on optimizing mixture design to enhance sound absorption and sustainability. Experimental formulations integrate recycled or low-impact materials such as oil palm kernel shell, cockleshell, oyster shell, polypropylene fibers, fly ash, and silica fume [299–302]. These additives modify the internal pore structure and acoustic impedance of the concrete matrix, improving its ability to absorb tire-induced vibrations and air pressure fluctuations.

In addition, textured pavements, including grooved, tined, or stamped surfaces, introduce controlled surface roughness to disrupt tire tread resonance and reduce tonal noise components [303,304]. The acoustic performance of such surfaces depends on texture geometry, spacing, and depth; however, excessively coarse textures may inadvertently increase rolling noise under specific traffic or weather conditions.

2.8. Question 8: How Are Modern Noise-Control Technologies and Smart Systems Transforming Sustainable Noise Management in Cities?

2.8.1. Active Noise Control Technologies

Active noise control (ANC) mitigates unwanted sound by generating opposing sound waves that cancel noise through destructive interference. In this process, sensors such as microphones detect incoming noise, which is then processed by a controller that drives actuators (e.g., speakers or vibration generators) to emit counteracting sound waves [305–308].

ANC has proven highly effective in controlled environments such as headphones, vehicle headrests, building interiors, HVAC systems, and indoor spaces like offices [309–312]. These settings allow for precise generation of anti-noise due to their relatively stable acoustic conditions. Efforts have also been made to apply ANC in outdoor urban environments where noise sources are consistent, though with limited success [313–315]. For instance, Sohrabi *et al.* ([316]) demonstrated that active noise barriers equipped with optimally placed control sources and error microphones can enhance construction noise attenuation by up to 16.4 dB in adjacent street zones compared to passive barriers.

However, outdoor urban noise environments pose significant challenges for ANC due to their diffuse sound fields, wide frequency ranges, and multi-directional noise sources, which limit the effectiveness of destructive interference [317]. ANC performs best for low-frequency, narrow-band noise and requires dense networks of sensors and speakers, making large-scale implementations costly and complex [308]. Additionally, environmental factors such as wind and temperature fluctuations,

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along with urban structural variations and high computational demands, further degrade ANC performance. Consequently, compared with passive noise control strategies, ANC remains less practical for large-scale outdoor applications due to infrastructure and cost constraints.

Recent advancements have sought to overcome these challenges through the development of intelligent and adaptive ANC systems. For example, spatially selective ANC approaches have been introduced to isolate noise directionally [318]. Advanced filtering techniques, such as filtered-x least mean squares (FxLMS) and generative fixed-filter active noise control (GFANC)-FxNLMS, have also enhanced real-time performance [319–321]. Furthermore, the integration of deep learning and meta-learning frameworks, such as modified model-agnostic meta-learning (MAML) and Monte Carlo Gradient initialization, has improved convergence speed and efficiency in multichannel ANC systems, indicating strong potential for urban noise mitigation in the future [322–325]. As an example, Mostafavi *et al*. ([326]) developed a deep learning–based ANC controller designed to mitigate complex, nonstationary noise from heavy machinery at construction sites. Their approach, which accommodates delay effects and nonlinearities, achieved broadband attenuation improvements and demonstrated promising potential for real-time noise reduction applications.

2.8.2. Sound Masking Systems

Sound masking systems enhance acoustic environments by emitting low-level background noise, typically shaped white or pink noise, to reduce the audibility of disruptive sounds, particularly speech [327]. By raising the ambient noise floor within the 250 Hz–4 kHz range, they improve speech privacy and reduce distractions. Advanced systems may employ techniques like time-reversed speech, reverberation, pitch-marked windowing, and variable frame sizing. Increasingly, natural or water-like sounds are used for better perceptual comfort [328–331]. These systems are widely applied in open-plan offices, hospitals, and call centers, where they reduce cognitive load, improve confidentiality, and support productivity [332–334]. They are particularly useful where architectural sound insulation is limited.

More recently, sound masking has expanded to outdoor urban environments, such as plazas, transit terminals, and parks, to counteract traffic and industrial noise. Natural and pleasant sounds (e.g., birdsong, water features, music) are used to enhance acoustic comfort [335–337]. For instance, fountain sounds have been shown to reduce perceived traffic noise in parks [338], and music has mitigated aircraft noise annoyance [339]. Adaptive masking systems, like that developed by Regazzi *et al*. ([340]), use white noise and low-frequency tones to reduce noise near substations. However, studies show varied effectiveness, birdsong offers limited masking, while low-decibel water sounds may positively influence mood and physiological responses [341,342]. Urban greenery has also been found to help mask traffic noise and support psychological restoration [343]. Additional studies explore masking in construction zones [344] and public areas using speech-shaped low-frequency noise to reduce annoyance and improve acoustic satisfaction [345].

Recent pilot projects integrate flexible, AI-based sound masking with real-time monitoring, directional speakers, and context-aware signals, offering promising alternatives in settings where conventional noise barriers are impractical [346].

2.8.3. Multifunctional Noise Barriers

There is a growing trend toward the deployment of multifunctional noise barriers along major roads, highways, and transport corridors. Unlike conventional walls that serve solely acoustic purposes, modern systems are being re-envisioned as integrated infrastructures addressing multiple urban and environmental challenges. In addition to mitigating traffic noise, these barriers now contribute to renewable energy generation, air-quality improvement, ecological enhancement, and infrastructure adaptability.

A notable example is the photovoltaic noise barrier (PVNB), which merges acoustic attenuation with solar energy production [347–349]. These systems enable bifacial energy generation and can be modularly adapted to roadsides, railways, and urban environments. Recent studies have explored

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their design and performance optimization. For instance, Bouguerra *et al*. ([350]) examined zigzag-shaped PVNBs along a Belgian highway, showing that fixed-cassette configurations maximized energy yield while low-rise barriers minimized shading. Acoustic modeling revealed comparable noise reduction between cassette and shingle designs, with smaller tilt angles and higher barriers enhancing attenuation. Similarly, Zhang *et al*. ([351]) demonstrated that PVNBs in could supply up to 5% of the electricity required for electric vehicle (EV) charging stations and, under optimized conditions, meet about 30% of the energy demand across 60 EV stations, 58% of which could be consumed locally. In parallel, innovative concepts such as piezoelectric noise barriers harvest vibration-induced mechanical energy from passing traffic and environmental noise [352]. Embedded piezoelectric transducers convert mechanical stress into electrical energy, providing an additional renewable source suitable for powering roadside sensors, monitoring devices, or lighting systems.

Furthermore, recent studies emphasize hybrid barrier systems that extend functionality toward air-pollution mitigation and ecological benefits [353]. For example, Tezel-Oguz *et al*. ([354]) reported that noise barriers can reduce average near-road NO_x concentrations by approximately 23%. Vegetation-based noise barriers (VNBs) further enhance air-pollutant capture, sound absorption, and biodiversity through green façades or vertical plantings. These bio-integrated systems improve local air quality and urban aesthetics, offering both environmental and psychological benefits. Hybrid photovoltaic–vegetation barriers combine renewable energy generation with carbon sequestration and ecological services, achieving synergy between technological and environmental performance.
Collectively, these developments highlight the transformative potential of multifunctional noise barriers to address the intertwined challenges of energy, pollution, and infrastructure. These next-generation barriers exemplify a resilient and adaptive approach to sustainable urban infrastructure.

2.9. Question 9: How Can Community-Driven Initiatives, Such as Citizen Science, Contribute to Equitable and Sustainable Urban Noise Management?

Answer:

Community involvement and public awareness play a pivotal role in effective urban noise management by fostering collaboration between residents, local authorities, and policymakers. Participatory approaches that integrate community perspectives into soundscape design and decision-making processes have become essential in developing equitable, context-sensitive noise strategies. Engaging residents through participatory sound mapping, citizen science projects, and noise complaint reporting enables communities to actively identify and monitor sources such as traffic, construction, loud music, and industrial activities [355–359]. These collaborative initiatives not only generate valuable environmental data but also strengthen the inclusion of lived experiences in urban planning and policymaking.

Citizen science, defined as the active participation of non-professional individuals in scientific research, is central to such community-based efforts [360–362]. Within sustainable noise management, it empowers citizens and neighborhoods to contribute to the collection, monitoring, and interpretation of environmental noise data [363]. The widespread availability of smartphones, wearable devices, and online platforms has democratized environmental monitoring, allowing for large-scale participation across diverse regions. However, ensuring the reliability and representativeness of citizen-generated data remains a key research challenge. Variations in device accuracy, sampling density, and reporting biases can affect data quality, emphasizing the need for validation protocols and integration with calibrated sensor networks [364].

Key elements of citizen science in noise monitoring include data collection using smartphones, wearable sensors (such as smartwatches), and low-cost fixed or portable monitoring devices deployed in homes, schools, parks, and transit hubs [365,366]. Residents can also report disturbances through digital tools such as government portals, mobile apps (e.g., 311 services), or social media platforms that use hashtags and community forums to flag noise issues. A prominent example is the Sounds of New York City (SONYC) project, which merges citizen-reported complaints with a network of acoustic sensors [367,368]. This hybrid approach combines subjective community input with objective

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sensor data, yielding a more thorough and actionable basis for policymaking. Similar frameworks are now being explored beyond the U.S., particularly in Europe [369,370] and Asia, where participatory soundscape mapping and local citizen networks are increasingly informing regional urban planning practices.

Citizen-generated data are analyzed to produce dynamic noise maps, identify dominant sound sources, and assess exposure patterns [371]. Advances in artificial intelligence and deep learning have enhanced the processing of these large, heterogeneous datasets, supporting automated sound classification, anomaly detection, and evaluation of data reliability [364]. As a result, citizen science not only generates valuable datasets but also enhances the precision, inclusiveness, and scalability of noise management strategies. The participatory nature of these approaches fosters a deeper public understanding of urban soundscapes and supports evidence-based policy development.

An informed and engaged public is more likely to advocate for noise reduction measures, such as stricter zoning regulations, investments in soundproofing infrastructure, and the creation of green buffer zones to mitigate urban noise [372]. Encouraging noise-conscious behaviors, observing quiet hours, moderating personal sound levels, and adopting sound-reducing technologies, further supports healthier urban environments. Collaboration among residents, city planners, transport authorities, and law enforcement ensures that community perspectives and soundscape experiences are integrated into official noise management strategies.

Public awareness campaigns reinforce these efforts by educating residents on practical ways to reduce noise emissions and promoting participatory soundscape assessment as a means of collective learning and empowerment. By connecting technological interventions with behavioral change, community involvement cultivates a sense of shared responsibility and strengthens the long-term sustainability and responsiveness of urban noise management, ultimately contributing to more livable and acoustically balanced cities.

2.10. Question 10: What Are the Key Challenges and Future Directions for Sustainable Urban Noise Management?

Answer:

2.10.1. Challenges

Urban noise assessment faces persistent challenges due to the high spatial and temporal variability of soundscapes across diverse urban typologies [373]. Noise levels fluctuate significantly by location and time, and perception varies by individual sensitivity, health, and socio-cultural background. This variability complicates standardized measurement and holistic assessment [374,375].

Data quality, accessibility, and privacy are major concerns. Low-cost sensors, while enabling broader spatial coverage, often suffer from calibration inconsistencies and environmental interference. Additionally, many noise monitoring systems rely on mobile or participatory methods that may collect location-linked or personally identifiable data, raising privacy concerns that limit public participation and data sharing. Monitoring efforts are further fragmented across agencies, restricting data interoperability and hindering longitudinal analysis. Uneven spatial distribution of noise pollution also leads to underrepresentation of critical hotspots.

To address these gaps, integrated monitoring approaches, combining fixed, mobile, and community-based methods, are essential. Strategic sensor placement and transparent data governance frameworks can improve spatial resolution, public trust, and engagement. However, the lack of standardized protocols undermines comparability across studies. Establishing consistent measurement practices and leveraging advances in AI and sensor technology can enhance precision, reliability, and privacy protections.

Moreover, current European approaches to noise exposure assessment often overlook individual mobility, the temporal dynamics of sound, and socio-economic disparities among exposed populations. Agent-based transport models offer promising opportunities to integrate spatial, temporal, and social dimensions into exposure estimation, though their alignment with environmental frameworks

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remains a challenge [376]. A comprehensive methodology should therefore incorporate space, time, individual behavior, and activity patterns to better capture real-world exposure processes and identify key limitations such as simplified acoustic dynamics, limited temporal resolution, and insufficient individual-level representation, as demonstrated in studies of the Lyon Metropolitan Area.

Despite increasing awareness of noise-related health risks, integration into urban planning remains limited. Economic and infrastructural priorities often overshadow noise mitigation, and collaboration between planners and acousticians is insufficient. Incorporating noise data into planning and aligning assessments with regulatory frameworks are critical for effective mitigation.

One of the operational challenges in continuous monitoring is maintaining an uninterrupted power supply to sensor networks. This is particularly problematic in remote or infrastructure-limited environments. A viable solution involves the use of energy harvesting technologies, such as solar or kinetic energy systems, which can enable autonomous and long-term sensor deployment with minimal maintenance requirements [377].

2.10.2. Future Trends

Urban noise pollution is increasingly managed through integrated, technology-driven approaches. Multisensory data fusion, which combines noise with environmental variables like air quality and temperature, is enhancing our understanding of urban dynamics. For instance, Govea *et al*. ([378]) developed a model that integrates IoT-based sensors and predictive analytics to generate real-time heat maps of PM2.5 and noise levels. This approach revealed strong spatial correlations between noise, air pollution, and proximity to industrial areas and traffic routes, informing targeted mitigation strategies.

The integration of acoustic monitoring into smart city frameworks offers another transformative direction. IoT-enabled sensors embedded in infrastructure can continuously monitor noise and trigger adaptive responses. Smart traffic systems may adjust flow patterns to reduce noise, while centralized platforms coordinate efforts across sectors, from zoning regulations to public alerts [379]. Cities like Singapore are already combining noise data with construction and traffic schedules to enable real-time mitigation, such as rerouting traffic or rescheduling noisy activities.

Urban design trends further support noise reduction. Biophilic and regenerative design principles, through green spaces, vertical gardens, and water features, not only absorb sound but also enhance ecological health and resident well-being [380]. The rise of electric vehicles (EVs) also promises quieter streets, though new challenges like pedestrian safety via synthetic alert sounds must be addressed.

Policy innovation is also evolving. Cities are testing quiet zones, time-based noise restrictions, and automated enforcement backed by real-time monitoring. Community engagement is rising through tools like participatory noise mapping apps, empowering residents to report and address local noise issues.

Promoting acoustic equity, ensuring all residents benefit equally from noise reduction regardless of socioeconomic status or location, is essential to modern urban planning. Research shows that low-income and marginalized communities disproportionately bear the burden of noise exposure due to proximity to highways and industrial zones [381–384]. These disparities are linked to serious health impacts, including cardiovascular issues and sleep disturbances. Conversely, underexposure to environmental sound, more common in affluent, quiet suburbs, may affect children's auditory development and social adaptation, highlighting a spectrum of acoustic access and risk.

Looking ahead, secure, decentralized AI systems will play a central role in urban noise governance. Blockchain technologies are emerging to ensure data integrity, personal privacy, and secure data sharing across city systems [385–387]. By enabling tamper-proof, transparent records of noise and environmental data, blockchain supports more trustworthy and resilient urban platforms. These advances underpin cybersecure AI, protecting both individual privacy and the operational integrity of smart city noise management systems.

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3. Conclusion

This review has systematically addressed ten interrelated questions to articulate a comprehensive framework for sustainable urban noise management. From foundational assessments of conventional monitoring technologies to the integration of advanced sensor networks and predictive analytics, the analysis underscores the transition toward proactive, data-informed strategies. Urban and transportation planning emerges as a primary lever, where traffic-demand management, low-emission zones, and modal shifts yield substantial noise reductions alongside mobility and air-quality gains. Green infrastructure and acoustically informed architectural design provide complementary, nature-based, and built-environment solutions that enhance resilience without compromising density or functionality. Material innovations and hybrid active–passive control systems further refine intervention precision, while community-engaged governance, through citizen science, co-design workshops, and digital participation platforms, ensures that solutions remain socially robust and adaptable to local contexts.

The synthesis reveals that effective noise mitigation is inherently interdisciplinary and multiscalar, requiring alignment across policy, design, technology, and civic spheres. Although significant technical and institutional barriers persist, notably retrofit costs, regulatory fragmentation, and uneven digital access, the convergence of maturing technologies and growing public awareness presents a viable pathway forward. Priority areas for future investigation include longitudinal evaluation of combined interventions, development of harmonized acoustic-performance indicators, and exploration of financing mechanisms such as noise-impact bonds or value-capture models. Standardizing evaluation protocols and expanding open-access soundscape repositories will further accelerate knowledge transfer across cities.

In conclusion, sustainable noise management transcends conventional abatement; it constitutes a strategic dimension of urban sustainability. By embedding acoustic criteria within planning and design processes, cities can mitigate health risks, reinforce ecological integrity, and cultivate environments conducive to cognitive restoration and social interaction. The discussion advanced here offers a actionable roadmap for researchers, practitioners, and policymakers committed to translating noise challenges into opportunities for more equitable and livable urban futures.

Author Contributions: S.K.: Writing—original draft preparation, writing—review and editing; K.S.: Writing—review and editing, supervision; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data supporting the results are available from the corresponding author on request.

Acknowledgments: During the preparation of this manuscript, the authors utilized ChatGPT (OpenAI, July 2025 version) to assist in the generation of graphics (Figure 1). All AI-generated content was carefully reviewed, revised, and validated by the authors, who assume full responsibility for the accuracy and integrity of the final published material. The author sincerely thanks H. P. Lee, Department of Mechanical Engineering, National University of Singapore, for providing access to relevant standards and for his valuable technical insights, which significantly contributed to the development of this work. The author also gratefully acknowledges the unwavering support and inspiration of his daughter, Srijanya Sah, throughout the preparation of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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