DIGITAL PUBLIC HEALTH AND CLIMATE ADAPTATION IN INDONESIA'S 3T REGIONS: A FISHBONE ANALYSIS

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ABSTRACT

Climate change increases environmental health risks, particularly in remote and underserved settings where access to healthcare services and institutional resources is limited. Digital public health offers potential opportunities to strengthen surveillance, risk communication, and public health responses. However, implementation requires consideration of workforce readiness, environmental conditions, and health-system governance. This study aimed to identify and synthesize contextual factors potentially influencing the development of digital public health for climate change adaptation using an adapted 6M Fishbone analytical framework. A qualitative document-based multiple-case analysis was conducted using three purposively selected published contexts: digital health cadre capacity building in Waingapu, community behavior and environmental conditions following a filariasis elimination programme in Southwest Sumba, and tropical disease policy implementation in West Papua and Central Maluku. Directly reported findings were distinguished from the authors' interpretations and mapped onto six Fishbone domains: Man, Method, Machine, Material, Measurement, and Environment. The selected studies respectively reported improvements in health cadre knowledge following education, limited sustained behavioral and environmental changes, and governance and resource-related implementation constraints. The Fishbone synthesis identified contextual considerations for the prospective development of digitally supported surveillance and environmental health responses. However, none of the three studies directly evaluated the effectiveness of digital interventions for climate change adaptation. Climate-responsive digital public health development requires an integrated consideration of human capacity, implementation processes, infrastructure, resources, monitoring systems, and environmental context. The findings provide exploratory implementation hypotheses rather than causal evidence or nationally representative conclusions.

Keywords: climate change adaptation; digital public health; environmental health; Fishbone analysis; remote settings.

INTRODUCTION

Climate change is increasingly recognized as one of the most significant global public health challenges of the twenty-first century [1]. Rising global temperatures, extreme weather events, shifting rainfall patterns, and environmental degradation are directly affecting environmental determinants of

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health, including water quality, sanitation, air pollution, food security, and vector ecology [2]. The 2024 Lancet Countdown report emphasizes that climate-related hazards are intensifying the burden of vector-borne diseases, heat-related mortality, and food insecurity, particularly in low- and middle-income countries [3]. Similarly, the World Health Organization estimates that between 2030 and 2050, climate change may cause approximately 250,000 additional deaths per year from malnutrition, malaria, diarrhoeal diseases, and heat stress. These projections underline the urgency of strengthening climate adaptation strategies within environmental health systems [4].

In response to these emerging risks, Digital Public Health has gained prominence as a transformative approach to enhance health system resilience. Digital Public Health refers to the integration of digital technologies—such as telemedicine, mobile health (mHealth), health information systems, geographic information systems (GIS), artificial intelligence, and real-time surveillance—into population health strategies [5]. The Global Strategy on Digital Health highlights that digital transformation can improve healthcare accessibility, strengthen surveillance systems, and enable data-driven decision-making, particularly in resource-constrained settings [6]. When integrated into climate adaptation frameworks, digital tools can facilitate early warning systems for climate-sensitive diseases, support environmental monitoring, and enhance community-level responsiveness [7].

The implementation of Digital Public Health remains uneven across geographical regions. In Indonesia, structural disparities in infrastructure, connectivity, and human resource capacity present significant challenges to digital transformation [8]. A systematic literature review on digital health implementation in Indonesia reports persistent barriers, including limited digital infrastructure, interoperability challenges, regulatory gaps, and disparities in digital literacy across regions [9]. These challenges are particularly pronounced in Indonesia's disadvantaged, frontier, and outermost regions (3T regions), which are characterized by geographical isolation, limited health workforce availability, inadequate transportation networks, unstable electricity supply, and restricted internet access [10]. Evidence from Eastern Indonesia illustrates the complexity of implementing health programmes in 3T contexts. A qualitative study conducted in Kodi Balaghar District, Southwest Sumba, East Nusa Tenggara, found that although a filariasis elimination programme improved awareness and participation in mass drug administration, significant behavioural and environmental changes were not sustained [11]. This finding demonstrates that environmental health outcomes are shaped not only by programme delivery but also by behavioural, contextual, and systemic factors—issues that become increasingly critical under climate variability.

At the policy and governance level, an analysis of public health policy in West Papua and Central Maluku highlights implementation constraints related to limited resources, geographical barriers, weak coordination mechanisms, and systemic challenges in tropical disease management [12][13]. These structural factors are highly relevant to Digital Public Health implementation, particularly when addressing climate-sensitive diseases in remote island and border regions. Capacity-building initiatives in 3T areas demonstrate that digital transformation requires local empowerment and technical strengthening. A study conducted in Waingapu reported that strengthening the digital capacity of health cadres significantly improved knowledge and readiness for digital health transformation

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in remote settings [6]. Despite increasing recognition of digital health transformation and climate adaptation, existing studies in eastern Indonesia have examined different dimensions of healthcare implementation without directly establishing how these dimensions collectively influence climate-responsive digital public health. Studies conducted in Waingapu [10], Southwest Sumba [11], and West Papua–Central Maluku [12] provide complementary evidence concerning digital health workforce readiness, community behavior and environmental health, and public health governance, respectively. However, these studies differ in methodological approaches, research objectives, and outcome measurements. Furthermore, none directly evaluates the effectiveness of integrated digital public health interventions for climate change adaptation. Consequently, a structured analytical synthesis is needed to distinguish directly reported contextual challenges from their potential implications for climate-responsive digital public health development.

The Fishbone (Ishikawa) analytical framework offers a systematic approach for organizing multidimensional contributing factors across interrelated operational and environmental domains [13]. Its applicability in healthcare process evaluation has been demonstrated by Prasetya et al. [14], who applied Fishbone analysis to identify factors contributing to inconsistent bacterial culture media quality. Additionally, research published in Nursing Sciences Journal on digital innovation for inclusive disaster preparedness highlights the relevance of accessible digital communication in strengthening preparedness activities [15]. Although these studies address different healthcare contexts, they provide complementary methodological and implementation perspectives. Therefore, the present study applies an adapted Fishbone 6M framework to identify and synthesize contextual factors related to workforce capacity, implementation procedures, technological infrastructure, operational resources, monitoring systems, and environmental conditions. By examining three purposively selected contexts from eastern Indonesia, this study seeks to generate evidence-informed implementation considerations and research priorities for climate-responsive digital public health without assuming causal relationships or generalizability to all designated 3T regions.

METHODS

Study Design and Unit of Analysis

This study employed a qualitative document-based multiple-case analytical design to explore contextual factors potentially influencing digital public health implementation for climate change adaptation in remote and underserved settings of eastern Indonesia. The analytical approach combined purposive document selection, qualitative thematic synthesis, and an adapted Fishbone (Ishikawa) framework.

The unit of analysis was the published document rather than individual participants, healthcare institutions, or administrative districts. Three published reports were purposively selected to capture complementary dimensions of health-system implementation: digital health workforce readiness, community behavior and environmental health, and public health governance.

The selected documents were analyzed to identify directly reported findings, contextual implementation barriers, and potential implications for climate-responsive digital public health. The analysis was exploratory and interpretative, rather than a systematic review, quantitative meta-analysis, or direct evaluation of

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digital health interventions. Because the sources differed in design, setting, and outcome measures, the analysis focused on identifying conceptual relationships and implementation considerations rather than estimating the prevalence, magnitude, or causal effects of specific barriers.

Data Sources and Search Strategy

The analysis focused on three published documents identified through purposive examination of the literature relevant to digital health readiness, environmental health behavior, and tropical disease policy implementation in eastern Indonesia. The focal documents were selected for their complementary analytical contributions rather than through a claim of exhaustive systematic retrieval.

Supporting literature was consulted to contextualize the findings within broader discussions of climate-resilient health systems, digital health implementation, surveillance, and implementation science. These supporting publications were used for conceptual comparison and interpretation and were not treated as additional empirical cases.

The initial literature exploration considered scientific information indexed through sources such as Scopus, PubMed, ScienceDirect, and Google Scholar. However, a complete dated search log, database-specific retrieval counts, duplicate-removal records, and screening documentation were not available for retrospective verification. Consequently, the present analysis does not claim to be a reproducible systematic literature review.

For future replication or extension, a potential search strategy could combine digital health-related terms with climate adaptation and geographical context, using the following Boolean expression:
("digital health" OR "digital public health" OR "telemedicine" OR "surveillance") AND ("climate change" OR "climate adaptation" OR "environmental health" OR "climate-sensitive disease") AND ("remote" OR "rural" OR "underserved" OR "Indonesia" OR "3T"). Any subsequent systematic update should document database-specific search strings, search dates, filters, retrieval counts, duplicate removal, and eligibility screening decisions.

Eligibility Criteria and Study Selection

Documents were considered eligible for focal analysis when they met the following criteria: (1) addressed digital health readiness, environmental health behavior, or implementation of public health policies; (2) reported empirical observations or identifiable policy-related evidence from eastern Indonesia; (3) provided sufficient contextual information to support classification into at least one Fishbone domain; and (4) contained findings relevant to understanding implementation challenges in geographically constrained or underserved healthcare settings.

Documents were excluded from direct case coding if they were purely theoretical, lacked identifiable study settings or methodological information, duplicated the same contextual evidence, or did not provide information relevant to the analytical framework.

Three studies were purposively selected based on complementary thematic contributions. The Waingapu study [10] was selected to illustrate health cadre education and digital health readiness. The Southwest Sumba study [11] was included to examine community behavior and environmental conditions relevant

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to infectious disease prevention. The West Papua and Central Maluku policy analysis [12] was selected to illustrate governance, resource allocation, and geographical implementation challenges.

These cases were considered analytically complementary rather than statistically or geographically representative. Their selection does not establish that all study localities hold the same official administrative 3T classification. Furthermore, the relevance of findings to climate-responsive digital public health was treated as an analytical interpretation whenever climate-specific digital interventions were not directly examined.

Data Extraction and Thematic Synthesis

Data extraction was conducted using a structured analytical matrix developed to ensure consistent comparison across the three selected documents. The extracted information included bibliographic characteristics, study setting, methodological approach, research objectives, directly reported findings, contextual barriers, and study limitations.

The analytical process comprised four sequential stages. First, the selected documents were examined to identify findings explicitly reported by the original investigators. Second, relevant findings were organized into descriptive themes related to human capacity, implementation processes, infrastructure, material resources, monitoring systems, and environmental conditions. Third, the identified themes were mapped onto the adapted Fishbone 6M framework. Fourth, the resulting categories were compared across the three contextual sources to identify complementary implementation considerations and areas requiring further investigation. To improve analytical transparency, the evidence matrix distinguished between directly supported evidence (S) and author-derived interpretations (I). The S designation referred to findings explicitly reported in the selected publications, whereas I indicated conceptual implications developed by the authors for prospective climate-responsive digital public health implementation.

This distinction was maintained throughout the results and discussion to avoid presenting interpretative assumptions as empirical findings. Supporting international and Indonesian literature was used to contextualize the analysis without attributing external findings directly to the three focal studies.

Analytical Framework: Fishbone (Ishikawa) Analysis

The Fishbone (Ishikawa) analytical framework was applied to organize potential contributing factors influencing the development of climate-responsive digital public health systems. Six predefined analytical domains were used consistently throughout the study.

Man represented workforce capacity, digital literacy, health care knowledge, and community engagement. Method included programme procedures, service delivery, intersectoral coordination, and implementation governance. Machine referred to technological infrastructure, telecommunications, digital equipment, software, and electricity-dependent systems. Material encompassed physical supplies, operational resources, and other inputs required to sustain health programmes. Measurement included surveillance indicators, data reporting, performance monitoring, evaluation, and feedback mechanisms. Environment represented geographical conditions, environmental exposures,

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ecological factors, and sociocultural circumstances that could influence programme implementation.

The categories were adapted to the context of digital public health and environmental health while maintaining a consistent six-domain structure. Financing was treated as a cross-cutting consideration related to resource availability and governance, particularly within the Material and Method domains, rather than as an additional Money category.

The resulting Fishbone diagram was considered an interpretative representation of potentially interrelated factors. It was not intended to demonstrate causal relationships or quantify the contribution of individual factors to programme outcomes.

Ethical Considerations

This study relied exclusively on secondary data from publicly available literature and did not involve human participants; therefore, ethical approval was not required.

RESULTS AND DISCUSSION

Results

Characteristic of Selected Studies

The three selected studies addressed different but complementary components of public health implementation in eastern Indonesia. The Waingapu study examined the educational capacity of health cadres in relation to digital health transformation [10]. The Southwest Sumba study investigated community behavior and environmental conditions following a filariasis elimination programme [11]. The West Papua and Central Maluku study analyzed policy-related challenges in tropical disease management [12]. Table 1 summarizes the characteristics, directly reported findings, and interpretative relevance of the selected publications.

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The distinction between source-supported findings and analytical implications is maintained to avoid overstating the strength of the evidence.

Table 1. Characteristics of the Selected Publications and Their Contribution to the Fishbone Analysis

Study context	Study approach	Directly reported finding (S)	Fishbone relevance (I)
Waingapu [10]	Health care education and capacity-building activity	Improvement in cadre knowledge following digital health education	Man, Method, and Measurement; suggests evaluating sustained digital competence and reporting performance
Southwest Sumba [11]	Qualitative investigation of behavior and environmental conditions following a filariasis programme	Limited sustained changes in community behavior and environmental conditions	Man, Method, and Environment; suggests incorporating community engagement and environmental-health practices
West Papua–Central Maluku [12]	Public health policy analysis of tropical disease management	Resource, coordination, policy implementation, and geographical constraints	Method, Material, Man, and Environment; suggests examining governance arrangements and operational sustainability

Note: S denotes directly reported findings; I denotes interpretative implications developed through the Fishbone framework.

Cross-Case Synthesis and Fishbone Interpretation

The cross-case synthesis identified several contextual dimensions relevant to prospective digital public health development. The strongest directly documented findings concerned health cadre knowledge, community behavior and environmental conditions, and institutional policy implementation. These findings were subsequently mapped onto the adapted Fishbone 6M framework.

Human capacity and community engagement emerged as relevant considerations across the selected contexts, although their operational meaning differed between studies. In Waingapu, evidence concerned short-term educational outcomes, while in Southwest Sumba, the findings emphasized limitations in sustained behavioral and environmental change. The West Papua and Central Maluku policy analysis provided additional evidence concerning governance and resource-related implementation challenges.

The available focal evidence was insufficient to establish the actual performance of digital surveillance systems, internet connectivity, electricity reliability, interoperability, or climate-linked early warning mechanisms across all

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three locations. These elements were therefore classified as prospective assessment priorities rather than directly demonstrated local barriers**.**

Table 2. Evidence-to-Implication Matrix for Climate-Responsive Digital Public Health

Implementation factor	Supporting evidence	Implication	Evidence level
Workforce readiness	Waingapu [10]	Evaluate digital literacy, sustained competence, and reporting skills	S for knowledge; I for sustained adoption
Community behavior	Southwest Sumba [11]	Integrate community participation and environmental risk communication	S for behavior; I for digital application
Governance and resources	West Papua–Central Maluku [12]	Assess coordination, financing, and operational responsibilities	S for policy constraints; I for digital systems
Digital infrastructure	Broader digital health literature [7–9]	Verify local network, equipment, and electricity readiness	Supporting literature; prospective local verification required
Climate-health surveillance	Surveillance literature [3,20]	Evaluate integration of health and environmental indicators	Conceptual implication; not directly tested in focal cases

The Fisbone Analysis

The Fishbone analysis identified multidimensional and interconnected implementation barriers across the three representative 3T regions. In Waingapu, weak digital health readiness was primarily influenced by limited digital literacy, insufficient training, inadequate digital equipment and software access, poor internet connectivity, and gaps in monitoring and data management systems. Geographic remoteness and infrastructure limitations further constrained digital health implementation. In Southwest Sumba, environmental health challenges were strongly associated with low health awareness, cultural practices affecting sanitation behavior, poor waste management, water scarcity, and limited WASH facilities. Additional constraints included insufficient disease surveillance and limited availability of climate-related health data, contributing to increased environmental health risks. In West Papua and Central Maluku, major barriers were related to workforce shortages, limited institutional capacity, weak coordination mechanisms, fragmented policy implementation, funding constraints, geographic isolation, and fragmented monitoring systems. These structural limitations collectively created strong implementation barriers for climate-responsive public health interventions. The findings demonstrate that challenges across human resources, infrastructure readiness, governance coordination, environmental

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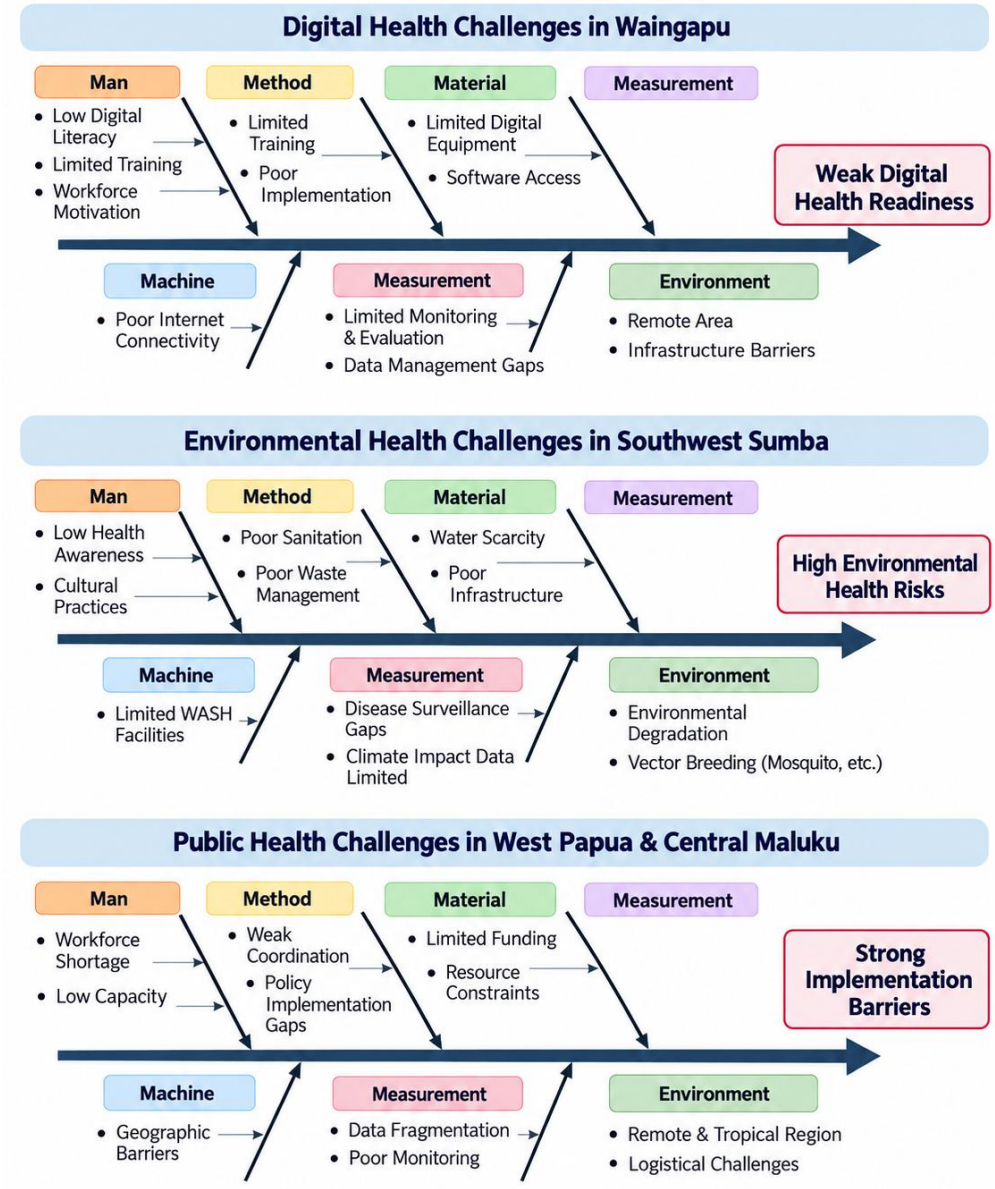
conditions, and data systems interact to influence the effectiveness of Digital Public Health implementation in Indonesia's 3T regions.

Figure 1. Adapted Fishbone (6M) framework illustrating potential contextual factors affecting the development of climate-responsive digital public health in three purposively selected eastern Indonesian settings. The diagram integrates directly reported findings and analytical interpretations and does not establish causal relationships or intervention effectiveness.

DISCUSSION

Interpretation of the Main Findings

The present study provides an integrated interpretation of contextual factors potentially influencing the development of climate-responsive Digital Public Health in selected remote and underserved settings of eastern Indonesia. Through



the adapted Fishbone 6M framework, the findings highlight the importance of human resource capacity, implementation procedures, technological infrastructure, operational resources, monitoring systems, and environmental

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conditions. These dimensions are conceptually interconnected and may influence the feasibility and sustainability of digital public health initiatives. However, the identified relationships should be interpreted as analytical propositions rather than empirically established causal mechanisms.

The three selected studies contribute complementary perspectives on public health implementation. The study conducted in Waingapu emphasizes the importance of strengthening health cadre knowledge concerning digital health transformation [10]. Evidence from Southwest Sumba illustrates the challenges of achieving sustained behavioral and environmental changes following a filariasis elimination programme [11]. Meanwhile, the policy analysis conducted in West Papua and Central Maluku identifies governance, geographical, and resource-related constraints affecting tropical disease management [12]. Although these studies address different outcomes, their synthesis provides a contextual foundation for identifying implementation considerations relevant to future digital public health and climate adaptation strategies. This interpretation is consistent with broader evidence indicating that digital health interventions in rural and remote Indonesia require coordinated improvements in institutional capacity, workforce readiness, governance, and technological infrastructure [7].

Digital Public Health Readiness in Waingapu

The Fishbone analysis of the Waingapu context highlights human resource readiness as an important component of digital health transformation. Under the Man domain, health cadre knowledge and technological literacy represent relevant factors influencing the potential adoption of digital health services. Hidayat et al. [10] conducted capacity-building activities involving 31 health cadres and reported improvements in participants' knowledge following workshops and educational interventions concerning digital health and telehealth. These findings indicate that structured educational activities can contribute to short-term improvements in digital health knowledge among frontline community health workers.

Improvements in knowledge should not automatically be interpreted as evidence of sustained technology adoption, improved health service performance, or successful implementation of climate-related digital surveillance. Digital literacy involves not only understanding technological concepts but also the ability to use digital applications, interpret health information, maintain data accuracy, and communicate information effectively. Therefore, future interventions should evaluate practical competencies, continued technology utilization, and the integration of digital reporting into routine healthcare activities.

Within the Method domain, standardized training procedures, operational guidance, and continuing technical assistance should be considered when designing digital health implementation programmes. The Machine and Material domains additionally highlight the need to assess device availability, telecommunications infrastructure, software compatibility, electricity reliability, and operational resources. Although these factors were not comprehensively measured in the Waingapu study, they have been identified as important implementation considerations in broader research concerning digital health systems in low-resource settings [7–9].

A scoping review by Wasir et al. [7] demonstrated that digital health interventions in rural and remote Indonesia can support healthcare continuity, service accessibility, information exchange, and frontline adaptation. However, the review also identified persistent constraints related to connectivity, digital literacy,

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fragmented information systems, and governance. These findings suggest that workforce capacity-building should be integrated with broader organizational and infrastructure readiness rather than implemented as an isolated educational activity.

The Measurement domain further emphasizes the importance of evaluating digital health performance through indicators that extend beyond immediate improvements in knowledge. Relevant measures may include reporting completeness, data accuracy, application usability, user retention, and timeliness of health information transmission. For climate-responsive applications, these indicators could be expanded to assess the capacity of digital systems to communicate environmental health warnings and support timely public health responses. However, such applications require prospective validation because their effectiveness was not directly evaluated in the Waingapu study.

Environmental Health Challenges in Southwest Sumba

The Fishbone analysis of Southwest Sumba emphasizes the importance of community behavior and environmental conditions in determining the sustainability of public health interventions. Under the Man domain, community knowledge, attitudes, participation, and preventive practices represent relevant considerations for environmental health management. Irfan et al. [11] investigated community behavior and environmental conditions following a filariasis elimination programme in Kodi Balaghar District, Southwest Sumba Regency. The study identified improvements in knowledge and medication adherence but reported limited changes in daily preventive behavior and environmental conditions.

These findings suggest that increased awareness and participation in a specific health intervention may not necessarily produce sustained improvements in environmental health practices. Community behavior is influenced by multiple contextual factors, including social norms, local resources, perceived health risks, and the feasibility of implementing preventive measures. Consequently, public health programmes should consider community engagement and locally appropriate behavioral strategies alongside the delivery of health information.

Similar considerations have been described by Prasetya et al. [24] in a community-based public health activity addressing clean and healthy living behavior (*Perilaku Hidup Bersih dan Sehat*, PHBS) for dengue prevention in Sidoarjo, Indonesia. Their study reported improvements in community understanding of dengue prevention and the implementation of environmental management activities following educational and participatory interventions. Although conducted outside the selected eastern Indonesian contexts, this publication provides complementary evidence regarding the relevance of community education, environmental management, and public participation in the prevention of vector-borne diseases.

From the Method perspective, environmental health programmes should integrate health education with practical approaches to sanitation, waste management, mosquito breeding-site reduction, and community-based environmental monitoring. The Environment domain emphasizes that local ecological conditions, water availability, settlement characteristics, and vector exposure may influence population vulnerability to infectious diseases.

Climate change introduces additional challenges because variations in temperature, rainfall, and extreme weather can influence environmental conditions and the geographical distribution of certain climate-sensitive diseases [1,3].

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However, the Southwest Sumba study did not directly establish a causal relationship between climate variability and the observed behavioral or environmental outcomes. Its relevance to climate adaptation should therefore be understood as contextual rather than as direct empirical evidence of climate-related intervention effectiveness.

The Measurement domain identifies an opportunity to investigate how routine environmental health indicators and disease surveillance data could be integrated into future digital public health systems. Previous research has highlighted the potential of digital technologies to improve the prediction, detection, and monitoring of vector-borne disease outbreaks [3]. Similarly, Villanueva-Miranda et al. [20] described opportunities for artificial intelligence and digital early warning systems in infectious disease surveillance.

The effectiveness of such technologies depends on data availability, surveillance quality, local technical capacity, and the translation of warnings into actionable public health responses. Therefore, integrating digital environmental monitoring with established community health programmes should be considered a prospective implementation strategy rather than an intervention already demonstrated to be effective in Southwest Sumba.

Public Health Implementation Barriers in West Papua and Central Maluku

The Fishbone analysis of West Papua and Central Maluku highlights governance and operational constraints as important contextual considerations for health programme implementation. Maruapey et al. [12] examined public health policies concerning tropical disease management and identified challenges related to geographical accessibility, resource limitations, institutional coordination, and policy implementation. Under the Man domain, workforce capacity and the availability of trained healthcare personnel are relevant considerations for programme continuity. In geographically dispersed settings, differences in staffing availability and institutional capacity may complicate the implementation of standardized healthcare services. These issues suggest the importance of assessing local personnel requirements, technical support mechanisms, and training arrangements before introducing additional digital reporting responsibilities.

The Method domain emphasizes the role of governance, intersectoral coordination, and operational procedures. Fragmented programme implementation and limited coordination may restrict the ability of health systems to translate available information into timely decisions. In the context of Digital Public Health, future interventions should establish clear institutional responsibilities for data collection, information verification, risk communication, and response coordination.

These considerations are consistent with the World Health Organization's Global Strategy on Digital Health 2020–2027, which emphasizes that successful digital transformation requires the integration of technological, organizational, financial, and human resources [5]. Digital technologies should therefore complement established public health structures rather than function as independent solutions to systemic governance challenges.

The Material domain includes the availability of operational resources, equipment, and programme support. Financial constraints should be considered a cross-cutting issue that influences resource allocation, infrastructure maintenance,

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workforce development, and implementation continuity. Within the adapted Fishbone framework, financing is incorporated into the Material and Method domains rather than introduced as an additional Money category, thereby maintaining consistency with the predefined 6M classification.

The Environment domain is particularly relevant to geographical accessibility and logistical challenges. Remote locations and dispersed island settlements may require context-specific approaches to healthcare delivery and technological infrastructure. Nevertheless, the extent of these constraints should be established using location-specific assessments rather than inferred solely from the geographical characteristics of a region.

The Measurement domain further indicates the need for coherent monitoring mechanisms and reliable information systems. Prospective digital public health initiatives should examine whether existing reporting structures can accommodate environmental indicators, infectious disease surveillance, and climate-related risk communication without introducing unnecessary administrative burdens.

Evidence from digital health implementation studies indicates that long-term sustainability is strongly influenced by governance quality, organizational integration, financing, and compatibility with existing healthcare workflows [8,9]. Therefore, future climate-responsive digital health programmes in West Papua, Central Maluku, or comparable underserved settings should be supported by locally validated assessments of infrastructure, institutional readiness, and operational feasibility.

Integrated Fishbone 6M Analysis and Comparative Synthesis

The integrated Fishbone analysis illustrates that the three selected contexts contribute different but complementary perspectives on public health implementation. Waingapu primarily provides evidence concerning short-term improvements in digital health knowledge among community health cadres. Southwest Sumba emphasizes the difficulties of maintaining behavioral and environmental changes following a public health programme. West Papua and Central Maluku contribute evidence regarding governance, resource allocation, and operational challenges in tropical disease management.

These findings can be organized into six interconnected analytical domains. Man represents the human capabilities required to understand, adopt, and sustain health interventions. Method encompasses programme procedures, implementation coordination, and institutional responsibilities. Machine represents technological and physical infrastructure required to operate digital systems. Material includes equipment, supplies, and operational resources. Measurement focuses on data quality, surveillance, performance evaluation, and feedback mechanisms. Environment incorporates geographical, ecological, and sociocultural conditions that may influence programme implementation.

Importantly, these domains should not be interpreted as independently validated causal determinants. Instead, the Fishbone framework provides a structured representation of contextual conditions and implementation hypotheses derived from the selected literature. The distinction between directly supported findings and author-derived interpretations is particularly important because the

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three publications differ in their research objectives, methodologies, and outcome measures.

The methodological relevance of Fishbone analysis is supported by Kumah et al. [13], who described cause-and-effect diagrams as tools for generating and organizing quality improvement ideas. In addition, Prasetya et al. [14] applied the Fishbone (Ishikawa) diagram to investigate factors contributing to inconsistent bacterial culture media quality in a healthcare laboratory. Their study emphasized the importance of examining process-related and organizational factors when identifying potential causes of quality problems. Although the research context of Prasetya et al. [14] differs from digital public health and climate adaptation, the study provides a relevant methodological example of structured problem analysis in healthcare. Its inclusion supports the selection of Fishbone as an analytical classification framework while not implying that the present synthesis has established causal relationships between the identified categories and health outcomes.

The broader literature also indicates that health-system resilience requires coordinated attention to workforce capacity, institutional governance, operational resources, infrastructure, and environmental preparedness. Sulistiadi et al. [6] highlighted the social, economic, and cultural dimensions of climate-related health-system resilience in Indonesia, while the World Health Organization emphasized integrated planning, risk assessment, surveillance, and institutional preparedness in its operational framework for climate-resilient health systems [4].

Accordingly, Digital Public Health should be conceptualized as a potentially enabling component of climate adaptation rather than as a standalone technological solution. Effective implementation requires consideration of local health-system capabilities, environmental risks, community participation, and the organizational arrangements necessary to transform information into public health action.

Relevance of Digital Innovation and Inclusive Health Communication

Digital health implementation also requires attention to communication accessibility and the diversity of intended users. Digital platforms may facilitate health education, disaster preparedness, and risk communication, but their usefulness depends on whether information can be understood and applied by different population groups. Christianingsih et al. [15], in a study published in Nursing Sciences Journal, investigated the use of interactive multimedia learning for inclusive disaster preparedness education among deaf students. Their research demonstrated the relevance of accessible digital learning approaches for improving preparedness-related knowledge within a specific vulnerable population.

Although the study did not evaluate climate-related surveillance or digital public health implementation in 3T regions, its findings provide a complementary perspective on inclusive communication. This is relevant to the development of digital public health strategies because technological interventions should accommodate differences in communication needs, health literacy, and accessibility. For remote and underserved communities, future digital health initiatives could consider accessible information formats, locally appropriate communication approaches, and alternative channels for settings with limited internet connectivity. These design considerations should be evaluated through participatory development and user-centered feasibility testing rather than assumed to be universally effective. Taken together, the publications by Prasetya

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et al. [14,24] and Christianingsih et al. [15] contribute three complementary perspectives: structured healthcare problem analysis, community-based environmental health education, and inclusive digital preparedness communication. These studies strengthen the methodological and conceptual interpretation of the present research but do not constitute additional empirical cases within the three-context Fishbone analysis.

Implications for Climate-Responsive Digital Public Health Development

The findings suggest several priorities for the future development and evaluation of climate-responsive Digital Public Health in remote and underserved settings. First, local implementation assessments should evaluate workforce readiness, community participation, institutional responsibilities, and existing healthcare workflows. Digital health training should be accompanied by practical assessments of technology use, reporting competence, and the ability of health workers to interpret and communicate environmental health information.

Second, technological readiness should be assessed through verified information concerning internet connectivity, electricity availability, device compatibility, data storage, cybersecurity arrangements, and technical maintenance. Where infrastructure is limited, prospective digital systems could explore offline functionality, low-bandwidth data transmission, and synchronization mechanisms appropriate to local conditions.

Third, governance arrangements should support collaboration between healthcare institutions, local government, environmental agencies, and relevant community organizations. This coordination is important for determining responsibilities for surveillance data, identifying locally appropriate response thresholds, and ensuring that information contributes to actionable public health decisions.

Fourth, climate-responsive surveillance should consider integrating routinely collected health indicators with relevant environmental and meteorological information. Potential applications include monitoring climate-sensitive infectious diseases, identifying environmental risk patterns, and supporting timely risk communication. However, the selection and interpretation of indicators must be adapted to local epidemiological conditions and available data.

The World Health Organization recommends that climate resilience indicators be selected according to relevant health-system priorities and the specific risks faced by the population [25]. Potential evaluation measures include surveillance reporting completeness, data timeliness, system availability, communication accessibility, response time following alerts, and continuity of essential public health functions during environmental disturbances.

Finally, future interventions should undergo prospective feasibility and effectiveness evaluations before broader implementation. Such evaluations should address not only technological performance but also community acceptability, operational sustainability, resource requirements, and equity in access to digital public health services. These proposed actions represent evidence-informed research and implementation priorities. The present study does not provide direct

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evidence that their implementation would independently reduce climate-related health risks or improve disease outcomes in the three selected settings.

Strengths and Limitations

The principal strength of this study is its structured integration of complementary contextual evidence through an adapted Fishbone 6M framework. By examining workforce readiness, community environmental behavior, and health-system governance within a common analytical structure, the study identifies implementation considerations that may be relevant to future climate-responsive digital public health research.

An additional strength is the explicit distinction between findings directly reported in the selected publications and interpretations developed by the authors. This distinction improves analytical transparency and reduces the risk of presenting conceptual implications as established empirical evidence. Nevertheless, several limitations should be acknowledged. First, the study was based on only three purposively selected publications with different research objectives, methodological approaches, and outcome measures. Consequently, the findings cannot be considered statistically representative of all disadvantaged, frontier, and outermost regions in Indonesia.

Second, only the Waingapu publication directly examined digital health education, whereas the Southwest Sumba and West Papua–Central Maluku studies focused on environmental health behavior and public health policy, respectively. None of the three studies directly evaluated the effectiveness of an integrated digital public health intervention for climate change adaptation.

Third, the study relied exclusively on secondary publications and did not include field observations, interviews, stakeholder validation, or direct measurement of digital infrastructure and surveillance performance. Therefore, the Fishbone categories represent analytical classifications and should not be interpreted as independently confirmed causal factors.

Fourth, the official administrative 3T classification of each study locality was not independently verified. The findings are consequently more appropriately interpreted as contextual evidence from selected eastern Indonesian settings rather than as conclusions representing all officially designated 3T territories.The original exploratory literature identification process did not retain complete database-specific search logs, retrieval counts, and screening records. This limitation restricts the reproducibility and comprehensiveness of source identification. Future research should employ a prospectively documented literature search or primary implementation study, supported by transparent eligibility criteria and appropriate methodological reporting standards [18,19,26]. Despite these limitations, the present analysis offers a preliminary conceptual framework for identifying implementation priorities and guiding future empirical investigations. Prospective studies involving local healthcare providers, community representatives, environmental health professionals, and policy stakeholders are required to validate the proposed relationships and evaluate the feasibility, sustainability, and effectiveness of climate-responsive Digital Public Health interventions.

CONCLUSION

This qualitative document-based analysis identified complementary contextual factors potentially relevant to the development of climate-responsive

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digital public health in three purposively selected eastern Indonesian settings. Directly reported evidence concerned improvements in short-term health cadre knowledge in Waingapu, persistent behavioral and environmental challenges in Southwest Sumba, and governance and resource-related constraints in West Papua and Central Maluku.

The adapted Fishbone 6M framework provided a structured approach to organizing these findings across human capacity, implementation procedures, technological infrastructure, operational resources, monitoring systems, and environmental context. However, the analysis did not establish causal relationships or demonstrate the effectiveness of digital public health interventions for climate change adaptation.

Future research should prioritize locally validated needs assessments, community participation, infrastructure and governance readiness, and prospective evaluation of digital surveillance and environmental health responses. Because the analysis was based on three heterogeneous and purposively selected sources, the findings should not be generalized to all 3T regions in Indonesia.

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest, either financial or non-financial, related to this research.

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