Integrating Smart City Technologies for Air Pollution Monitoring and Management in Calabar Metropolis

[1] Dr. Oruk Ohon Egbai; [2] Dr. Oham Sunday Bassey;
[3] Akim Ogar Okang; [4] Dr. Prince-Charles O Itu;
[5] Udousoro Idorenyin; [6] James Effiong Edide;
[7] Dr. Chinasa Uttah; [8] Dr. Uquetan, Uquetan Ibor;
[9] Ajom Simon. Kanong-Osowo;
[10] Edwin Onuaha; [11] Osibu, Daniel O.
Corresponding Author: **Osibu, Daniel O.**
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Abstract:

This study on the integration of smart city technologies in the monitoring and management of air pollution in Calabar metropolis was framed to address the infrastructural, financial, and technical requirements for real-time air pollution monitoring and assessing its influence on urban governance and environmental sustainability. A mixed-methods research approach was employed, integrating both qualitative and quantitative techniques. Data were collected through structured questionnaires administered to 300 respondents, with findings analyzed using multiple regression analysis. The result showed that key infrastructural requirements for effective air quality monitoring involved IoT-enabled sensors (21.7%), high-speed internet connectivity (15.7%), smart data platforms (18.3%), and a reliable power supply (24.3%). Financial barriers such as high initial investment costs (23.0%) and operational expenses (25.0%) were identified as significant challenges. In terms of impact, real-time data provision for traffic and zoning regulations (23.7%) and guiding green infrastructure planning (21.0%) were notable contributions. The statistical analysis revealed a strong positive correlation ($R = 0.812$, $R^2 = 0.659$), with urban planning ($\beta = 0.447$, $p = 0.000$), environmental policy enforcement ($\beta = 0.362$, $p = 0.000$*), and public health management ($\beta = 0.527$, $p = 0.000$*) that significantly influenced air quality outcomes. Based on these findings, it is recommended that government agencies and policymakers invest in smart monitoring infrastructure, secure sustainable funding sources, and strategically place sensors in pollution-prone areas. By integrating smart technologies, cities can improve air quality management, mitigate environmental hazards, and enhance public health outcomes.*

Key words: *Air Pollution, Environmental Policy, Public Health, Smart City Technologies, Urban Planning.*

Introduction

Smart city technologies have emerged as transformative solutions for enhancing urban sustainability, efficiency, and quality of life. These technologies rely on interconnected IoT devices, big data analytics, and AI-driven systems to manage critical urban resources such as energy, transportation, waste, and air quality (Myeong & Shahzad, 2021). By enabling real-time monitoring and data-driven decision-making, smart city solutions address key urban challenges like traffic congestion, energy consumption, and environmental degradation. Moreover, digital platforms promote citizen engagement, allowing residents to contribute to governance through participatory mobile applications and interactive services (Kaginalkar, Kumar, Gargava, & Niyogi, 2023). The overarching goal of smart city initiatives is to create more resilient, livable, and sustainable urban environments that align with the needs of modern societies.

Across the world, smart technologies are increasingly being deployed to tackle urban air pollution, a critical environmental and public health concern. Advanced solutions, including IoT-enabled air quality sensors, AI-powered analytics, and big data systems, provide real-time insights into pollution levels, helping authorities take swift action (Zhang, 2023). In London, for example, smart lampposts equipped with air quality sensors monitor pollutants such as nitrogen dioxide (NO_2) and particulate matter (PM2.5), allowing policymakers to implement immediate interventions (Chen, Tam, Zhao, Yuan, Wang, Lin, & Chiang, 2023). Similarly, in Beijing, the integration of AI-driven monitoring systems and drone-based air surveillance has significantly improved urban air quality management (Liu, Xu, Fan, Li, Shao, & Zheng, 2021). These examples highlight the transformative role of technology in environmental governance and public health protection.

Developed countries have taken the lead in adopting smart air quality monitoring systems, incorporating them into broader sustainability initiatives. In Singapore, an extensive network of IoT sensors continuously tracks air pollution levels, enabling authorities to forecast trends and mitigate emissions from vehicular traffic and industrial activities (Brauer, Davaakhuu, Nuñez, Hadley, Kass, Miller, & Armstrong-Walenczak, 2021). The European Union's Green Deal has further promoted smart air quality monitoring, with cities like Amsterdam deploying mobile air monitoring stations to ensure compliance with stringent environmental regulations (Myeong & Shahzad, 2021). These initiatives demonstrate both the technical feasibility and effectiveness of integrating data-driven air quality management into urban planning, fostering healthier and more sustainable cities.

In developing nations, the adoption of smart air quality monitoring systems is expanding, although challenges such as limited funding and infrastructural deficits persist. In Nairobi, for instance, pilot projects utilizing IoT-based air quality sensors have been implemented in partnership with international organizations to track pollution from traffic and industry (Akomolafe, Olorunsogo, Anyanwu, Osasona, Ogugua, & Daraojimba, 2024). Similarly, in Nigeria, major urban centers like Lagos are exploring the integration of smart technologies to address increasing air pollution concerns (Kaginalkar, Kumar, Gargava, Kharkar, & Niyogi, 2022). Government agencies such as NESREA have initiated small-scale monitoring projects, though large-scale adoption remains limited. These efforts indicate a growing recognition of technology's potential in environmental policy enforcement and public health management across the developing world.

As a relatively less industrialized city, Calabar has a unique opportunity to proactively implement smart air quality monitoring systems before pollution levels become unmanageable. Strategic deployment of air quality sensors in high-traffic areas such as Marian Market, Watt Market, MCC Road, and Murtala Mohammed Highway would provide real-time data on pollution levels, enabling authorities to optimize traffic flow, regulate waste disposal, and enforce environmental policies (Ekah, Akwagiobe, Uda, Ekah, Akpan, & Christopher, 2023). By taking inspiration from cities like Cape Town, which has successfully integrated digital monitoring systems into urban planning, Calabar could set a precedent for other Nigerian cities (Kaginalkar, Kumar, Gargava, & Niyogi, 2023). Combining technological innovation with proactive environmental management, Calabar can enhance urban sustainability and improve public health outcomes.

Problematic

Integrating smart city technologies for air pollution monitoring in Calabar Metropolis faces several challenges, beginning with the city's infrastructure limitations. While the concept of smart cities thrives in more developed urban centers, Calabar's current infrastructure may not fully support the installation and operation of advanced technologies like IoT sensors or a reliable data transmission network. This lack of a technological foundation makes it difficult to deploy a city-wide monitoring system, particularly when it comes to ensuring that air quality data is collected consistently from all parts of the city, including high-traffic areas like Marian Market and Murtala Mohammed Highway. Moreover, the high cost of acquiring and maintaining these technologies could place a significant strain on the city's budget, which may already be stretched thin by competing priorities.

Additionally, the successful implementation of these technologies requires overcoming issues related to data privacy, security, and technical expertise. The collection of real-time environmental data raises concerns about how personal information will be protected, especially given the risks of cyber-attacks. Ensuring the security of this data is vital for maintaining public trust. Furthermore, Calabar may face challenges in finding and retaining the skilled personnel needed to maintain the systems and analyze the collected data. A shortage of trained professionals in these emerging technologies could delay or complicate the establishment of an effective air quality monitoring system. Without proper technical know-how, the systems could fall into disrepair, diminishing their effectiveness.

Calabar faces hurdles related to public awareness, governance, and sustainability. Many residents may be unfamiliar with or even suspicious of smart city technologies, leading to potential resistance to their implementation. Educating the public about the benefits of air pollution monitoring will be key to gaining acceptance. Furthermore, the city will need strong coordination between government agencies, private enterprises, and environmental organizations to ensure that these technologies are effectively integrated into urban management policies. Without proper governance structures and clear regulatory frameworks, efforts could become fragmented. The ongoing maintenance of smart technologies also poses a challenge, as power outages and environmental factors like humidity could disrupt the system’s operations. Ensuring the sustainability of these technologies through consistent funding and proactive maintenance plans will be crucial for their long-term success.

3.1 Study Area

Calabar Metropolis is the capital of Cross River State, Nigeria, and host both Calabar Municipality and Calabar South Local Government Areas. It lies between longitude 8^0 17^1E of the Greenwich Meridian and $8^0 20^1$E and latitude 4^0 50^1N and 5^0 10^1N of the equator. And is situated in a coastal area characterized by its proximity to the Atlantic Ocean and the convergence of several rivers such Calabar River to the west, the Great Kwa River to the east, with the Cross River Estuaryn and the Atlantic Ocean to the south. The topography is generally flat with some gently undulating areas towards the coast. The area has tropical mosoon climate with a long wet season (about 7-9 months) and short dry season; with average annual temperatures ranging between 26-27^0C and monthly average temperature typically ranging from 25^0C in the cooler months (July-August) to about 28^0C in warmer months (February-March).

Materials and method

This study adopts a mixed-methods research design, integrating both quantitative and qualitative approaches to assess the impact of smart air quality monitoring systems on urban planning, environmental policy enforcement, and public health management. Primary data was collected through structured questionnaires and key informant interviews with urban planners, environmental regulators, and public health officials. Additionally, secondary data was sourced from existing air quality reports, smart city policy documents, and relevant academic literature. The study employed geospatial analysis and IoT-based air monitoring systems to track pollution levels in selected urban areas. Data analysis involved descriptive statistics for survey responses and thematic analysis for qualitative insights, ensuring a comprehensive understanding of the role of smart technologies in air quality management.

Results

Table 1: Critical Infrastructural Requirement for Implementing Real-Time Air Pollution Monitoring

Critical Infrastructural	Frequency	Percentage (%)
IoT-enabled air quality sensors	65	21.7
High-speed internet connectivity	47	15.7
Smart data processing platforms	55	18.3
Reliable power supply	73	24.3
All of the above	60	20.0
Total	300	100.0

Table 2: Financial Challenge Hindering Smart Air Quality Monitoring Deployment

Financial Challenge	Frequency	Percentage (%)
High initial investment costs	69	23.0
Lack of government funding and grants	53	17.7
Limited private sector involvement	61	20.3
High operational and maintenance expenses	75	25.0
All of the above	42	14.0
Total	300	100.0

Table 3: Contribution of Smart Air Quality Monitoring to Urban Planning and Development

Contribution of Smart Air	Frequency	Percentage (%)
Providing real-time data for traffic and zoning regulations	71	23.7
Improving waste management strategies	45	15.0
Guiding green infrastructure planning	63	21.0
Influencing industrial location policies	67	22.3
All of the above	54	18.0
Total	300	100.0

Table 4: Strategic Placement of Smart Air Quality Monitoring Stations

Strategic Placement	Frequency	Percentage (%)
Near industrial zones and factories	59	19.7
In densely populated urban centers	77	25.7
Along major roads and highways	51	17.0
Around schools, hospitals, and public spaces	73	24.3
All of the above	40	13.3
Total	300	100.0

Table 5: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.812	0.659	0.648	2.314

Table 6: ANOVA

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	589.72	4	147.43	27.55	0.000**
Residual	305.19	95	3.21		
Total	894.91	99			

(Significance Level: $p < 0.05$)

Table 7: Coefficients

Variables	Unstandardized Coefficients (B)	Standardized Coefficients (Beta)	T	Sig.
(Constant)	2.109	-	4.372	0.000**
Urban Planning	0.521	0.447	6.225	0.000**
Environmental Policy Enforcement	0.378	0.362	5.014	0.000**
Public Health Management	0.604	0.527	7.131	0.000**
Financial & Infrastructural Constraints	-0.293	-0.219	-3.409	0.001**

Discussion of findings

The data in Table 1 highlights the key infrastructural components necessary for the effective deployment of real-time air pollution monitoring using smart city technologies. Reliable power supply ranks as the most critical requirement, with 24.3% of respondents identifying it as essential, reflecting the challenge of maintaining uninterrupted operation of monitoring systems in areas with unstable electricity. IoT-enabled air quality sensors (21.7%) and smart data processing platforms (18.3%) are also significant, as they facilitate data collection and interpretation for informed decision-making. High-speed internet connectivity (15.7%) is recognized as another important component, ensuring real-time data transmission and accessibility. Interestingly, 20.0% of respondents selected "All of the above," indicating that an integrated approach incorporating all these elements is necessary for a fully functional smart air quality monitoring system. The successful implementation of real-time air pollution monitoring in smart cities relies heavily on robust infrastructural frameworks. According to Popović, Radovanovic, Vajs, Drajic, and Gligorić (2022), low-cost sensing infrastructures based on fog computing can enhance urban air quality monitoring by decentralizing data processing and improving real-time responsiveness. Similarly, Sharma and Arya (2022) highlight the role of unmanned aerial vehicles (UAVs) in providing long-range environmental monitoring, particularly in cities where fixed sensor networks may be difficult to deploy due to urban congestion. However, Kaginalkar, Kumar, Gargava, and Niyogi (2023) stress that integrating air quality monitoring systems requires a well-structured urban data governance ecosystem to ensure interoperability and effective decision-making. Without proper infrastructural investment, cities like Calabar may struggle with fragmented data collection and unreliable monitoring networks.

Table 2 examines the financial constraints associated with implementing smart air quality monitoring systems. The highest proportion of respondents (25.0%) cited high operational and maintenance expenses as the most significant challenge, highlighting the recurring costs of sustaining these systems. High initial investment costs were also a major concern (23.0%), reflecting the financial burden of acquiring advanced monitoring technologies. Limited private sector involvement (20.3%) was noted as another challenge, suggesting the need for increased partnerships and investments in environmental monitoring. The lack of government funding and grants (17.7%) points to the necessity for stronger public-sector support and policy interventions. Meanwhile, 14.0% of respondents believed that all these factors collectively hinder the deployment of smart air quality monitoring, emphasizing the need for comprehensive financial planning and investment strategies. The financial aspect of smart city air pollution management is another major challenge, as highlighted by several scholars. Hui, Dan, Alamri, and Toghraie (2023) discuss the economic feasibility of integrating urban natural resources with smart technologies to promote environmental sustainability, noting that funding constraints often hinder the widespread adoption of these systems in developing regions. Similarly, Salman and Hasar (2023) emphasize that the cost of deploying IoT-based air quality monitoring systems remains a barrier, particularly for cities with limited environmental budgets. While some cities have successfully leveraged public-private partnerships to finance smart monitoring technologies, Neo, Hasikin, Lai, Mokhtar, Azizan, Hizaddin, and Razak (2023) argue that artificial intelligence-assisted air quality monitoring could offer cost-efficient solutions by optimizing resource allocation and reducing maintenance expenses. Nevertheless, without sustainable financial models, the long-term viability of these technologies remains uncertain.

The technical requirements for integrating smart air pollution monitoring involve advanced data analytics, governance frameworks, and emerging technologies. Myeong and Shahzad (2021) highlight the importance of integrating big data analytics with air quality management, stating that AI-driven predictive models can enhance real-time decision-making and policy enforcement. Meanwhile, Gibson (2021) explores how Internet of Things (IoT) infrastructures contribute to urban big data analytics, improving the accuracy and efficiency of pollution tracking. However, Vershitsky, Egorova, Platonova, Berezniak, and Zatsarinnaya (2021) caution that technical challenges such as sensor calibration, data standardization, and system interoperability often pose barriers to implementation. Kaginalkar, Kumar, Gargava, Kharkar, and Niyogi (2022) propose the SmartAirQ big data governance framework as a solution for urban air quality management, emphasizing that well-regulated data ecosystems are crucial for ensuring the reliability and effectiveness of smart air pollution monitoring. These technical requirements must be met for Calabar to fully leverage smart city technologies in managing air pollution effectively.

The responses in Table 3 illustrate the various ways in which smart air quality monitoring contributes to urban planning and development. Providing real-time data for traffic and zoning regulations (23.7%) is seen as the most significant contribution, reflecting the importance of air quality data in optimizing urban mobility and land-use planning. Influencing industrial location policies (22.3%) follows closely, highlighting the role of monitoring in mitigating industrial pollution. Guiding green infrastructure planning (21.0%) is another key benefit, as it aids in designing environmentally sustainable urban spaces. Improving waste management strategies (15.0%) received the lowest percentage, though it remains a vital aspect of environmental management. Finally, 18.0% of respondents believe that all of these contributions are crucial, demonstrating that air quality monitoring has a multidimensional impact on sustainable urban development. Smart air quality monitoring systems play a crucial role in urban planning by providing real-time data that aids in designing more sustainable cities. According to Zhang (2023), wireless sensor networks integrated into smart cities enhance environmental pollution analysis, allowing urban planners to identify pollution hotspots and implement targeted mitigation strategies. Similarly, Kaginalkar, Kumar, Gargava, Kharkar, and Niyogi (2022) propose the SmartAirQ big data governance framework, which facilitates air quality management by integrating multiple data sources for more effective urban planning decisions. Myeong and Shahzad (2021) argue that data-driven strategies and advanced technologies such as AI-driven predictive models help in forecasting pollution trends, enabling proactive urban development policies that minimize environmental risks. In this context, smart air quality monitoring ensures that city layouts, green spaces, and industrial zones are strategically planned to reduce pollution exposure.

The impact of smart air quality monitoring on environmental policy enforcement is also significant, as it provides regulatory bodies with real-time, verifiable data for decision-making. Kaginalkar, Kumar, Gargava, and Niyogi (2023) emphasize that stakeholder collaboration in air quality data governance is crucial for enforcing urban environmental policies effectively. In a related study, Chen, Tam, Zhao, Yuan, Wang, Lin, and Chiang (2023) highlight how environmental action plans based on smart monitoring technologies enhance cities' ability to adapt to climate change by ensuring compliance with air quality standards. Additionally, Liu, Xu, Fan, Li, Shao, and Zheng (2021) argue that integrating AI-driven environmental monitoring into corporate regulations helps hold industries accountable for emissions, reducing industrial pollution. These studies collectively indicate that smart air quality monitoring strengthens policy enforcement by making pollution data more transparent, actionable, and enforceable.

Table 4 explores the optimal locations for placing smart air quality monitoring stations. The highest percentage (25.7%) of respondents identified densely populated urban centers as the most strategic locations, likely due to higher pollution levels from traffic and human activities. Around schools, hospitals, and public spaces (24.3%) was also a popular choice, emphasizing the need to monitor air quality in areas with vulnerable populations. Near industrial zones and factories (19.7%) was another critical placement, given the significant emissions from manufacturing and processing activities. Along major roads and highways (17.0%) was seen as less critical but still important, as vehicle emissions contribute to air pollution. Finally, 13.3% of respondents selected "All of the above," reinforcing the idea that a well-distributed monitoring network is essential for comprehensive air quality assessment and management. From a public health management perspective, smart air quality monitoring significantly contributes to reducing pollution-related diseases and promoting healthier urban living. Brauer, Davaakhuu, Nuñez, Hadley, Kass, Miller, and Armstrong-Walenczak (2021) discuss how clean air initiatives in smart cities lead to improved cardiovascular health outcomes by reducing exposure to harmful pollutants. Akomolafe, Olorunsogo, Anyanwu, Osasona, Ogugua, and Daraojimba (2024) further emphasize that air pollution is a major contributor to respiratory diseases, and real-time monitoring allows health authorities to issue timely public health advisories, such as air quality warnings and exposure reduction strategies. Moreover, smart air quality data can be integrated into urban healthcare systems to support epidemiological research and pollution-related disease tracking (Myeong & Shahzad, 2021). Therefore, smart monitoring systems not only provide critical insights into pollution levels but also empower public health agencies to implement targeted interventions, ultimately improving overall urban well-being.

Hypotheses testing

H_0: Smart air quality monitoring systems do not have a significant impact on urban planning, environmental policy enforcement, and public health management.

H_1: Smart air quality monitoring systems have a significant impact on urban planning, environmental policy enforcement, and public health management.

The Model Summary (Table 5) provides key insights into the overall performance of the regression model. The R-value (0.812) indicates a strong positive correlation between smart air quality monitoring and its impact on urban planning, environmental policy enforcement, and public health management. The R-Square value (0.659) suggests that 65.9% of the variability in the dependent variable is explained by the independent variables included in the model. The Adjusted R-Square (0.648), which accounts for the number of predictors, shows a minimal reduction, reinforcing the model's reliability. The Standard Error of the Estimate (2.314) measures the average deviation of observed values from the predicted values, suggesting an acceptable level of prediction accuracy.

The ANOVA table (Table 6) evaluates the statistical significance of the model. The F-statistic (27.55) and the p-value (0.000) confirm that the model is statistically significant, meaning at least one predictor significantly affects the dependent variable. The Coefficients table (Table 7) further examines the individual contributions of the predictors. The coefficients for Urban Planning (0.521, $p = 0.000$), Environmental Policy Enforcement (0.378, $p = 0.000$), and Public Health Management (0.604, $p = 0.000$) are all positive and statistically significant, indicating that these factors strongly influence the effectiveness of smart air quality monitoring. However, Financial & Infrastructural Constraints (-0.293, $p = 0.001$) show a negative impact, suggesting that financial and infrastructural limitations hinder the effectiveness of these technologies. The high t-values for significant variables further confirm their strong contribution to the model, reinforcing the importance of integrating smart air quality monitoring into urban planning and policy frameworks while addressing financial and infrastructural barriers.

Conclusion

This study examines the infrastructural, financial, and technical requirements for real-time air pollution monitoring using smart city technologies and evaluates their impact on urban planning, environmental policy enforcement, and public health management. The findings highlight the critical need for IoT-enabled air quality sensors, high-speed internet connectivity, smart data processing platforms, and reliable power supply to facilitate effective implementation. Financial constraints, including high initial investment costs, lack of government funding, and high maintenance expenses, were identified as major barriers to deployment. The study further establishes that smart air quality monitoring systems significantly contribute to urban planning by providing real-time data for zoning regulations, guiding green infrastructure planning, and influencing industrial location policies. Additionally, the strategic placement of these monitoring stations near industrial zones, major roads, and public spaces ensures optimal data collection for effective pollution control. Statistical analysis using multiple regression confirms that smart air quality monitoring has a significant positive impact on urban development, with urban planning, environmental policy enforcement, and public health management emerging as strong predictors of its effectiveness. However, financial and infrastructural constraints negatively affect its implementation, emphasizing the need for increased investment and policy support. The study concludes that integrating smart air quality monitoring into urban governance can enhance sustainability efforts and improve overall public health, particularly in developing urban centers.

Recommendations

To enhance the effectiveness of smart air quality monitoring systems, this study recommends, first, that government agencies such as the National Environmental Standards and Regulations Enforcement Agency (NESREA) and local urban planning departments invest in critical infrastructure, including IoT-enabled sensors, reliable internet connectivity, and smart data processing platforms, to facilitate real-time air pollution tracking. Second, financial constraints should be addressed through increased government funding, public-private partnerships, and international grants to support both the initial deployment and long-term maintenance of these monitoring systems. Lastly, strategic placement of air quality sensors in high-risk areas such as industrial zones, densely populated urban centers, and public institutions should be prioritized to ensure accurate data collection, enabling policymakers to implement evidence-based environmental regulations and public health interventions.

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Author Address:
[1]Environmental Management Senior Lecturer, Department of Environmental Management, University of Calabar, Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[2] Environmental Education Lecturer**,** Department of Environmental Education University of Calabar, Calabar**,** University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[3]Environmental Management Lecturer, Department of Environmental Management, University of Calabar, Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[4]Geography and Environmental Science Lecturer, Department of Geography and Environmental Science, University of Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[5]Environmental Management Doctoral Researcher, Department of Environmental Management, University of Calabar, Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[6]Geography and Environmental Science Lecturer, Department of Geography and Environmental Science, University of Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[7]Geography and Environmental Science Lecturer, Department of Geography and Environmental Science, University of Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[8]Geography and Environmental Science Senior Lecturer, Department of Geography and Environmental Science, University of Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[9]Environmental Management Senior Lecturer, Department of Environmental Management, University of Calabar, Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[10]Geography and Environmental Science Senior Lecturer, Department of Geography and Environmental Science, University of Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria
[11]Environmental Management Lecturer, Department of Environmental Management, University of Calabar, Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria

[12]Environmental Management Doctoral Researcher, Department of Environmental Management, University of Calabar, Calabar, University of Calabar, P.M.B. 1115, Calabar, Cross River State, Nigeria

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