

Environmental Health in the Era of Climate Crisis and Urbanization: A Review of Determinants, Risks, Technology, and Sustainable Governance

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ABSTRACT

Environmental health is increasingly determined by the convergence of air pollution, water and sanitation limitations, waste management, climate change, urbanization, and social inequalities that shape unequal exposure and vulnerability. This article aims to synthesize the latest evidence on the relationship between environmental determinants and public health risks and identify governance, technology, mitigation-adaptation, and stakeholder participation strategies that support sustainable environmental health, with special attention to the context of developing countries and Indonesia. The research uses qualitative literature review with thematical-interpretive synthesis of peer-reviewed articles, especially in the period 2020 to 2026 which are searched in a directional manner through databases and scientific platforms. The results of the synthesis show that environmental health risks are interrelated: exposure to particulates and chemical pollutants is associated with respiratory, cardiovascular, and metabolic diseases; unsafe WASH services increase the risk of infectious diseases; new sewage and contaminants expand the path of exposure; Meanwhile, climate change amplifies the dangers of heat, vector-based diseases, and pressures on water and food. The most consistent response requires prevention at source, strengthening of basic services, mitigation-adaptation integration, sensor- and data-based monitoring, cross-sectoral governance, and equitable community participation. The article proposes an integrated environmental health model based on risk, justice, and planetary health as a policy framework and future research agenda

INTRODUCTION

Environmental health is a field of public health that examines how physical, chemical, biological, and social and spatial characteristics of the environment affect health exposure, vulnerability, and outcomes. In the context of rapid urbanization, land-use change, increased energy needs, and material consumption, these determinants do not work in isolation. The urban literature shows that air quality, characteristics of the built environment, access to green space, noise, temperature, water, and sanitation interact with socioeconomic conditions resulting in different risk patterns between population groups (Salgado et al., 2020; Ebi et al., 2020).

The urgency of environmental health is increasing as the burden of modern exposure takes place simultaneously with classic risks. Air pollution remains associated with a wide range of respiratory and cardiovascular outcomes, while long-term PM_{2.5} exposure is associated with mortality and cardiovascular disease incidence. At the household level, air pollution from solid fuels also remains an important source of risk, especially in groups with limited access to clean energy (Chen and Hoek, 2020; Dominski et al., 2021; Lee et al., 2020).

Indonesia represents a context that shows the overlap of these risks. Indonesia's data-driven study showed an association between PM_{2.5} exposure and diabetes prevalence, while an evaluation in Jakarta documented the substantial health and economic burden of PM_{2.5} and ozone. Other research shows that national survey data have great potential for exposure-response studies, but the quality of exposure estimation, data interconnectedness, and spatial representation still need to be strengthened. The findings in the Maros industrial estate also remind that particulates can carry toxic elements with different risk implications for children and adults (Suryadhi et al., 2020; Agustian et al., 2020; Rauf et al., 2021; Syuhada et al., 2023).

At the same time, water, sanitation, and hygiene (WASH) remain the foundation of environmental health. The Indonesian study shows that WASH research has evolved, but research on implementation, behavior change, financing, and geographic distribution of evidence remains unbalanced. Large-scale sanitation program evaluation shows the importance of political commitment, local government capacity, planning, financing, monitoring, and supervision in improving sanitation achievements. Globally, intervention evidence also suggests that improved water quality, sanitation, and handwashing can lower the risk of diarrhoea in children in low- and middle-income countries (Odagiri et al., 2020; Satriani et al., 2022; Wolf et al., 2022).

Climate change increases complexity because it functions as a risk multiplier. Rising temperatures, extreme weather events, changes in rainfall patterns, and vector ecological dynamics can change disease patterns, aggravate children's vulnerability, reduce water availability, and disrupt health systems. Indonesia's evidence on the relationship between climate and vector-based diseases shows an important relationship, as well as methodological heterogeneity and the need for higher quality data. Thus, environmental health is no longer adequate if it is treated as a separate collection of technical issues; it

requires a systems perspective that connects human health with the stability of ecological systems (Helldén et al., 2021; Berrang-Ford et al., 2021; Marina et al., 2023).

Another challenge is the environmental justice dimension. Exposure to pollutants and the ability to avoid or mitigate risks are influenced by income, residential location, housing quality, access to public services, and social position. Evidence on inequality of PM_{2.5} exposure and community participation literature suggests that environmental health responses need to take into account the distribution of benefits, burdens, sounds, and adaptive capacity, not just technical efficiency. The planetary health framework expands this orientation by placing human health within the boundaries and functions of the earth's life support systems (Tessum et al., 2021; Hügel and Davies, 2020; Ebi et al., 2020).

Based on these gaps, this article develops a qualitative synthesis that connects determinants, pathways of exposure, vulnerability, health outcomes, and intervention options in one analytical flow. Two research questions were used. RQ1: How do the interactions of key environmental determinants—air quality, water and sanitation, waste, climate change, and urban environmental characteristics—shape public health risks in the up-to-date literature? RQ2: What strategies for governance, technology, mitigation-adaptation, and stakeholder participation are most consistently supported by the literature to strengthen sustainable environmental health, especially in the context of developing countries such as Indonesia?

In line with these two questions, the objectives of the article are: (1) to describe and synthesize the conceptual mechanisms that link environmental determinants to health exposures, susceptibility, and outcomes; (2) compare evidence regarding key risks to the domains of air, WASH, waste, climate, and the urban environment; and (3) formulate policy implications in the form of an integrated environmental health management model that combines prevention, justice, technology, mitigation-adaptation, and cross-sectoral governance. With this orientation, the article is expected to make a conceptual and operational contribution to discussions on environmental health and sustainable development (Pham et al., 2023; Whitmee et al., 2021).

LITERATURE REVIEW

Definition and Scope of Environmental Health

Conceptually, environmental health can be understood as the study and practice that focuses on external factors that affect health as well as actions to prevent or reduce adverse exposures. Its scope spans environmental media—air, water, soil, food, and the built environment—as well as the social mechanisms that determine who is exposed, to what extent, and with what protective capacity. A study of urban health determinants shows that relevant environmental indicators include pollutant exposure, spatial characteristics, mobility, resource access, and ecosystem quality, so the operational definition of environmental health must be multidimensional (Salgado et al., 2020; Manisalidis et al., 2020).

The development of the concept of planetary health emphasizes that environmental health is not limited to local pollution control. Biodiversity degradation, climate change, pressures on food and water systems, and changes in the Earth's systems form the basic conditions for population health. Therefore, the contemporary environmental health agenda is moving from a single hazard control paradigm to systemic, transdisciplinary, and cross-scale risk management that connects health, ecology, economics, and social justice (Ebi et al., 2020; Butler et al., 2021; Pham et al., 2023).

Conceptual Framework: Determinants, Exposures, Vulnerabilities, and Health Outcomes

A useful framework for reading the environmental health literature is a set of hazard sources–exposure pathways–receptors–outcomes. Sources of hazards can be vehicle and industrial emissions, domestic waste, water contamination, extreme heat, or ecological change. Pathways of exposure include inhalation, ingestion, dermal contact, exposure through food, and indirect exposure through socio-economic changes. The magnitude of the impact is further modified by biological vulnerability, age, comorbidities, occupation, housing conditions, and access to health services and environmental infrastructure (Dominski et al., 2021; Helldén et al., 2021).

The framework needs to be equipped with an inequality dimension because the distribution of exposure is not random. Urban structures, emission source patterns, spatial segregation, and resource inequality can put certain groups at a combination of higher hazards and lower adaptation capacity. Studies on PM_{2.5} source inequality show that almost all major source categories can contribute to exposure disparities, while green space studies show that the quality and accessibility of spaces, not just their existence, affect potential health benefits (Tessum et al., 2021; Nguyen et al., 2021).

The theoretical implication is that environmental health assessments should not stop at pollutant concentrations or facility indicators. The analysis needed to correlate exposure intensity, duration, vulnerability, spatial distribution, and health consequences, and then test whether the intervention reduced total risk or simply shifted the risk between spaces and between groups. This orientation is in line with the need for a transdisciplinary and multi-scale approach in the human and planetary health agenda (Ebi et al., 2020; Pham et al., 2023).

Air Quality and Health Risks

Air pollution is one of the domains with the most consistent epidemiological evidence. Mapping of systematic review and meta-analysis showed the relationship between air pollution and various outcomes, especially respiratory and cardiovascular diseases, with PM_{2.5}, PM₁₀, and NO₂ as the most frequently studied pollutants. Meta-analysis of long-term exposure to PM also supports associations with all-cause mortality and a number of specific causes, so that controlling emissions at sources remains a fundamental public health strategy (Chen and Hoek, 2020; Dominski et al., 2021).

The proposed biological mechanisms include oxidative stress, systemic inflammation, endothelial dysfunction, autonomic changes, and atherosclerotic

processes. Consistent with these mechanisms, a long-term PM_{2.5} meta-analysis found an increased risk of ischemic heart disease and stroke outcomes, while studies combining human and animal evidence showed an association with blood pressure, coronary syndrome, arrhythmias, and heart failure. Thus, air quality indicators need to be positioned as health indicators, not solely environmental indicators (Alexeeff et al., 2021; Lederer et al., 2021).

Indoor exposure is also important, especially in households that use solid fuels or are in environments with high outdoor pollution penetration. Household air pollution studies linked exposure to respiratory, cardiovascular, maternal, and pediatric outcomes. Individual-level interventions such as HEPA filters and appropriate respirators can reduce exposure in certain situations, but personalized strategies cannot replace population emission control and clean energy transition (Lee et al., 2020; Allen and Barn, 2020).

In the Indonesian context, Suryadhi et al. (2020) found a positive association between PM_{2.5} exposure and diabetes prevalence in national data, while Syuhada et al. (2023) showed that Jakarta's air pollution produces a large health and economic burden. Agustian et al. (2020) affirmed the potential of IFLS for exposure-response studies, and Rauf et al. (2021) pointed out the need for attention to particulate-bound toxic elements in industrial estates. This evidence supports the need for emission inventories, quality monitoring, high-resolution exposure data, and health-environmental information integration (Haryanto, 2020; Morimoto et al., 2020; Suryadhi et al., 2020; Agustian et al., 2020; Rauf et al., 2021; Syuhada et al., 2023).

Water, Sanitation, and Hygiene as Health Infrastructure

Safe drinking water, sanitation, and hygiene form a chain of protection that works from the prevention of source contamination, water treatment and distribution, excrete separation, to handwashing behavior. A meta-analysis of interventions in low- and middle-income countries showed that increased levels of water, sanitation, and handwashing services lowered the risk of children's diarrhoea, although the magnitude of the effects varied by type and quality of the intervention. Other studies have shown that WASH improvement can interact with nutritional status and fecal environmental exposure, so that health outcomes are influenced by a combination of infrastructure and behavior (Wolf et al., 2022; Bekele et al., 2020; Goddard et al., 2020).

In outbreak circumstances and vulnerable contexts, the effectiveness of WASH also depends on implementation. The review of cholera prevention guidelines shows the importance of a combination of household and community interventions, but the quality of the recommendations and the context of implementation need to be considered. This suggests that water treatment technologies without adoption, maintenance, continuous access, and risk communication are not enough to produce stable health protection (D'Mello-Guyett et al., 2020; Wolf et al., 2022).

Indonesian literature shows a similar agenda. Satriani et al. (2022) found the dominance of social themes in WASH research and limited implementation studies and behavior change. The evaluation of Odagiri et al. (2020) shows that strengthening government capacity, planning, financing, monitoring, and

political mobilization is related to improving sanitation achievements. In the archipelago, Birawida et al. (2021) showed that behavior and density of housing are related to the vulnerability of clean water. Thus, WASH needs to be understood as a service system that combines infrastructure, institutions, behaviors, and geographical conditions.

Waste, Hazardous Materials, and New Contaminants

Waste management forms an exposure pathway through air, soil, water, food, and work contact. A systematic review of municipal solid waste found indications of health risks in populations living around landfills, incinerators, and open dumping/open burning sites, although the heterogeneity of the study design limited the inference to specific technologies. The incineration study also emphasizes the importance of technology, maintenance, emission characteristics, and a prudent approach in risk interpretation (Tait et al., 2020; Vinti et al., 2021).

In many low- and middle-income countries, the open burning of plastic waste is a special issue because it can release particulates, organic compounds, and toxic elements. A review focusing on Global South shows a potential high risk to informal workers and communities around the burn site. E-waste adds complexity because it contains heavy metals and persistent organic pollutants; Recent systematic reviews show specific vulnerabilities in children and pregnant women in exposed areas (Velis and Cook, 2021; Parvez et al., 2021).

Microplastics are expanding the environmental health agenda to new contaminants. Current evidence identifies pathways of exposure through ingestion, inhalation, and contact, but causal relationships with human clinical disease still face exposure uncertainty, standardization of methods, and limitations of longitudinal studies. Therefore, the synthesis of evidence must distinguish between the existence of exposure, mechanistic plausibility, and certainty of clinical impact; the principle of prudence remains relevant without exaggerating the available evidence (Rahman et al., 2021; Vethaak and Legler, 2021; Cho and Choi, 2021; Huang et al., 2021).

Climate Change, Heat, and Vector-Based Diseases

Climate change affects health through direct and indirect pathways. Direct pathways include extreme heat and weather-related disasters; Indirect pathways include changes in air quality, water availability, food production, infectious diseases, population displacement, and pressures on health systems. The Lancet Countdown report and global literature mapping show that the evidence on the climate-health link is growing rapidly, but the geographic distribution of evidence remains uneven and many vulnerable regions are underrepresented (Watts et al., 2021; Vicedo-Cabrera et al., 2021; Romanello et al., 2021; Berrang-Ford et al., 2021).

Children are a very vulnerable group due to their stages of biological development, dependence on caregivers, and longer life spans to experience the cumulative consequences of climate change. The conceptual framework of child health places social determinants, food, water, infectious diseases, and direct exposure as interconnected pathways. This perspective is relevant for environmental health in general because it shows that climate risks cannot be managed with a single health intervention (Helldén et al., 2021; Friel, 2020).

For Indonesia, the review of Marina et al. (2023) found evidence of a link between climate variability and vector-based diseases, but also highlighted the heterogeneity of methods and quality of the evidence. The implication is the need for surveillance systems that combine weather, environmental, vector, and disease data with adequate space-time resolution. The adaptation approach needs to be directed at strengthening health systems, early warning, vector control, water resilience, and protection of vulnerable groups (Marina et al., 2023; Romanello et al., 2021).

Urbanization, Green Space, and Environmental Justice

Urbanization generates opportunities as well as health risks. Density can support efficient public services, but without planning it can increase transportation emissions, urban heat, water and sanitation pressure, noise, and inequality of access to healthy amenities. Green space is one of the built-up environmental interventions that is associated with health benefits, including physical, mental, and sleep health, but the effects are influenced by quality, affordability, safety, and actual use (Gianfredi et al., 2021; Nguyen et al., 2021; Shin et al., 2020).

Spatial studies show that green-blue space works through a number of pathways: increased physical activity, psychological restoration, social interaction, heat mitigation, and changes in pollution exposure. However, the mere existence of green space does not guarantee benefits if the target group is unable or unwilling to use it. Therefore, quantity indicators need to be complemented by quality and access indicators, and evaluated with the risk of displacement or green gentrification so that interventions do not deepen inequality (Labib et al., 2020; Rugel and Brauer, 2020; Yessoufou et al., 2020).

Environmental justice provides a normative basis for the design. Studies of PM_{2.5} inequality show that pollution sources can generate systemic disparities, so policies that only pursue average population declines have the potential to leave hotspots vulnerable. The principle of justice demands an evaluation of the distribution of exposure, representation of affected groups, transparency of information, and the ability of communities to influence decisions concerning the environment in which they live (Tessum et al., 2021; Mukherjee and Sastry, 2022).

Technology, Monitoring, Participation, and Governance

Low-cost sensors, the Internet of Things (IoT), geospatial data, artificial intelligence, and real-time monitoring platforms open up opportunities to improve the resolution of environmental health information. Systematic review of IoT-based air quality sensor systems shows the potential for sensor integration, connectivity, and remote monitoring, while AI review in waste management shows applications in waste character prediction, route optimization, charge rate detection, and system planning. However, sensor quality, calibration, interoperability, representativeness, and data governance are prerequisites for digitalization not to produce biased data-driven decisions (Saini et al., 2021; Abdallah et al., 2020).

Technology also needs to be placed within participatory institutions and processes. The climate adaptation participation literature shows a paradox

between participatory aspirations and decision-making practices that remain top-down. In environmental health interventions, the way a problem is defined affects who is considered to have responsibility and how far the community is involved. Thus, co-design, two-way risk communication, and accountability mechanisms are part of the effectiveness of interventions, not social accessories (Hügel and Davies, 2020; Mukherjee and Sastry, 2022).

Evidence of community engagement in low- and middle-income countries suggests that social mechanisms—changing norms, cohesion, community capacity, and shared leadership—can support disease control, but their effectiveness is highly contextual. For environmental health, the implication is that the sustainability of WASH interventions, waste management, vector control, and climate preparedness will improve when communities have a real role in planning, implementation, and evaluation (Questa et al., 2020; Odagiri et al., 2020).

Environmental Health and Sustainable Development

The relationship between environmental health and sustainable development is two-way. Energy development, transportation, housing, food, water, and industry determine the exposure profile; Conversely, the burden of environmental diseases affects productivity, inequality, and development capacity. Planetary health emphasizes that long-term health achievement depends on the maintenance of natural systems that sustain life, so environmental health strategies need to assess co-benefits and trade-offs across sectors (Ebi et al., 2020; Whitmee et al., 2021).

The latest literature also places intergenerational justice and biodiversity restoration as health issues. Health protection is not enough with adaptation to an ever-deteriorating environment; Climate change mitigation, pollution reduction, ecosystem conservation, and changes in production-consumption patterns are upstream actions. This framework is relevant for developing countries because it avoids the pseudo-dichotomy between economic growth and environmental health, and encourages investment that simultaneously improves the health, resilience, and quality of ecosystems (Friel, 2020; Ingle and Mikulewicz, 2020; Butler et al., 2021).

METHODOLOGY

This article uses qualitative literature review with a narrative-interpretive synthesis orientation, not a systematic literature review. The approach was chosen because the main objective of the study was not to calculate the combined effect size or claim exhaustive coverage of the evidence, but to integrate concepts, mechanisms, evidence patterns, contradictions, and policy implications from the literature across environmental health domains. The methodological literature emphasizes that narrative review can remain rigorous if the objectives, selection logic, interpretive position, and synthesis process are transparently explained; review as an independent study must also have questions, evidence collection strategies, and a coherent reporting process (Sukhera, 2022; Kraus et al., 2022).

The search was carried out in a targeted manner to peer-reviewed articles mainly published in 2020–2026 with keywords and a combination of themes related to environmental health, air pollution, PM2.5, WASH, water and sanitation, waste management, microplastics, climate change and health, vector-borne disease, urban green space, environmental justice, environmental monitoring, IoT, artificial intelligence, community engagement, Indonesia, and planetary health. Sources are prioritized from reputable journals and verifiable scientific records through DOIs, PubMed, or publisher pages. Articles are considered when relevant to RQ, make substantive conceptual/empirical contributions, and have traceable bibliographic information; duplicate sources, unverifiable references, and claims that are not supported by sufficient evidence are not used. This procedure follows the principles of transparency, relevance, and traceability recommended for rigorous knowledge synthesis and qualitative research (Barry et al., 2022; Yadav, 2022).

The analysis was conducted through comparative readings and thematic groupings into eight domains: determinant-exposure-vulnerability, air pollution, WASH, waste and new contaminants, climate change, urbanization and green space, technology and governance, and sustainable development/planetary health. The findings were then synthesized across themes to identify causal-conceptual relationships, risk reinforcement factors, intervention strategies, trade-offs, and implications for Indonesia. Because this approach is qualitative and does not use the systematic review/PRISMA protocol, the results are positioned as a verified literature-based analytical synthesis, rather than a comprehensive estimate of all available publications (Barry et al., 2022; Sukhera, 2022).

RESULTS AND DISCUSSION

Challenges and Strategies for Environmental Health Management

Cross-literature synthesis shows that current environmental health challenges are convergent. Sources of emissions, quality of basic services, material and waste management, climate change, and the shape of cities create a combination of exposures that take place simultaneously. A single-hazard approach can identify specific relationships, but policies often work on the same system: for example, a clean transportation transition can simultaneously lower air pollution and greenhouse gas emissions, while green space can be beneficial for heat, physical activity, and mental health. Therefore, the management analysis unit should shift from "pollutants" to "risk systems" and intervention packages with co-benefits (Salgado et al., 2020; Romanello et al., 2021; Gianfredi et al., 2021).

Evidence also shows that institutional capacity is an important mediator between technical solutions and health outcomes. Sanitation systems, air monitoring, waste management, climate early warning, or sensor technologies do not produce full benefits when maintenance, financing, coordination, enforcement, and accountability are weak. Evaluation of Indonesia's sanitation and participation literature shows that institutional environmental support and

stakeholder mobilization can change the effectiveness of implementation (Odagiri et al., 2020; Hügel and Davies, 2020; Questa et al., 2020).

Key Issues in Environmental Health: Risk Convergence

In the air domain, the consistency of the evidence regarding PM_{2.5} places emission control as an upstream priority. Environmental health policies should not only encourage individual protective behavior on a polluted day, but need to target transportation, industry, open combustion, household energy, and other sources according to local emissions inventories. Personal interventions such as filtration and respirators can be additional protection for vulnerable groups, but they do not replace emission standards and improve ambient air quality (Chen and Hoek, 2020; Allen and Barn, 2020; Alexeeff et al., 2021).

In the Indonesian context, evidence from Jakarta, national data, and industrial areas shows the need for the integration of monitoring and epidemiology. Concentration measurement alone is not enough; Data need to be linked to exposed populations, health outcomes, vulnerability characteristics, and socio-economic costs. This will allow the prioritization of sources and regions based on health burden, not just violations of quality standards. The approach can also increase policy relevance as pollution control benefits translate into health outcomes that decision-makers can understand (Agustian et al., 2020; Suryadhi et al., 2020; Rauf et al., 2021; Syuhada et al., 2023).

In WASH, the synthesis shows that the main problem is not just the availability of facilities, but the continuity of secure services. Available but contaminated water, toilets without fecal sludge management, or handwashing facilities without soap and water provide partial protection. Effectiveness increases when the service chain from source to end use is functional and hygienic behaviors can be maintained. Therefore, WASH monitoring needs to measure quality, functionality, affordability, and usage, not only the existence of facilities (Wolf et al., 2022; Satriani et al., 2022).

Waste shows a similar pattern. Open dumping and open burning move material problems into air, soil, and water exposure, while formal systems that do not pay attention to emissions control and occupational safety can also create risks. The literature on solid waste, plastic incineration, and e-waste shows the need for a hierarchy of prevention: reduction of incision, safer product design, sorting, universal collection, controlled recycling, as well as residue treatment with strict emission and safety standards (Tait et al., 2020; Vinti et al., 2021; Velis and Cook, 2021; Parvez et al., 2021).

Climate change is strengthening all of these domains. Drought can reduce the quantity and quality of water; flooding can spread contaminants and damage sanitation; heat increases physiological pressure and cooling needs; Changes in rainfall and temperature modify the vector habitat. Therefore, climate risk assessment in environmental health must examine how climate hazards interact with infrastructure weaknesses and social vulnerabilities, rather than being treated as separate sectors (Watts et al., 2021; Helldén et al., 2021; Marina et al., 2023).

Environmental Threat Mitigation and Adaptation Strategy

The most conceptually powerful mitigation is an upstream action that eliminates or mitigates hazards before exposure occurs. In the air, this means energy transition, low-emission vehicles and transportation, industrial control, as well as open combustion prevention. In WASH and waste, upstream actions include water source protection, safe sanitation services along the chain, reduction of hazardous material generation, and collection systems that prevent dumping or burning. This principle is consistent with evidence that reducing population exposure is more sustainable than relying solely on individual protection (Dominski et al., 2021; Wolf et al., 2022; Velis and Cook, 2021).

Adaptation is necessary for risks that cannot be eliminated immediately, especially the impacts of climate change. Environmental health adaptation priorities include heat-health action plans, early warning for extreme weather and vector-based diseases, resilience of water and sanitation facilities to flood-drought, preparedness of health facilities, and mapping of vulnerable populations. The climate-health literature suggests that adaptation needs to be integrated with mitigation because strategies that are only reactive can increase long-term costs and not address structural causes (Romanello et al., 2021; Berrang-Ford et al., 2021).

The concept of co-benefits provides the basis for prioritizing interventions. Cities that reduce fossil fuel vehicles, expand active transportation, and provide quality green space have the potential to reduce emissions, pollution, heat, while improving physical activity and well-being. However, implementation needs to ensure equitable access so that benefits are not concentrated in high-income areas. Thus, good mitigation and adaptation must be assessed based on total health benefits, benefit distribution, and possible trade-offs (Rugel and Brauer, 2020; Nguyen et al., 2021; Tessum et al., 2021).

The Role of Technology in Maintaining Environmental Health

Digital technology can improve three main functions: detection, prediction, and response. Distributed sensors can increase the monitoring density; IoT integration enables real-time transmission; Analytics and AI can help detect patterns, optimize waste collection routes, or predict risky conditions. Technology value arises when data leads to operational decisions—for example, health alerts, emission source inspections, service adjustments, or response mobilization (Saini et al., 2021; Abdallah et al., 2020).

However, digitalization also presents epistemic and governance risks. Low-cost sensors can drift, location bias can ignore marginalized communities, and predictive models can reinforce inequality when training data is not representative. Therefore, technology needs to be accompanied by calibration, quality assurance, interoperability standards, metadata, openness of methods, data protection, and audit mechanisms. Within the framework of environmental health, technology should function as a decision-support that expands human and institutional capacity, not as a substitute for contextual assessment or community participation (Saini et al., 2021; Ebi et al., 2020).

The Future of Environmental Health in Sustainable Development

The future of environmental health will increasingly be determined by the ability to link health sector policies with energy, transportation, housing, food, water, industry, and spatial planning. Most of the determinants of exposure are outside the authority of the health sector, so health-in-all-policies and cross-sectoral coordination mechanisms are important. The health sector can contribute through surveillance, health impact assessment, risk communication, and burden-based prioritization, while other sectors control the source of exposure (Ebi et al., 2020; Pham et al., 2023).

Planetary health adds a long-term horizon: policy is not only asked whether it reduces current health risks, but also whether maintaining ecosystem capacity underpins the health of future generations. This perspective places climate mitigation, biodiversity restoration, reduction of consumption of at-risk materials, and low-carbon urban systems as part of health policy. The agenda demands a change in the measure of success from program outputs to health outcomes, socio-ecological resilience, and equitable distribution of benefits (Whitmee et al., 2021; Butler et al., 2021; Friel, 2020).

Efforts to Implement a Sustainable Integrated Environmental Health Model

Based on the synthesis, this article proposes an integrated management model with five components. First, intelligence: a data system that combines environmental monitoring, health data, social data, and climate information. Second, prevention at source: reducing emissions and contamination before reaching the population. Third, resilient services: water, sanitation, sewage, and health facilities that are able to withstand climate disruptions. Fourth, equitable governance: priority in groups with high exposure and low adaptive capacity. Fifth, learning systems: continuous evaluation that links intervention outcomes to policy improvement. These five components integrate evidence from the domains of pollution, WASH, climate, technology, and environmental justice (Odagiri et al., 2020; Syuhada et al., 2023; Saini et al., 2021; Tessum et al., 2021).

Implementation can begin with mapping multi-risk hotspots in cities/districts. Instead of creating separate maps for PM_{2.5}, flooding, sanitation, or poverty, governments can develop indexes or dashboards that maintain component information and mark areas with accumulated risks. These areas then become priorities for intervention packages—such as local emissions control, WASH improvements, waste collection, shady green spaces, and disease communication and surveillance. A multi-risk approach can avoid budget fragmentation and increase co-benefits opportunities (Salgado et al., 2020; Labib et al., 2020; Marina et al., 2023).

The next stage is the evaluation of outcomes and equity. Success is not sufficiently assessed by the number of sensors, the length of the water network, the tonnage of trash transported, or the area of green space. Indicators need to include exposure reduction, exposure gap reduction, health outcomes, service functioning, community satisfaction and trust, and system ability to respond to extreme events. This approach makes environmental investments accountable based on real health benefits (Nguyen et al., 2021; Mukherjee and Sastry, 2022; Questa et al., 2020).

The Critical Role of Stakeholders in Realizing Sustainable Environmental Health

The central government plays a role in setting standards, regulatory frameworks, data interoperability, fiscal incentives, and national health-environment targets. Local governments have important functions in licensing, local resource supervision, service management, spatial planning, waste handling, and risk communication. Evidence of Indonesia's sanitation shows that political support and local institutional capacity can have a real impact on achievement; therefore, decentralization needs to be balanced with adequate resources, technical capacity, and accountability mechanisms (Odagiri et al., 2020; Satriani et al., 2022).

The private sector is responsible for reducing externalities through clean production technologies, emissions compliance, extended liability, data transparency, and innovations that do not shift risk to workers or communities. Meanwhile, universities and research institutions play a role in improving exposure estimation, causal evaluation, health impact assessment, and testing policy effectiveness. In Indonesia, strengthening the relationship between environmental and health data is a special area that can accelerate the transition from administrative monitoring to evidence-informed policy (Agustian et al., 2020; Rauf et al., 2021).

The community is not just an educational recipient, but an owner of local knowledge about exposures, behaviors, service barriers, and risk priorities. Community engagement studies show that shared leadership, participation scope, and social capacity affect the effectiveness of interventions. Meaningful participation can also improve the legitimacy of decisions, detect risks invisible to formal data, and improve the maintenance of interventions after the project has ended (Questa et al., 2020; Hügel and Davies, 2020; Mukherjee and Sastry, 2022).

Analysis and Synthesis in Answering Research Questions

The answer to RQ1 is that environmental determinants of health shape risk through a network of interactions, not a single pathway. Air pollution contributes to respiratory, cardiovascular, and metabolic diseases; Unsafe WASH facilitates infectious diseases and worsens nutritional vulnerability; waste opens up exposure pathways to new particulates, chemicals, and contaminants; climate change amplifies heat, vector-based diseases, water insecurity, and system disruptions; Meanwhile, urbanization determines proximity to the source of danger and access to protective factors such as basic services and green space. Biological and social vulnerabilities modify all of these pathways, so that actual risk is a function of hazard, exposure, vulnerability, and adaptive capacity simultaneously (Lee et al., 2020; Wolf et al., 2022; Parvez et al., 2021; Marina et al., 2023; Gianfredi et al., 2021).

For Indonesia, the synthesis of RQ1 shows the importance of dual burden of environmental risk. Classic risks such as water and sanitation have not been fully resolved at a time when urban-industrial risks such as PM2.5, toxic elements, complex waste, and climate heat are increasing. The available national and local evidence is sufficient to justify action, but there are still gaps in

longitudinal exposure data, health-environment data integration, and regional representation outside of research centers. Therefore, national strategies need to combine strengthening basic services with modern exposure control (Satriani et al., 2022; Suryadhi et al., 2020; Syuhada et al., 2023).

The answer to RQ2 is that the most consistent strategies supported by the literature have six characteristics: preventing hazards at the source; ensuring safe and sustainable basic services; combining mitigation and adaptation; using technology to strengthen, not replace, governance; prioritizing fairness, distribution, exposure, and benefits; and building institutional participation and learning. Effectiveness comes from a combination of instruments – regulation, investment, data, service design, behavior change, and participation – not from a single technology or campaign (Allen and Barn, 2020; Odagiri et al., 2020; Saini et al., 2021; Hügel and Davies, 2020; Ebi et al., 2020).

Thus, the objectives of the article are achieved through the formulation of an integrated model that connects intelligence–prevention–resilient services–equitable governance–learning systems. The model is compatible with the context of sustainable development because it pursues health and environmental co-benefits, while maintaining a focus on the most vulnerable groups. Conceptually, this model bridges classic environmental health with planetary health: local exposure control remains necessary, but long-term effectiveness depends on the transformation of energy, material, city, water, and governance systems that underpin human health and ecosystems (Ebi et al., 2020; Pham et al., 2023; Whitmee et al., 2021).

CONCLUSION

This study shows that contemporary environmental health must be understood as a risk system that connects hazard sources, exposure pathways, vulnerabilities, and health outcomes. Air, water and sanitation pollution, waste, climate change, as well as the characteristics of the urban environment do not stand alone. Interactions between these factors can create an accumulation of exposure, especially in populations with low housing quality, limited access to services, comorbidities, or low adaptive capacity. Therefore, a fragmented policy approach risks reducing a single issue without fixing the total risk.

Answering RQ1, the latest evidence indicates that the public health risk profile is formed by a combination of physical-chemical-biological determinants and social-spatial determinants. In Indonesia, the combination of uneven WASH issues and urban-industrial risks such as PM_{2.5}, toxic contaminants, waste management, and climate threats shows the need for a dual burden framework. Measures of success should not only use environmental indicators or coverage of facilities, but also changes in exposure, health outcomes, service functioning, and gaps between groups.

Responding to RQ2, the most robust responses are intervention packages that prioritize prevention at source, secure basic services, mitigation-adaptation integration, quality-assured monitoring technologies, cross-sectoral governance, and meaningful community participation. This article formulates five components of an integrated model – intelligence, prevention at source, resilient

services, equitable governance, and learning systems—that can be used as a framework to link health, environmental, spatial planning, transportation, energy, water, and materials management policies.*

For policy in Indonesia, practical priorities are to build health-environmental data interoperability, expand high-resolution monitoring to underrepresented regions, strengthen WASH and waste services along the chain, and implement health and equity impact assessments on infrastructure investments. Community participation needs to be placed from the problem definition stage to evaluation, while the private sector needs to be assessed based on the reduction of externalities and transparency of environmental performance. This approach allows policy to shift from response after a disease has occurred to risk-based prevention.

Future research needs to strengthen longitudinal and quasi-experimental studies to assess the causal relationship between exposure and health outcomes; developing a multi-exposure/exposome approach that tests the mixture of pollutants and their interactions with heat or social vulnerability; and evaluate the implementation, cost-effectiveness, and distributional impact of interventions. For Indonesia, specific needs include safe environmental-health data linkage, development of validated sensors and exposure models, WASH and waste research outside of key research centers, integrated climate-vector surveillance, and testing of participatory governance models. The agenda should be designed transdisciplinarily so that scientific evidence can be translated into decisions that improve health, justice, resilience, and ecological sustainability.

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