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Omar Abdulkarim Saeed Alhammadi^{1*} , Hajer Ibrahim Mohamed¹ , Shuaibu Saidu Musa² , Mohamed Mustaf Ahmed³ , Misha Abayneh Lemma⁴ , Uwamahoro Joselyne⁵ , Bananeza Roméo⁶ , Yinusa Abdullahi⁷ , Zhinya Kawa Othman⁸ , Mohammed Raihanatu Hamid⁹ , Omar Kasimieh¹⁰ , Don Eliseo Lucero-Prisno III^{11,12,13} , Safouane Labyad¹⁴ , Olalekan John Okesanya¹⁵ 

¹Department of Medical Laboratory, University of Hargeisa, Hargeisa, Somalia

²Department of Nursing Science, Ahmadu Bello University, Zaria 810106, Nigeria

³Faculty of Medicine and Health Sciences, SIMAD University, Mogadishu, Somalia

⁴Department of Plastic, Reconstructive, and Hand Surgery, St. Paul's Hospital Millennium Medical College, Addis Ababa 3000, Ethiopia

⁵Department of Nursing Science, Mount Kenya University, Kigali 5826, Rwanda

⁶Faculty of Clinical Medicine and Community Health, University of Rwanda, Kigali 4285, Rwanda

⁷Department of Electrical and Electronic Engineering, Olabisi Onabanjo University, Ago-Iwoye 120107, Nigeria

⁸Department of Pharmacy, Kurdistan Technical Institute, Sulaymaniyah 46001, Kurdistan Region, Iraq

⁹Department of Mathematics and Computer Science, College of Education Billiri, Gombe 771101, Nigeria

¹⁰Department of Family and Community Medicine, University of the East Ramon Magsaysay Memorial Medical Center, College of Medicine, Quezon City 1113, Philippines

¹¹Department of Global Health and Development, London School of Hygiene and Tropical Medicine, WC1E 7HT London, United Kingdom

¹²Faculty of Management and Development Studies, University of the Philippines Open University, Los Baños 4031, Philippines

¹³Faculty of Public Health, Mahidol University, Bangkok 73170, Thailand

¹⁴Faculty of Medicine and Pharmacy, University of Hassan II, Casablanca 9154, Morocco

¹⁵Department of Public Health and Maritime Transport, University of Thessaly, 38222 Volos, Greece

***Correspondence:** Omar Abdulkarim Saeed Alhammadi, Department of Medical Laboratory, University of Hargeisa, Bepsi Street, Hargeisa, Somalia. alhammadiomar05@gmail.com

Academic Editor: Zhaohui Gong, Ningbo University, China

Received: July 22, 2024 **Accepted:** October 24, 2024 **Published:** November 25, 2024

Cite this article: Alhammadi OAS, Mohamed HI, Musa SS, Ahmed MM, Lemma MA, Joselyne U, et al. Advancing digital health in Yemen: challenges, opportunities, and way forward. *Explor Digit Health Technol.* 2024;2:369–86. <https://doi.org/10.37349/edht.2024.00035>

Abstract

The health sector in Yemen has experienced significant challenges due to prolonged conflict and suboptimal governance, making the development of digital health (DH) crucial. This study highlights the urgent need for the strategic implementation of health interventions in a country where fully functional healthcare facilities, low-income levels, damaged infrastructure, and suboptimal governance limit the effectiveness of traditional interventions. It discusses the prioritized step for advancing DH as a root issue that needs to be addressed first and highlights the importance of effective and efficient management of available resources. The development of telecommunication infrastructure is a fundamental pillar for advancing DH in the

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country. This comes along with consideration of effective management of the available resources and collaborative efforts among all parties, which are critically important to remove restrictions and constraints relevant to the administrative division and fragmentation of the healthcare system and objectively ensure universal coverage of telecommunications and healthcare services nationwide. By leveraging DH technologies (DHTs), Yemen can overcome these obstacles and revolutionize healthcare delivery. Implementing DHTs and related projects can ensure equitable access to high-quality healthcare services, particularly for impoverished individuals. However, the success of these initiatives relies on a well-established supportive policy and regulatory framework, improved public communication systems, targeted strategies, community engagement, and collaboration between medical service providers and community healthcare workers. Awareness campaigns, workshops, research collaborations, and engagement with international organizations are highly recommended to address challenges and foster the growth and development of DH in Yemen.

Keywords

Yemen, digital health, advancing, technology, data

Introduction

Several revolutionary discoveries in digital technologies have been made globally over the past decade, transforming all service sectors. Some of these digital technologies are employed to enhance healthcare services, indicating enormous promise for universal health coverage (UHC). However, many must understand the different prospects of the intersection of healthcare and digital technologies [1, 2]. Digital health technologies (DHTs) are systematic applications of information and communications technologies for data exchange and exploiting computer science and digital discoveries to support informed decision-making by individuals, the health workforce, and the healthcare system, to strengthen resilience to disease, to increase accessibility to healthcare services, and to improve their quality [3, 4].

When using intensive data sources, the nature of the health sector can be easily combined with the use of technology for analytics, improving health outcomes, responding to public health crises, and efficiently and equitably allocating resources [2]. DHTs can provide accurate and robust solutions for current and forthcoming outbreaks with measures to support health sector for advanced decision-making, timely case detection, constant surveillance, access to healthcare services, and virtual consultations. These technologies can serve key roles in achieving UHC because they can be rapidly implemented and scaled to provide solutions; however, their use must be strategic and wise to recognize issues regarding the privacy and rights of the patient [5, 6]. Billions of dollars have been invested in new DHTs' entrepreneurship since it became dramatically exciting [7]. Technologies considered to be DH include telemedicine, health information technologies, mobile health, wearable devices, and personalized medicine [8]. Simultaneously, myriad data on health behavior have been produced in behavioral science, which have changed strategies to implement effective human-delivered interventions. Recently, increasing attention has been devoted to developing DHTs; however, this has outpaced research [6].

Various DHTs have the capability to transform healthcare delivery and accessibility and promote UHC, particularly in challenging environments, such as Yemen. Electronic health records (EHRs) streamline information management and ensure continuity of care. Telemedicine and telehealth facilitate remote consultations, allowing healthcare providers to reach underserved areas. Telepharmacy ensures that individuals can access the necessary medications and counsel without visiting the pharmacy. Artificial intelligence (AI) and machine learning (ML) are increasingly being utilized to analyze health data, predict outcomes, and improve decision-making processes. AI and ML tools also increase the feasibility of leveraging precision medicine, such as clinical practices, to be used in oncology and support the treatment of various types of cancers. For instance, advanced computational analytics is a significant tool for delivering real-time feedback and promoting healthcare services for chronic diseases and cancer. Electronic

hospitals integrate these technologies to create comprehensive interconnected systems that enhance patient care. Mobile health applications empower users with health management tools, offer personalized insights, and promote preventive care [9].

War and political conflict are the most destructive issues affecting the health sector worldwide. For instance, the healthcare system in Yemen has “collapsed” because of an ongoing conflict [10–12]. The infrastructure of all sectors, particularly the health sector, has gradually become more fragile during the previous decades. The healthcare system is crippled, and the quality of its services has deteriorated due to collapse and fragmentation [13]. More than half of the health facilities have been destroyed by terrorist attacks, which has led to a shortage of healthcare professionals (HCPs) and healthcare services. Consequently, it is difficult to deliver and provide essential healthcare services, displacement, migration of specialized doctors and HCPs, and inequality in providing healthcare services for all regions. The limited accessibility and availability of HCPs and healthcare services have increased morbidity and mortality among civilians [4, 14–16]. Since 2014, approximately 100,000 people have died. Since 2015, the public health infrastructure and sanitation services have collapsed, prompting aid agencies to warn of a worsening humanitarian situation. Therefore, infectious diseases such as cholera outbreaks have affected the country. The pandemic was further compounded by a continued lack of public awareness and limited accessibility to available facilities [10–12, 17]. High rates of medical errors and weaknesses in health management and information systems have been exacerbated by a lack of continuing education for healthcare staff [4, 18]. The exacerbation was evident during the first wave of COVID-19 when many staff panicked and did not go to work at public hospitals, forcing some hospitals to close [12].

Additionally, the communication system in Yemen was unsatisfactory, hampering effective healthcare management and risk mitigation. Information on complaints is collected regionally and hampered in each region, resulting in information not being distributed. Furthermore, public communication is poor, and engagement with communities remains suboptimal and dependent only on the initiatives of individuals or humanitarian organizations [10, 19]. Moreover, problematic determination and difficulties in the implementation of policies to provide healthcare services aggravated due to an administrative division of the healthcare system between the two authorities, which imposed further restrictions [13, 20]. On the other hand, some irregularities occur, such as practices under suboptimal governance, leading to unequal distribution and accessibility [21, 22]. Therefore, advancing DH in the country will provide sustainable solutions to the communication challenges faced by healthcare systems. Hence, this study explored the potential of advancing DHTs and discussed the implications of these newly implemented innovations in Yemen to enhance healthcare accessibility and quality.

DH landscape in Yemen

Obviously, Yemen’s health system has structural vulnerabilities, and its healthcare system has suffered the most [10]. However, implementing DHTs can play a crucial role in revolutionizing the health sector. Accordingly, telecommunication infrastructure will be discussed in this section, which helps to explore the potential of implementing DHTs effectively in the country.

Digital (telecommunication) infrastructure and connectivity

Yemen’s DH landscape is still in the early stages of development. Yemen had 9.10 million internet users by 2023, with an internet penetration of 26.7% [23]. The capacity of telecommunications acutely underperforms in regional and global trends in access, quality, and costs. In addition, Yemen faces severe challenges in its power industry, leaving a significant deficit in the telecommunications sector. Due to infrastructure weaknesses, the coverage of telecommunication services is limited, which imposes constraints on ensuring a wide range of internet coverage and leveraging the emerging technologies nationwide. Accessibility to mobile-based services has complications, which has led to 27% of the population having access to some form of internet connectivity. This is very poor compared with the average accessibility for the Middle East and North Africa (MENA) region (65%) and the world (49%). Due to the centralization of the government system, the infrastructure of the telecommunications sector has not

been distributed equally nationwide, indicating a disparity in telecommunication coverage and cost across the country. Furthermore, the security embargo significantly restricts the expansion of internet accessibility in remote regions. The national fixed backbone network consists of outdated elements that are not suited to high-speed internet. Approximately 50% of the fixed lines were only active in providing telephone and internet services in the country [24].

Because the availability of 3G and 4G technologies is very limited in the country, where the available internet has low speed and bandwidth in most areas, the quality of services available to internet users is considered the weakest in the world. Consequently, time-critical services, intensive programs, and media downloads are not available and exceed the available capacities. In addition, the cost of internet, mobile, and modern phone services far exceeds the local per capita income by 26.2% of the average monthly income, with performance below the global average. In 2021, the average cost of 1 GB reached approximately \$15.98, which is the highest in the region and North Africa. Therefore, the cost of telecommunication services is an issue that should be considered (Table 1) [24–28].

Health infrastructure and the Yemeni context relevant to DHTs

The structural vulnerabilities of the health sector are demonstrated by disparities in the distribution of health facilities and suboptimal governance [16]. According to some studies, 30.6% of the total population spends more than half an hour traveling to the nearest fully or partially functional public healthcare facility and 42.4% spend one hour traveling to the nearest fully or partially functional public hospital. Access to healthcare facilities varies widely according to the district and type of healthcare services. Substantial variability in accessibility has been demonstrated, particularly between those at the frontlines of unsettled districts and others [29]. A survey conducted in Mukalla district is a notable example that indicates the variability in accessibility to health facilities in Yemen. This study aimed to highlight the importance and role of geographic information systems in disaster management to support decision-makers in obtaining information about the distribution of health facilities in the study area, as well as the availability of doctors, nurses, beds, and ambulances. In the study area, there are 35 health facilities concentrated in the middle of the city where accessibility is demonstrated by the study to be affected by several obstacles obstructing people from receiving quality and on-time healthcare services. Obstacles include long distances and interruption of access to these facilities. The study also noted that hospitals in Mukalla city have a significant shortage of specialists, physicians, and nurses. Additionally, when a disaster occurs, hospitals in the city are certainly unable to provide adequate support to those who are injured or in need of care. Accordingly, this creates confusion for officials and decision-makers because the analysis shows that most of the hospitals in Mukalla are in the middle area, except for Ibn Sina Hospital, which is the main and largest hospital in terms of the number of doctors, nurses, and beds [30]. However, this study highlights the importance and role of information and communication technology (ICT) in supporting decision-makers in disaster management. The study demonstrated that these systems and technologies help decision-makers prepare and put future plans to determine the readiness of each facility and identify appropriate locations for new health facilities based on multiple criteria, such as (population density, distance from the flood stream's location, etc.). The National Digital Health Strategy (NDHS), launched in 2019, aimed to improve the quality and efficiency of healthcare systems by providing access to DHTs services [31]. Further information on existing data relevant to the context of DHTs is provided in Table 2.

However, poor internet access and low levels of digital literacy among certain groups are notable challenges that need to be addressed [36, 40]. Furthermore, although sound, Yemen's public service system must be developed and improved as technology advances. Numerous flaws and abnormalities remain, as evidenced by inefficient data processing and excessive deviations [10]. When analyzing traditional healthcare services and their impact, data and research findings substantiate the prevalence of corruption, inefficiency, and unequal resource distribution. For instance, the distribution rate of healthcare facilities between rural and urban areas demonstrates huge disparities and unequal distribution but indicates a promising DH implementation and equality for all. Ensuring this requires advancing DH in Yemen with consideration to telecommunication sector empowerment and development in the first place.

Table 1. Data on telecommunication infrastructure and connectivity [24–28]

Data categories	Value (percentage or number)	Descriptions	Indications and clarifications	
Internet penetration rates (overall and by region/demographics)	Approximately 95% of female and 88% of male respondents in rural areas	Reported that the internet is rarely or never accessible	Urban areas show greater telecommunication adoption than rural ones	
	89% of female and 83% of male respondents in urban areas	Reported never having access to a telephone		
	30% of rural women	Have phone access rarely or never		
	27% of urban women			
Mobile phone/smartphone ownership and usage	81% of households	Owned a mobile phone	According to the household budget survey, these data were found	
	84% to 92% among households	An increase in mobile phone ownership among households between the year 2014 and 2021		Despite the ongoing conflict, Yemen's population uses mobile phones widely, with Samsung and Huawei being popular choices
Availability of broadband internet access	6 subscribers per 100 people	Rate of mobile-broadband subscriptions	Despite frequent reliability issues, the internet is available in most urban areas, while remote and rural regions are deeply underserved	
	Less than 2 subscribers per 100 people (only 391 thousand people)	Rate of fixed-telephone services subscriptions		
	18% of respondents	They declared access to the internet from their homes, cafés, and workplaces, respectively		Highlighting the limited connectivity available to conduct day-to-day activities
	34% of respondents			
	6% of respondents			
	0.7 (Mbp/s)	The estimated download speed in Yemen		This is primarily driven by the limited availability of 3G and 4G technologies
	29.8 (Mbp/s)	The average of the world's download speed		
11.7 (Mbp/s)	The average of the regional download speed			
Electricity access and grid reliability	12 h to 23 h a day	Number of hours of electricity blackouts in urban areas	The telecommunication network's infrastructure is crucial for delivering sustainable digital services like distance education, digital health, smart energy grids, and cash transfers. Damage to the electricity infrastructure poses another challenge to the telecommunication network. Frequent power outages due to electricity supply damage can result in extended internet service disruptions. The severe damage limits both access to and the affordability of internet services at the household level	
	Up to 20 h per day	Number of hours of electricity blackouts in rural areas		

Table 1. Data on telecommunication infrastructure and connectivity [24–28] (continued)

Data categories	Value (percentage or number)	Descriptions	Indications and clarifications
	40%	Percentage of the Yemenis population having access to electricity	
	35%	Percentage of Yemenis living without any access to electricity	
	30%	The percentage of Sabafon coverage was out of service due to high fuel-related electricity costs	
	2,444 MW	The total value of national power generation	
	3,102 MW	The total value of national power generation demanded	

Table 2. Key indicators influencing digital health (DH) adoption in Yemen [32–39]

Data categories	Value (percentage or number)	Descriptions	Indication
Data on DH technologies (DHTs) adoption in Yemen			
Percentage of healthcare facilities with access to electronic medical records (EMR)	55% fully operational 31% functioning partially 13% non-operational Specific data on EMR adoption rates in Yemen is scarce	Percentage of functional health facilities in Yemen	Yemen faces significant challenges due to ongoing conflict that affects health infrastructure. However, adopting health information technology, including EMRs, has improved access to care, especially for underserved communities
Utilization rates of telemedicine/telehealth services	22%	The national telehealth utilization rate among adults by mid-2021 was down from the early pandemic peak but still above pre-pandemic levels	The adoption of telemedicine in Yemen is promising, especially during the COVID-19 pandemic. Clinicians have increasingly used telehealth modalities, including video-based and audio-only services
Use of mHealth apps and other DH tools by healthcare providers	66% 66% 49% 41%	Telehealth Electronic health records (EHRs) Patient portals Health information exchange	As in other regions, mHealth apps play a crucial role in Yemen. While specific data is limited, adopting DH tools has expanded access to healthcare. Clinicians have used such tools

Table 2. Key indicators influencing digital health (DH) adoption in Yemen [32–39] (continued)

Data categories	Value (percentage or number)	Descriptions	Indication
Barriers to DHTs adoption (lack of training, funding, regulations, etc.)	39%	Prescription drug monitoring programs	Challenges of using DHTs include: Incomplete and difficult-to-use health information exchange interfaces for providers. Internet/broadband access and poor connectivity are another challenge for patients
	27%	Remote/home monitoring	
	22%	Wearable devices	
	53%	Time constraints	
	51%	Cost considerations	
Data and healthcare system indicators			
Number of functioning healthcare facilities	45%	Percentage of healthcare facilities in Yemen that are functioning and accessible to the public	The shortage of functioning healthcare facilities demonstrates the importance and the urgent need for DH implementation, which promotes healthcare intervention and universal health coverage nationwide
	247	Number of healthcare facilities have been destroyed or damaged due to the ongoing conflict	
Distribution of healthcare facilities (urban vs. rural)	80%	Percentage of the population in urban areas who have access to healthcare services	The disparities that exist within the distribution of healthcare facilities between rural and urban areas demonstrate the importance and urgent need for DH implementation in the country
	25%	Percentage of the population in rural areas who have access to healthcare services	
Healthcare worker density and training levels	10 healthcare workers per 10,000 people	The average of healthcare workers	The density of healthcare workers is very low. Yemen falls well below the international standard of 41 per 10,000
	More than 90% of the health centers	The percentage of the health centers that reported an acute shortage of qualified nurses	In contrast, the surveyed percentage of those who reported an acute shortage of qualified nurses indicates that the training level for healthcare workers is weak. Several training institutions to prepare certified professionals have been closed, and the available training programs failed to offer the kind of practical and task-oriented instruction required in real-life healthcare settings. Consequently, healthcare centers have under-trained staff, capable of providing the most basic services only
Disease burden and mortality rates	62.7 years to 65.8 years	There was an increase in life expectancy at birth in Yemen between 2000 and 2021	However, the country still faces health challenges, including high levels of child malnutrition, low immunization rates, and outbreaks of infectious diseases
	1,471.7 deaths to 1,069.4 deaths per 100,000 population	The decrease of all-causes age-standardized mortality rate between 1990 and 2019	
Data on socioeconomic and demographic factors			
Poverty and income levels	55%	The percentage of the population estimated by the United Nations Development Program who lives below the poverty line	Poverty rates are higher among rural residents than urban residents and among women than men

Table 2. Key indicators influencing digital health (DH) adoption in Yemen [32–39] (continued)

Data categories	Value (percentage or number)	Descriptions	Indication
	18.4%	The percentage of the population estimated by the United Nations Development Program who lives in extreme poverty	
Education attainment	Over 56% of women Nearly 18% of men Only 14% of women 40% of men	Percentage of those having no formal schooling Percentage of those having at least a secondary-level education	Educational attainment among women in Yemen is currently very low In contrast, Yemen ranks 155 out of 156 in the World Economic Forum’s Global Gender Gap Index regarding gender disparities. Women remain significantly underrepresented in public and elected office, holding only 4.1% of managerial and decision-making positions

Benefits of advancing DH

The potential for establishing better healthcare system in Yemen can help develop DHTs and understand their capabilities and benefits. A survey showed that 80% of the population faces significant challenges in accessing healthcare system, and approximately 50% of health facilities are fully or partially functional, reflecting the importance of DHTs in providing feasible, measurable, and straightforward solutions (World Bank Group, 2021) [36]. DHTs can provide equitable and available access to healthcare systems that are characterized by excellent quality and efficiency via digital platforms [41]. A notable example of the benefits of DHTs in improving the quality of healthcare services is illustrated by a case study of Yemen hospitals in Sana’a. This study aimed to identify the impact of using the information technology (IT) system to improve the quality of healthcare services. It identified four dimensions for attitudes about healthcare IT adoption: time, effort, cost, and safety. Accordingly, the study demonstrated that the IT system positively affects healthcare services, such as saving (time, effort, and cost), enhancing safety and quality of care for patients, increasing efficiency, supporting decisions, and increasing satisfaction for both patient and health workers [42]. This study highlights the benefits of DHTs for improving the quality of healthcare services in Yemen. However, it highlights the importance of improving the database’s effectiveness to ensure providing healthcare services with high efficiency, the need to adopt the IT in each hospital and integrate them into one national system, attention to the maintenance of devices and websites, and challenges, attracting HCPs specialized in the use of computer systems and rehabilitation of hospital staff by holding training courses.

DHTs can revolutionize the healthcare landscape, especially in low-income countries. Its adoption among conflict-affected populations can improve access to quality care and overcome geographic barriers through interorganizational/professional cooperation with accurate data, self-care management, transparency, and stakeholder support [17]. The traditional approach to monitoring chronic diseases represents a major challenge for hospitals and the Ministry of Health in Yemen. In contrast, DHTs represent a fundamental solution to provide remote and real-time monitoring for patients with chronic diseases and help in the storage and analysis of data. A case study aimed at developing a Remote Patient Health Monitoring System (RPHMS) using bluetooth-enabled medical sensors and mobile phones showed that doctors could obtain accurate and timely data regarding patients’ chronic illnesses. Furthermore, the study demonstrates that the RPHMS improves the control of the heart rate, blood pressure, and oxygen percentage in the blood (SPO₂) because it provides real-time monitoring of chronic patients. The

study adopts the Rational Unified Process software, which is connected to central hospital software to store the feedback and prescriptions in the hospital database and then forward the data as SMS to the doctor. These databases can be accessed by the patient using a mobile application that enables them to receive feedback from the doctor [43]. RPHMS has been developed using mobile phones and general packet radio services; a wireless technology that allows mobile phones to transmit data over cellular networks. Therefore, it provides a solution for mobility, which enables patients to be monitored anywhere and anytime. In addition to the mobility solution, this study provides other important benefits to patients, doctors, and healthcare centers. However, the study avoided using internet technology due to the existence of obstacles faced by both patients and doctors, which is the unavailability of the internet. While the study demonstrated how DHTs are beneficial, it indicates the gap within ICT and highlights the importance of improving the telecommunications sector to ensure UHC nationwide.

Both healthcare system processes and healthcare outcomes can be improved if DH interventions (DHIs) focus on scalability, integration, and sustainability. The technology, architecture, and scientific underpinnings of DH solutions allow the identification of strengths and weaknesses. It helps stakeholders within the health ecosystem communicate with external partnerships, whereas structural integrity at scale can be assessed in terms of operations and financial health [40]. Therefore, Yemen can benefit from several experimental applications of successfully implemented DHTs initiatives. For instance, telemedicine initiatives in Ghana, in which social health workers utilized mobile phones in outback societies and regions, showcased successful DHTs initiatives depending on the end-user's insights. User-dependent design is a critical factor in achieving success. This has resulted in sustained exploitation and use. This strategy enabled telemedicine services to expand and be rolled out widely in Ghana and provided measurable benefits to the healthcare system, including reductions in unnecessary referrals of cases to hospitals [44, 45]. Additionally, studies in Palestine have reported the effectiveness of DH in improving the quality and efficiency of healthcare services in the country [4]. In general, leveraging DHTs will cover the gaps within health sector and improve health outcomes in Yemen. Nonetheless, the parties involved must strive together through political action and policy interventions to provide healthcare services to those in need [20, 46].

Challenges and opportunities

Yemen has been overwhelmed by several challenges since 1990 owing to political conflicts that have resulted in one of the most significant humanitarian crises in the world, which deters the successful advancement of DH in the country. Such challenges include inadequate technical facilities with a lack of electricity, poor internet access, the absence of the internet in elevated regions, and lower levels of digital literacy among certain groups [36, 40]. Other notable challenges include insufficient infrastructure, fragmented healthcare system, reduced availability and quality of data, lack of skilled manpower, governance, supportive policies, and interoperability [47]. The challenges and opportunities of the electronic disease early warning system have been evaluated in Sana'a Governorate in Yemen and it was found that the overall level of system performance was good, with an average (86%) but the relevant considerations and issues were highlighted. The system's performance at the health facility, governorate, and high/central levels in terms of attributes such as simplicity, representativeness, acceptability, flexibility, and stability were 84%, 100%, 84%, 91%, and 70%, respectively.

Furthermore, stakeholders reported that the main strength was the rapid detection and response to diseases and outbreaks, particularly those at high and central levels. Fifty percent of them reported that the data had high accuracy owing to validation, which is also one of the strengths. On the other hand, stakeholders at the high and central levels said that the main weakness is network weakness in some remote areas. The director of the system at the central level said that "there is no operational cost for maintenance of the electronic instruments and mobiles". This indicates isolation and a weak connection within the healthcare system. Governmental support for strengthening stability is recommended since the program is completely supported by donors and further evaluation for generalizing the findings on all sites. UHC can be ensured via DHTs, but telecommunication infrastructure advances nationwide [48].

Reasonably, the scarcity of data from remote and rural areas is a remarkable challenge. However, it is mandatory to enhance the network within the healthcare system at the district, regional, and national levels and improve telecommunication infrastructure to ensure communication, data and information exchange, and UHC.

Successful implementation of the DHIs and projects in other countries can be beneficial for developing and creating well-established strategies for improving DHTs and its services in Yemen. For instance, 5-year global strategy to establish DH was launched in 2020 by the World Health Organization (WHO). Its purpose is to promote health and wellbeing worldwide. It was established with a vision aimed at increasing accessibility to healthcare systems, empowering members of all societies, and guaranteeing equity and human rights for all. Consequently, several DH projects and initiatives have been implemented worldwide [49]. Some of these initiatives and projects have been implemented in Yemen to improve the healthcare system. These initiatives include the NDHS, which was launched in 2019 to enhance the quality and efficiency of healthcare systems by providing access to DH services and reducing their time and costs [31, 41]. Based on the status of healthcare system in Yemen, the initiative experimented with and developed a national project in the UK called “Digital Health Hubs” that can also be beneficial for advancing DH in Yemen due to its capabilities to address the inequalities of access to healthcare system. It is important to note that DH literacy presentation and the use of DH tools in places that guarantee safety and privacy for members of society play an essential role in the initiative’s success [31, 50]. The influence of these initiatives and others is high. This increases the availability and accessibility of healthcare systems and enhances their quality. Furthermore, it provides an opportunity to promote healthcare services nationwide.

Discussion

When asking about the prioritized step for advancing DH in Yemen, the roots of issues must be examined and evaluated carefully, considering the aspects of each issue and their overlapping or interference size with each other. The maximum interference size of an issue is the root of solving all the relevant issues. As the available data indicate, the infrastructure of the health and telecommunication sector is suffering due to a decade of conflict and limited resources; fortunately, resources are not absent. Effective and efficient management of resources is critical to address current issues and advance health sector via DH in Yemen.

Clearly, the country needs more resources and well-developed infrastructure. However, available resources, financial funding, and opportunities should be managed effectively and distributed equally among all governorates at rural and urban levels. Furthermore, collaborative efforts among parties and associations of international entities are critically important to remove constraints and ensure the universal coverage of telecommunications and healthcare services nationwide. Several issues and challenges within the health sector and the shortage of healthcare services can be solved by utilizing and benefiting from emerging technologies. Accordingly, telecommunication is a prioritized step in improving health sector by advancing DH in Yemen. Furthermore, a well-developed telecommunication infrastructure facilitates communication at the national and international levels, fosters international collaboration, and promotes the provision of data. For instance, if the telecommunication infrastructure is developed, accessibility and availability to the internet will increase, and the data shortage will be solved. Some emerging technologies, such as sensing and check-in tools, can be used for data collection. Additionally, investors can obtain data, encouraging them to invest in Yemen. In contrast, a well-developed telecommunication infrastructure will help HCPs who have left the country to participate in the provision of healthcare services and DH advancement and facilitate the human support system in Yemen.

A case study on local telemedicine experience in Yemen illustrates the prioritization of improving healthcare services quality through telemedicine technology and raising awareness for both HCPs and the community. This study examined international collaboration procedures and the process of transferring complex medical cases requiring second opinions. The establishment of a new international company in the USA initiates this process, with branches opening in countries such as the UK and Jordan. In 1997, the company began its operations with the procurement of an advanced digitizer to send medical reports to second-opinion facilities in the USA, the UK, and Jordan. A few years after the first stage, the Swinfen

Charitable Trust from the UK introduced a complementary service. Three hundred initial cases elicited 1–3 responses each, whereas 80 later cases yielded 5–50. Both groups received telemedicine services.

The study proved beneficial for patients as it enabled local doctors to access secondary opinions, resulting in enhanced management and treatment decisions without requiring patients to travel abroad. Local physicians gained valuable educational insights through specialist consultation. In the first phase, Jordan received most cases, with fewer cases going to the UK and USA, representing various specialties for adults and children, such as neurology, dermatology, and oncology. A critical surgical recommendation by an expert in the USA was instrumental in saving a child who had fallen from a height and sustained multiple fractures. A brain cancer assessment determined that further treatment abroad would not be advantageous as it would save the patient and family from unnecessary travel.

Approximately 200 patients received consultations through the Swinfen Charitable Trust, with many continuing to seek follow-up advice over an extended period [51]. However, this study highlights both the potential benefits of DHTs and the challenges that must be addressed to advance DH in the region. This highlights the existing gaps and the necessity of prioritizing bridging them for successful advancement. The recommendations include developing ICT to support telemedicine needs, establishing local telemedicine care units in hospitals, and fostering connections with international telemedicine services as viable alternatives to the scarcity of specialized services within the country. Moreover, these findings underscore the importance of addressing the technical, administrative, and legal challenges specific to Yemen's context, which are crucial for future comprehensive studies and effective solutions to the technological obstacles facing telemedicine.

Starlink, which is a high-speed internet service via satellite, declared launches in Yemen on 18 September, 2024 [52], we suggest directing and managing available resources toward the telecommunications sector and promoting its infrastructure. Due to the poverty level, such a service needs to be cost-effective and available nationwide. Furthermore, enhancing the quality of data and research publications is critical. This suggestion is crucial for advancing the DH in Yemen. Once telecommunication infrastructure becomes suitable for the implications of the most advanced digital tools and technologies, other related issues and challenges can be solved. Well-developed telecommunication infrastructure are the fundamental pillars for increasing the accessibility of internet users, ensuring UHC, promoting communication and collaboration at the national and international levels, and facilitating digital literacy and community engagement. Additionally, it is the core solution for the limited capabilities, lack of skills, and availability of HCPs. HCPs can receive training and communicate with international experts for consultation and experience sharing, utilizing the most advanced digital tools to become familiar with, enhancing their skills and qualifications, and playing a crucial role in advancing DH and promoting the governance of emerging technologies in Yemen.

Clearly, the development of telecommunication services is a pivotal step and the core solution for all relevant issues of advancing DH and the development of health sector. Once telecommunication infrastructure is enhanced, researchers and HCPs can provide standardized quality data and studies with reliable extracted findings. Promoting data and research findings aims to provide sufficient information necessary to attract opportunities, secure funding from international donors, and increase investment and resources nationwide. Furthermore, it manages resources through evidence-based decision-making. Research and data are the basis for establishing, measuring, planning, implementing, and evaluating enterprises and policy implications within the service sectors. To ensure the best practices towards the most developed trends and industry demands.

As stated by a survey [53], system quality, service quality, and information quality should be considered to ensure the successful implementation of a health information system program and advance DHTs. A health data framework for advancing DHTs was proposed in this study, which aimed to test the investigation and examine the effect of the categories of factors and the quality of the health information system and its users in Yemeni hospitals. Accordingly, validation and analysis of the collected data have been used to enhance the framework of developing or promoting health information systems for users. The framework considers the impact of the factors on health information system users. This study indicated a

successful model that integrates the quality of the health information system and its user variables in the context of Yemeni hospitals. This study confirmed the importance of evaluating and promoting the quality factors of health information systems and their users to maximize the impact of implementing DH in non-developed countries such as Yemen. In contrast, utilizing resources effectively and promoting international cooperation and communication are essential for the successful implementation of DHTs.

Way forward

DHTs are a promising field with the capability to extend beyond traditional medicine, where cancer and rare abnormalities can be controlled within precision medicine. In Yemen, some cancer risk factors appear to differ from those in other parts of the world. Precision medicine, which highly depends on DHTs such as data mining and ML, should be developed in Yemen. A notable case study aimed at exploring cancer risk factors using data mining techniques in Yemen extracted useful knowledge by mining the data available at the National Cancer Control Foundation. The study succeeded in building and designing a model to predict cancer risk factors, which contributes to clarifying the ambiguity about cancer risk factors in Yemen. The model produced was found to have a high performance, and the rules extracted from the model tree had a high value for both people and health sector [54]. In contrast, the study mentions that the prediction power of the model has limitations that need to be considered when interpreting the rules of the discovered model. These limitations include restrictions imposed by the type and quality of the data. Furthermore, the study highlights the importance of providing data and recommends paying more attention to data mining, as one study is not enough to decide everything about this kind of risk factor and calls for action on conducting research. However, this study highlights the importance of DHTs and exhibits a new era represented by precision medicine.

Creating a supportive policy and regulatory framework is essential for the safe and effective utilization of DHTs. The Yemeni government, international organizations, and stakeholders can create this framework. The government can establish policies and regulations that promote DHTs while ensuring patient safety and privacy. Global organizations can provide technical assistance and funding to support the development of DH infrastructure in Yemen. Stakeholders, including healthcare providers, patients, and technology companies, can collaborate to develop best practices for using DHTs [36]. The benefits of creating a supportive policy and regulatory framework for DHTs include tailoring solutions to community needs, simultaneously promoting innovations in safety and privacy, and addressing the challenges faced by the Yemen healthcare system. The WHO global strategy on DH 2020–2025 provides principles that can be adopted in Yemen to develop such a framework and advocate its use by people. Community engagement and education are also crucial for the successful implementation of the DHIs in Yemen [44, 50–55]. Encouraging the participation of local societies in adopting DH solutions tailored to their needs can lead to the successful utilization of initiatives in the country [56–59].

Several strategies can be implemented to enhance digital literacy and community engagement for the advancement of DH in Yemen. First, it is crucial to establish an ongoing critique and evaluation process for the community. This participatory approach allows individuals to assess the ease of use and viability of advanced medical devices, helps to identify areas that require improvement, and ensures that technological advancements align with the specific needs of local populations. In addition, preparing workshops and educational programs for both healthcare providers and community members is essential. These initiatives can highlight the benefits and applications of DHTs, fostering mindfulness, improving numeracy skills, and promoting awareness of innovations in healthcare. Collaboration with regional medical service providers such as clinics and treatment centers are also vital. By engaging HCPs in the planning and implementation phases, trust in and recognition of new healthcare arrangements can be bolstered within the community. Community health workers (CHWs) can serve as vital intermediaries between advanced healthcare programs and their communities. They can facilitate coaching, preparation, and feedback as well as help navigate language and skill barriers. To improve access further, it is important to ensure that health IT-based devices are available in local languages. This effort can enhance understanding and decision-making among community members, particularly those with limited English proficiency. Special attention should

be paid to women and disadvantaged groups when designing online healthcare services. It is essential to involve these populations in program planning to ensure that their specific needs and social contexts are addressed. Finally, organizing community-led mindfulness campaigns can effectively raise awareness about the benefits and uses of advanced medical devices. Collaborating with community advocates, local organizations, and key stakeholders to utilize various media such as radio, television, and community events can help reach a broader audience and foster greater engagement within the community. However, the potential to establish a better healthcare system in Yemen can be achieved through the development of a DHTs and an understanding of its capabilities and benefits. According to a World Bank Group survey, 80% of the population faces significant challenges in accessing healthcare system, and 50% of health facilities are fully functional, reflecting importance of DHTs in providing feasible, measurable, and straightforward solutions [36]. It can provide equitable and available access to healthcare systems with excellent quality and efficiency through a digital platform. Planning and effective implementation of strategies such as the NDHS, which was launched to enhance the quality and efficiency of healthcare system by providing access to DH services, can enhance healthcare system and their outcomes and ensure open accessibility for a larger population [31, 41].

To ensure advancing DH in Yemen, which aims to address the identified public health problems, we propose the following actionable recommendations arranged according to priority. First, we recommend establishing a clear vision and strategy for DH, outlined with objectives and timelines for implementation. Developing a comprehensive NDHS based on evidence, considering successful strategies implemented in other countries, and suggesting strategies from global entities. Consideration must implicate telecommunication infrastructure in guiding and supporting research for further evaluation and analysis. These steps are critical for managing and allocating resources effectively and efficiently as well as for enhancing strategies for better implementation. Second, we recommend strengthening the DH infrastructure. Supportive policies, regulations, and standards of conduct should then be developed to ensure successful implementation and achieve the desired outcomes. Furthermore, enforcing policies and regulations is required to protect data and privacy and to ensure the confidentiality, integrity, and availability of digital healthcare services. These steps are critical because they serve as fundamental pillars for ensuring a successful DH future. Third, DH platforms and interoperable health information systems must be developed. The implementation of telemedicine and remote healthcare services with expanding its scope should be ensured to increase accessibility to healthcare services in rural areas, along with promoting digital literacy and capacity building among healthcare providers, policymakers, and the community to ensure well adaption and proper use. Fourth, we recommend fostering public-private partnerships and collaboration among all stakeholders to leverage resources, expertise, and innovation to advance DH. This facilitates interoperability and data exchange to ensure the adoption of standardized health data exchange protocols and enable the seamless sharing of patient information. Finally, we recommend investing in research and supporting evaluations for further development.

Conclusions

Developing DH in Yemen is critical for improving the quality of healthcare system and increasing the accessibility of healthcare facilities. Yemen's health sector has suffered the most due to long-term, repeated, and ongoing conflicts, which require the urgent, intensive, and strategic implementation of healthcare interventions. The application of technologies to digitally improve healthcare system has the capability and basic structure to provide alternative solutions to the humanitarian and health crises that the country is going through, characterized by obstacles that the health sector in Yemen faces. Implementation of DHIs and projects guarantees equitable access to healthcare systems for all individuals, which can provide them with high-quality services. Furthermore, they can provide timely healthcare system to societies with a high percentage of poverty. Moreover, these advantages can be obtained when there is a well-established supportive policy and regulatory framework for implementing DHIs. Improving the public communication system with a bunch-specific quick reply, strategies to address challenges that depend on scientific research, and plans to involve the local community are critical factors in advancing DH. Hence, capacity

development workshops, cooperation with medical service providers in the region and CHWs, community-led mindfulness campaigns, and improvement of neighborhood dialects aimed at raising awareness of DHTs, encouraging the participation of the local community to advance DHTs, gathering efforts for further research, and communicating stakeholders with international organizations for further development are essential for addressing these challenges, leading to the growth and development of DH in Yemen.

Abbreviations

DH: digital health

DHIs: digital health interventions

DHTs: digital health technologies

HCPs: healthcare professionals

ICT: information and communication technology

IT: information technology

ML: machine learning

NDHS: National Digital Health Strategy

RPHMS: Remote Patient Health Monitoring System

UHC: universal health coverage

Declarations

Author contributions

OASA: Conceptualization, Formal analysis, Methodology, Project administration, Data curation, Visualization, Writing—original draft, Writing—review & editing. HIM: Writing—original draft. SSM: Supervision, Writing—review & editing, Project administration. MMA: Data curation, Investigation, Methodology, Writing—review & editing, Supervision, Validation, Project administration. MAL, UJ, BR, YA, MRH, OK, SL, and OJO: Writing—review & editing. ZKO: Data curation, Investigation, Validation, Writing—review & editing. DELP: Supervision, Writing—review & editing.

Conflicts of interest

The authors declare that they have no conflicts of interest or competing interests related to this study.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and materials

Not applicable.

Funding

Not applicable.

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