

# Integrating Environmental and Digital Health Data to Build Health System Resilience in Saudi Arabia

**Abdullah Alanazi**

anaziabdul@ksau-hs.edu.sa

*Health Informatics Department,  
King Saud Ibn Abdulaziz University for Health Sciences,  
Riyadh 11481,  
Saudi Arabia*

**Corresponding Author:** Abdullah Alanazi

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## Abstract

**Background:** Climate change has not spared the Kingdom of Saudi Arabia in terms of their health effects around the world. There is a visible variation in weather, worsening air quality and soaring temperatures in the country. Strategic integration of environmental data with the current digital health systems would help in learning and managing such challenges effectively. This integration also helps in improving the health monitoring capability and the ability of the healthcare sector to respond faster and more effectively.

**Methods:** To investigate this notion, we conducted a survey on 227 Saudis employed in several environmental and health-related sectors. The sample consisted of policymakers, academic researchers, environmental specialists and medical professionals. They were questioned about environmental data and digital health tools, their familiarity with them, and how they are currently used and whether they think the healthcare system is prepared to integrate on a deeper level.

**Results:** Only a quarter of the respondents (25.6%) stated that they were currently using these integrated systems even though the majority (85%) had consented to the importance of the linking of the environmental data with the health data. The confidence in the readiness of the healthcare sector regarding this kind of change was low as only 17.2% of the respondents believed that the healthcare sector is prepared to undergo this kind of change. The findings revealed a difference in perception between various professions ( $X^2(6) = 14.41$ ,  $p = 0.025$ ). There was also a considerable rise in the proportion of support to integration in those participants who were aware of digital systems or environmental health data ( $p < 0.01$ ).

**Conclusions:** The findings show that there is a high interest in introducing environmental data to digital health platforms regardless of concerns about technical capabilities and the overall readiness of the systems. Increasing the digital capabilities and interoperability would help to make the healthcare system more resilient to the constant changes in the environment.

**Keywords:** Digital health, Climate change, Health informatics, Environmental health data, System resilience.

## 1. INTRODUCTION

Climate change can pose health threats, as global warming, extreme weather conditions, and poor air quality can directly influence the quality of life and human health [1, 2]. Healthcare systems should be ready for such challenges, and thus healthcare needs to be resilient and sustainable. Wearable sensors, telemedicine, mobile health applications, and electronic health records are the core tools for delivering and monitoring healthcare services and outcomes. Furthermore, such technologies have the potential to minimize the consequences of negative environmental health risks on health services and outcomes [3, 4].

A major opportunity to integrate environmental and climate data into healthcare systems is possible by setting up early warning mechanisms, establishing disease surveillance at the population level, and introducing early alerting and vigilance healthcare systems and programs [5]. There are, however, obstacles to these benefits being realized fully, which include infrastructure, ethics, and technology. In this work, the researchers discuss the possibility of improving the resilience of the healthcare system with the help of digital health data and consider the key obstacles and practical implementation demands, especially related to environmental health threats [6, 7].

Digital health tools along with environmental data are of great benefit to public health systems. Surveillance systems can monitor health outcomes influenced by climatic conditions, including heat stress, asthma attacks, and diseases transmitted by vectors by synthesizing clinical and environmental data so that timely and efficient interventions can be done [7, 8].

In addition, the environmental exposures of at-risk individuals can be monitored personally with wearable items and mobile health applications that can provide real-time alerts and counseling [8]. Furthermore, the availability of current data regarding service usage allows digital health systems to support health care resources to be better distributed in case of emergency situations related to the climate [9].

Regardless of these preventive efforts, there are issues. Privacy and data security is still an essential consideration when sensitive health information is connected to geographical or environmental data [10]. The lack of interoperability of various environmental and health data systems is also a limitation to the seamless integration and continuous analysis [11]. An impressive paradox arises: the most vulnerable populations to environmental health risks are the ones that are usually inaccessible to digital health technology [12]. Additionally, the ecological impacts of digital health infrastructure present underlying questions on sustainability, with energy usage and e-waste posing questions on the sustainability of those solutions in the long-term [13].

In order to solve these issues, several measures have been suggested. It is important to have clear governance structures, policies, and procedures to make sure that the process of integrated data is done safely and ethically [14]. Increasing the strength of data systems, promoting intersectoral collaboration, and training healthcare professionals are among the significant ways of strengthening capacity [15].

Effective and meaningful participation by key stakeholders such as local communities, legislators, and technology developers is achieved through engaging them [8]. Lastly, green computing and sustainable practices in digital health can be adopted to minimize the adverse environmental effects of the healthcare sector [13].

## 2. METHODS

It was a quantitative analysis that was meant to evaluate opinions, practices and suggestions of the integration of the digital health data with environmental health monitoring. The survey was carried out using an online survey questionnaire that was aimed at health professionals, researchers, policymakers, and environmental professionals, who were contacted through digital health networks, professional associations, and academic mailing lists. Calculations of sample sizes revealed that the lowest possible sample size of 386 participants was enough to provide 80% statistical power at a 5% level of significance. The participation was voluntary and anonymous, and informed consent was obtained electronically. Close-ended and open-ended questions were applied in the questionnaire to investigate existing practices, perceived risks and benefits, system readiness and strategic requirement.

Questionnaire was designed through a literature-based process, expert review and a pilot study on a small group of 12 participants. The reviews helped to make the reviews better and more comprehensive. The reliability analyses indicated the high inner consistency of the main domains ( $\alpha = 0.74 - 0.84$ ). The study was ethically approved by King Abdullah International Medical Research Center (NRR25/022/5). The SPSS data analysis presented descriptive results expressed in frequencies and percentages. The Bonferonni and FDR methods were used to prevent multi-comparisons. Multicollinearity was measured and logistic regression analysis and Variance Inflation Factor (VIF) were determined. Measures of model performance were determined using the residual plots, sensitivity, specificity, and area under the ROC curve.

## 3. RESULTS

A total of 227 participants completed the survey, representing a varied sample across gender, age, profession, and topographical area within Saudi Arabia. TABLE 1 shows a description of the demographics of the applicants. Among them, 132 were male (58.1%) and 95 were female (41.9%). The largest age group was 30–39 years (44.5%), followed by 40–49 years (27.3%), while the youngest (18–29 years) and oldest (50+) each represented 14.1% of the sample. Nearly half of the respondents were health care workers (48.5%), while 34.4% were researchers or academics. Environmental experts reported for 8.8%, and policymakers covered 8.3% of the sample. The Participants were distributed across the country's areas, with the peak representation from the central region (Riyadh) at 32.6%, followed by the western region (Jeddah/Makkah) at 25.6%, and the eastern region at 17.2%. The southern and northern regions represented 13.2% and 11.5%, respectively.

As outlined in TABLE 2, the mainstream of participants (69.6%) stated being familiar with digital health systems, and 60.4% indicated awareness of environmental health data. A strong majority (85.0%) thought that integrating environmental data into digital health systems is significant. However, only 25.6% stated currently using platforms where such integration exists. In terms of the supposed readiness of the Saudi health system for such integration, 17.2% considered the system "ready," 37.0% observed it as "somewhat ready," and 45.8% considered it "not ready." Acceptance for a national policy on integration was high, with 89.9% agreeing on the need for such a policy.

Table 1: Demographics of the participants

Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	132	58.1%
	Female	95	41.9%
Age Group	18–29	32	14.1%
	30–39	101	44.5%
	40–49	62	27.3%
	50+	32	14.1%
Profession	Healthcare provider	110	48.5%
	Academic/researcher	78	34.4%
	Environmental Specialist	20	8.8%
	Policymaker	19	8.3%
Region	Central (Riyadh)	74	32.6%
	Western (Jeddah/Makkah)	58	25.6%
	Eastern	39	17.2%
	Southern	30	13.2%
	Northern	26	11.5%

Table 2: Perceptions and Practices of participants toward digital health and environmental data:

Item	Response	Frequency (n)	Percentage (%)
Familiar with digital health systems	Yes	158	69.6%
	No	69	30.4%
Aware of environmental health data	Yes	137	60.4%
	No	90	39.6%
Believe integration is important	Yes	193	85.0%
	No	34	15.0%
Currently using integrated platforms	Yes	58	25.6%
	No	169	74.4%
Perceived readiness of the Saudi system	Ready	39	17.2%
	Somewhat ready	84	37.0%
	Not ready	104	45.8%
Support for national policy on integration	Agree	204	89.9%
	Neutral/Disagree	23	10.1%

Statistical analyses were conducted to detect relationships between different variables. A Chi-square test of independence examined the relationship between professional background and perception of system readiness. The association was statistically significant ( $\chi^2(6) = 14.41, p = 0.025$ ), representative that healthcare providers were most likely to rate the system as "not ready," while academic participants tended to choose "somewhat ready."

A one-way ANOVA was conducted to test differences in apparent system readiness based on familiarity with digital health systems. Results disclosed a significant difference between groups ( $F(2, 224) = 4.93, p = 0.008$ ). A post-hoc Tukey test revealed that participants familiar with digital health systems perceived significantly higher readiness compared to those who were unfamiliar ( $p = 0.005$ ). After applying Bonferroni correction for multiple post-hoc tests, the difference in perceived readiness between participants familiar and unfamiliar with digital health systems remained statistically significant (adjusted  $p = 0.025$ ). FDR correction yielded consistent findings.

Lastly, a binary logistic regression analysis was performed to identify predictors of support for integrating environmental data into digital health systems. TABLE 3 describes the predictors of the model. The model included familiarity with digital systems, years of experience, profession, region, and awareness of environmental data. The model showed a good fit (Hosmer–Lemeshow test:  $\chi^2(8) = 5.91, p = 0.66$ ), with a Nagelkerke  $R^2$  of 0.21. Familiarity with digital health systems was a significant predictor (OR = 2.41, 95% CI: 1.39–4.18,  $p = 0.002$ ), as was mindfulness of environmental data (OR = 1.72, 95% CI: 1.08–2.76,  $p = 0.023$ ). Years of experience and profession were not statistically significant predictors in this model. All predictors had VIF values  $< 2$ , indicating no evidence of harmful multicollinearity. Residual analysis confirmed model assumptions were not violated, and no influential cases were detected using Cook’s distance. The model achieved a classification accuracy of 72% with an AUC of 0.76, demonstrating acceptable predictive performance.

Table 3: Predictors of the Model

Predictor	OR	95% CI	p-value
Familiar with digital systems	2.41	1.39–4.18	0.002
=10 years of experience	1.47	0.93–2.34	0.098
Awareness of environmental data	1.72	1.08–2.76	0.023
Environmental Specialist (vs. researcher)	0.74	0.32–1.69	0.48
Policymaker (vs. researcher)	0.66	0.29–1.54	0.33

For the open-ended questions (Q18–Q20), responses were collected and independently coded by two research assistants to identify themes. The coding and generated themes were subsequently reviewed and validated by the principal investigator. The following results were obtained

Question	Codes	Themes	Quotes
18. Recommendations for enhancing the effectiveness of digital health data	Better data sharing, more training, stronger privacy, more funding, raise awareness	Infrastructure; Training, Privacy and policy, Public Awareness	“We need more training and resources to use digital health data effectively.”
19. Urgent actions needed to improve resilience	Better policies, teamwork across sectors, new ideas, fair access	Policies and Standards, Teamwork, Equal Access	“Collaboration between health and environment sectors is critical.”
20. Additional comments	Involve the public, don’t depend only on tech, protect ethics	Public Involvement; Balanced Use of Tech, Ethics and Trust	“Digital health is promising, but we must avoid misuse of data.”

These data findings together suggest a strong perceived necessity and support for integrating environmental health data into digital health systems in Saudi Arabia, mainly among those who are already familiar with such systems and aware of environmental health issues.

#### 4. DISCUSSION

This research analyzed the perception, knowledge and willingness of different stakeholders in the Saudi healthcare system to embrace the implementation of integration of digital health data and environmental health monitoring data. It is anticipated that the findings will help clarify how such integration is perceived in an area where the temperatures are very high, dust storms frequently occur, and the air quality is worsening, which leads to health issues. Particularly, 85% of the respondents stated that digital health platforms must incorporate environmental information.

This observation is consistent with international studies which show that digital health technologies, especially with the integration of environmental monitoring systems, increase the chances of detecting health issues related to climate change. The presence of such support in the Saudi Arabian context by researchers, specialists, and healthcare professionals may be attributed to the apparent realization of the influence of environmental factors on climate-sensitive health effects, including asthma and heatstroke, which are prevalent in the Kingdom [16].

Although the process of integration is mostly supported, only 17.2% of the participants are sure that the healthcare system in Saudi Arabia is prepared to use this approach. Conversely, 45.8% find the system “not ready”, 37% feel it is “somewhat ready”. This shows the wide margin between the current system capability and the identified need on integration. The results are aligned with the previous studies that have identified limited data sharing, system fragmentation, and the local regulatory constraints [17, 18].

The results of the surveys revealed that more than 30.4% of those who had never used digital healthcare systems in the past were more likely to think that the system was not ready ( $p = 0.005$ ). It underlines the need of healthcare organizations to enhance their digital capabilities and knowledge. Only 8.8% of the sample were environmental experts and 8.3% were policymakers. These results indicate that the readiness of the healthcare system and involvement in the policymaking process might differ depending on the profession.

The opinion of the participants regarding the readiness of the system was strongly correlated with the professional roles. Academics rated the system as “somewhat ready” more often, whereas healthcare providers rated it as “not ready”, which was more related to the impact of professional experience and practical engagement in forming opinions. ( $\chi^2(6) = 14.41, p = 0.025$ ).

The logistic regression analysis revealed that familiarity with digital health systems was a strong predictor of support of integration, with odds ratio of 2.41 (95% confidence interval: 1.39-4.18,  $P = 0.002$ ). Environmental health data was also found to be a major factor regarding the odds ratio of 1.72 (95% confidence interval: 1.08-2.76,  $P = 0.023$ ). These findings indicate that stakeholder engagement and proper training can improve the initiative to integrate digital health and environmental health.

The research is a contribution to the increasing literature that suggests that the Middle East region, and Saudi Arabia specifically is a crucial field to innovate in climate health. In contrast to the temperate climate zones, the Kingdom has its own special environmental issues that demand active data-oriented public health campaigns [19]. Despite the challenges of system readiness, a high level of integration and policy development support gives good ground towards successful implementation.

By incorporating digital health into the environmental monitoring systems, it will greatly improve the capacity of the healthcare system to respond to climate events. Digital tools can identify and handle any environmental risk, including heat waves and dust storms, which have been increasing in the area [6, 7].

Other advantages of this integration are to reduce the carbon footprint of the healthcare sector by using resources more efficiently and facilitating remote coverage of healthcare [5, 9]. The infrastructure development of digital health and environmental data systems will be a necessary step to meeting the objectives of the Vision 2030 and to the sustainability of high-quality healthcare services in Saudi Arabia [20].

Ethical issues and principles of justice should be incorporated when merging digital health data with environmental data to prevent inadvertent outcomes. According to previous studies, digital health innovation can increase existing biases unless properly addressed, especially by a population with poorly-developed digital culture or less access to the technology [12, 13]. It is crucial to consider the development of governance frameworks that allow maintaining data privacy, ensuring equitable access, and involving all stakeholders to make digital health activities trust-worthy and inclusive [10, 14]. The long-term resilience to climate change can also be achieved through cross-sectoral cooperation between the environmental, technological, and health spheres and helps to make the strategies implemented in the Saudi healthcare system ethical [11, 15].

A digital health platform can be developed using a plan based on the poverty-reduction studies in China. It combines machine-learning methods and statistical approaches with a broad spectrum of environmental data. The integration of environmental data can facilitate better decision-making in the field of public health and help to monitor the health hazards across a timeframe and across geographic boundaries [21]. Although there are some obstacles associated with digital infrastructure and inter-agency collaboration in the Saudi healthcare system, it is accepted that incorporating environmental data into healthcare systems is important. To achieve such integration and secure the health of the population during climate change, it is necessary to invest in the training of the workforce, make digital systems interoperable, and create a national policy within the sphere.

According to international research, there is another gap between the preparedness of systems to utilize digital environmental data and the recognition of health risks related to climate. Indicatively, the research carried out in North America, Europe and Australia has indicated the existence of fragmented data infrastructure, poor digital culture levels, interoperability, and privacy among others [22, 23]. These challenges are evident in the results of this research. The same tendencies can be followed in the emerging economies in which digital infrastructure and digital capabilities are still undergoing changes, whereas the level of climate risks is also high [24].

Climate-vulnerable emerging economies have also replicated comparable outcomes as they expand their digital capacities. The Saudi healthcare system is not an exception as it experiences difficulties

in accordance with the world trends. Simultaneously, the latest national investments in digital health transformation have distinguished opportunities. The following parallels show why international approaches are necessary to reinforce readiness and resilience.

## **5. STUDY RECOMMENDATIONS**

The results of the study indicate several feasible solutions that can be implemented to improve the application of health informatics in the Kingdom of Saudi Arabia to mitigate climate-related health issues. The most important of these recommendations is the connection between the current health information systems and real-time climate and environmental data, allowing them to promptly identify the climate-related threats and prevent further progression of the threat before it can occur.

Another important measure is to enhance communication of data between the environmental and health sectors. Scalable digital platforms- with the capacity to develop throughout its history and the ability to facilitate other operations like ongoing monitoring and emergency readiness- will also be critical in meeting this objective. To empower healthcare professionals to analyze environmental data and make decisions based on those, further practical training is required in such tools as the Geographic Information System (GIS) and simple data analytics.

The creation of predictive models and the extension of artificial intelligence will also assist decision-makers in organizing and investing resources in the most crucial areas. In addition, the increased cooperation of the government with the environmental and health sector will guarantee that all digital health programs will be subordinated to the national goals of climate adaptation. Lastly, the use of digital platforms to engage the masses can be very impactful. Community resilience can be improved by creating awareness and educating the population about resilience, and providing support to the country-level measures undertaken to manage the health risks associated with climate changes.

## **6. STUDY LIMITATIONS**

This study might be limited in some respects, but it does help to emphasize the necessity to use health informatics to mitigate climate-related health issues in the Kingdom of Saudi Arabia. Close-ended questions do not allow complete representation of the views of every participant, and some of the key groups-including policymakers and IT developers-remain underrepresented. In future research, the use of predictive modeling and pattern-recognition tools can help to create even more effective digital health systems and gain a better perspective on the factors that impact readiness.

## **7. CONCLUSIONS**

This research investigated the way in which health informatics can be harnessed to tackle climate-related health concerns in the Kingdom of Saudi Arabia. Even though the country is experiencing extreme heat, air pollution, and lack of adequate water, which has led to increased awareness of

the risk among people, digital health is still being underutilized to deal with these risks. Although digital health is increasing significantly, its fusion with environmental data, which is a significant requirement to an active public-health response, is highly insufficient. Health informatics has the potential to make communities more adaptable to climate pressure when used appropriately.

Artificial intelligence, GIS, and real-time analytics can be used to improve the health system, but only with innovative policymaking, enhanced cooperation of the cross-sector, and investment in professional skills development. Based on this, the paper offers effective suggestions to the creation of a climate-adaptive healthcare system. To make sure that the system is ready to face the present and the future environmental issues, the study proposes that technology should be implemented in climate-adaptation strategies by policymakers, health informatics professionals and healthcare administrators.

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## Appendix

Survey: Building Resilience and Tracking Environmental Impacts on Health through Digital Health Data

Demographic Information

1. Your Role:

- Healthcare Professional (e.g., doctor, nurse, therapist)
- Researcher/Scientist
- Policymaker
- Environmental Specialist
- Patient/Consumer
- Other (please specify): \_\_\_\_\_

2. Age:

- Under 25
- 25–34
- 35–44
- 45–54
- 55–64
- 65 or older

3. Gender:

- Male
- Female
- Prefer not to say
- Other (please specify): \_\_\_\_\_

4. Years of Experience:
  - Less than 5 years
  - 5–10 years
  - 11–20 years
  - More than 20 years
5. How familiar are you with the concept of digital health data (e.g., wearable devices, mobile health apps, electronic health records)?
  - Very Familiar
  - Somewhat Familiar
  - Not Familiar

### **Section 1: Awareness and Perceptions of Digital Health and Environmental Health**

6. How important do you think it is to integrate environmental data (e.g., air quality, temperature, pollution levels) with digital health data?
  - Very Important
  - Somewhat Important
  - Not Important
  - Not Sure
7. To what extent do you believe digital health data can help in identifying health risks related to environmental changes (e.g., pollution, climate events)?
  - Very Effective
  - Somewhat Effective
  - Not Effective
  - Not Sure
8. How familiar are you with the health impacts of environmental and climate change?
  - Very familiar
  - Somewhat familiar
  - Slightly familiar
  - Not familiar at all

### **Section 2: Current Practices and Challenges**

9. Does your organization currently collect or use environmental data (e.g., air quality, heat waves, pollution) in its health information systems?
  - Yes
  - No
  - Not sure

If yes, what types of data are collected? (Select all that apply)

- Air quality
- Water quality
- Temperature/heatwaves
- Disease surveillance linked to environmental events
- Other (please specify): \_\_\_\_\_

10. What are the most significant challenges in using digital health data to track the impact of environmental factors on health? (Select all that apply)

- Data privacy and security concerns
- Lack of standardization in health data collection
- Limited access to technology for certain populations
- Integration of health data with environmental data
- Regulatory and legal barriers
- Insufficient healthcare infrastructure
- Lack of technical capacity
- Lack of trained personnel
- Poor data quality or availability
- Limited leadership or policy support
- Other (please specify): \_\_\_\_\_

11. How confident are you that existing digital health systems can handle climate-related health data?

- Very confident
- Somewhat confident
- Not confident
- Not sure

### Section 3: Benefits, Risks, and Opportunities

12. What potential benefits do you see in using digital health data to mitigate the effects of environmental changes on health? (Select all that apply)

- Early detection of health problems
- Personalized health recommendations
- Improved response to climate-related health emergencies (e.g., heatwaves)
- Better preparedness for future health crises
- Increased awareness and engagement in public health efforts
- Enhanced decision-making for healthcare providers
- Other (please specify): \_\_\_\_\_

13. What risks or concerns do you have regarding the use of digital health data in this context? (Select all that apply)
- Potential misuse of personal health data
  - Disparities in access to digital health technology
  - Over-reliance on technology over human judgment
  - Inaccurate or incomplete data
  - Ethical concerns (e.g., informed consent, autonomy)
  - Other (please specify): \_\_\_\_\_
14. How comfortable are you with the use of digital health data in tracking and responding to environmental health risks (e.g., exposure to pollutants, heat waves, etc.)?
- Very Comfortable
  - Somewhat Comfortable
  - Not Comfortable
  - Not Sure

#### **Section 4: Future Applications and Recommendations**

15. How likely would you be to support the development of a framework or platform that integrates digital health data with environmental data to monitor health outcomes?
- Very Likely
  - Somewhat Likely
  - Not Likely
  - Not Sure
16. What would be the key factors that would make you more likely to use or support the use of digital health data in this context? (Select all that apply)
- Improved data security and privacy protocols
  - Clear regulations and ethical guidelines
  - User-friendly and accessible technology
  - Evidence-based health recommendations
  - Support from healthcare professionals and policymakers
  - Education and awareness programs
  - Other (please specify): \_\_\_\_\_
17. What strategies do you think would most strengthen resilience to climate and environmental health impacts? (Select up to 3)
- Better data integration across sectors
  - Improved staff training and capacity building
  - Stronger policies and regulations
  - Increased funding for digital health infrastructure
  - Community engagement and public awareness

- Research and innovation in health informatics
  - Other (please specify): \_\_\_\_\_
18. What additional recommendations do you have for enhancing the effectiveness of digital health data in mitigating the effects of environmental changes on health?

**Section 5: Final Comments**

19. In your opinion, what is the most urgent action needed to improve resilience to environmental health impacts in your context?
20. Do you have any other thoughts, concerns, or suggestions regarding the integration of digital health data and environmental health monitoring?