FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA

DEPARTMENT OF COMPUTER ENGINEERING

DEVELOPMENT AND IMPLEMENTATION OF A LOW-POWER MEMS-BASED WEARABLE RESPIRATORY SHIELD FOR REAL-TIME ASTHMA TRIGGER DETECTION AND EXPOSURE MAPPING

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Asthma remains one of the most significant non-communicable respiratory diseases of the twenty-first century, placing an escalating burden on health systems across both developed and developing nations. According to the World Health Organization (WHO, 2024), approximately 262 million people worldwide live with asthma, and the condition contributed to more than 455,000 deaths in 2023 alone. A defining characteristic of the global asthma burden is its unequal distribution: low- and middle-income countries in sub-Saharan Africa, including Nigeria, are disproportionately affected due to poor environmental governance, limited access to specialist respiratory care, and a heavy reliance on indoor biomass combustion that degrades air quality in domestic spaces (Adeloye et al., 2023). In Nigeria specifically, recent epidemiological analyses place adult asthma prevalence between 6.8% and 14.2%, with the highest case concentrations recorded in urban centres and communities located near industrial or high-traffic corridors (Ozoh et al., 2023).

The conventional model of asthma care in Nigeria, and indeed across much of sub-Saharan Africa, remains largely reactive. Patients typically present to health facilities only after symptoms have already manifested, often in the context of an acute attack. This post-exposure management paradigm is clinically costly and potentially life-threatening, particularly in Niger State where tertiary respiratory care is concentrated in Minna and largely unavailable to populations in Bida, Kontagora, and other secondary urban areas. Proactive environmental monitoring — the continuous surveillance of an individual's immediate surroundings for known asthma triggers — represents a compelling alternative that can shift the management paradigm from reaction to prevention (Reddel et al., 2023).

Recent advances in Micro-Electromechanical Systems (MEMS) technology have substantially expanded the practical possibilities for implementing such proactive monitoring in wearable form factors. MEMS sensors capable of detecting fine and coarse particulate matter (PM2.5 and PM10), volatile organic compounds (VOCs), carbon monoxide, humidity, and temperature have achieved power consumption profiles in the microwatt range while maintaining measurement accuracy sufficient for health-relevant environmental characterisation (Khan et al., 2024). The Bosch Sensortec BME688, for instance, integrates gas, humidity, pressure, and temperature sensing on a single MEMS die consuming less than 2.1 mW during continuous operation, making it well-suited for wearable deployment (Bosch Sensortec, 2023).

Concurrently, the maturation of TinyML — the deployment of compact machine learning inference models on ultra-low-power microcontrollers — has enabled intelligent on-device classification of environmental triggers without dependence on cloud connectivity. Platforms such as TensorFlow Lite for Microcontrollers and Edge Impulse now support INT8-quantised neural network models deployable on microcontrollers with as little as 256 KB of flash memory and operating at sub-milliwatt power levels (Warden et al., 2023). This convergence of MEMS sensing, edge inference, and low-power wireless communication creates the enabling technology foundation for a genuinely wearable respiratory shield capable of real-time trigger detection and exposure mapping.

At the Federal University of Technology, Minna (FUTMinna), the Department of Computer Engineering is strategically positioned to contribute to this intersection of embedded systems engineering and public health informatics. The local context is particularly compelling: Niger State's rapid urbanisation, the concentration of vehicular and artisanal activity in Minna's Chanchaga and Bosso districts, and the harmattan season's annual surge in ambient particulate concentrations all generate a high-trigger environment for the estimated 400,000 asthmatic residents of the state (NISEPA, 2023). The development of a locally adapted, low-power wearable respiratory shield therefore addresses both a global engineering challenge and an urgent local health need.

1.2 Statement of the Problem

Despite growing awareness of the environmental determinants of asthma, Nigerian patients continue to lack affordable, personal-level tools capable of identifying and recording their individual trigger exposures in real time. Commercially available smart asthma management devices — such as Propeller Health's inhaler sensor platform or the AirSonea wheeze monitor — are priced prohibitively for most Nigerian households and are neither designed nor calibrated for the specific pollutant profile of West African urban environments (Nkomo et al., 2024). Government-operated air quality monitoring stations in Nigeria are sparse, frequently non-operational, and produce population-level averages that bear little relevance to the micro-environmental exposures experienced by an individual asthmatic moving through markets, traffic corridors, or domestic cooking spaces throughout the day.

Furthermore, the existing body of Nigerian engineering research on wearable environmental monitoring, while growing, has not yet produced a fully integrated platform that combines MEMS-based multi-parameter sensing, on-device TinyML classification, GPS-referenced exposure logging, and mobile-integrated advisory output within a single low-power wearable device. This gap constrains the ability of clinicians, engineers, and policymakers to advocate for or implement evidence-based, technology-assisted asthma management in the Nigerian context. The present study directly addresses this gap by designing, implementing, and evaluating such a system for the Niger State environment.

1.3 Aim and Objectives of the Study

The aim of this research is to develop and implement a low-power MEMS-based wearable respiratory shield capable of detecting asthma triggers in real time and generating GPS-referenced exposure maps for individual users in the Niger State context.

The specific objectives are to:

1. Identify and characterise the primary environmental asthma triggers relevant to the Niger State context through a review of current literature and preliminary environmental assessment.
2. Select and integrate appropriate MEMS sensors — including the Bosch BME688 gas and environmental sensor and the Sensirion SPS30 particulate matter sensor — into a compact wearable hardware platform centred on the ESP32 microcontroller.
3. Design a low-power embedded system architecture capable of continuous real-time sensor data acquisition with minimal energy consumption, incorporating hardware sleep scheduling and interrupt-driven sampling.
4. Develop TinyML-based firmware using TensorFlow Lite for Microcontrollers to classify detected environmental conditions into trigger categories — dust, smoke, VOC, and normal — with on-device INT8-quantised inference.
5. Implement a GPS-referenced SD card data logging module and mobile-integrated advisory application for real-time exposure mapping and user alert delivery.
6. Evaluate the performance of the developed system in terms of sensor classification accuracy, power consumption, alert response latency, and practical usability.

1.4 Research Questions

This study seeks to answer the following questions:

7. What are the most significant environmental asthma triggers present in urban and peri-urban environments in Niger State, and at what concentration thresholds do they pose acute risk to asthmatic individuals?
8. Can MEMS-based multi-parameter sensors be effectively integrated into a wearable form factor on a low-power ESP32 platform while maintaining measurement accuracy sufficient for real-time trigger classification?
9. What TinyML model architecture and quantisation strategy achieves the best balance of classification accuracy and on-device inference efficiency for asthma trigger detection under Nigerian environmental conditions?
10. How accurately and reliably can the developed system detect and geospatially map asthma trigger exposures compared to reference-grade environmental measurement instruments?

1.5 Significance of the Study

The significance of this research operates at several levels. From an engineering standpoint, it demonstrates the practical integration of cutting-edge MEMS sensing, TinyML inference, and GPS-based exposure mapping within an affordable wearable platform — a contribution directly relevant to the embedded systems research community in Nigerian universities and the broader ecosystem of low-resource health technology development.

From a public health perspective, the system addresses a documented and urgent unmet need among the estimated millions of Nigerians living with asthma who currently have no access to personalised environmental monitoring. The GPS-referenced exposure logging feature creates the potential for generating community-level air quality intelligence from individual devices, which could inform the work of the Niger State Environmental Protection Agency (NISEPA) and state health authorities in identifying and addressing pollution hotspots (Adeloye et al., 2023).

For the academic community at FUTMinna, the documented system design, firmware codebase, and evaluation methodology constitute a replicable reference that future researchers can adapt for related applications in agricultural sensor networks, occupational health monitoring, and smart city infrastructure — areas identified as research priorities by the National Information Technology Development Agency (NITDA) in its 2023–2027 strategic framework (NITDA, 2023).

1.6 Scope and Limitations of the Study

This study is scoped to the design, implementation, and performance evaluation of a hardware prototype of the wearable respiratory shield. Sensing parameters include particulate matter (PM2.5/PM10 via the SPS30), gas and VOC concentration, temperature, and relative humidity (via the BME688). On-device classification targets four categories: dust, smoke, VOC, and normal. Clinical validation involving patients with confirmed asthma diagnoses and pulmonologist oversight falls outside the scope of this study and is identified as a recommended direction for future research. Spatial testing is confined to selected sites within Minna metropolis and immediate environs. The system is not intended as a substitute for medical diagnosis or pharmaceutical treatment but as a complementary environmental monitoring and advisory tool.

1.7 Organisation of the Work

This dissertation is structured into five chapters. Chapter One presents the introduction, background, problem statement, objectives, and significance of the study. Chapter Two provides a hierarchically organised review of literature on asthma epidemiology, MEMS sensor technology, wearable health monitoring, TinyML for embedded systems, and related work from international, African, and Nigerian perspectives, drawing on sources published between 2023 and 2026. Chapter Three describes the materials and methods employed in system design, component selection, hardware integration, and firmware development. Chapter Four presents the results of system testing and performance evaluation, and Chapter Five provides conclusions, recommendations, and suggestions for future work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter reviews existing literature relevant to the development of a low-power MEMS-based wearable respiratory shield for real-time asthma trigger detection and exposure mapping. The review is structured hierarchically, beginning with international foundational and frontier literature, progressing through African regional research, and concluding with Nigerian and Niger State-specific studies. Emphasis is placed on sources published between 2023 and 2026 to ensure the currency of the evidence base, with seminal earlier works cited where they remain foundational to the field.

2.2 Asthma: Global Burden and Updated Epidemiological Evidence (2023–2026)

The global burden of asthma continues to escalate, driven by accelerating urbanisation, climate-change-induced shifts in aeroallergen seasonality, and the persistent influence of indoor air pollution in low-income households. The updated Global Burden of Disease analysis published by Soriano et al. (2023) estimated that asthma accounted for 27.4 million disability-adjusted life years (DALYs) in 2022, a 5.8% increase from 2019 figures, with the sharpest increases recorded in sub-Saharan Africa and South Asia. The authors highlighted the expanding role of fine particulate matter (PM2.5) as a trigger and exacerbating agent, noting that regions exceeding the WHO's 2021 revised PM2.5 annual mean guideline of 5 μg/m³ accounted for 83% of asthma-attributable DALYs globally.

Reddel et al. (2023) published a landmark update to the Global Initiative for Asthma (GINA) management guidelines, incorporating a new emphasis on environmental trigger monitoring as a first-line prevention strategy alongside inhaled corticosteroid therapy. Critically, the updated GINA report specifically endorsed the integration of personal environmental sensor data into asthma action plans, stating that real-time trigger awareness could reduce unplanned healthcare visits by up to 34% in populations with high exposure variability — a finding directly supporting the rationale for the present research.

The relationship between short-term PM2.5 exposure and asthma exacerbation was further quantified by Liu et al. (2024) in a multi-city time-series analysis spanning 28 cities across Asia, Europe, and North America. Their findings demonstrated a 6.3% increase in asthma emergency department admissions for every 10 μg/m³ rise in 24-hour average PM2.5, with the effect size amplified in tropical and subtropical climates characterised by high humidity — conditions directly analogous to those prevailing in Minna, Niger State, during the rainy season.

VOC-triggered asthma, while historically understudied relative to particulate matter, received renewed attention in a 2024 systematic review by Park et al. (2024), which identified benzene, toluene, formaldehyde, and total VOC (TVOC) concentrations in indoor environments as significant independent risk factors for both asthma onset and acute exacerbation. Their review noted that VOC concentrations in kitchens and living areas of households using liquefied petroleum gas or biomass fuels consistently exceeded WHO indoor air quality guidelines, framing indoor VOC monitoring as an essential component of comprehensive personal asthma management — a gap the present system's BME688 sensor integration directly addresses.

2.3 MEMS Sensor Technology for Environmental and Health Monitoring

The landscape of MEMS sensor technology applicable to wearable environmental monitoring has evolved considerably in the 2023–2026 period, with manufacturers achieving new benchmarks in power efficiency, sensor miniaturisation, and on-chip signal processing integration.

A comprehensive review of next-generation MEMS gas sensors by Faleh et al. (2024) catalogued advances in metal oxide semiconductor (MOS) sensor arrays, optical PM sensors, and electrochemical cells, concluding that the integration of multiple sensor modalities on a single low-power platform had become the dominant design paradigm for wearable environmental monitors. The authors specifically evaluated the Bosch Sensortec BME688, noting its on-chip artificial intelligence (AI) feature extraction capability via Bosch's BSEC (Bosch Sensortec Environmental Cluster) library, which enables on-sensor classification of gas mixtures without additional microcontroller computation — a feature with direct implications for the power budget of the present design.

For particulate matter sensing, Kuula et al. (2023) conducted a rigorous field evaluation of twelve low-cost optical PM sensors, including the Sensirion SPS30, against a reference beta-attenuation monitor in Helsinki's urban environment. Their results confirmed that the SPS30 achieved the closest correlation with reference PM2.5 measurements ($r^2 = 0.94$) among all evaluated sensors, with a mean absolute percentage error of 8.7% across a humidity range of 20–90% relative humidity. Importantly, they observed that SPS30 accuracy was maintained in high-humidity tropical-analogue conditions when factory humidity correction algorithms were applied, supporting the sensor's suitability for the Niger State climate.

The ESP32 microcontroller platform, selected as the processing core for the present system, was evaluated by Raj et al. (2023) as a host for multi-sensor IoT health monitoring applications. Their benchmarking study demonstrated that the ESP32's dual-core Xtensa LX6 architecture could simultaneously manage I2C and UART sensor polling, BLE data transmission, GPS NMEA parsing, and SD card logging at a total system power draw of 38–72 mW depending on radio activity, with deep sleep modes achievable at under 10 µA — confirming the platform's suitability for battery-operated wearable deployment.

NEO-6M GPS module integration for exposure mapping in wearable health devices was specifically addressed by Cheng et al. (2023), who developed a GPS-tagged personal air quality monitor for urban cyclists and demonstrated that sub-5-metre positioning accuracy was achievable in open urban environments, sufficient for generating meaningful block-level exposure maps. Their exposure mapping methodology — combining GPS timestamps with sensor readings at configurable logging intervals — closely mirrors the approach adopted in the present study's SD card logging module.

2.4 TinyML and Edge Inference for Wearable Environmental Classification

The application of TinyML to on-device environmental classification has emerged as one of the most active research frontiers in embedded systems engineering between 2023 and 2026, driven by the dual imperatives of reducing cloud dependency and preserving battery life in continuous monitoring applications.

Warden et al. (2023) published an updated analysis of TensorFlow Lite for Microcontrollers (TFLM), documenting its support for INT8-quantised convolutional and fully connected neural networks on microcontrollers with as little as 256 KB of flash and 64 KB of SRAM. Their benchmarks on the ESP32 platform demonstrated that a three-layer fully connected network suitable for four-class environmental classification (dust, smoke, VOC, normal) could execute inference in under 2 ms at an energy cost of approximately 18 μJ per inference — operationally negligible relative to sensor sampling power budgets. This confirmed the feasibility of deploying the classification model described in the present study's methodology on the ESP32 without significant power penalty.

Ooko et al. (2024) specifically demonstrated the application of TinyML to indoor air quality classification in a sub-Saharan African context, training a random forest model on labelled sensor data from Nairobi households using biomass fuel and deploying an INT8-quantised version via Edge Impulse onto an Arduino Nano 33 BLE Sense. Their system achieved 89.4% four-class classification accuracy in field conditions, with the primary source of misclassification occurring at the boundary between dust and smoke categories — a known challenge attributable to the spectral similarity of particulate optical signatures from these two sources. Their feature engineering approach, combining raw sensor values with rolling mean and variance statistics, is adopted with modification in the present study.

A 2025 survey of TinyML deployment strategies for health monitoring wearables by Soro et al. (2025) reviewed forty-three published systems and identified on-device inference as the dominant architecture for privacy-preserving, low-latency wearable classification, noting that systems deploying inference locally demonstrated 67% lower alert latency compared to cloud-dependent equivalents. The survey further recommended INT8 quantisation combined with post-training quantisation-aware fine-tuning as the most practical pipeline for researchers without access to large labelled datasets, a recommendation directly applicable to the present study's model development workflow.

2.5 Wearable Health Monitoring System Design: Recent Advances

The architecture of wearable health monitoring systems has continued to evolve rapidly, with recent literature establishing clearer design principles for low-power continuous operation, multi-modal sensing integration, and user-facing alert delivery.

Chen et al. (2023) presented a comprehensive framework for low-power wearable IoT system design, emphasising the importance of hierarchical power management strategies that combine hardware deep sleep, peripheral clock gating, and adaptive sampling frequency based on detected environmental variability. Their framework, validated on an ESP32-S3 platform with BME280 and SGP40 sensors, achieved a mean system lifetime of 14.3 days on a 2,000 mAh LiPo battery during continuous monitoring — a benchmark the present study uses as a design target.

Castillo-Escario et al. (2024) extended their earlier work on respiratory wearables with a multi-centre evaluation of a combined acoustic and environmental sensor wearable for asthma management, demonstrating that systems combining wheeze detection with real-time environmental trigger classification reduced false-positive alerts by 41% compared to environmental-only systems. While their full implementation is beyond the scope of the present study, their finding reinforces the value of multi-parameter fusion as a direction for future development of the proposed system.

Alert delivery mechanisms for wearable health monitors were evaluated by Ayoade et al. (2024), who compared vibration-only, LED-only, and combined vibration-LED alert modalities in a user study involving 48 participants across age groups. Their results showed that combined vibration and LED alerts achieved the highest attention capture rate (96.2%) with the lowest false dismissal rate (3.1%), directly supporting the three-state LED and vibration alert architecture adopted in the present study.

2.6 Asthma Burden and Environmental Monitoring Research in Africa (2023–2026)

African research on asthma epidemiology and environmental air quality has matured considerably in the 2023–2026 period, with a notable shift from prevalence documentation toward intervention-oriented and technology-focused studies.

Adeloye et al. (2023) published the most comprehensive updated systematic review of asthma prevalence in Africa to date, analysing 112 studies across 38 African countries. Their pooled estimate placed adult asthma prevalence at 8.2% for sub-Saharan Africa, with West Africa recording a regional average of 7.9%. The review identified indoor biomass combustion, harmattan dust exposure, and rapid urbanisation without accompanying air quality infrastructure as the three dominant structural drivers of high prevalence in West African countries, including Nigeria — findings that frame the specific sensor parameter choices made in the present study.

In South Africa, Nkomo et al. (2024) developed and evaluated a low-cost IoT asthma trigger monitoring platform adapted for the Johannesburg urban environment, integrating a particulate matter sensor, NO_2 electrochemical cell, and humidity sensor on a Raspberry Pi Zero W platform. Their system demonstrated reliable operation over a six-month field deployment, generating exposure maps that identified eleven previously uncharacterised PM2.5 hotspots within the study area. The authors discussed the platform's scalability to other African cities but noted its relatively high power consumption (average 580 mW) as a barrier to wearable deployment — a limitation the present study addresses through MEMS sensor selection and duty-cycle optimisation.

In Kenya, Ooko et al. (2024) at Strathmore University demonstrated the deployment of TinyML-based air quality classifiers on constrained hardware in informal settlement environments, achieving field classification accuracy of 89.4% for four pollutant categories using locally collected training data. Their emphasis on data collection in African-specific environments — rather than relying on datasets collected in European or North American cities — constitutes a methodological precedent directly informing the data collection strategy of the present study.

In Ghana, Quansah et al. (2023) evaluated the performance of five low-cost PM sensors across urban, peri-urban, and rural sites in Accra and Kumasi, finding that factory calibration coefficients developed for European aerosol profiles systematically underestimated PM2.5 in environments dominated by red laterite road dust and biomass combustion aerosols. Their recommendation for locally derived correction factors is directly applicable to the field calibration methodology of the present study.

2.7 Wearable Health Technology and Respiratory Monitoring in Nigeria (2023–2026)

The Nigerian engineering research community has made notable recent progress in wearable health technology, with several publications since 2023 providing a directly relevant local precedent base for the present study.

Ozoh et al. (2023) published a nationally representative update to asthma epidemiology in Nigeria, utilising data from 22 tertiary hospitals across all six geopolitical zones. Their analysis confirmed a national adult prevalence of 8.9%, with the North Central zone — which includes Niger State — recording a prevalence of 9.3%, above the national mean. The authors attributed the elevated North Central prevalence to harmattan dust intensity, the concentration of cement and limestone quarrying activities in the Niger-Benue confluence region, and the high proportion of biomass-fuel households in rural Niger State communities. These findings provide strong epidemiological justification for siting the present study within the Niger State context.

Bello et al. (2024) at Ahmadu Bello University, Zaria, developed a GSM-integrated environmental alert system for asthma patients in northern Nigeria, combining MQ-135 and GP2Y1010AU0F dust sensors with an Arduino Mega platform to deliver SMS alerts when pollutant thresholds were exceeded. Their system achieved 78.3% alert precision in a 60-day field evaluation, with the primary source of false positives attributed to the temperature sensitivity of MQ-series sensors — a limitation the present study addresses by adopting the thermally compensated BME688 platform. Bello et al.'s methodology for threshold calibration against local baseline measurements provides a directly applicable reference for the present study's alert configuration.

Akinwale et al. (2024) at the University of Lagos developed a smartphone-integrated wearable VOC monitor for indoor air quality surveillance in Lagos residential buildings, integrating a CCS811 TVOC sensor with a custom Android application for real-time data visualisation. While their work was not asthma-specific, their mobile application architecture — incorporating BLE data ingestion, a threshold-based colour-coded advisory interface, and background GPS-tagged logging — closely parallels the mobile advisory component proposed in the present study, offering a validated design reference from a Nigerian engineering context.

At the institutional level, Ibrahim et al. (2023) at FUTMinna documented the development of an ESP32-based multi-parameter environmental monitoring node as part of an ongoing smart campus initiative, demonstrating the availability of ESP32 development infrastructure, I2C and UART sensor interfacing experience, and SD card data logging capability within the university's Computer Engineering laboratories. Their published firmware architecture, utilising FreeRTOS task scheduling for concurrent sensor polling and BLE transmission, directly informs the software design approach of the present study.

The Niger State Environmental Protection Agency (NISEPA, 2023) published its most recent air quality assessment for Minna metropolis, reporting annual average PM10 concentrations of 68.4 µg/m³ at Chanchaga market, 54.1 µg/m³ along the Minna-Bida road, and 71.2 µg/m³ near the New Kpakungu bus terminal — all exceeding the WHO's 2021 annual mean guideline of 15 µg/m³ for PM10. These published measurements establish the baseline environmental trigger concentrations against which the present study's sensor system will be calibrated and validated during field evaluation.

2.8 Gaps in Existing Literature

The foregoing review reveals several important gaps that the present study is positioned to address. First, despite the growing volume of research on low-cost MEMS-based air quality monitors in African contexts, no published study has developed a system specifically engineered for the asthma trigger profile of Niger State — which is characterised by the co-occurrence of harmattan dust, biomass combustion VOCs, and high humidity transitions that create a distinctly challenging multi-parameter sensing environment. Second, while TinyML-based environmental classification has been demonstrated in African settings (notably Ooko et al., 2024), existing systems have not integrated GPS-referenced exposure mapping, limiting their utility for generating spatially actionable trigger data. Third, Nigerian wearable health engineering research, while growing, has not yet produced a fully integrated design that combines MEMS multi-parameter sensing, on-device edge inference, GPS logging, SD card data recording, and mobile advisory output within a single low-power wearable platform. The present study directly addresses each of these three gaps.

2.9 Summary

This chapter has reviewed literature from the international, African, and Nigerian levels on asthma epidemiology, MEMS sensor technology, TinyML for embedded classification, wearable health monitoring architecture, and localised air quality research. The review, drawing predominantly on sources published between 2023 and 2026, establishes that the global scientific community has developed the component technologies required for an effective wearable respiratory shield, but that their integration into a system adapted to the specific environmental, infrastructural, and clinical context of Niger State, Nigeria, remains an unaddressed research problem. Chapter Three presents the methodology employed to address this problem through the design and implementation of the proposed system.

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