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Review
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GENERAL REVIEW OF SMARTPHONE USABILITY IN NOISE MAPPING

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Abstract: The global urban population is steadily increasing, with more than half of the world's population currently residing in cities, and this trend is expected to double by 2050. As urbanization continues, noise pollution becomes a significant concern, affecting over 60% of major city dwellers and impacting human health on both physiological and psychological levels. To address this issue, governments and organizations are striving to develop effective noise assessment, regulation, and mitigation policies. This literature review explores the role of noise mapping and the potential of smartphones in collecting noise data to inform these policies. Traditional noise mapping techniques and smartphone-based data collection methods are discussed, along with their importance in urban planning, environmental studies, and public health. Key research questions are identified, including the methodologies employed for smartphone-based noise mapping, the accuracy of smartphone-collected data compared to traditional measurements, practical applications, challenges, and emerging trends. The review reveals that smartphones offer a cost-effective and widespread means of gathering noise data, enabling real-time insights and enhancing various domains' practical applications. However, challenges such as data accuracy, privacy concerns, and device limitations must be addressed. The future of smartphone-based noise mapping looks promising, with advancements in sensor technologies, artificial intelligence, and data analysis tools empowering researchers, urban planners, and policymakers to make informed decisions about noise pollution in urban environments.

Keywords: Noise, Noise measurement, Smartphone, Noise mapping

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1. Introduction

As stated by World Bank (2023), today, 56% of the world's population, or 4.4 billion people, live in cities, a trend that's expected to double by 2050, with nearly 7 in 10 residing in urban areas. In their report Luzzi and Vassiliev (2005) concludes that noise pollution is on the rise, affecting over 60% of major city dwellers, impacting around half of the global population. With a singular sound being the source of a noise measured with decibel (dB), it is designated as "Noise" when it reaches beyond the limits of human threshold up to a level it could identified as noise pollution or environmental problem in respect to the effect of human health both physiological and psychological aspects. Governments, national and supranational organizations who strive to reduce noise, tried to determine how noise is assessed, regulated, and mitigated as an environmental policy issue Murphy et al. (2020).Thus, Noise data collection and mapping techniques plays a major role in order to effectively draft and implement those policies.

Noise mapping using smartphones has evolved significantly over the years, initially relying on the use of normal geotagged microphones but calibrated to internationally recognized standards such as Class 2 of IEC standards to collect noise data. Early studies, such as those by demonstrated the feasibility of utilizing smartphones equipped with microphones to gather noise data and create noise maps. And forward came the research of accuracy standardization of standard microphones for noise mapping such the study conducted by Bostanci (2018) and Celestina et al. (2018) the environmental scenarios like soundscape, and the method of collecting highly stable reliable data that could potentially affect the equipment while collecting noise data as conducted by Murphy and King (2014a). These pioneering works laid the foundation for subsequent research exploring the potential of smartphones for noise mapping purposes.

As technology advanced, so did the methodologies for noise mapping using smartphones. Researchers began integrating additional sensors and improving algorithms to enhance the accuracy and reliability of noise measurements. For instance, the study by Socoró et al. (2015) introduced a method that combined smartphone data with machine learning techniques to improve noise mapping accuracy. Similarly, advancements in signal processing algorithms, such as those described by Socoró et al. (2015), have further refined the process of extracting noise data from smartphone recordings.

Today, the trend in noise mapping using smartphones continues to evolve with the emergence of crowd-sourced data collection platforms and the integration of cutting-edge sensor technologies. Studies like the works of Picaut et al., (2019) and Lee et al. (2020) highlight the potential of leveraging crowdsourcing and participatory sensing to gather large-scale noise data sets for more comprehensive mapping efforts. Furthermore, the integration of advanced sensors such as MEMS microphones and accelerometers, as explored in the research by Zamora et al. (2017) promises to further enhance the capabilities of smartphones for noise mapping applications. Overall, the trajectory of research in this field underscores the ongoing efforts to harness the ubiquity and sensing capabilities of smartphones for effective noise mapping.

Different methodologies are used for the preparation of a noise map: Noise levels can be determined by on-site measurements at predetermined points Tsai et al. (2009) Noise maps can be generated from the results obtained with noise prediction models (Aletta and Kang, 2015; Ventura et al., 2017; Zhou et al., 2017); Hybrid models can also be used in a mixed system, i.e., to complement and validate measurements obtained mainly through prediction programs; (Cai et al., 2015; Maisonneuve et al., 2010). Recently, advances have been made in generating noise maps using sound sensors of smartphones (Dubey et al., 2020; Lee et al., 2020; Picaut et al., 2019).

While multiple recent studies have explored the potential of using smartphones for noise mapping and measurement. The NoiseSPY project, conducted by Kanjo (2010), developed a mobile phone application that could measure environmental noise levels and map noise pollution in urban areas using crowdsourced data from citizens carrying smartphones with the installed application. Over a two-week trial with eight participants in Cambridge, UK, the Noise-SPY system collected 72,626 noise data entries from approximately 50,000 different locations, demonstrating the feasibility of using crowdsourced mobile phone sensors for environmental noise monitoring and mapping in urban areas.

This literature review focuses on traditional noise mapping and smartphone-based data collection methods and probable gaps existing smartphone applications to improve further.

1.1. Literature Questions and Objectives

This literature review addresses several key research questions and objectives:

- How have smartphones been utilized in noise mapping, and what methodologies and technologies are commonly employed for this purpose?
- What is the accuracy and reliability of noise data collected through smartphones compared to traditional noise measurement equipment?
- What are the practical applications of smartphone-based noise mapping in different domains, and what case studies demonstrate their effectiveness?
- What challenges and limitations are associated with smartphone-based noise mapping, and what are the potential solutions or areas for improvement?
- What emerging trends and technologies are shaping the future of noise mapping using smartphones?

In their study, Murphy and King (2016c) the current state of smartphone-based noise mapping, including its methodology and perspectives. They concluded that smartphone-based noise mapping is a rapidly developing field with the potential to revolutionize the way we measure and manage noise pollution. Picaut et al. (2019) investigated the use of smartphone-based participatory sensing and crowdsourcing for environmental noise monitoring. They concluded that these approaches are emerging as cost-effective methods for environmental noise supervision.

Andrachuk et al. (2019) discussed the innovation of citizen science in open science, society, and environment. They highlighted the role of smartphone technologies in community-based environmental monitoring. They also found that this approach has broadened the scope of noise mapping, making it more participatory and data rich.

Berglund et al. (2000) developed guidelines for community noise. They summarized the studies on noise mapping in countries like China, Brazil, and Ecuador, finding that traffic noise prediction models such as RLS-90 and NMPB were primarily utilized. The most common mapping programs employed was Sound PLAN and ArcGIS, with a standard grid size of 10 × 10 m.

Bocher et al. (2017) proposed collaborative noise measurement via smartphones as a more accessible and participatory way of assessing noise levels. They recognized the health impacts of noise pollution and emphasized the need for alternative methods to classical noise assessment approaches.

Brambilla and Pedrielli (2020) reviewed the use of smartphone-based noise and soundscape mapping in urban planning. They discussed the growing traction of the soundscape concept, which treats sound as a resource rather than waste.

2. Review

Geographic Information Systems (GIS) are information systems designed for collecting, storing, processing, and presenting both graphical and non-graphical information derived from location-based data, offering a comprehensive view to users Yomralıoğlu (2000).

Various analyses can be made using noise data measured by sound sensors in mobile phones and stored in GIS. Thanks to these analyses, it is possible to make location-based decisions, query noise data, and display this data on maps Uygunol (2009). Noise mapping involves determining the disturbance experienced by a population in a region due to noise and modeling the environmental noise exposure over a specific time period. Developed countries such as Germany, France, the Netherlands, the United Kingdom, and Sweden are among those where significant studies on noise mapping have been conducted.

Aletta and Kang (2015), argued for a comprehensive approach to managing urban sound environments, as suggested by the European Environment Agency (EEA) guidelines. Noise Mapping emphasizes the integration of traditional noise mapping with soundscape methods in urban redevelopment projects. It offers insight into the spatial and temporal variations of noise in urban and suburban areas, helping policymakers, urban planners, and researchers make informed decisions. Noise maps facilitate the identification of noise hotspots, the assessment of noise exposure, de Kluijver and Stoter (2003) and the development of effective noise abatement strategies.

Noise maps are needed to investigate current noise level distributions, examine noise level regulations and identify noise sources (Tsai et al., 2009). According to de Kluijver and Stoter (2003), the following steps are followed in noise mapping:

- collecting raw data, preparing, storing and querying this data;
- calculation of noise levels in computer models;
- cumulative noise levels (when there are different sources);
- identification of noise contours;
- determination of noise impacts;
- presentation of the impact of noise.

Studies on noise maps have been carried out in European countries for many years. For example, studies on this subject have been carried out in Germany for more than 25 years. With the 2002/49/EC Declaration on Assessment and Management of Environmental Noise, the European Union made noise mapping studies mandatory for some regions in cities with a population of more than 100,000 for member states until 2008. (Tsai ve ark. 2009; Bostancı, 2018).

Noise measurement devices are used to measure with higher accuracy and precision under laboratory and field conditions. According to the standards or regulations of many countries, the instrument must meet at least Type I (Figure 1) requirements for the measurement to have official validity (Guidelines for Environmental Noise Measurement and Assessment, 2010).

In addition, noise measurements are carried out using measurement instruments of various types and sensitivities, including cell phones (Bostancı, 2018). In recent years, the proliferation of smartphones with built-in microphones, GPS, and various sensors has sparked interest in their potential as data collection devices for noise mapping. This development offers an opportunity for cost-effective, widespread noise data collection, enabling more extensive and detailed noise maps Cho et al. (2007). Smartphones, carried by individuals as they move through their daily routines, can capture data that reflects the real experiences of residents and commuters Maisonneuve et al. (2010).

Figure 1. Type 1 noise measurement device.

2.1. Noise Mapping using Smartphones.

Regarding the methodology for noise measurement and mapping with smartphone applications, the NoiseSPY project by Kanjo (2010) provides a practical example. The NoiseSPY application, developed for Nokia Symbian smartphones, used the phone's microphone as a noise sensor and the GPS for location tracking. The application measured sound levels in decibels (dB) use the phone's microphone, applying A-weighting filtering to account for human hearing perception. The sound level data was combined with GPS coordinates and uploaded to a server over GPRS/cellular network in real-time or at specified intervals. The server processed the data, combining noise measurements from multiple users, and provided visualizations through a web interface, including noise maps overlaid on geographic maps.

Kardous and Shaw (2016) conducted a study to evaluate the accuracy of selected smartphone sound measurement applications (apps) when using external calibrated microphones. They tested four iOS apps (SoundMeter, SPLnFFT, SPL Pro, and NoiSee) with two different external microphones (Dayton Audio iMM-6 and MicW i436).

Can et al. (2023) conducted a study to ascertain whether noise measurement could be an effective way to assess sound environments and encourage people's involvement in sound environment issues. The article evaluates a collaborative approach between researchers and local authorities in the city of Rezé (France) on the use of the smartphone application NoiseCapture, which enables a resident-based urban noise diagnosis and participatory measurement of sound levels. They proposed a method that could be used as an alternative to regulatory noise maps. The researchers used smartphone apps to measure sound levels. Any user could measure sound levels through their smartphone and send the data to a server for evaluation. This approach not only allowed data to be collected from various locations but also involved residents in the data collection process. The utilization of smartphones for noise mapping has given rise to various methodologies.

2.1.1. Crowdsourced data collection

Harnessing the ubiquity of smartphones, crowdsourced data collection involves citizens contributing noise data through dedicated apps. This approach leverages large-scale, real-time data collection. For example, as per the studies of multiple researchers like Picaut et al. (2019), and Dubey et al. (2020) it is now possible to collect and map noise data using social media (Figure 2).

2.1.2. Dedicated noise mapping applications

Numerous apps specifically designed for noise mapping enable users to record noise levels, often incorporating GPS and timestamp data. These apps streamline the data collection process.

2.1.3. Smartphone sensors

Certain research such as Zamora et al. (2017)employs smartphone sensors such as microphones, accelerometers, and GPS for noise measurement and mapping. This method provides adaptability by making the most of the device's innate features. Data collection involves complex and multifaceted legal situations between different governments or service providers. Concerns are being raised about the establishment of the legal framework governing how end users can participate in passive data collection or provide informed consent.

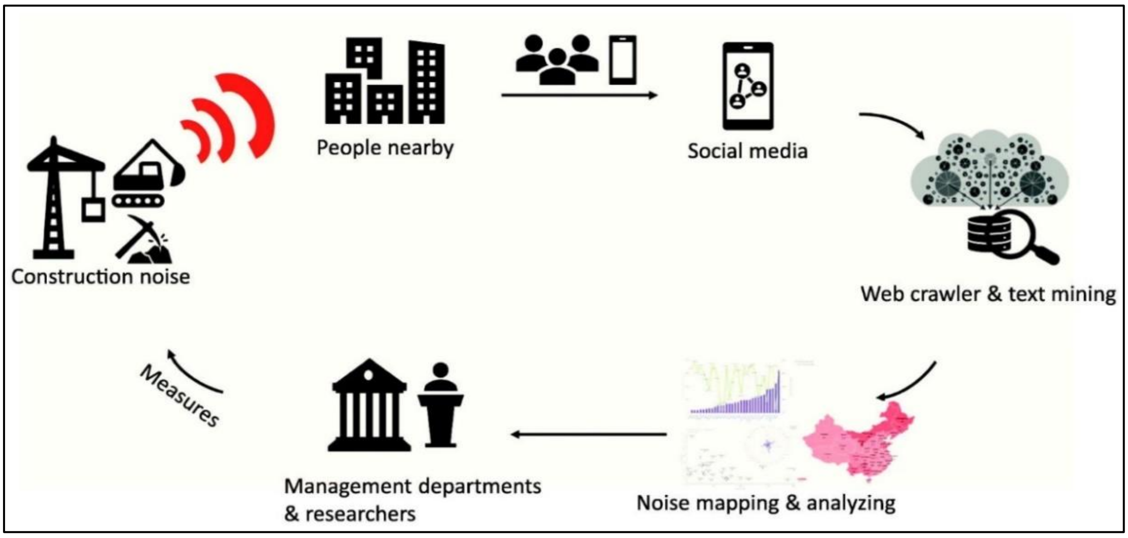

Figure 2. Noise Crowd sourcing from social media using Smart phones (Zhou et al., 2017).

2.2. Smartphones as Data Collection Devices

Smartphones, with their global presence, offer unique capabilities for data collection.

2.2.1. Built-in microphones

Smartphones are equipped with built-in microphones that can capture ambient noise levels. This feature facilitates convenient data collection without the need for additional equipment.

2.2.2. GPS and sensors

The integration of GPS and various sensors, such as accelerometers, provides valuable metadata, including geolocation and timestamp information. This contextual data enhances the precision of noise mapping.

2.2.3. Real-world data

Smartphones accompany individuals in their daily activities, making them ideal for capturing real-world noise experiences. This user-centric approach provides data that reflects actual living conditions.

2.3. Applications and Use Cases

Smartphones' potential for noise mapping is evident in various practical applications:

2.3.1. Urban planning

Noise mapping informs urban planners on land use, zoning, and transportation infrastructure, helping design cities that prioritize residents' well-being as such study conducted by Bangtao et al. (2019); Zhao et. Al., (2019).

2.3.2. Environmental studies

Murphy et al. (2020), in noise mapping assesses noise pollution's impact on ecosystems, aiding in public health and in ecological research is made to assess available state-of-th-Art for conservation efforts and biodiversity preservation.

2.3.3. Public health

Public health experts employ noise maps to assess noise exposure and its impact on public health, helping shape interventions aimed at protecting community well-being. For instance, in 2011, noise maps created under the EU Environmental Noise Directive (END), as per a study by the World Health Organization (WHO), revealed that in Europe, one out of every three people is bothered by daytime noise, and one out of every five experiences sleep disruption solely due to traffic noise Murphy and King (2014b).

2.4. Data Accuracy and Quality

The accuracy and reliability of noise data collected through smartphones are essential considerations throughout all the literatures reviewed so far:

Quality Factors: Various factors, including smartphone specifications, parameters and mathematical models of applications used to clean, categorize noise data, environmental conditions, and data processing techniques were the key influencers of data quality through calibration procedures. These factors must be carefully managed to ensure accurate results in mass data collection. For example, Lee et al. (2020) developed an app for both Android and iOS and ask 29 graduate students to collect noise recordings and data in the streets.

Whether measuring noise levels with smartphones is sufficient has not yet been fully demonstrated, but it is an interesting avenue that has been researched in recent years due to its potential to contribute to this field. Figure 3 shows how smartphones can contribute to urban noise monitoring and noise mapping measurement processes in article of Padilla-Ortiz et.al. (2023).

Kardous and Shaw (2016) conducted a study to evaluate the accuracy of selected smartphone sound measurement applications (apps) when using external calibrated microphones. They tested four iOS apps (SoundMeter, SPLnFFT, SPL Pro, and NoiSee) with two different external microphones (Dayton Audio iMM-6 and MicW i436). The researchers generated pink noise from 65 to 95 dB SPL in a reverberant chamber and compared the app measurements to a reference sound level measurement system. Their study found no evidence of differences between the four apps when using either external microphone, or the measurements from the apps did not differ significantly from the reference system. The researchers concluded that using external calibrated microphones significantly enhances the accuracy and precision of smartphone-based noise measurements compared to using the built-in microphones.

Ventura et al. (2017) conducted a flow up study by using the Ambiciti app to determine the quality of noise measurements obtained from various Android phones. To evaluate the accuracy of the smartphones, pink and narrowband noises were used at levels ranging from background noise to 90 dB(A) in the laboratory. This data was used to improve the calibration model of the cell phones. As a result, the standard deviation of the noise measurements for 12 of the 15 phones calibrated in the laboratory was below 1.2 decibels over a wide range of noise levels [45 to 75 dB(A)]. This deviation is very good for noise measurements using cell phones.

Comparison to Traditional Devices: Zamora et al. (2017) assessed smartphone-derived noise data against measurements from traditional noise measurement devices as a benchmark was crucial over the literatures reviewed. Understanding the degree of accuracy and potential discrepancies is fundamental to assessing the reliability of smartphone-based data.

Alvares-Sanches et al. (2021) conducted a study aimed at developing an improved approach for mapping urban noise pollution from all sources and at fine spatial resolution across entire cities. They argue that conventional noise mapping methods based on traffic flow data and propagation algorithms may not accurately reflect true noise exposure levels because they fail to consider noise from non-traffic sources and may leave spatial gaps. Their method involved conducting mobile surveys by walking 733 km of routes throughout the city of Southampton, UK, while continuously recording audio clips. Machine learning models were then built to predict mean sound levels in 30m pixels across the city as a function of urban form characteristics and modeled traffic data. The results showed that the spatial patterns of predicted noise levels differed across frequency bands, highlighting the importance of considering the full frequency spectrum relevant for health impacts. The authors concluded that mobile surveys combined with machine learning offer an alternative way to comprehensively map noise exposure from all sources at high spatial resolution, potentially providing a more accurate representation of true exposures compared to conventional strategic noise mapping approaches.

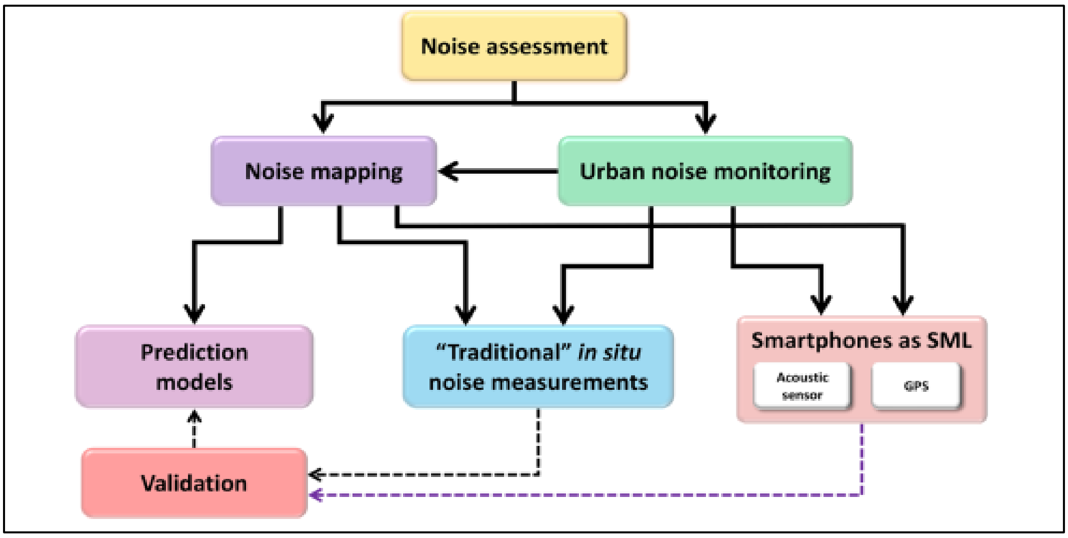

Figure 3. Schematic of smartphone use for noise assessment: Creating noise maps and monitoring urban noise (Padilla-Ortiz et al., 2023).

2.5. Challenges and Limitations

Despite the promise of smartphone-based noise mapping, several challenges and limitations must be acknowledged:

Data Privacy: Issues regarding the privacy of individuals who contribute data via smartphones need to be addressed. Safeguarding privacy while collecting valuable data is a delicate balance.

Battery Life: Continuous data collection can strain smartphone battery life. Managing power consumption is critical to ensure the feasibility of long-term noise mapping.

Crowdsourced Data Representativeness: Assessing the representativeness of crowdsourced data is vital. Variability in user behaviors and device types can impact data accuracy.

Gap of Data Processing and method of Noise Measurement procedures: Most of the literatures reviewed had focused on standardizing smartphone based noised measurement hardware and noise filtering specifications in respect with environmental conditions to be assessed.

2.6. Future Trends and Technologies

The field of smartphone-based noise mapping is poised for innovation and growth, with several emerging trends and technologies:

2.6.1. Advancements in smartphone sensors

Ongoing improvements in smartphone sensor technologies, including microphones and accelerometers, will enhance data collection accuracy and expand the scope of noise mapping applications.

2.6.2. Artificial intelligence (AI)

AI-powered algorithms can impower noise filtering before filed as formal data and can support to analyze vast datasets collected by smartphones, offering real-time insights into noise levels, trends, and potential interventions.

2.6.3. Community-sourced data collection

Smartphones make large-scale data collection possible. By utilizing people using smartphones, researchers can collect noise data from geographical locations and comprehensive noise mapping can be performed.

2.6.4. Data analysis and visualization tools

Advanced data analysis and visualization tools will make noise mapping more accessible and actionable for researchers, urban planners, and policymakers.

3. Conclusion

In this general review, we have explored the evolving landscape of noise mapping using smartphones, uncovering its potential to address the pressing challenges of noise pollution in urban environments. The utilization of smartphones as data collection devices for noise mapping offers a cost-effective and widespread means of gathering data, leading to real-time insights and enhanced practical applications in urban planning, environmental studies, and public health.

While smartphone-based noise mapping holds promise, it is not without challenges. Data accuracy, privacy concerns, and device limitations necessitate careful consideration. Nevertheless, these limitations are increasingly being addressed through technological advancements and innovative methodologies.

Looking ahead, the future of smartphone-based noise mapping is bright. Advancements in sensor technologies, but with further need to apply artificial intelligence, and improved data analysis tools will empower researchers, urban planners, and policymakers to make more informed decisions regarding noise pollution. With ongoing developments, smartphone-based noise mapping stands as a valuable tool in the pursuit of quieter, healthier, and more sustainable urban environments.

Author Contributions

The percentage of the author(s) contributions is presented below. All authors reviewed and approved the final version of the manuscript.

	F.M.O.	B.B.
C	20	80
D	70	30
S	50	50
DCP	80	20
L	70	30
W	50	50
CR	20	20
SR	20	80

C= concept, D= design, S= supervision, DCP= data collection and/or processing, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declare that there is no conflict of interest.

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