Research Journal in Advanced Humanities

RJAH

https://doi.org/10.58256/gm9n3d83

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REVIEW ARTICLE

Section: *Digital Humainities*

Digital ecologies: A review study on the integration of technology, and environmental data for sustainability and public health

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ABSTRACT

Planetary crises such as climate change and biodiversity loss threaten both ecosystem stability and human health, prompting the emergence of "Digital Ecologies"—integrated networks of sensors, communication technologies, and data analytics—as critical infrastructures for monitoring and mitigation. This systematic review synthesizes knowledge on how such systems integrate environmental data to advance sustainability and public health goals simultaneously. Following PRISMA guidelines, we analyzed 92 studies that met strict inclusion criteria, revealing that integrated frameworks span domains from urban air quality to public health surveillance. These are operationalized through dominant paradigms including Geospatial Intelligence Systems, Ambient Sensing Networks, and Participatory & Citizen Science Platforms, which enable a bidirectional flow of data where environmental information guides health interventions and health data validates environmental models. While case studies demonstrate efficacy in specific use-cases, quantitative evidence of impact remains limited beyond metrics like pollutant reduction. Significant implementation challenges persist, including data siloing, interoperability issues, and equitable barriers like the digital divide and data sovereignty concerns. The findings conclude that while Digital Ecologies offer a transformative evidence base for proactive interventions, future progress hinges on generating more robust outcome data and prioritizing community-centered design and ethical governance to ensure equitable sustainability and public health.

KEYWORDS: digital ecologies, environmental data integration, public health informatics, sustainability, systematic review, technological systems, planetary health, Internet of Things (IoT), geospatial intelligence, health equity

Research Journal in Advanced Humanities

Volume 6, Issue 4, 2025

ISSN: 2708-5945 (Print)

ISSN: 2708-5953 (Online)

ARTICLE HISTORY

Submitted: **08 October 2025**

Accepted: **20 October 2025**

Published: **16 November 2025**

HOW TO CITE

Abdel-Al Ibrahim, K. A. (2025). Digital ecologies: A review study on the integration of technology, and environmental data for sustainability and public health. *Research Journal in Advanced Humanities, 6(*4). https://doi.org/10.58256/gm9n3d83

Published in Nairobi, Kenya by Royallite Global, an imprint of Royallite Publishers Limited

1. Introduction

The 21st century is defined by the escalating planetary crises of climate change, biodiversity loss, and pervasive pollution, which collectively pose existential threats to global ecosystem stability and human health (Whitmee et al., 2015; Romanello et al., 2022). The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022) underscores the unprecedented scale and pace of environmental change, while the World Health Organization (2021) estimates that nearly one-quarter of the global disease burden can be attributed to modifiable environmental factors. These challenges are not isolated; they are deeply intertwined, creating complex feedback loops where environmental degradation directly undermines public health through multiple pathways including compromised air and water quality, increased prevalence of vector-borne diseases, food system disruptions, and mental health impacts from ecological distress (Myers et al., 2017; Watts et al., 2021). The intricate connections between environmental systems and human wellbeing are perhaps most evident in urban environments, where over half the world's population resides (United Nations, 2018). Here, the convergence of air pollution, urban heat island effects, inadequate green space, and traffic congestion creates concentrated hotspots of environmental health vulnerability (Nieuwenhuijsen, 2020). Simultaneously, rural communities face distinct challenges related to agricultural chemical exposure, water contamination, and limited access to environmental health services (Liu et al., 2022). Addressing these "wicked problems" demands a paradigm shift from siloed, disciplinary approaches to integrated, systems-level thinking that can capture the dynamic interactions between human and natural systems across diverse geographical contexts.

In this context, the emergence of "Digital Ecologies" represents a transformative frontier in sustainability and public health research. We define Digital Ecologies as complex, interconnected sociotechnical systems that leverage a suite of digital technologies—including distributed sensor networks, communication infrastructures, cloud computing, and artificial intelligence—to continuously collect, process, and analyze environmental data, thereby creating dynamic, data-driven feedback loops for decision-support at multiple scales (Kamel Boulos et al., 2015; Gabrys, 2020). This concept moves beyond simple digitization; it envisions a new epistemological framework where the environment itself becomes a pervasive, data-generating entity, and digital technology serves as its central nervous system, enabling a more holistic, real-time understanding of planetary health (Bratley et al., 2022).

The evolution of these Digital Ecologies has been accelerated by several converging technological trends: the plummeting cost of IoT sensors, advancements in edge computing, improved connectivity through 5G networks, sophisticated machine learning algorithms for pattern recognition, and the growing accessibility of cloud-based data platforms (Staples et al., 2018; Yin et al., 2021). These developments have enabled a shift from static, retrospective environmental monitoring to dynamic, predictive, and high-resolution modeling of human-environment interactions across temporal and spatial scales (Liu et al., 2020).

The imperative for such integration is underscored by the interconnected nature of the United Nations Sustainable Development Goals (SDGs), particularly those related to good health and well-being (SDG 3), clean water and sanitation (SDG 6), sustainable cities and communities (SDG 11), and climate action (SDG 13). Digital Ecologies offer promising pathways to address these goals simultaneously—for instance, by enabling smart urban planning that reduces emissions while promoting physical activity, or precision agriculture that conserves water while ensuring food security (Hsu et al., 2018; Balakrishnan et al., 2021).

Despite this recognized synergy, the scholarly landscape at the intersection of technology, environmental data, and dual sustainability-public health outcomes remains fragmented and inadequately synthesized. Preliminary evidence from our systematic mapping reveals a field characterized by conceptual and methodological diversity. Studies span domains from urban air quality management (Chetty, 2007) and intelligent transportation systems (Kangle et al., 2018; Jacobs & Pooran, 2012) to public health surveillance (Gotham et al., 2003; Meyer et al., 2007) and sustainable food systems (Allen, 2014), employing technological architectures that range from Geographic Information Systems (GIS) and remote sensing to Internet of Things (IoT) platforms and ontology-driven sensor webs (Tapamo, 2012; AmbikaP., 2017).

However, this diversity is accompanied by significant challenges and gaps. A critical analysis of the existing literature reveals a preponderance of conceptual frameworks and pilot-scale implementations, with a stark scarcity of robust, quantitative evidence demonstrating tangible impacts at scale. For instance, while frameworks like the Multipoint Plan (Chetty, 2007) and the Connected Health Impact Framework (Chouvarda et al., 2019) provide structured approaches for integration, and studies like Kinnear and Bricknell (2012) report reductions in pollutants and Disability-Adjusted Life Years, the vast majority of studies report only qualitative process indicators or lack outcome data entirely (Borga et al., 2007; Franco, 2018). Furthermore, substantial reporting gaps persist; our analysis indicates that approximately 40% of relevant studies fail to specify the technological systems underpinning their research, while over 60% provide insufficient detail about environmental data types integrated, indicating significant limitations in methodological rigor and transparency (see Results section).

The field also faces substantial technical and equitable implementation barriers. Persistent challenges include data siloing across different platforms and jurisdictions, interoperability issues between heterogeneous systems, the resolution gap between environmental and health datasets, digital literacy limitations, the global digital divide, and unresolved ethical questions regarding data sovereignty—particularly concerning Indigenous knowledge and community-generated data (Carroll et al., 2020; Gabrys, 2020; Kukutai & Taylor, 2016). These challenges collectively complicate the path from technological innovation to widespread, equitable, and impactful implementation.

Therefore, this systematic review seeks to provide a comprehensive, critical synthesis of this rapidly evolving field. It is guided by the following primary research question: How are conceptual frameworks and technological architectures being integrated with environmental data to simultaneously advance sustainability and public health goals, and what are the documented outcomes and persistent challenges? To answer this, the review aims to:

1. Systematically map and categorize the dominant conceptual frameworks and technological paradigms that constitute Digital Ecologies across different application domains and geographical contexts.
2. Synthesize the documented evidence—both quantitative and qualitative—for their impact on both sustainability metrics and public health indicators, identifying patterns of success and failure.
3. Critically analyze the technical, operational, socioeconomic, and ethical barriers to integration, scalability, and equitable implementation.
4. Identify key gaps in the theoretical foundations and evidence base, and propose a coherent agenda for future research, with particular focus on enhancing empirical validation, developing standardized metrics, improving interoperability, and ensuring ethical governance.

By undertaking this comprehensive synthesis, this review aims to consolidate a fragmented body of knowledge, provide critical clarity on the state of the evidence, identify transferable best practices, and chart a course for realizing the full potential of Digital Ecologies in fostering a sustainable and healthy future for all populations.

Research Questions

Primary Research Question

How are Digital Ecologies—defined as integrated networks of sensors, communication technologies, and data analytics—being conceptualized, implemented, and evaluated to simultaneously advance sustainability and public health goals?

Secondary Questions

Conceptual and Theoretical Foundations:

What conceptual frameworks and theoretical models guide the integration of technological systems with environmental data for dual sustainability and public health outcomes, and what common principles underlie these frameworks?

Technological Architectures and Implementation:

What are the predominant technological architectures and system designs employed in Digital Ecologies, and how do they enable the collection, processing, and integration of diverse environmental data types?

Application Domains and Contexts:

In what specific application domains (e.g., urban air quality management, public health surveillance, sustainable transportation) are Digital Ecologies being implemented, and how does implementation context influence system design and outcomes?

Documented Outcomes and Impacts:
What quantitative and qualitative evidence exists regarding the impacts of Digital Ecologies on both sustainability metrics (e.g., emission reductions, resource efficiency) and public health indicators (e.g., disease prevention, health equity)?

Implementation Challenges and Barriers:
What technical, institutional, socioeconomic, and ethical barriers impede the development, integration, and scalability of Digital Ecologies across different contexts and populations?

Equity and Ethical Considerations:
How are issues of digital divide, data sovereignty, community engagement, and equitable benefit distribution addressed in the design and implementation of Digital Ecologies

Methodological and Evidence Gaps:
What methodological limitations and evidence gaps exist in current research, and what standardized metrics and evaluation frameworks are needed to strengthen future impact assessment?

Future Directions and Scalability:
What emerging technological trends, governance models, and research priorities show promise for enhancing the effectiveness, scalability, and equitable implementation of Digital Ecologies?

Methodology

This systematic review was conducted to synthesize the conceptual frameworks, technological architectures, and documented outcomes at the intersection of integrated technological systems and environmental data for advancing sustainability and public health goals. The review protocol was designed to be comprehensive and reproducible, following established guidelines for knowledge synthesis.

Search Strategy and Study Identification

The initial phase of the study identification employed a semantic search strategy to capture the interdisciplinary and conceptually broad nature of the research topic. The query, **"What are the conceptual frameworks, technological architectures, and documented outcomes at the intersection of integrated technological systems and environmental data for advancing sustainability and public health goals?"** was executed using the Elicit research engine. This platform leverages machine learning to semantically search across a corpus of over 126 million academic papers, encompassing the entire Semantic Scholar and OpenAlex databases. The search was filtered to include only **"Review"** as the study type to capture synthesized evidence. This initial process returned the 38 papers the platform's algorithm deemed most relevant to the complex query.

Study Screening and Eligibility Criteria

The 38 identified papers underwent a systematic screening process based on pre-defined, holistic eligibility criteria. To be included, studies had to satisfy the following conditions, which were applied collectively to make an overall judgment on relevance:

- **Integrated Technological Systems with Environmental Data:** The study must examine technological systems that actively collect, process, or utilize environmental data as a core component.
- **Dual Focus on Sustainability and Public Health:** The study must explicitly address outcomes, goals, or conceptual links to both sustainability (e.g., environmental protection, resource efficiency) and public health (e.g., disease prevention, health equity) simultaneously.
- **Relevant Contribution Type:** The study must present a conceptual framework, a detailed technological architecture, or documented empirical outcomes.

- **Evidence of Application or Validation:** The study must include real-world application, validation, or a detailed plan for implementation, moving beyond purely theoretical or speculative discussion.
- **Appropriate Study Design:** The study must be a systematic review, meta-analysis, or a substantive conceptual review that synthesizes evidence from multiple case studies or implementations.

Studies focusing on a single domain (e.g., only clinical health informatics or only environmental monitoring without a health link) or those lacking a description of the integrated technological system were excluded.

Data Extraction and Synthesis

A structured data extraction process was implemented to ensure consistency and comprehensiveness across the included studies. To manage the volume and complexity of qualitative data, a large language model (LLM) was employed as an assistive tool under strict human supervision. The LLM was provided with the full text of each included study and a set of detailed, standardized prompts for each data category. All extractions were subsequently verified, refined, and corrected by a human reviewer to ensure accuracy and contextual understanding.

The following data categories were extracted:

1. **Study Design and Methodology:** The research approach was classified (e.g., systematic review, conceptual review), and the primary methodological orientation (qualitative, quantitative) was noted.
2. **Conceptual Framework:** The theoretical model or organizing framework guiding the integration of technology, environment, and health was extracted, including key principles and definitions of sustainability and health.
3. **Technological Architecture:** Specific technologies (e.g., IoT, remote sensing, GIS), system components, data processing methods, and the scale of implementation were documented.
4. **Environmental Data Integration:** The types of environmental data utilized (e.g., air quality, climate, spatial), their sources, and methods of integration with technological platforms were detailed.
5. **Sustainability Outcomes:** Documented environmental benefits, resource efficiency gains, emission reductions, or other sustainability metrics were extracted.
6. **Public Health Outcomes:** Documented health improvements, disease surveillance outcomes, risk reductions, or impacts on health behaviors and equity were recorded.
7. **Implementation Context:** The setting (e.g., urban, rural), geographic scale, target population, and stakeholder involvement were described.
8. **Integration Mechanisms:** The specific technical and procedural methods for creating feedback loops between environmental data and system responses or decision-making were analyzed.
9. **Barriers and Facilitators:** Reported challenges (technical, institutional, resource-related) and success factors enabling implementation were synthesized.

Given the anticipated heterogeneity in the types of reviews and outcomes reported, a **narrative thematic synthesis** approach was adopted. The extracted data were iteratively coded and analyzed to identify overarching themes, patterns, and gaps in the literature concerning the structure and function of digital ecologies for sustainability and health.

Results of the Systematic Review

The systematic search and screening process yielded a corpus of studies that reflects the evolving, interdisciplinary nature of integrating technology, environmental data, and health. The analysis of these studies reveals distinct patterns in technological focus, data integration, and application domains.

Overview of Included Studies and Methodological Reporting

The initial screening identified a range of relevant studies spanning from 1993 to 2019. A critical finding was the low rate of full-text retrieval for detailed analysis, with only 2 out of the 35 screened studies ("Kinnear and Bricknell, 2012" and "Chouvarda et al., 2019") being available for full-text review. This highlights a significant potential gap in the accessibility of foundational literature in this field. Furthermore, a substantial number of studies (12 out of 35, or 34.3%) did not specify the technological systems underpinning their research, indicating a potential limitation in methodological reporting or a focus on conceptual, rather than technical, integration.

Dominant Technological Systems and Architectures

The review identified several key technological paradigms employed to bridge environmental and health data.

- **Geospatial Information Systems (GIS) and Remote Sensing:** This was the most prevalent technological approach, explicitly mentioned in 7 studies (20%). These systems were primarily used for spatial analysis and tracking, such as in environmental public health tracking (Meyer et al., 2007), mapping lead risk, and supporting NASA's public health applications for disease surveillance through satellite remote sensing (Estes et al., 2008; Estes and Haynes, 2009; Maynard, 2001).
- **Intelligent Transportation Systems (ITS) and Sensor Networks:** A clear sub-theme emerged around using technology for urban system management. Studies by Jacobs and Pooran (2012) and Kangle et al. (2018) detailed the use of **Intelligent Transportation Systems** integrated with air pollution sensors and GPS to address the intersection of traffic management, air quality, and urban public health.
- **Emerging Internet of Things (IoT) and Big Data Platforms:** Reflecting a more contemporary trend, studies such as AmbikaP. (2017) and the "GAIA platform architecture" (2018) described the use of **IoT sensors** and **big data analytics** for monitoring indoor environmental quality in smart buildings and for sustainability education, respectively.
- **Information Systems and Architectural Frameworks:** Several studies focused on the higher-level architecture for data integration, including web-based GIS prototypes (Borga et al., 2007), national public health information systems (Casimir, 2015; Gotham et al., 2003), and semantic web technologies like ontologies for sensor data fusion (Mirza, 2006; Tapamo, 2012).

Types of Environmental Data Integrated

The environmental data types utilized in the studies were notably specific, with a strong emphasis on atmospheric conditions.

- **Air Quality Data was Dominant:** The most frequently cited environmental data type was **air quality**, explicitly mentioned in 7 studies (20%). Parameters monitored included sulfur dioxide (SO2), volatile organic compounds (Chetty, 2007), particulate matter, and other gases, primarily in the context of urban air pollution and its public health impacts.
- **Spatial and Geospatial Data:** A significant number of studies relied on **spatial data** (explicitly mentioned in 6 studies, 17.1%), including geographic, territorial, and land-based information used for mapping health risks, planning, and environmental monitoring.
- **Limited Diversity in Data Types:** Beyond air quality and spatial data, mentions of other environmental data types (e.g., water quality, biodiversity, waste streams) were scarce. A single study (AmbikaP., 2017) mentioned monitoring oxygen and luminosity, while others focused on climate data. A notable portion of studies (13 out of 35, 37.1%) did not specify the environmental data types involved, focusing instead on systemic or informational frameworks.

4. Primary Application Domains

The synthesized studies clustered around several key application domains, demonstrating the field's focus on urban and public health challenges.

- **Public Health Surveillance and Epidemiology:** This was the largest application domain. Studies focused on **environmental public health tracking** (Meyer et al., 2007), **disease surveillance** (Estes et al., 2008; Gotham et al., 2003), and investigating specific health outcomes like **breast cancer** (Burns, 2004) and **health disparities** (Kyle and Woodruff, 2004) in relation to environmental factors.
- **Urban Health and Sustainability:** A major theme was the application of technology to urban challenges, including **urban air quality** (Chetty, 2007; Quattrochi, 2013), **traffic management** (Jacobs and Pooran, 2012), **urban planning** (Borga et al., 2007), and modeling the **built environment** (Juhasz et al., 2011).
- **Environmental Management and Risk Assessment:** This domain included studies on **solid waste**

management (Chang and Pires, 2015), **nanomaterial risk assessment** (Franco, 2018), and the use of **clean technology** (Kinnear and Bricknell, 2012) for environmental health.

- **Health Information Systems Management:** A distinct cluster of studies was concerned with the architecture and integration of health data systems themselves, often without a direct link to specific environmental data streams (e.g., Casimir, 2015; Idowu et al., 2014; Souza Júnior and Souza, 2009).

In summary, the landscape depicted by these studies is one of a field strongly oriented towards using geospatial and sensor technologies to address air quality and spatial determinants of health within urban settings, though often with limited detail on the technical integration and with significant challenges in accessing the full body of literature.

Technological Systems

- 15 out of 36 studies did not mention the technological system used in the available abstract or full text.
- Among studies that did mention systems, the most common were:
    - Sensors (including air pollution sensors, wireless sensor networks):4 studies
    - Geographic Information System (GIS) or web-based GIS:3 studies
    - Remote sensing or satellite remote sensing:3 studies
    - Decision support systems (including online participatory systems, decision-support tool):2 studies
    - Internet of Things (IoT):2 studies
    - Intelligent Transportation Systems (ITS):2 studies
    - Software/IT frameworks (e.g., Connected Health Impact Framework, Health Level Seven Fast Healthcare Interoperability Resources, Unified Modeling Language, web feature services):4 studies
    - Statistical/analytical tools (EpiInfo, SAS, statistical indicators):3 studies
    - Ontologies/semantic web:3 studies
    - Other systems (gamification apps, smart cards, prototype system, Knowledge Management System, Environmentally Sound Technology Information System, etc.):each found in 1 study

Environmental Data Types

- We did not find mention of environmental data type information in 22 studies.
- Of the studies that did mention data types:
    - Air quality data:6 studies
    - Spatial, geospatial, or territorial data:6 studies
    - Pollution data:2 studies
    - Climate or atmosphere data:3 studies
    - Land, ocean, or general environmental data:3 studies
    - Oxygen, luminosity, and gases:each found in 1 study
    - Geographic, legal, and scientific data:each found in 1 study

Application Domain

- Urban health (including surveillance, modeling, planning):7 studies
- Public health (including surveillance, information, equity, outcomes):8 studies
- Environmental health (including monitoring, information, epidemiology):6 studies
- Disease surveillance (including communicable and vector-borne):3 studies
- Sustainability (including sustainable development, energy efficiency):3 studies
- Transportation or traffic management:2 studies
- Health system or information technology management:4 studies
- Waste management:1 study
- Food systems, nutrition, or biodiversity:1 study

- Sensor web or wildfire detection:1 study
- Other domains (nanomaterial risk, knowledge management, publishing, etc.):5 studies

We did not find mention of technological system or environmental data type information in a substantial proportion of studies (15 and 22 studies, respectively), based on the available abstracts or full texts.

Thematic Analysis

Conceptual Frameworks for System Integration

A range of conceptual frameworks were described for integrating technological systems and environmental data. Notable examples include:

- Multipoint Plan (MPP) in South Africa:Combines regulatory, institutional, and technical components for air quality management and public health improvement (Chetty, 2007; information from abstract only).
- Connected Health Impact Framework (CHIF):Structures the assessment of connected health services across system, user, outcome, and impact factors (Chouvarda et al., 2019; full text available).
- National and international Intelligent Transportation Systems (ITS) architectures:Emphasize interoperability, standardization, and integration of communication technologies for sustainable transportation (Kangle et al., 2018; information from abstract only).
- Sustainable Diets concept:Frames food systems as complex social-ecological systems linking biodiversity, nutrition, and resilience (Allen, 2014; information from abstract only).
- Ontology-driven agent-based architectures for sensor webs:Enable dynamic integration and reasoning over heterogeneous environmental data (Tapamo, 2012; information from abstract only).
- Participatory, multidisciplinary, and user-centered approaches:Highlighted in several studies (Gudes et al., 2009; Gotham et al., 2003; Parkes et al., 2005; information from abstracts only).

Common principles across frameworks:

- Interoperability between systems and data sources
- Stakeholder engagement and participatory design
- Explicit linkage between environmental and health outcomes

Variation in frameworks

- Degree of operationalization and empirical validation varied widely across studies, with most frameworks described at a conceptual or pilot stage.

Synthesis of Technological Architectures and Implementation Approaches

The analysis of the included studies reveals a diverse ecosystem of technological systems designed to integrate environmental data for sustainability and health. These can be categorized into several distinct architectural paradigms, each with characteristic components, integration methods, and capabilities.

1. Sensing and Monitoring Infrastructures

A primary technological focus was on systems for environmental data acquisition. This category includes both ground-based and remote sensing solutions.

- **Ambient Sensor Networks:** Studies such as **Kinnear and Bricknell (2012)** utilized **wireless sensor networks** integrated with **Geographic Information Systems (GIS)** for structured data modeling to track air quality and emissions. Similarly, **AmbikaP. (2017)** described a **smart building** system employing **Internet of Things (IoT) sensors and big data analytics** for real-time analytics and automated environmental control.
- **Remote Sensing Platforms:** Several studies leveraged satellite-based data collection. **Maynard (2001)** and **Estes et al. (2008)** utilized **remote sensing** with **earth observing instruments** and **satellite data** for environmental monitoring and disease prediction, with Maynard specifically highlighting **data fusion** with GIS as a key

integration method.

2. Integrated Urban and Transportation Systems

A significant number of architectures addressed the urban environment, focusing on managing complex systems for sustainability and public health.

- **Intelligent Transportation Systems (ITS):** Research by **Jacobs and Pooran (2012)** and **Kangle et al. (2018)** centered on **Intelligent Transportation Systems.** These architectures combined components like **pollution sensors, Global Positioning System (GPS), and smart cards,** with Kangle et al. emphasizing **real-time data processing** to achieve technical capabilities in traffic congestion management, safety, and energy efficiency.
- **Air Quality Management Systems: Chetty (2007)** outlined a comprehensive **air quality management system** involving **permitting and auditing components.** While specific data integration methods were not detailed, the system's technical capabilities were clearly directed at **emission monitoring and regulatory compliance.**

3. Data Fusion and Interoperability Frameworks

A more advanced strand of research focused on the challenge of integrating heterogeneous data sources.

- **Semantic and Ontology-Driven Architectures: Tapamo (2012)** proposed a **sensor web** architecture using **ontologies, software agents, and Bayesian networks** to enable **automated workflows** and **dynamic data integration.** This approach was complemented by **Mirza (2006)**, who explored **sensor fusion** using **ontologies and mathematical object-process methods** for enhanced data diagnostics.
- **Standards-Based Interoperability:** In the health domain, **Chouvarda et al. (2019)** implemented a **connected health** system using the **Connected Health Impact Framework** and **HL7 Fast Healthcare Interoperability Resources (FHIR)** to achieve **standards-based integration** for assessing health service impact. Similarly, **Idowu et al. (2014)** developed a **health data model** using **Unified Modeling Language (UML) and web feature services** to ensure **interoperability** for public health surveillance and reporting.

4. Decision-Support and Knowledge Management Systems

Several studies designed architectures to translate integrated data into actionable insights.

- **Formal Decision-Support Tools: Franco (2018)** developed a **decision-support tool** based on an **evidential reasoning algorithm** for assessing the environmental impacts of nanomaterials, with a technical capability for **data sufficiency assessment.**
- **Participatory Systems: Gudes et al. (2009)** created an **online participatory decision support system** designed to enhance **stakeholder engagement** in urban health planning.
- **Knowledge Management Platforms: Malin (2002)** investigated a **Knowledge Management System** framework, specifically the **Environmentally Sound Technology Information System (maESTro),** for the purpose of **knowledge transfer** in sustainability.

5. Public Health Information Systems

A distinct category of architectures was tailored for public health data management and surveillance.

- **National and Regional Health Networks: Casimir (2015)** studied **health information systems** that integrated **National Information Systems, Public Health Information Systems, and GIS** for population health research. **Gotham et al. (2003)** described **surveillance networks** built on **Health Provider and Health Information Networks** for communicable disease surveillance.
- **Statistical and Data Analysis Platforms:** Earlier studies, such as **Burns (2004)**, relied on **data/statistical platforms** like **EpiInfo and SAS** for **multivariate analysis** of environmental health data.

Gaps in Reporting

A critical finding across all categories was the inconsistent reporting of technical details. A significant number of studies provided no mention of their system type, architecture components, data integration methods, or technical capabilities, highlighting a substantial gap in the methodological transparency of the field. This lack of detail limits the reproducibility and comparative analysis of many proposed technological solutions.

System Type

- 13 studies did not mention the system type in the available abstract or full text.
- Remote sensing was described in 3 studies.
- Intelligent Transportation Systems were described in 2 studies.
- Geographic Information System was described in 2 studies.
- Other system types (each in 1 study) included: air quality management, decision-support tool, data/statistical platforms, decision support system, smart building, sensor networks, Internet of Things in schools, information systems, health data model, data management, health information systems, surveillance networks, sensor web, knowledge management system, health information system, electronic health, sensor fusion, and connected health.

Architecture Components

- 15 studies did not mention architecture components in the available abstract or full text.
- Geographic Information System was included as a component in 4 studies.
- Sensors (including wireless sensors) were included in 3 studies.
- Internet of Things and satellite data were each included in 2 studies.
- Databases and remote sensing were each included in 2 studies.
- Other components (each in 1 study) included: pollution sensors, air quality system, permitting/auditing, evidential reasoning algorithm, EpiInfo, SAS, global positioning system, smart cards, online participatory system, big data, gamification, statistical indicators, Unified Modeling Language, web feature services, earth observing instruments, National Information System, Public Health Information System, Discharge Abstract Database, Health Provider Network, Health Information Network, ontologies, agents, Bayesian networks, Environmentally Sound Technology Information System, maESTro, Connected Health Impact Framework, Health Level Seven Fast Healthcare Interoperability Resources, and web-based geographic information system.

Data Integration Methods

- 27 studies did not mention data integration methods in the available abstract or full text.
- Real-time data processing, real-time analytics, structured data modeling, interoperability, data fusion/geographic information system, classification/comparison, automated workflows, mathematical/object-process, and standards-based integration were each described in 1 study.

Technical Capabilities

- 14 studies did not mention technical capabilities in the available abstract or full text.
- Data fusion was described as a capability in 2 studies.
- All other technical capabilities were described in 1 study each, including: emission monitoring, compliance, data sufficiency assessment, multivariate analysis, traffic monitoring, pollution monitoring, congestion, safety, energy, stakeholder engagement, automated environmental control, air quality, emissions tracking, disease prediction, energy efficiency, education, data access, planning, surveillance, reporting, environmental monitoring, health applications, prototype system, population health research, disease surveillance, dynamic data integration, knowledge transfer, system integration, diagnostics, and health service impact.

Synthesis of Documented Outcomes for Sustainability and Public Health

The analysis of documented outcomes reveals significant patterns in how Digital Ecologies contribute to sustainability and public health goals, while also highlighting critical gaps in empirical evidence across the field.

Quantitatively Documented Impacts

A small subset of studies provided robust quantitative evidence of system effectiveness. The most substantial documented outcome came from Chetty (2007), whose Multi-Point Plan implementation achieved a 45% reduction in sulfur dioxide emissions while attaining World Health Organization air quality guidelines, demonstrating concrete progress in both sustainability and public health through policy integration and multistakeholder engagement. Similarly, Kinnear and Bricknell (2012) documented measurable improvements including reduced pollutant levels, improved air quality, and reduction in Disability-Adjusted Life Years (DALYs), though the authors noted limitations in the comprehensiveness of their quantitative data.

Qualitative and Process-Oriented Outcomes

The majority of studies reported qualitative impacts and process-oriented successes rather than quantitative metrics. In sustainability applications, Jacobs and Pooran (2012) documented reduced air pollutants and improved mobility through Intelligent Transportation Systems expansion, while AmbikaP. (2017) achieved automated energy optimization in smart buildings through IoT integration. Several studies, including Franco (2018) with nanomaterial risk assessment and Malin (2002) with ecological sustainability focus, developed decision-support tools and frameworks without providing quantitative outcome metrics.

In public health applications, qualitative outcomes predominated. Batterman (2005) established health-pollution linkages and respiratory disease patterns through stakeholder processes, while Chouvarda et al. (2019) documented improved self-efficacy, safety, and health literacy using their Connected Health Impact Framework. Multiple studies, including Gudes et al. (2009) and Mullins-Owens (2016), reported enhanced collaboration and chronic illness management through system implementation, though these remained qualitative assessments.

Implementation and Methodological Success Indicators

Across both domains, success was frequently measured through implementation milestones rather than outcome metrics. Studies such as Meyer et al. (2007) with disease monitoring implementation, Kangle et al. (2018) with ITS deployment, and Idowu et al. (2014) with interoperable data models emphasized system deployment and framework development as primary indicators of success. Conceptual advances, including Allen's (2014) sustainable diets framework and Allison's (2012) complexity framework for urban health, were presented as foundational achievements despite lacking empirical validation.

Significant Evidence Gaps and Limitations

A critical finding across the corpus was the substantial absence of outcome data, with 23 studies explicitly reporting no quantitative metrics or outcome data. Limitations included Borga et al. (2007) and Maynard (2001) acknowledging the prototype nature of their systems, while Souza Júnior and Souza (2009) reported improved health quality through system integration without quantitative support. Numerous studies, including Estes et al. (2008), Gotham et al. (2003), and Tapamo (2012), focused on technological capabilities and framework development without linking these to measured environmental or health outcomes.

The evidence base demonstrates a clear predominance of proof-of-concept implementations and qualitative assessments over rigorously documented impacts. While technological innovation and framework development are advancing rapidly, the field shows a substantial need for more systematic outcome measurement and long-term impact evaluation to validate the proposed benefits of Digital Ecologies for sustainability and public health.

Outcome Category

- 7 studies focused on sustainability.
- 8 studies focused on public health.
- 4 studies addressed both sustainability and public health.
- 17 studies did not mention an outcome category in the available abstract or full text.

Measured Impacts

- Quantitative outcome data was found in 2 studies (Chetty, 2007; Kinnear and Bricknell, 2012).
- Only qualitative or process impacts (such as improved planning, collaboration, or disease monitoring) were found in 17 studies.

- 17 studies did not mention any measured impacts in the available abstract or full text.

Success Indicators

- 17 studies reported implementation of a tool, framework, or system as a success indicator.
- 18 studies reported only process or analysis (such as framework analysis, review, or planning) as a success indicator.

Limitations

- 23 studies explicitly stated "no quantitative metrics" or "no outcome data."
- 2 studies had limited or partial quantitative data.
- 2 studies had some quantitative outcome data.

Overall, quantitative outcome data was rare; most studies reported only qualitative impacts or process indicators.

Cross-System Integration Patterns and Scalability

Integration patterns described in the studies:

- Automated, real-time data flows between environmental sensors and management platforms (AmbikaP., 2017; Tapamo, 2012; information from abstracts only).
- Use of ontologies and agent-based systems for dynamic data integration and reasoning (Tapamo, 2012; Mirza, 2006; information from abstracts only).
- Standards-based interoperability, such as Health Level Seven Fast Healthcare Interoperability Resources (Chouvarda et al., 2019; full text available) and web feature services (Idowu et al., 2014; information from abstract only).
- Participatory and user-centered design processes to ensure system relevance and adoption (Gudes et al., 2009; Gotham et al., 2003; information from abstracts only).
- Scalability was discussed in terms of replicability, such as the Multipoint Plan being adopted nationally (Chetty, 2007; information from abstract only), but empirical evidence on large-scale implementation was limited.

Barriers to integration and scalability

- Technical challenges, including data standardization and system interoperability
- Institutional inertia and resource constraints
- Lack of robust outcome data

Facilitators of integration and scalability

- Political commitment
- Stakeholder engagement
- Advances in data modeling and interoperability standards

Summary

- The included studies described a wide range of conceptual frameworks, technological architectures, and implementation approaches for integrating technological systems and environmental data to advance sustainability and public health.
- Most studies focused on frameworks, system designs, or pilot implementations, with only a small number reporting measurable environmental or health benefits.
- Quantitative outcome data was rare; most studies reported qualitative or process-oriented impacts.
- Common themes included the importance of interoperability, stakeholder engagement, and explicit linkage between environmental and health outcomes.
- Barriers to integration and scalability were frequently mentioned, including technical, institutional,

and data-related challenges.

- Facilitators included political commitment, stakeholder engagement, and advances in interoperability standards.
- The evidence base is characterized by conceptual innovation and diversity, but empirical validation and standardized outcome metrics were limited in the available studies.

Conclusion

This systematic review has synthesized the current state of knowledge regarding Digital Ecologies—the integrated networks of sensors, communication technologies, and data analytics designed to address interconnected sustainability and public health challenges. Our analysis of the literature reveals a field marked by both significant promise and substantial challenges, representing a crucial but still-maturing paradigm for understanding and managing planetary health.

The review demonstrates that Digital Ecologies encompass a diverse technological landscape, with dominant architectures including Geospatial Intelligence Systems, Ambient Sensing Networks, and Participatory & Citizen Science Platforms. These systems facilitate a bidirectional flow of data where environmental information guides public health interventions, while health data simultaneously validates and refines environmental models. Studies such as Chetty (2007) and Kinnear and Bricknell (2012) provide compelling evidence that well-integrated systems can achieve measurable impacts, including significant reductions in air pollutants and improvements in public health metrics like Disability-Adjusted Life Years.

However, the field faces critical limitations that must be addressed to realize its full potential. Most notably, there exists a substantial evidence-practice gap characterized by a preponderance of conceptual frameworks and pilot-scale implementations with limited empirical validation. Our findings indicate that quantitative outcome data remains scarce, with only a small subset of studies providing robust metrics of environmental or health impact. Furthermore, significant reporting gaps in methodological details—particularly regarding system architectures and data integration methods—hinder reproducibility and comparative analysis across studies.

The implementation of Digital Ecologies is further constrained by persistent technical and ethical barriers. Technical challenges include data siloing, interoperability issues between heterogeneous systems, and the resolution gap between environmental and health datasets. Perhaps more critically, equity concerns such as the digital divide, data sovereignty issues—particularly concerning Indigenous knowledge—and algorithmic bias risk perpetuating existing health disparities unless proactively addressed through community-centered design and ethical governance frameworks.

Looking forward, three critical priorities emerge for advancing the field. First, there is an urgent need to strengthen the evidence base through longitudinal studies employing standardized outcome metrics that capture both sustainability and health impacts. Second, the field must prioritize the development of interoperable data standards and scalable architectural models that can bridge existing technical divides. Third, and most importantly, future research and implementation must embrace participatory approaches that ensure equitable benefit distribution, respect data sovereignty, and align technological development with community-identified needs and priorities.

In conclusion, while Digital Ecologies represent a transformative approach to addressing planetary health challenges, their current state reflects a field in transition from conceptual innovation to demonstrated impact. The technological foundations and theoretical frameworks are firmly established, but the path forward requires greater methodological rigor, ethical commitment, and empirical validation. By addressing these challenges through collaborative, interdisciplinary efforts that prioritize both technological excellence and equity considerations, Digital Ecologies can fulfill their potential as vital infrastructures for building sustainable, healthy, and resilient communities in an increasingly complex world.

Funding
The author extends their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the Project number (PSAU/2025/02/36503).

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