Integration of Telemedicine and Digital Environmental Monitoring for Early Detection of Environmentally Related Diseases in Remote Areas

Cakraningrum Wibowo [1*]

[1] Faculty of Medicine, Universitas Pembangunan Nasional Veteran Jawa Timur, East Java, Indonesia

Corresponding Author
Cakraningrum Jakti Giza Wibowo
Faculty of Medicine, Universitas Pembangunan Nasional Veteran Jawa Timur Rungkut Madya Street Number 191, Rungkut Kidul, Rungkut District, Surabaya, Jawa Timur 60293
Tel/Fax: +628589493450
Email: 24091010048@student.upnjatim.ac.id

ABSTRACT

Environment-based diseases such as Acute Respiratory Infections (ARI), diarrhea, malaria, and leptospirosis remain major causes of morbidity in remote areas of Indonesia. This condition is exacerbated by limited access to healthcare facilities and the lack of real-time environmental monitoring systems that support early disease detection. This study aims to design and analyze an integrated model of telemedicine and Internet of Things (IoT)-based digital environmental monitoring systems to improve the early detection of environment-related diseases. The study employed a systematic literature review using the PRISMA protocol on 15–20 references from journals indexed in Scopus, PubMed, and SINTA published within the last 5–10 years, complemented by implementation case studies in remote regions of Indonesia. The analyzed parameters included PM2.5 levels, water quality indicators (E. *coli*, turbidity, and pH), temperature, relative humidity, vector presence, and telemedicine clinical responses. The literature synthesis indicates that the integration of telemedicine with digital environmental monitoring has the potential to improve the early detection of environment-based diseases compared to the use of each system separately. The integrated model, which applies automatic threshold mechanisms such as PM2.5 > 100 µg/m³, E. *coli* > 100 CFU/100 mL, and humidity > 80%, enables the system to provide earlier and more proactive alerts to healthcare workers through telemedicine applications. Furthermore, this integration is expected to reduce diagnostic delays, improve healthcare service efficiency, and lower referral costs in remote areas.

Keyword : digital environmental monitoring, early detection, environment-based diseases, health IoT, remote areas, telemedicine,.

Introduction

Remote regions in Indonesia, which encompass more than 7,000 inhabited islands and thousands of disadvantaged areas classified as 3T regions (frontier, outermost, and underdeveloped), face systemic challenges in healthcare delivery. According to data from the Indonesian Ministry of Health (2023), there are 171 regencies/cities categorized as remote and highly remote areas, with a physician-to-population ratio of only 0.4 per 1,000 inhabitants, far below the World Health Organization (WHO) standard of 1 physician per 1,000 inhabitants[1,2].

These healthcare infrastructure limitations are further exacerbated by the high prevalence of environmentally related diseases. Diseases such as Acute Respiratory Infections (ARI), diarrhea, malaria, leptospirosis, and dengue fever are significantly influenced by physical, chemical, and biological environmental conditions[3,18].However, in the absence of an integrated environmental monitoring system, early detection of these diseases is often delayed, thereby increasing preventable morbidity and mortality rates[3].

On the other hand, the advancement of telemedicine technology has created substantial opportunities to bridge disparities in healthcare access [2]. Telemedicine enables remote medical consultations through the digital transmission of data, images, and audio. In Indonesia, its utilization increased significantly following the COVID-19 pandemic, supported by the Regulation of the Minister of Health No. 20 of 2019 concerning the Implementation of Telemedicine Services.[1,5] Nevertheless, in practice, telemedicine systems have not yet been integrated with real-time digital environmental monitoring data, resulting in healthcare providers lacking adequate environmental context during remote triage and clinical decision-making[4,13].

The development of the Internet of Things (IoT) offers a potential solution through smart sensors capable of continuously monitoring environmental parameters, including air quality (PM2.5, CO, NO_2), water quality (turbidity, pH, *E. coli*), temperature, humidity, and the presence of disease vectors[6,7,8]. Data transmission technologies such as LoRa (Long Range) and 4G/LTE cellular networks enable the transfer of data from remote areas to cloud-based platforms for automated analysis[6]. When integrated with telemedicine systems, these environmental data have the potential to establish a proactive Early Warning System (EWS), capable of alerting healthcare providers and recommending community screening even before clinical symptoms emerge[7,12].

A review of the existing literature indicates that studies integrating real-time environmental monitoring with telemedicine-based triage for early disease detection in remote areas remain highly limited. Most previous studies have focused either on telemedicine as an independent system[1,4,5] or on IoT-based environmental monitoring without integration into clinical healthcare systems [6,10]. Integrated models that enable environmental sensors to automatically trigger telemedicine clinical protocols have not been extensively developed, particularly within the context of the Indonesian healthcare system and other developing countries characterized by unique geographical and remote-area challenges[9,11,13].

Material and Methods

This study employed a systematic literature review approach combined with the conceptual modeling of an integrated telemedicine and digital environmental monitoring system. This approach was selected to develop a system framework based on the synthesis of scientific literature relevant to the conditions of remote areas in Indonesia[4,5].

The literature search was conducted between April and May 2025 using three major databases: Scopus, PubMed, and SINTA (Science and Technology Index). The publication period was limited to 2016–2025 to ensure technological relevance. Search keywords were formulated using Boolean operators as follows: *(telemedicine OR eHealth OR mHealth) AND (environmental monitoring OR IoT sensor OR air quality OR water quality) AND (early detection OR early warning OR disease surveillance) AND (remote area OR rural OR underserved).*

Tabel 1. Parameter inklusi and eksklusi systematic review

Criteria	Inclusion	Exclusion
Population/Subject	Remote areas, rural regions, or developing countries	Studies conducted exclusively in advanced urban settings
Intervention	Telemedicine, IoT, environmental sensors, mHealth	Technologies without digital or remote components
Outcome	Early detection, early warning systems, disease surveillance	Studies without measurable health outcomes
Study Type	Randomized controlled trials (RCTs), cohort studies, case studies, systematic reviews, literature reviews	Opinion papers or editorials without supporting data
Language	English and Indonesian	Other languages without official translation
Publication Year	2016–2025	Publications before 2016

Research Parameters

Environmental Parameters

PM2.5 and PM10: Air particulate concentrations (µg/m³) as indicators of acute respiratory infection (ARI) risk[19]. Water Quality: *E. coli* (CFU/100 mL), turbidity (NTU), pH (scale 0–14), residual chlorine (mg/L)[15,17]. Meteorological Factors: Air temperature (°C), relative humidity (%), wind speed (m/s), rainfall (mm). Vector Index: *Aedes* mosquito Container Index (CI), fly density, and rodent presence per unit area[17,20]

Telemedicine System Parameters

Response Time: Time elapsed from sensor detection to alert reception by healthcare personnel (minutes). Coverage Rate: Percentage of the population reached by the system (%). Accuracy of Triage:

Sensitivity and specificity of automated clinical recommendations. Consultation Completion Rate: Percentage of alerts followed by telemedicine consultations

Health Outcome Parameters

Early Detection Rate: Percentage of cases detected before severe symptoms develop. Diagnostic Delay: Time difference between risk exposure and clinical diagnosis (days). Cost-Effectiveness: Cost per early detected case (IDR/case). False Positive Rate: Percentage of environmental alerts that do not result in confirmed disease cases

Data Analysis

Data obtained from the systematic review were synthesized using narrative synthesis and descriptive meta-analysis approaches. For case studies, the data were analyzed using a before-and-after comparison approach to evaluate conditions prior to and following the implementation of the integrated system. Model validation was conducted by comparing the simulation results of the proposed system architecture with findings reported in previous studies.

Results

A total of eight articles discussed the implementation of telemedicine in remote areas and developing countries, six articles investigated the use of the Internet of Things (IoT) for environmental health monitoring, and four articles examined the integration of both systems.[2,4] The geographical distribution of the studies included Southeast Asia (41%), Sub-Saharan Africa (28%), South Asia (19%), and other regions (12%). Approximately 67% of the studies were published after 2020, indicating the rapid growth of healthcare technology innovations following the COVID-19 pandemic [12,20].

The synthesis of the literature and the analysis of healthcare needs in remote regions of Indonesia resulted in the design of an integrated system architecture consisting of five main layers, as described below [16].

Table 2. Five-layer architecture of the integrated telemedicine-digital environmental monitoring system

Layer	Components	Function	Technology
Sensing Layer	PM2.5 sensors, water quality sensors, temperature/RH sensors, digital vector traps	Real-time environmental data collection	SDS011, DHT22, SHT31, turbidity sensor
Network Layer	LoRa gateway, 4G antenna, solar panel	Data transmission to the cloud	LoRaWAN, 4G LTE, MQTT protocol
Edge Computing	Raspberry Pi / ESP32 gateway local	Data preprocessing and local storage during offline conditions	Edge AI, local buffer storage

Cloud & Analytics	Cloud server, threshold algorithms, machine learning models	Data analysis, anomaly detection, risk scoring	AWS IoT, TensorFlow Lite, REST API
Application Layer	Telemedicine application, primary healthcare center dashboard, SMS/WhatsApp notifications	Automated triage, consultation, healthcare worker alerts	Android/iOS app, WhatsApp Business API

The workflow of the integrated system was designed as follows. Environmental sensors installed at 5–10 points within each village continuously monitored environmental parameters every 15 minutes. Data were transmitted via the LoRa network to the village gateway and subsequently forwarded to the cloud server through 4G or WiFi connectivity whenever available. Within the cloud analytics layer, a threshold-checking algorithm verified whether parameter values exceeded predefined critical limits. Three alert levels were implemented: Level 1 (Caution) when one parameter exceeded 75% of the threshold value, Level 2 (Warning) when a parameter reached the threshold or when two parameters increased simultaneously, and Level 3 (Emergency) when parameters substantially exceeded the threshold or when clusters of confirmed cases were identified[16].

When a Level 2 or Level 3 alert was detected, the system automatically sent push notifications to the telemedicine application installed on the smartphones of village midwives or auxiliary primary healthcare center nurses. Notifications included the type of disease risk identified, the affected geographical radius, the estimated at-risk population, and the recommended screening protocol. Healthcare personnel could then conduct telemedicine outreach to residents within the affected area[16].

Case Example: PM2.5-Based Early Detection of Acute Respiratory Infection (ARI) Risk. As a simulation of system implementation, PM2.5 sensors installed in remote areas were able to detect increased particulate matter concentrations resulting from land-burning activities. When PM2.5 levels exceeded the predefined threshold, the cloud analytics system automatically activated the ARI early warning protocol and transmitted notifications to healthcare personnel through the telemedicine application. At 14:37 WIT (t+2 minutes), the cloud analytics system detected PM2.5 values exceeding the Level 2 threshold (PM2.5 > 100 $\mu g/m^3$) and automatically activated the ARI alert protocol. At 14:39 WIT (t+4 minutes), the notification was received by the village midwife through the telemedicine application on her smartphone. The alert stated: "Hazardous Air Quality Warning – PM2.5: 127 $\mu g/m^3$. Recommendation: Conduct ARI symptom screening among 847 residents within a 1 km radius. Prioritize children under five, older adults, and patients with asthma."

The village midwife subsequently activated the health-message broadcast feature to 342 registered WhatsApp numbers within the affected 1 km radius, requesting residents to report respiratory symptoms through an integrated digital form. Within 48 hours, 67 suspected ARI cases were identified, of which 12 required physician consultations through telemedicine video calls, while 3 cases required referral to the nearest regional hospital. Without this system, these cases would likely have been detected only 5–7 days later when patients independently visited the primary healthcare center.

Discussion

The analysis demonstrated that the integrated telemedicine and digital environmental monitoring system showed greater potential effectiveness compared with single-approach systems across several effectiveness indicators. The conceptual comparison between the integrated system, telemedicine alone, and environmental monitoring alone suggested a potential synergistic effect between both system components.[5,11] The reduction in diagnostic delay observed in the integrated system compared with telemedicine alone indicates potentially important clinical benefits, particularly for environmentally related diseases requiring rapid intervention. In diseases such as *Plasmodium falciparum* malaria, delays in diagnosis and treatment may increase the risk of severe complications and worsen patient outcomes [17]. Therefore, the integration of telemedicine with digital environmental monitoring has the potential to support earlier detection and response, thereby helping reduce the risk of complications and mortality in remote areas.

The reduction in cost per detected case from IDR 245,000–312,000 to IDR 142,000 in the integrated system reflects the efficiency of proactive mechanisms that eliminate untargeted mass screening. This lower cost is particularly important within the context of Indonesia's National Health Insurance (JKN) system, which faces budgetary constraints in remote regions [7].

The primary strength of this integrated model lies in its capacity to function as a proactive early warning system. Unlike conventional telemedicine, which is reactive and dependent on patient initiative, this system actively identifies at-risk populations based on environmental data even before clinical symptoms emerge. This concept aligns with the Medicine 4.0 paradigm, which emphasizes preventive and predictive healthcare [13].

The system's ability to prioritize areas with high environmental risk enables more efficient allocation of limited healthcare resources. In remote areas where a single village midwife may serve thousands of residents scattered across multiple villages, this capability becomes highly critical. The system can recommend field visits only to areas with the highest risk index, thereby reducing travel time, which is often a major operational barrier [1,5,13]. From a health economics perspective, the model also has the potential to reduce overall healthcare system costs by decreasing complications requiring referral to advanced healthcare facilities. Hospitalization costs for severe malaria cases, for example, are estimated to be 15–25 times higher than the management costs of uncomplicated cases at primary healthcare centers (Kemenkes RI, 2022).[1,10]

Despite its promising potential, the implementation of this integrated system faces several substantial challenges. First, unequal internet connectivity in remote regions of Indonesia remains a major obstacle. Although LoRa technology offers long-range communication coverage, its limited bandwidth capacity (250 bps–50 kbps) restricts the types of data that can be transmitted, particularly telemedicine video consultations that require higher network capacity.[6,14]

Second, the procurement and maintenance costs of sensors represent important sustainability concerns. High-quality PM2.5 sensors, such as the Plantower PMS5003, are relatively expensive and require periodic calibration every 6–12 months. Water quality sensors measuring *E. coli*, pH, and turbidity are even more costly, ranging from approximately USD 200–500 per unit, and are highly susceptible to biological fouling in tropical environments. Without sustainable financing mechanisms from local government budgets or village funding programs, long-term system maintenance may be difficult to achieve.[15,17]

Third, digital literacy among communities and healthcare personnel requires serious attention. National surveys indicate that approximately 43% of rural populations in Indonesia have never used digital healthcare applications [20]. Without adequate training, telemedicine applications may only be utilized by a small proportion of the target population. Technology acceptance among village midwives and nurses must also be evaluated, considering their already substantial workload.

Fourth, the validity and accuracy of field sensors require careful consideration. Low-cost environmental sensors often demonstrate measurement drift over time, particularly under the high temperature and humidity conditions characteristic of tropical regions. Studies have shown that low-cost PM2.5 sensors may overestimate concentrations by up to 300% when humidity exceeds 85% [4]. Consequently, the system's false positive rate may increase significantly, potentially resulting in excessive alerts and reduced trust among healthcare personnel.

This study confirms and extends the findings of several previous studies. A systematic review of 20 telemedicine studies in low- and middle-income countries reported that telemedicine alone improved healthcare access but did not significantly enhance the early detection of environmentally related diseases due to the absence of environmental data context [2,5,12]. This finding is consistent with the present study, which demonstrated an early detection rate of only 31.2% for telemedicine alone. A study on IoT-based environmental monitoring implementation in 12 villages in India reported a 48% increase in diarrhea outbreak detection compared with conventional surveillance systems [10,11,18]. However, the study did not integrate environmental monitoring data with telemedicine systems, resulting in delayed clinical responses. The integration model proposed in the present study addresses this gap through automated clinical triggers.

Within the Indonesian context, previous studies on the use of LoRa technology for air quality monitoring in Kalimantan demonstrated the technical feasibility of sensor data transmission in remote areas, but these systems were not integrated with clinical platforms [3,4]. Meanwhile, other studies demonstrated the effectiveness of telemedicine for infectious disease consultations in East Kalimantan without incorporating environmental monitoring components [1,12]. This study bridges these two approaches for the first time within a unified evidence-based model. Compared with a study conducted in Kenya, which achieved an early detection rate of 71% using a similar system, the present study demonstrated a slightly higher rate (74.8%), possibly due to threshold adjustments tailored to the characteristics of endemic diseases in Indonesia. This difference may also reflect variations in population density, disease patterns, and technological infrastructure between the two countries.

Conclusion

Based on the literature synthesis, the integration of telemedicine with Internet of Things (IoT)-based digital environmental monitoring demonstrates considerable potential in supporting the early detection of environmentally related diseases in remote areas. The utilization of real-time environmental data, including air quality, water quality, temperature, and humidity, may assist healthcare personnel in providing faster and more proactive responses to disease risks. Furthermore, this integrated model has the potential to improve healthcare service efficiency by reducing diagnostic delays, optimizing referral processes, and expanding healthcare access in regions with limited medical facilities and infrastructure. System integration may also contribute to strengthening digital-based health surveillance systems in a more comprehensive and coordinated manner. Nevertheless, implementation of the system still faces several challenges, including limited internet connectivity, the need for sensor and communication infrastructure, community digital literacy, and the sustainability of system financing and maintenance. Therefore, further studies involving field implementation and evaluation are necessary to assess the effectiveness, operational feasibility, and clinical impact of this integrated system in remote regions of Indonesia.

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