Abstract: Healthcare, and in particular, clinical laboratories, are major contributors to carbon emissions and waste. Sustainability in healthcare has shifted from an environmental concern towards a holistic definition that includes balancing socio-ecological and socio-technical systems, including health services effectiveness and cost efficiency. Digital transformation can reduce waste and the cost of services by enhancing effectiveness while maintaining quality. Digital health interventions can provide personalized patient-centered care on a global scale and include decision support systems that have the potential to improve the performance and quality of healthcare. The right interfaces must be used so that the advantages of going digital are felt throughout the health system: a successful and sustainable implementation of digital innovation depends on its integration into a functional health ecosystem. Telehealth has the potential to reduce carbon emissions due to the reduced daily commute of health professionals, although research is limited. Recently, economic models have changed from the linear “take-make-dispose” to circular models based on recycling and upcycling that have the goal of keeping products, components, and materials at their highest utility and value. The previous linear models threaten human health and well-being and harm natural ecosystems.

Keywords: clinical laboratory; digital; sustainability.

Introduction

In response to environmental changes and concerns, the Sustainable Development Goals were created in 2015 by the United Nations to provide a framework for implementing environment-driven policies, and have been used as indicators of progress [1]. Healthcare, and in particular, clinical laboratories, are major contributors to carbon emissions and waste. Non-biological solids represent a significant part of waste in clinical laboratories, and it includes plastics, paper, and electronic waste. It has been suggested that 850 million tonnes of greenhouse gases were produced through the production and incineration of plastics, and these emissions could rise to 2.8 billion tonnes by 2050 [2]. Additionally, around 15% of healthcare waste is infectious, radioactive, or toxic. In developed nations, it is projected that 0.5 kg of hazardous waste is generated per hospital per day, while in developing countries, the estimate drops to 0.2 kg [3]. Concerning energy consumption, clinical laboratories use 3–6 times more energy than a standard of a office building, due to the need for temperature and humidity control, ventilation systems, and the permanent functioning of specialized laboratory equipment [4].

Several documents and legislations have been created to move forward the sustainability agenda, namely, the European Green Deal, which aims to transform Europe into the first climate-neutral continent by 2050; and the legislation concerning the registration, evaluation, authorization, and restriction of chemicals (REACH), which prevented expenditure in adverse health outcomes and environmental impacts due to the release of chemical hazards in €100 billion over 25–30 years [5]. Furthermore, the European Commission has promoted a project to transform around 15,000 European hospitals into zero-carbon institutions with renewable energy systems [5].

The digitalization of healthcare has been rapidly growing and extending its reach, even more so after the COVID-19 pandemic [6]. Digital technology has the potential to offer more effective, efficient, and personalized healthcare systems, thus contributing to the creation of
sustainable healthcare models [7]. Even though there are potential environmental benefits in digital transformation, there are also possible ecological drawbacks [6]. This review explores current evidence on digital technologies’ impact in healthcare and clinical laboratories.

**Definition of sustainability in healthcare**

Sustainability in healthcare has shifted from an environmental concern towards a holistic definition that includes balancing socio-ecological and socio-technical systems [8], including effectiveness and cost efficiency of health services [9]. The Viable System Model of Stafford Beer proposes organizational structures as a complex network of components and active interactions that occur over a specific period, working towards shared goals [8]. Healthcare can be defined by this model, as it represents dynamic interactions of people, information, and physical assets, which can create value for the whole system [10]. These different aspects of sustainable development create complexity and opposing economic, ethical, and emotional expectations that require a multi-disciplinary approach [11].

Digital transformation represents a tool through which interactions between the actors that populate healthcare organizations can be enhanced, and resources can be shared more efficiently, thus contributing to the sustainability of the whole system [8]. Navigating through complex healthcare systems can create challenges for patients, including a lack of equity of access, effectiveness, and value for money [12]. Digital solutions can help to solve these issues by securing healthcare delivery to all citizens and improving clinical practice while preserving privacy and access to trusted information [12]. The Principles for Digital Development were created in 2012, and emphasize sustainable development, user-centered design, and design for scale [13]. These principles are now endorsed by more than 300 organizations, having the goal of improving the effectiveness and scaling of innovative technologies [13].

**Reducing waste**

Digital transformation can reduce waste and the cost of services by enhancing effectiveness while maintaining quality [8]. Recently, a study analyzed best practices for smart waste management, proposing that information and communication technologies (ICT) can improve the visualization of such management systems [14].

In Greece, during the COVID-19 pandemic, a national e-prescription system was established by using previously existing infrastructure and services [12]. This system consisted of a paperless e-referral for diagnostic tests and e-prescription of drugs through email or text message, including reissuing prescriptions for chronic patients [12]. Additionally, in Finland, there is now widespread use of ICT infrastructure for e-health applications and telemedicine, which decreased the use of paper and waste generation [15]. In Croatia, paper reports on sick leave do not have to be attached to paper financial compensation requests, since eHealth services for employers have been implemented that integrate all the necessary information [12].

In clinical laboratories, there is a general trend toward personalized remote point-of-care testing (POCT), making use of microscale fluid manipulation (microfluidics) [16]. This represents both a national and international interest since this technology can be applied to disease control programs, improving universal health care or outbreak response [17]. However, single-use POCTs are mostly plastic-based, which can generate toxic pollutants when improperly incinerated and persist for hundreds of years in the soil when dumped in landfills [16]. Incineration can release combustion by-products (e.g. nitrous oxide, furans, dioxins) into the atmosphere and generate residual ash. With the advent of 3D printing software, affordable bio-based biodegradable polymers such as polylactic acid have been developed and improved through digital technologies – for example, Tothill et al. manufactured a 3D-printed device for a glucose assay [18].

**Improving efficiency**

According to the Food and Drug Administration (FDA), digital health includes personalized medicine, wearable devices, telehealth and telemedicine, mobile health, and health information technology [19]. It is a lean innovation that can increase cost efficiency through computing platforms, connectivity, software, and sensors used in a wide range of applications [8]. Digital health interventions can provide personalized patient-centered care on a global scale [6] and include decision support systems that have the potential to improve the performance and quality of healthcare [15]. The personalization of care generally leads to increased costs, although digital technologies
present the ability to constrain it by an enhanced process efficiency [8]. Big data is key in the enhancement of data management performance and cost reduction of digital systems [20].

Additionally, ICT has been identified as key for enhanced accessibility to healthcare service delivery [15] and active patient participation that improves self-management [8]. The latter is promoted by the decrease in information asymmetry between patients and doctors, made possible by democratic access to information through digital health tools [21]. Digital transformation can decrease waiting times and space constraints while maintaining healthcare service effectiveness [8].

In the digital transformation process that occurred in Greece (see above), electronic prescription renewal for chronic patients decreased in-person visits, therefore promoting efficiency [12]. Telemedicine has been reported to provide better coordination and time management in primary care [15]. During the implementation of the-emergency services (TES) in the Himalayas, a significant number of ambulance and helicopter transfers were avoided, thereby promoting financial savings and reducing carbon print [22]. A survey of 140 users of TES suggested savings concerning out-of-pocket expenses of 20 thousand dollars, as well as the reduction of emotional stress and physical discomfort [22]. Additionally, during the COVID-19 pandemic, e-hackathons in Estonia promoted the creation of several digital solutions, including a live map to help logistics companies. This could represent a solution for clinical laboratories, to distribute and share reagents in a laboratory network [12]. Similarly, in Slovakia, the National Health Information Centre (NHIC) has updated information from both public and private hospitals concerning bed availability, material equipment, and drugs [12]. A comparable approach could be used to monitor inventories in clinical laboratories, thus keeping the minimum reagents necessary in stock and promoting reagent sharing.

Digital laboratories have been reported as positive experiences, particularly in hospitals (when compared with primary care) and ICT applied to radiology has been suggested to decrease turnaround times, therefore allowing for faster availability of results [15]. Teleradiology and telelaboratory services appear relevant, especially in remote countryside healthcare centers [15]. POCT methods must follow the ASSURED guidelines defined by the World Health Organization (WHO) – affordable, sensitive, specific, user-friendly, robust and rapid, equipment-free, and deliverable to all people [23]. These methods have the potential to reduce costs in clinical laboratories and improve efficiency because of their speed and low use of reagents, which also decreases their environmental impact [24]. Furthermore, the implementation of middleware software that interfaces POC clinical chemistry and hematology POCT has been reported to decrease serious errors and duplicated results [25], which decreases the number of performed tests and the environmental impact of the laboratory. Middleware algorithms can be used to decrease the number of tests in a laboratory – a recent study reported the implementation of automatic cancellation of same-day white blood cell differentials with more than 10 thousand tests canceled corresponding to 5.4% of all tests, thus reducing costs and waste [26]. The use of POCT can induce operational efficiency by promoting decentralization. In the case of diabetes mellitus, these devices allow for early detection and close monitoring of the disease by measuring biomarkers in an integrated process that can be home-based [27]. Transitioning from optical to electrochemical reading methods is key to guaranteeing cost savings [27]. Another method of portable on-site testing is smartphone aptasensing, which is portable, cost-efficient, adaptable, and does not require specialized equipment or operators [28]. These methods are only possible because of a digitalized society and the development of information technology. Some experiments can be replaced by digitally simulated environments – a recent study developed a framework to test the development of a clinical study, thus identifying potential operational issues [29]. Such platforms can be used in the context of a laboratory, to possibly replace selected experiments and decrease the use of reagents. Similarly, artificial intelligence algorithms can be used to predict the results of laboratory tests that were not directly quantified, therefore decreasing the number of tests and their environmental impact, as well as decreasing turnaround time and enhancing cost efficiency [30]. Additionally, data analytics can suggest testing cascades that suggest a new test following the result of another, which decreases the number of blood draws and generated waste [30]. Overall, artificial intelligence could potentially improve the efficiency of a laboratory by suggesting solutions to automatically detected operational problems.

**Healthcare systems integration**

To maximize the use of digital systems in healthcare, interoperability is key and involves a collaborative environment, thoughtful planning, regulatory interventions, and internationally agreed standards [12]. The right interfaces must be used so that the advantages of going digital are felt throughout the health system: a successful and sustainable
implementation of digital innovation depends on its integration into a functional health ecosystem [7].

In Scotland, the NHS ICT infrastructure created a real-time public health system integration during the COVID-19 pandemic, achieved by integrating information from the community using a suite of digital tools [12]. In a study exploring primary care in Sweden, an eHealth system applied to diabetes care presented the goal of improving self-care and healthcare through the integration of information, including blood glucose monitoring [31]. Identified key aspects of implementation based on data collected from patients and nurses were health parameter surveillance, data-driven feedback, unconstrained access to healthcare, self-care knowledge, tailoring to individual needs, and adequate and timely decision-making [31]. Additionally, in Catalonia, technological innovation is integrated into the Digital Health Strategy, which has allowed for a unique entry point for citizens to eHealth services, and integrations between ICT and service providers [12]. This allows for more efficient information sharing, including of laboratory testing, thereby decreasing the number of tests performed and the reagents used. Moreover, this integration promoted the implementation of remote working, decreasing the carbon footprint related to the commute of professionals and patients [12]. In the United Kingdom (UK), a web-based patient management portal entitled Patients Know Best (PKB) was created to allow all patients with inflammatory bowel disease open access to care through telephone and email [32]. This platform synchronized the integration of patient-entered symptom tracking with laboratory and imaging results, which allowed for rapid and efficient support for patients at scale and improvement of clinical outcomes [32]. A global integrated ICT infrastructure was created in Estonia (National Health Information System) so that patients and physicians could access SARS-COV-2 test results, as well as information about patients treated in primary care and hospitals [12]. Furthermore, DocBox24 is an example of a digital health platform that connects patients and doctors, promoting multi-actor interactions that allow for resource exchange and system sustainability [8]. Digital tools to execute actions for diagnostics and treatment, as well as sharing of information between health professionals are essential to provide an integrated high-quality service with less resource consumption [15]. In Greece, the management of resources in health units (ex: ICU beds, laboratory testing) was monitored and coordinated through the National Reporting Business Intelligence System, thus providing one more example of resource optimization through digital transformation [12]. Concerning smartphone aptasensors, some devices with Wi-Fi connection can communicate data to smartphones, thereby allowing for real-time monitoring of clinically relevant biomarkers (e.g., cytokine monitoring from Hao et al.) [28]. Glooko® Enterprise represents another example of health information integration for diabetes patients and it is one of the largest diabetes data management platforms [19]. It integrates medical data, insulin pumps, injection pens, and activity from wearable devices, including decision support for physicians [19]. This optimizes laboratory data, potentially decreasing the number of tests performed. OneDrop is a company that provides similar services to diabetic patients, namely, integration of weight, medication, blood pressure, and glycated hemoglobin [19].

**Telemedicine and teleworking**

Telehealth has the potential to reduce carbon emissions due to the reduced daily commute of health professionals, although research is limited [6]. Telecommuting was a term first mentioned in the 1970s as a solution to traffic, urban pollution, and poor work-life balance [33]. Teleworking can improve air quality in urban areas, quality of life, and the company’s reputation and corporate image [34]. During the COVID-19 pandemic in Estonia, out of 200 thousand consults, 40% were carried out online, thus demonstrating telemedicine as a viable alternative [12]. Moreover, in Finland, due to the lack of accessibility to healthcare in some areas of the country, the implementation of telemedicine has been accelerated, including teledermatology and telepsychiatry [15]. Telediagnosis and telelaboratory services were mentioned as exerting a positive influence on a significant portion of questionnaire respondents [15]. Tele-emergency services have also provided higher retention of physicians in the United States, decreased number of emergency transfers, and fewer delays in timely treatment [22]. Nevertheless, the success of implementing remote working policies is dependent on effective e-leadership practices, with adequate technological, social, and organizational support [34]. The telelaboratory has recently seen developments with POCT devices, including portable nano-devices with several incorporated tests [24] and smartphone-enabled aptasensors – the portability, low cost, and adaptability of these devices allow for home testing applications [28]. Specifically, Wu et al. built an aptasensor for multiplex antibiotic detection, and Pereira et al. a colorimetric aptasensor for osteopontin [28]. Colorimetric lateral flow assays represent another example of a POCT technology market that is expected to reach 12.6 billion dollars in 2026 – these tests are
Circular economic models and management

Recently, economic models have changed from the linear “take-make-dispose” to circular models based on recycling and upcycling that have the goal of keeping products, components, and materials at their highest utility and value [14]. The previous linear models threaten human health and well-being and harm natural ecosystems [36]. Thus, there is significant pressure for companies to shift from an economic-financial perspective to one concerned with narrowing, slowing, and closing material and energy flows, as well as service-based business models and collaborative partnerships [37]. In a study analyzing Brazilian chemical companies, it was found a medium to high investment in the circular economy, and the degree of innovation in this new framework was associated with better market, productive, economic, financial, and social performance [36]. Additionally, environmental risks and the cost of waste disposal can be improved by circular business models [38]. Digital transformation through the internet of things could potentially create synergies with the circular economy, in which digital applications offer insightful knowledge about the location, condition, and availability of resources [14]. To implement change, training and empowerment of digital skills to professionals and patients is key, even though ICT literacy has been reported as high in healthcare professionals [15]. In Catalonia, educational materials on telemedicine tools were provided as well as user-friendly guidelines for the inclusion/exclusion of patients and best practices for both professionals and patients [12].

Barriers to entry

The 2020 Riyadh Declaration on Digital Health provides recommendations concerning privacy, security, misinformation, and ethical issues of data sharing [6]. System heterogeneity hinders implementation and scalability and the need for end-to-end security is a major barrier to digital transformation [14]. In Finland, there are secured communications for patient privacy that are globally available for healthcare services [15]. Most designed systems, however, do not consider security and privacy or ways to verify these properties, while the diversity of these systems hinders the capacity of analysing all vulnerabilities and select suitable control mechanisms [14]. In the United States, data from 2016 to 2022 suggests that approximately 30% of all major cyber incidents aimed at data abuse concerned healthcare organizations [39]. This number has continuously increased, although healthcare institutions have invested more than $65 hundred million in cyber protection [40].

Moreover, ICT is associated with approximately 3.5% of global carbon emissions, the necessary raw materials require intensive mining, and the generated electronic waste has significant environmental implications [41]. Additionally, storing large quantities of data requires large servers that use significant amounts of electricity, especially when considering cloud services [6]. Health data represents roughly 30% of the world’s total data, while sending files through email or cloud, or copying and storing them takes approximately one million times more energy than saving directly to devices [42].

Frequently, digital transformation fails because of a lack of user-centered design and too much focus on the implementation of new technology instead of considering the end-users early on [7]. The Sustainable Healthcare Team at the National Health System of England has developed an approach to implementing digital applications that accompanies the process from its inception until implementation and maintenance to insure sustainability [43].

POCT testing, when decentralized, raises concerns about its quality. Nevertheless, several studies have demonstrated that education, training, and quality assurance programs improved test performances over time, namely, in HbA1c assays in Australia and Switzerland, with accuracies similar to that of central laboratories [44]. Furthermore, the creation of standard operating procedures, training, and generators have been reported as variables that improved implementation in a tele-emergency service [22]. Supportive context and financial and political commitment are key to the sustainability and scalability of digital innovations [7], while infrastructure resources such as facilities and dedicated professionals can represent barriers to entry [20]. Recently, algorithmic transparency has been gaining relevance due to the use of machine learning in healthcare, to avoid bias and promote accountability [29].

Conclusions

Digital transformation has become a focus in healthcare institutions, including clinical laboratories, having
the ability to improve their environmental, social, and economic performance. However, digitalization must have adequate planning so that large scale implementation is possible without negative environmental consequences.

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