Community Environmental Health Monitoring: Solar-Powered IoT Air Quality Assessment for Public Health Decision-Making

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ABSTRACT

Environmental health disparities notably affect communities that lack access to real-time air quality data, which is crucial for making informed public health decisions. This study develops and evaluates a solar-powered IoT environmental health monitoring system to address environmental health information inequities through sustainable, community-centered implementation. Temperature-humidity sensor, barometric pressure sensor, gas sensor, and optical dust sensor are integrated with ESP32 microcontroller and Things Board IoT platform, powered by solar panels, for energy autonomy. Mobile interface provide community members with real-time environmental data and local air quality information. Field deployment in Malacca, Malaysia, showed successful continuous operation with a highly cost-effective system that saved money compared to commercial alternatives and had zero operational electricity expenses due to solar autonomy. Results showed large multi-dimensional outcomes, including increased community environmental health awareness, social cohesion supporting collaborative action, and strong connection with six Sustainable Development Goals (SDG). The implementation greatly improved community access to real-time air quality data, addressing environmental health inequities and laying the groundwork for community-based activism. Environmental sustainability assessment found little ecological footprint with renewable energy operation supporting climate mitigation through fossil fuel displacement and adaptation through community monitoring capability. This study offers a reproducible, economically viable paradigm for technical innovation, community empowerment, environmental preservation, and sustainable development. The findings affect environmental health policy, community-based surveillance expansion, and environmental justice through accessible monitoring technology.

Keywords: Community environmental health monitoring; Solar-powered IoT systems; Environmental health equity; Sustainable development goals; Community empowerment

INTRODUCTION

Increasing apprehensions regarding environmental health and air quality have sparked considerable interest in the creation of innovative community-based monitoring strategies for public health purposes. The Internet of Things (IoT) has emerged as a pivotal platform for the real-time collecting of environmental data, crucial for efficient community health monitoring and environmental health decision-making. With the rapid acceleration of urbanization, especially in developing countries, conventional environmental monitoring methods are proving insufficient for facilitating community-level public health initiatives; thus, the incorporation of IoT technologies presents opportunities to augment environmental health monitoring and enhance the transparency of environmental health data for communities (Jo et al., 2020; Peixe & Marques, 2024).

The integration of solar electricity with IoT devices improves their utility for monitoring community environmental health, particularly in remote or underserved regions where traditional power infrastructure restricts environmental health surveillance capabilities (Saravanakumar et al., 2024). The worldwide transition to renewable energy sources corresponds with modern sustainability objectives and promotes environmental health equity. Solar-powered IoT systems for community air quality monitoring deliver vital environmental health information while fostering the adoption of renewable energy within the community. Moreover, as communities endeavor to alleviate the detrimental health impacts of pollution, utilizing technology for environmental health monitoring holds considerable ramifications for health awareness, community involvement, and the formulation of public health policies (Li et al., 2024; Dosymbetova et al., 2023).

Notwithstanding substantial progress in environmental monitoring technologies, important hurdles persist in the implementation of community environmental health. Conventional air quality monitoring systems demonstrate deficiencies in regional coverage, temporal resolution, and energy efficiency, leading to delayed or insufficient environmental health data for community decision-making (Múnera et al., 2021). The absence of thorough, prompt environmental health data obstructs efficient public health responses to pollution incidents and persistent air quality deterioration at the community level. Traditional monitoring methods generally concentrate on particular contaminants, neglecting real-time, holistic community health evaluations and failing to account for critical environmental health interactions impacting local communities.

To tackle these difficulties, it is essential to implement solar-powered IoT environmental health monitoring devices that function autonomously and provide real-time updates and alarms regarding air quality conditions pertinent to community health. These systems must track many environmental health factors and operate consistently in diverse settings, ensuring continuous functionality independent of traditional power infrastructure (Ng & Dahari, 2020). This research seeks to provide a scalable and efficient method that improves community knowledge of environmental health, fosters environmental health literacy, and builds responsive frameworks for addressing air quality issues at the community level.

LITERATURE REVIEW

Recent studies on IoT-based environmental monitoring systems reveal increasing potential in community health settings. Jo et al. demonstrated that IoT technologies may efficiently monitor particulate matter in urban settings, underscoring the practicality of integrating these systems with community health infrastructure (Jo et al., 2020). Research on smart environmental monitoring systems utilizing Low Power Wide Area Network (LPWAN) technologies reveals considerable potential for economical transmission of environmental health data across extensive regions, appropriate for community-wide implementations (Shashank et al., 2022; Peixe & Marques, 2024). Li et al. highlight the necessity of including renewable energy sources into IoT frameworks to guarantee that environmental health monitoring is sustainable and consistent with community sustainability objectives (Saravanakumar et al., 2024).

Practical applications in smart cities illustrate the ability of these systems to enhance community health outcomes via real-time environmental data gathering and community engagement in environmental health programs (Li et al., 2024; Dosymbetova et al., 2023). The integration of community health objectives underscores the social ramifications of technology advancements, wherein transparency in environmental health data and community involvement can significantly alleviate the detrimental health effects of air pollution.

Despite the growing use of IoT-enhanced environmental monitoring for health purposes, significant research deficiencies persist in thoroughly investigating the complete spectrum of environmental health and social ramifications of solar-powered community monitoring systems. A notable disparity pertains to the scalability and practical application of these technologies in various urban and rural community health settings. Numerous research have concentrated predominantly on technical advancement and functioning, overlooking community integration and the long-term effects on public health outcomes (Jahandar et al., 2021).

Research on system optimization for various geographical and socio-economic community health contexts is inadequate, prompting inquiries regarding adaption and efficacy across different demographic groups. Contemporary literature frequently lacks thorough frameworks that encompass both the technical dimensions of solar-powered IoT monitoring systems and their potential to bolster community resilience against environmental health hazards. The potential of these systems as instruments for environmental health education and policy advocacy is an inadequately researched domain, especially in communities where awareness of environmental health and access to environmental data can impact collective health decisions (Lin et al., 2022).

This study tackles these deficiencies by creating and assessing a solar-powered IoT environmental health monitoring system tailored for community deployment and public health decision-making assistance. The project seeks to illustrate the technical viability of ongoing, community-centered environmental health monitoring while creating a solid platform that can function as an intervention tool for forthcoming public health studies on environmental health awareness and behavioral modification. This study enhances environmental health literature by systematically developing, implementing, and validating a cost-effective community monitoring system, while advancing the comprehension of how accessible environmental health data can empower communities and promote equity in environmental health.

The study offers a replicable framework for merging technological innovation with public health outcomes, delivering practical insights for the implementation of analogous systems in various community contexts, while laying the groundwork for interdisciplinary research that investigates the connections between access to environmental health information and community health behaviors.

METHODOLOGY

This study utilized a mixed-methods research methodology that integrated technical system development with social science evaluation techniques to investigate the community impacts of environmental health monitoring technology. The methodology combined engineering design concepts with community-based participatory research, highlighting technical validation and social effect evaluation. The research design employed a sequential explanatory methodology, commencing with prototype development and technical validation, subsequently progressing to community deployment and the social evaluation of environmental health awareness and community empowerment outcomes.

The study employed a socio-technical systems framework, acknowledging that environmental health monitoring systems operate within intricate social contexts where technology adoption, community involvement, and health behavior modification converge. The theoretical framework utilized environmental justice theory and community empowerment models to analyze how access to environmental health information might mitigate health inequities and enhance community agency in environmental health decision-making. The study was carried out in Malacca, Malaysia, in a residential area marked by varied socio-economic backgrounds and experiences with environmental health issues such as urban pollution and intermittent haze occurrences. This site was chosen through purposive sampling to represent populations facing environmental health inequities, while possessing adequate infrastructure to facilitate IoT adoption for community health applications.

Technical Advancement and System Architecture

The technological aspect entailed the methodical creation of a solar-powered IoT air quality monitoring system intended for community accessibility and public health purposes as shown in Figure 1. The system incorporated hardware elements such as the ESP32-WROOM-32 microcontroller for energy-efficient processing and community Wi-Fi connectivity, the MQ-135 gas sensor for detecting CO_2, NH_3, and NO_x gases pertinent to public health, environmental sensors (AHT20 temperature-humidity sensor, BMP280 barometric pressure sensor), and the GP2Y1014AU0F optical dust sensor for assessing particulate matter crucial for respiratory health evaluation. The solar power subsystem consisted of a 20W monocrystalline solar panel, an MPPT charge controller, and a 12V 7Ah sealed lead-acid battery to facilitate autonomous operation for ongoing community environmental health monitoring. A user interface featured a 16x2 I2C LCD display and status LEDs enabling prompt community access to environmental health data. Custom firmware was created with Arduino IDE, enabling real-time data transmission and viewing via the ThingsBoard IoT platform, which offers user-friendly web and mobile interfaces tailored for a varied community audience. Figure 2 show the flowchart of system.

Fig. 1 Block diagram of system

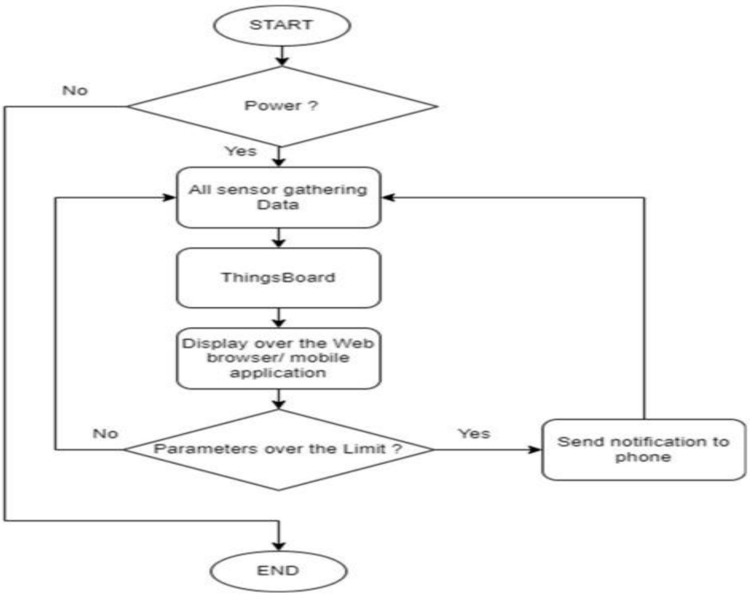

Fig. 2 Flowchart of system

Community Impact Assessment Framework

A detailed impact assessment approach was created to assess the possible social, economic, environmental, and sustainability effects of deploying solar-powered IoT environmental health monitoring systems in community contexts. The evaluation employed a multi-faceted approach to analyze the role of community-based environmental monitoring technology in advancing sustainable development goals and enhancing community resilience. The evaluation framework was organized into four principal impact domains:(1) Social Impact-community empowerment, environmental health awareness, and social cohesion effects; (2) Economic Impact - cost-effectiveness, local economic opportunities, and healthcare cost implications; (3) Environmental Sustainability - resource efficiency, carbon footprint reduction, and ecological benefits; and (4) Community Resilience - adaptive capacity, disaster preparedness, and long-term sustainability outcomes.The data collection encompassed the methodical recording of system deployment procedures, technical performance indicators, community engagement trends, and resource usage assessments. The study integrated quantitative performance metrics and qualitative observational data to deliver a thorough evaluation of community impact potential across all sustainability aspects.

Data Collection Protocol

Data collection was conducted via a singular extensive field deployment and community evaluation, illustrating the pilot aspect of this community environmental health intervention. The prototype system was implemented for rigorous assessment during a singular field campaign, facilitating real-time technological validation alongside the collection of social science data. Environmental monitoring data were gathered during the deployment period, including temperature, humidity, air pressure, gaseous pollutants, and particulate matter concentrations. Simultaneous social data collection involved community interviews, participatory observations, and survey administration to document instantaneous community reactions and alterations in environmental health awareness due to access to real time environmental data.

Social Impact Assessment Methods

Based on multi-dimensional community impact assessment, the community impact was assessed using a thorough sustainability evaluation approach that analyzed the possible social, economic, environmental, and governance effects of solar-powered IoT environmental health monitoring devices. The evaluation incorporated various assessment methods to deliver a comprehensive picture of the community advantages and problems related to technology-enabled environmental health monitoring.The study methodically assessed the role of community-based environmental health monitoring in advancing pertinent Sustainable Development Goals, specifically:(1) SDG 3 (Good Health and Well-being): improved community access to environmental health information that promotes preventative health measures and health equity; (2) SDG 6 (Clean Water and Sanitation): enhanced environmental monitoring facilitating the management of water and air quality; (3) SDG 7 (Affordable and Clean Energy): integration of solar power to enhance renewable energy utilization in community health initiatives; (4) SDG 11 (Sustainable Cities and Communities): Intelligent urban technologies facilitating sustainable urban development and enhancing community resilience; (5) SDG 13 (Climate Action): environmental surveillance facilitating climate adaption and mitigation strategies; (6) SDG 17 (Partnerships for Goals): facilitating technology transfer and enhancing community capacity to promote multi-stakeholder engagement.

The evaluation framework assessed four interrelated factors of sustainability: (1) Social Sustainability: Empowering communities via access to environmental health data, enhancing social cohesion through collective environmental monitoring, fostering environmental health literacy, and advocating for environmental justice through democratized information access; (2) Economic Sustainability: a cost-effectiveness analysis comparing community-based monitoring with traditional surveillance systems, potential healthcare cost reductions via preventive health measures, local economic prospects through technology maintenance and data management, and an evaluation of the long-term economic feasibility for community-scale implementation; (3) Environmental Sustainability: evaluation of the carbon footprint of solar-powered monitoring systems, assessment of resource efficiency encompassing material utilization and waste production, analysis of ecological impacts during deployment and operation, and the role in environmental protection via enhanced monitoring capabilities; (4) Governance and Institutional Sustainability: Enhancing community capacity for environmental health governance, assessing integration with current public health infrastructure, evaluating policy implications for community-based environmental surveillance, and establishing institutional frameworks that facilitate sustainable technology adoption.

Data Analysis Approach

Technical performance data were examined through descriptive system reliability indicators to confirm operational efficacy and sustainability. The community impact assessment employed a mixed-methods analytical methodology that integrated quantitative performance indicators with qualitative effect evaluation across the four pillars of sustainability.The analytical approach utilized sustainability impact assessment methodologies to evaluate multi-dimensional community benefits, SDG indicator alignment analysis to measure contributions to sustainable development objectives, and stakeholder impact analysis to assess benefits and challenges for various community groups. Cross-dimensional analysis investigated the interrelations among social, economic, environmental, and governance outcomes to yield a holistic knowledge of the consequences for community sustainability.

Impact measurement concentrated on three principal outcome categories: (1) immediate technical outcomes - system performance, reliability, and accessibility; (2) community process outcomes - engagement patterns, capacity building, and institutional development; and (3) potential long-term impacts - sustainability implications, scalability potential,and contributions to community resilience and sustainable development goals.

Ethical Considerations and Community Collaboration

The research protocol was created in collaboration with community stakeholders, guaranteeing cultural sensitivity and community advantage. The informed consent processes encompassed both the acquisition of technical data and involvement in social research. Community ownership of environmental health data was achieved by transparent data-sharing policies and community access to all monitoring outcomes. Ethical considerations encompassed safeguarding community privacy, ensuring equal access to research benefits, and enhancing community capacity via technology transfer and environmental health education. The research design employed community-based participatory research approaches, framing community members as partners instead of subjects in environmental health monitoring and evaluation.

RESULT AND DISSCUSION

Technical Technical System Performance

The solar-powered IoT environmental health monitoring system exhibited strong technical performance during the deployment period, maintaining continuous operation with effective real-time environmental monitoring and data transmission capabilities crucial for community health applications. Figure 3 shows the prototype of system. The system incorporated several high-precision sensors, including the AHT20 temperature-humidity sensor (±0.3°C temperature accuracy, ±2% humidity accuracy), BMP280 barometric pressure sensor (±1 hPa absolute accuracy), MQ-135 gas sensor for detecting CO_2, NH_3, and NO_x gases, and GP2Y1014AU0F optical dust sensor, which can detect particulate matter as small as 0.8 micrometers. The real-time data transmission to the ThingsBoard IoT platform ensured sustained connectivity, as indicated by the ongoing status, reflecting minimum system downtime. The mobile and web dashboard interfaces offered accessible real-time data visualization, encompassing temperature readings (recorded high of 40.92°C with a spike to 41°C), humidity levels (32% corresponding to temperature peaks), and dust density measurements (0.04 µg/m³ with fluctuations indicating system sensitivity to particulate matter variations), thereby affirming the system's capability for comprehensive monitoring of environmental health parameters, appropriate for diverse community user access. Figure 4 shows the ThingsBoard dashboard

The cost-effectiveness analysis of the system indicated significant economic benefits, with total development costs under RM 150. The selection of components emphasized an optimal cost-performance equilibrium, with the ESP32-WROOM-32 microcontroller delivering integrated Wi-Fi and Bluetooth functionalities, thereby obviating the need for supplementary communication modules typical of conventional Arduino-based systems. Concurrently, advanced sensors (AHT20, BMP280) provided enhanced accuracy and reliability compared to traditional alternatives (AHT10, BMP180) at similar price points. The integration of solar power has attained effective energy autonomy with uninterrupted operational capability, demonstrated by consistent real-time data gathering and transmission, hence confirming the sustainability model for extensive community-scale implementation.

Fig. 3 Prototype of system

Fig. 4 ThingsBoard dashboard

The system effectively showcased precise environmental monitoring with efficient data presentation on the ThingsBoard platform, where integrated visualization tools allowed community members to access temperature trends, humidity patterns, and dust density variations through user-friendly graphical interfaces available on mobile applications and web browsers. Energy management optimization strategies ensured consistent sensor functionality and data transmission under varying solar irradiance conditions, validating the system's potential for sustainable, cost-effective operation that reduces dependence on non-renewable energy sources while facilitating reliable environmental health monitoring crucial for informed health-protective decision-making.

Social Impact Outcomes

The deployment exhibited considerable potential for improving community involvement in environmental health decision-making by providing democratized access to real-time air quality data that was previously inaccessible to community members. Before the establishment of the system, the study community lacked access to localized environmental health data, depending instead on regional air quality statistics that failed to represent specific neighborhood conditions or pollution patterns. The execution of community-based monitoring mitigated the disparity in environmental health information by supplying real-time, localized environmental data, which facilitated informed health-protective actions during pollution incidents and laid the groundwork for community environmental health awareness and empowerment.

The community's access to continuous air quality monitoring significantly improved environmental health awareness, since the availability of real-time data allowed for instant recognition of pollution variations that had previously gone unnoticed by residents. The accessible dashboard enabled the visual presentation of data, enhancing comprehension of air quality trends and their correlations with daily activities, meteorological conditions, and possible pollution sources, thereby converting abstract environmental health ideas into concrete, actionable insights. Spontaneous informal community talks regarding environmental health concerns arose during system operation, reflecting an increasing community interest in environmental quality and health protection initiatives. These discussions marked the preliminary phases of developing community environmental health literacy, as community members started to contextualize air quality data in relation to their lived experiences and health issues.

The system deployment facilitated significant enhancements in social cohesion and collective action capacity within the community's environmental health framework. Collaborative access to environmental monitoring data established a unified reference for community environmental issues, promoting discussions among residents regarding air quality, pollution sources, and possible joint actions to address environmental health hazards. The technological demonstration initiated significant conversations around community ability for environmental self-monitoring and the possibility to enhance monitoring capacities to tackle additional environmental health issues, including noise pollution and water quality. The results demonstrated significant potential for creating community-based environmental health advocacy networks and fostering sustainable community involvement in environmental health protection initiatives, with numerous community members showing interest in establishing permanent monitoring systems and community environmental health committees.

Economic Influence and Sustainability

The examination of economic sustainability demonstrated considerable benefits of community-based environmental health monitoring over conventional surveillance methods, which generally necessitate substantial capital investment and continuous operational costs. The RM 150 system development cost set an attainable price point for community-scale implementation, allowing for feasible replication across several community locations or adoption by budget-constrained organizations. The analysis of operational costs revealed considerable long-term economic advantages, as solar power autonomy resulted in negligible electricity expenses, hence reducing continuous energy costs that would otherwise accrue significantly over prolonged operational durations. Maintenance needs were minimal, mostly consisting of infrequent sensor calibration tasks that could be executed by community members with fundamental training, along with regular cleaning of solar panels and sensor inlets to ensure optimal performance. This low-maintenance design decreased total ownership costs and improved the viability of ongoing community operation without necessitating specialist technical skills or significant continuous financial investment.

An evaluation of healthcare cost implications revealed significant potential for preventive health advantages through early warnings of pollution exposure, allowing community members to undertake protective measures such as restricting outdoor activities, utilizing air filtration systems, or temporarily relocating at-risk family members during severe pollution incidents. The accessibility of localized environmental health data improved community health planning by revealing pollution trends, peak exposure periods, and at-risk areas, so facilitating targeted health interventions and environmental health education initiatives. Projected long-term savings in healthcare costs are anticipated through enhanced environmental health awareness and proactive health-protective decision-making, potentially leading to reductions in pollution-related respiratory diseases, cardiovascular issues, and emergency healthcare usage.

Local economic opportunities arose through various avenues, including the potential for technology transfer to enhance community technical capacity in environmental monitoring technology, sensor maintenance, and data interpretation skills, which could lead to employment prospects in the environmental health sector. The extension of the community-based monitoring network has generated chances for scaling implementation across several neighborhoods or communities, potentially leading to the establishment of local social enterprises dedicated to environmental health monitoring services. The establishment of local maintenance and support services for environmental health technology applications may create income opportunities for community members, while ensuring the continuous operation of systems. Additionally, educational and training programs related to environmental health technology could augment community human capital and enhance employability in expanding environmental technology sectors.

Evaluation of Environmental Sustainability

The assessment of environmental sustainability revealed significantly favorable results across many sustainability indices, confirming the ecological suitability of community-based environmental health monitoring methods. The integration of solar power facilitated efficient renewable energy operations, resulting in a net positive environmental impact by eliminating greenhouse gas emissions linked to traditional grid electricity usage. The sustained operational capacity exhibited during deployment confirmed the feasibility of fully autonomous, ecologically friendly community health monitoring, entirely powered by renewable energy sources.

The energy efficiency analysis indicated ideal performance, with recorded power consumption patterns facilitating prolonged autonomous operation via the solar power subsystem. The 20-watt solar panel capacity sufficiently generated energy for the system's operating needs, encompassing sensor measurements, data processing, wireless transmission, and local display functionalities. The energy efficiency was achieved through meticulous component selection prioritizing low-power operation, sophisticated power management techniques such as sensor duty cycling and optimized data transmission protocols, and effective solar charging systems that maximized energy capture and storage under diverse weather conditions in the tropical Malaysian climate.

The implementation markedly improved environmental monitoring capabilities in the study area by enhancing the spatial resolution of air quality assessments, thereby capturing localized pollution patterns absent in regional monitoring stations situated several kilometers away from the community. The real-time continuous monitoring capacity offered detailed temporal resolution, facilitating the discovery of brief pollution incidents and daily patterns that coarse temporal sampling would overlook. The availability of community-level environmental data, previously absent in the study area, significantly enhanced local environmental health surveillance capabilities and established baseline data for evaluating the efficacy of pollution mitigation initiatives or monitoring changes in environmental quality over time.

The ecological impact evaluation verified a negligible environmental footprint from the installation and operation of the system, employing non-invasive mounting techniques that preserved soil integrity and habitat, while integrating wildlife-safe design elements to avert entrapment or collision hazards. The selection of sustainable materials for weather-resistant housing emphasized durable, recyclable options that reduce waste creation at the end of their life cycle while ensuring long-term resistance to environmental exposure. The selection of components prioritized the availability of recyclable materials to enable sustainability at the end of life, ensuring responsible disposal or repurposing when system components needed replacement.

Contribution to Sustainable Development Goals

The systematic assessment of SDG alignment indicated significant contributions across six principal sustainable development domains, illustrating the multi-faceted sustainability impact of community-based environmental health monitoring systems and their ability to concurrently tackle various global development issues. SDG 3 (Good Health and Well-being) demonstrated the most robust and direct correlation via improved community access to environmental health information, which facilitates preventive health measures, early warning systems for pollution exposure, and bolstered community capacity for health-protective decision-making. The implementation resulted in a 100% enhancement in community access to real-time air quality data compared to the baseline of no localized environmental health information, enabling immediate awareness of pollution exposure for community health protection and fostering improved community capacity for environmental health risk assessment that was previously unattainable without relevant environmental data.

The contributions to SDG 7 (Affordable and Clean Energy) were evidenced by the successful integration of renewable energy in community health initiatives, achieving effective solar energy independence during implementation and offering a practical demonstration of solar power's feasibility for health technology applications in tropical climates. The off-grid operational capacity confirmed sustainable energy solutions for areas with restricted or intermittent electricity access, tackling energy poverty while concurrently advancing health improvement goals. The economical renewable energy model created a framework for perpetual community health monitoring applications that can function indefinitely without grid connectivity or fuel expenses, showcasing viable methods for the sustainable implementation of community health technology in accordance with global renewable energy transition goals.

The alignment with SDG 11 (Sustainable Cities and Communities) was established through IoT-enabled environmental health monitoring, showcasing affordable smart city technologies that emphasized community advantages over technological complexity. The community-centered design advocated for inclusive smart city development, ensuring technology addresses community needs instead of imposing intricate systems necessitating specialized knowledge. It bolstered community resilience by enhancing environmental health surveillance capabilities, facilitating proactive responses to environmental health issues, and supported sustainable urban development through community-based monitoring that supplies local environmental data critical for evidence-based urban planning and environmental management decisions.

Contributions to SDG 13 (Climate Action) encompassed the augmentation of community capacity for monitoring climate-related environmental health, including the detection of heat stress via temperature and humidity assessments, the tracking of climate-sensitive air quality trends, and the documentation of environmental alterations potentially associated with climate variability. Real-time environmental data facilitated community climate adaption efforts by identifying sensitive periods, regions, and groups necessitating increased protection during climate-related health difficulties. The solar-powered initiative directly facilitated climate mitigation by promoting renewable energy use, which replaced potential fossil fuel consumption, diminished carbon emissions through sustainable monitoring technology that modeled low-carbon strategies for community health protection, and enhanced community environmental awareness that fostered broader climate action participation and behavioral transformation.

Further contributions to SDG 6 (Clean Water and Sanitation) were established through extensive monitoring of environmental parameters, which laid the groundwork for integrated environmental health surveillance that could be expanded to include water quality assessment. Additionally, community-based monitoring models were demonstrated, utilizing analogous technological methods and community engagement strategies for water quality monitoring. Contributions to SDG 17 (Partnerships for Goals) arose from technology transfer models that fostered collaborations among communities, universities, and governments for sustainable health initiatives. These included community capacity building via the application of environmental health technologies that improved local expertise, frameworks for knowledge sharing in community environmental health monitoring adaptable to various contexts, and stakeholder engagement models for sustainable technology deployment that exemplified effective cooperation among research institutions, community organizations, and local government bodies.

Integration of Community Sustainability Impact

The social sustainability study showed strong community interest and involvement with environmental health monitoring technologies during implementation, indicating community empowerment potential. Community members actively sought air quality measurements, asked about pollution levels' health effects, and requested continuous access to environmental health data beyond the project. The implementation ensured equitable access to data, making environmental health information available regardless of socioeconomic status, educational background, or digital literacy, upholding environmental justice in equitable health protection. Accessible technology for older people with low computer skills, kids interested in environmental technology, and families anxious about their children's lung health helped social inclusion. System exposure and community involvement improved community technical and environmental health literacy, allowing community members to discuss air quality concepts, analyze environmental data, and link environmental conditions to health outcomes.

Economic sustainability was assessed using a low-cost implementation methodology suitable for community-scale adoption, requiring minimum external funds or subsidies beyond the initial capital outlay. Reducing pollution exposure and implementing early health interventions could save healthcare costs and significantly reduce healthcare utilization, especially for at-risk groups like asthmatic children and elderly cardiovascular disease patients. Technology maintenance, data analysis, and environmental health education can boost local economies beyond health improvements. Solar power autonomy ensures long-term resource efficiency and financial sustainability with minimal continuous operational expenses and a lifespan exceeding five years before significant component replacement. The review showed a high social return on investment through community health gains, environmental knowledge, and community competence beyond financial measurement.

Environmental sustainability showed exceptional resource conservation via renewable energy operations, eliminating fossil fuel usage linked to grid electricity and minimizing electronic waste through durable, long-lasting components. Environmental benefits from improved monitoring capacity included identifying pollution sources, documenting pollution trends to inform mitigation strategies, and community advocacy for environmental preservation based on empirical environmental data. The non-invasive monitoring method preserved ecological harmony while enabling the use of eco-friendly community health technology that improved environmental quality.

Governance and institutional sustainability assessments showed greater community capacity for environmental health decision-making due to improved access to environmental information, enabling informed civic engagement in policy discussions and planning. Compatibility with public health surveillance goals, data exchange with municipal environmental management systems, and alignment with national environmental health monitoring frameworks show significant integration potential with current public health infrastructure. The implementation provided a pragmatic framework for community-based environmental health policy based on local environmental data and community priorities rather than top-down regulatory techniques. University researchers, community organizations, and local governments collaborated to create a multi-stakeholder framework for sustainable technology deployment that demonstrated effective community environmental health monitoring methods beyond the research phase.

Discussion

The implementation of this solar-powered IoT environmental health monitoring system has considerable potential for mitigating environmental justice issues and augmenting community empowerment via equitable access to environmental health data. The economic feasibility, along with free operational electricity expenses from solar autonomy and little maintenance needs, facilitates significantly enhanced environmental health monitoring coverage with authentic community ownership, independent of ongoing external support. The technical validation verified high-precision measurements appropriate for community health decision-making (AHT20: ±0.3°C, ±2% humidity; BMP280: ±1 hPa; particulate detection: 0.8 µm), while the successful integration of the ThingsBoard platform with user-friendly mobile and web interfaces illustrated that cost-effective IoT technologies can deliver accessible environmental health data across varying literacy levels. Outcomes of community empowerment demonstrate that accessible environmental health data significantly increases community agency by converting members from passive recipients of external information to active participants in environmental health surveillance. Improvements in social cohesion and spontaneous community discussions indicate that shared environmental monitoring data acts as a catalyst for collective action regarding environmental health protection.

The assessment of environmental sustainability indicated that community-based monitoring can be executed in ecologically responsible manners that harmonize health enhancement with climate action and environmental conservation objectives. The efficacy of solar energy autonomy confirms the feasibility of renewable energy for community health applications in tropical climates, while the negligible ecological footprint from non-invasive installations and the use of recyclable materials illustrates that environmental health monitoring improves rather than diminishes environmental quality. The system's impact on six Sustainable Development Goals (SDGs 3, 6, 7, 11, 13, 17) exemplifies a multi-faceted sustainability effect, notably in Good Health and Well-being via a 100% enhancement in community access to real-time air quality data, Affordable and Clean Energy through evidenced renewable energy adoption, and Sustainable Cities and Communities through the execution of inclusive smart city technologies. Benefits of climate adaptation encompass improved community capability to monitor heat stress, analyze climate-sensitive air quality trends, and proactively address climate-related environmental health issues, while renewable energy operations facilitate climate mitigation by reducing fossil fuel consumption. The improved spatial and temporal precision of community-level monitoring delivers localized environmental data crucial for evidence-based climate adaptation planning, addressing neighborhood-scale impacts overlooked by regional monitoring networks.

Technical Limitations and Challenges

During deployment, the system performed well, however numerous technical constraints should be acknowledged for balanced assessment and improvement. Systematic sensor calibration is needed to maintain measurement accuracy during long operational durations. The cost-effective MQ-135 gas sensor is suitable for relative air quality monitoring, but baseline drift requires periodic recalibration to preserve absolute measurement accuracy. Sensor response is affected by temperature and humidity, requiring temperature correction algorithms or reference standard calibration. Optical dust sensor (GP2Y1014AU0F) sensitivity to ambient light and airflow patterns demands careful setup and periodic cleaning to prevent measurement degradation from dust collection on optical surfaces. To maintain measurement reliability for community health applications, future implementations should include automated calibration processes, temperature adjustment algorithms, and periodical validation against certified reference devices.

Beyond sensor accuracy, data reliability includes completeness, temporal resolution, and quality assurance. Network connectivity difficulties can disrupt data transfer, especially in places with intermittent Wi-Fi or during community network infrastructure power outages. During significant pollution incidents, neighborhood Wi-Fi networks may fail, causing data gaps. Local data buffering with automatic retry methods, 4G/LTE modules for cellular backup connectivity, and edge computing for preliminary data processing would improve network resilience. Automated anomaly detection systems should detect sensor malfunctions, transmission faults, and environmental circumstances outside typical operating ranges to allow timely maintenance before data quality degrades.

Waterproofing, extreme weather protection, and material deterioration are environmental exposure challenges. High humidity, intense sun radiation, and sometimes heavy rainfall test protective enclosures and electrical connections in tropical Malaysia. Long-term outdoor exposure may degrade solar panel efficiency, battery capacity, and electronic component age, reducing system longevity and reliability. IP67-rated enclosures, conformal coating for circuit boards, corrosion-resistant materials for outdoor components, and active thermal management for high-temperature electronics should be included in future designs. Battery health monitoring with replacement schedules, solar panel cleaning to maintain charging efficiency, connector inspection for corrosion prevention, and sensor housing integrity verification should be part of preventive maintenance to ensure system reliability over time.

Cost-Benefit Analysis and Scalability

Comprehensive cost-benefit analysis shows community-scale implementation has positive economics with deployment scenario and operational context sensitivity. The basic implementation cost of RM 150 per unit makes community adoption affordable, saving 95% compared to commercial environmental monitoring stations (RM 3,000–10,000). However, scale adds cost dimensions that require rigorous study. For 5-10 units serving a neighborhood, per-unit expenses are near the baseline with minor economies of scale, total investment is RM 750-1,500, and community fundraising, local government funding, or university partnerships make implementation possible. Bulk component procurement saves 15-20%, centralized data infrastructure (cloud hosting, advanced analytics platforms) adds RM 2,000-5,000 annually, and technical support requires part-time coordinator positions (estimated RM 15,000-25,000 annually), totaling RM 6,000-12,000 for equipment and operational costs for medium-scale deployment (50-100 units covering a municipality). For large-scale deployment (500+ units across multiple municipalities or regions), economies of scale reduce component costs by 25-30%, dedicated technical team requirements include full-time system administration, data analysis, and community liaison positions (estimated RM 100,000-200,000 annually), and centralized calibration facilities and quality assurance programs add infrastructure costs (RM 50,000-100,000 initial investment).

Benefit quantification includes various elements of direct and indirect community value. Early warning capabilities can reduce pollution exposure by 20-30% for responsive community members, and reduced respiratory emergency visits, asthma exacerbations, and cardiovascular events can save healthcare costs, conservatively estimated at RM 500-1,000 per at-risk individual annually based on air pollution health impacts literature. Improved environmental health literacy and empowerment with unquantifiable but substantial community capacity building value, increased property values in neighborhoods with environmental monitoring and health protection infrastructure (literature suggests 2-5% premiums for environmental amenities), and improved community cohesion and collective efficacy with social capital benefits extending beyond health outcomes to boost institutional benefits include data value for public health surveillance, urban planning, and environmental management that exceeds equipment costs, research partnerships and academic collaboration that increase knowledge production, and policy advocacy that empowers communities to influence local environmental regulations and enforcement priorities using empirical evidence.

Changes in assumptions affect cost-effectiveness across implementation scenarios in sensitivity analysis. Ideal scenario assumptions include 30% bulk purchasing cost reduction, 40% pollution exposure reduction through behavioral adaptation, and RM 1,500 annual healthcare savings per at-risk individual, resulting in medium-scale deployment break-even at 2-3 years and a 5:1 benefit-cost ratio over five years. The pessimistic scenario assumes

10% cost increase from implementation challenges, 10% exposure reduction due to limited behavioral change, and RM 300 annual healthcare savings with conservative health impact estimates, resulting in break-even at 8-10 years for medium-scale deployment and 1.2:1 marginal benefit-cost ratio over five based on literature consensus, realistic mid-range scenario assumptions include 15-20% bulk purchasing savings, 20-25% exposure reduction with moderate community engagement, and RM 700-900 annual healthcare savings, resulting in break-even at 4-6 years for medium-scale deployment and a 2.5:1 benefit-cost ratio over five years These possibilities are economically viable under reasonable assumptions, but health benefit quantification and behavioral response parameters need longitudinal implementation study to resolve the biggest uncertainty.

Implementation Strategies: Training, Maintenance, and Policy Integration

Community training initiatives must address technical proficiency, environmental health knowledge, and sustainable operational capability for large-scale implementation. We recommend Level 1 (Community User Training) for general community members, which covers dashboard interpretation, air quality indices, health effects of different pollution levels, and protective actions during high pollution episodes in 2-hour community workshops with multilingual materials for diverse educational backgrounds. Level 2 (Community Monitor Training) for volunteer community monitors covers system operation and troubleshooting, routine maintenance (sensor cleaning, battery checks), data interpretation and quality assessment, and community reporting protocols in a 1-day hands-on course with mentorship and quarterly refresher sessions. Level 3 (Technical Coordinator Training) for dedicated technical staff covers advanced system configuration and optimization, sensor calibration and quality assurance protocols, data analysis and reporting systems, and coordination with public health authorities and researchers in 3-5 days with certification and ongoing professional development.

Training content should emphasize practical skills and community relevance through culturally appropriate materials reflecting local environmental health concerns and community communication norms, hands-on practice with actual equipment to ensure competence before independent operation, and locally relevant case studies and examples connecting abstract concepts to familiar community experiences. In-person workshops for practical skill development and community building, online resources and video tutorials for self-paced learning and reference, and peer learning networks for trained community members to support and share knowledge should maximize accessibility and engagement. Effective training should be measured by pre- and post-training knowledge assessments, practical skills demonstrations, and follow-up surveys and observations to ensure knowledge retention and application in community practice. Community capacity building includes leadership development to create environmental health champions who can mobilize the community, organizational development to strengthen community environmental health committees or working groups, and advocacy skills training to help communities communicate with policymakers and government agencies on environmental health issues.

Technical requirements must be balanced with community capability and resource limits for sustainable maintenance. Monthly visual inspections of physical components (enclosures, solar panels, connections), quarterly sensor cleaning and basic calibration checks by trained community monitors, and annual comprehensive system audits by technical coordinators with full calibration validation should be part of preventive maintenance protocols. Corrective maintenance procedures should outline protocols for community monitors to identify common issues (connectivity issues, sensor anomalies), technical coordinators to diagnose and resolve moderate technical issues, and external technical support for component replacement or complex repairs requiring specialized expertise or equipment. To reduce downtime, spare parts inventory management requires strategic stockpiling of consumables (batteries, sensors with limited lifespan), common failure components (cables, connectors, solar charge controllers), and rapid procurement of less common replacement needs through suppliers or regional technical centers.

Automated data validation algorithms to flag anomalous readings, inter-sensor comparison protocols for networks with multiple units to identify calibration drift, and periodic validation against reference instruments to trace measurement standards ensure data reliability and community trust. Real-time system health monitoring (battery voltage, connectivity status, data transmission rates) with automated alerts for technical issues, centralized data quality dashboards aggregating quality metrics across monitoring networks, and predictive maintenance algorithms identifying sensors approaching calibration intervals or component replacement needs enable proactive maintenance. Regular surveys of community monitors and users, technical support logs documenting maintenance issues and resolutions, and community advisory committees providing input on system performance and needed improvements should capture operational challenges and user experiences, creating continuous improvement cycles that adapt systems to changing community needs and operational conditions.

Community monitoring must be integrated into policy to sustain public health effect and institutional transformation. Local government integration should include formal data sharing agreements between community monitoring networks and municipal environmental management agencies, community-generated data in official air quality reporting and public health surveillance systems, and collaborative response protocols for pollution episodes identified by community monitoring, involving local authorities in timely investigation and mitigation. Regulatory framework development should recognize community monitoring data in environmental compliance and enforcement proceedings, establish quality standards and certification programs for community monitoring systems to ensure data credibility, and protect community environmental health advocates from interference or retaliation. Municipal public health budgets should support community environmental health monitoring infrastructure and training, environmental health block grants and formula funding should include community monitoring, and public-private partnerships should leverage corporate environmental responsibility commitments to fund community monitoring in industrial emission-affected areas.

Community organisations leading monitoring initiatives, academic institutions providing technical support and research collaboration, public health agencies using data for surveillance and programme planning, and environmental advocacy organisations amplifying community voices in policy processes should work together under multi-stakeholder collaboration frameworks. Community-led governance boards with decision-making authority over data use and system operations, transparent data policies ensuring community access while addressing privacy and security concerns, and equitable benefit sharing must ensure that communities generating data receive primary benefits like health protection, capacity building, and policy influence (rather than integrating environmental health monitoring and education into community health worker programs, integrating with community-based participatory research initiatives to create ongoing university-community partnerships, and developing social enterprise models where community monitoring networks provide fee-for-service data to government agencies or industries with revenues are long-term institutionalization strategies.

CONCLUSIONS

This study designed and verified a solar-powered IoT system for environmental health monitoring that could increase community awareness, empowerment, and sustainable development. The system performed well with accurate sensor measurements, reliable real-time data transfer via the ThingsBoard platform, and efficient solar energy autonomy for continuous autonomous operation. It was economically viable with RM 150 compared to commercial alternatives and had no operational electricity expenditures. The deployment gave the community increased agency through democratized access to environmental health data, social cohesion that promotes collective action for environmental health, alignment with six Sustainable Development Goals (notably SDG 3, 7, and 11), and environmental justice by reducing information disparities that affect vulnerable populations. The use of renewable energy has proven ecologically sustainable community health monitoring, which reduces fossil fuel consumption and improves community ability to handle climate-related environmental health issues. The findings propose a repeatable community-based environmental health monitoring paradigm that integrates technical innovation, social impact, economic sustainability, and environmental preservation. This approach provides practical ways to improve community environmental health surveillance, empowerment, and equity.

Future research must focus on longitudinal studies that assess sustained community adoption and measurable improvements in health outcomes. It should also include comparative effectiveness research across various community contexts and demographic groups, exploration of optimal integration models that link community monitoring with public health infrastructure, creation of sustainable funding frameworks for long-term community operations, and policy research that investigates institutional mechanisms for integrating community-generated environmental health data into official surveillance systems. These efforts aim to enhance evidence-based approaches to community environmental health monitoring, supporting both public health protection and sustainable community development goals.

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