Systemic Approach to the Environmental Sustainability of Mobile Health

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Abstract.

Information and communication technologies play an increasingly important role in healthcare systems, through the development of technological ecosystems known as electronic health (eHealth) and mobile health (mHealth). While this digitalization of healthcare is often considered as a lever for reducing the environmental impacts of the sector, the systemic changes induced by these new technologies are often neglected. A systematic review of the scientific literature explores the considerations on environmental sustainability of mHealth technologies. The selection of relevant articles is performed according to the PRISMA methodology and an overview of the articles addressing this subject is provided. The considerations regarding environmental impacts are analyzed through a content analysis along three dimensions: the scope of the system whose impacts are considered, the direct or indirect nature of these impacts and the indicators used to characterize them. The results of this analysis highlight the limitations of the current environmental sustainability evaluations in the literature. They show that mHealth environmental sustainability literature is still in its early stages and barely addresses the specificities of mHealth devices. More importantly, the impacts of mHealth at the system level are only considered positively, either through the reduction of transportation or the optimization of care procedures, but overlook many potential indirect impacts. To address these limitations, the LES model of Hilty and Aebischer, originally from the field of ICT, is applied to mHealth systems in order to provide a broader approach. Examples inspired from the literature are used to illustrate the systemic environmental impacts of wearable devices.

This is a working version of the article, which has not been peer-reviewed.

1. Mobile Health

eHealth, which is the common abbreviation of electronic health or digital health, usually refers to the use of information and communication technologies (ICT) applied to healthcare. This emerging technological ecosystem stands at the convergence of electronics, informatics, Internet, and mobile technologies with health services, in order to improve the quality and efficiency of healthcare [1]. In the same way that ICT has

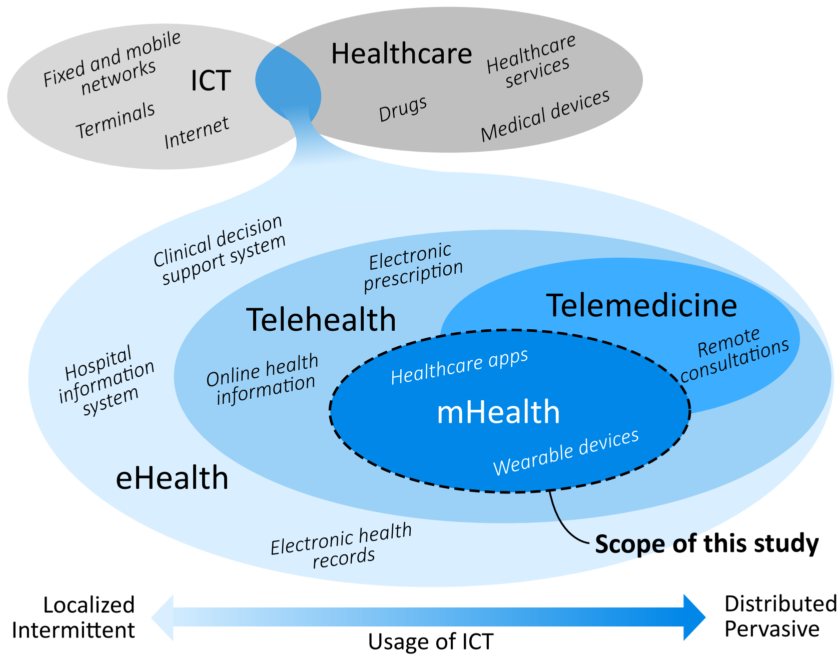

Figure 1. eHealth technological ecosystem and subcategories. eHealth stands at the intersection of ICT and healthcare and may be subdivided in more specific concepts. Examples of technological applications appear in italic. This work focuses on the category of mobile health technologies.

impacted many other sectors (e.g., work, retail, communication), eHealth may represent a significant shift in paradigm for the healthcare sector in the near future [2].

eHealth is a loosely defined concept which includes a wide array of technological solutions as shown in Fig. 1. Other underlying categories such as telehealth, telemedicine, or mobile health have been proposed with definitions that vary significantly. In this work, based on the classification proposed by Doarn *et al.* [3], we will refer to the category of telehealth as the electronic means used to provide clinical and non-clinical services outside the usual medical settings, i.e., hospitals and medical practices. Within telehealth, telemedicine is limited to the provision of remote clinical services only, typically for consultations via telephone or videoconference. Finally, mobile health (mHealth) refers to the "medical and public health practice supported by mobile devices" [4], which sometimes overlaps with telemedicine. mHealth devices mainly include software health applications for smartphones or other portable devices, and custom hardware wearable devices that are used to monitor biophysical or biochemical parameters. Some examples of mHealth technologies are smartphone apps for sleep or stress reporting, mobile telemedicine and health prevention services, fitness trackers or devices for remote monitoring of blood sugar levels, cardiac disorders or neurological conditions. While this work focuses on mHealth and wearable devices, some of the discussions also include eHealth as they share many characteristics and impacts on the healthcare system. The classification illustrated in Fig. 1 also corresponds to an increasing level of pervasiveness of ICT devices, both temporally and spatially.

Indeed, while some eHealth examples such as clinical decision support software or health digital databases remain constrained to the hospital computer infrastructure, mHealth and telemedicine rely on electronic devices being distributed in many households and sometimes used continuously. It is this property of ubiquity of mobile devices and remote communication that enables a significant shift in the healthcare paradigm [2]. Indeed, over the last decades, healthcare has been focused on curing diseases when they appeared, mainly thanks to doctors knowledge in an infrastructure centered around the hospital. As it is now possible to interact with the patient and collect data outside the usual medical settings, new possibilities are open for preventing diseases before their manifestation, relying on data to provide new insights on medical disorders, in an infrastructure that is more widely distributed [5]. However, this ubiquity also introduces new challenges due to its vast deployment and its consequences on the healthcare system.

mHealth is expected to play different roles in healthcare management: (1) prevention, by promoting healthy lifestyles; (2) monitoring, by enabling early screening and frequent health assessment; (3) treatment, with a personalized and more effective care; and (4) support, by ensuring proper information and communication for the patient and caregiver [6]. Until now, mHealth and eHealth have been mostly considered as a solution to compensate for the limitations of the healthcare sector. For example, they have been presented as an answer to issues such as the lack of access to health services in low-income countries [7], the shrinking workforce in the health sector [8], the ageing population in the Western countries [9], or the increasing weight of chronic diseases [10]. They are also expected to improve cost efficiency in healthcare and clinical efficacy, though this is still under debate [11, 12]. More generally, mHealth is often considered as a tool for carving the path towards a more sustainable healthcare system. Sustainability is usually divided in three interconnected pillars which are environmental, social and economic sustainability, each featuring multiple dimensions [13]. The economic pillar looks at the creation of economic value, financial viability, proper governance, risk management and prosperity. The social pillar includes the promotion of equity, the respect of human rights, or the enhancement of the well-being of stakeholders. The environmental sustainability is evaluated with regard to several aspects, e.g., the emission of greenhouse gases (GHG) and climate change, the protection of biodiversity and ecosystems, the generation of waste or the depletion of natural resources. Despite the growing body of research on the question, it is still unclear whether mHealth actually enhances these different dimensions of sustainability for the healthcare sector [14].

This work focuses on the environmental aspects of sustainability and on how mHealth technologies can contribute to reducing the ecological impacts of the healthcare sector. In general, a technology has direct effects on the environment which are due to its life cycle impacts, that is, for its production, during its use phase or at its end of life. It can also induce indirect effects, i.e., increase or decrease the impacts of other goods or services due to a modification of behaviors, organizations or processes. With eHealth and mHealth, the switch from physical to ICT-supported services has significant implications for the environment, both direct and indirect. For instance, while often referred to as virtualization, this change of medium is actually supported by a large distributed infrastructure. This is particularly true for mHealth which relies on the massive deployment of portable and wearable devices, as well as the underlying Internet network and datacenters, which all have direct environmental impacts. Through the digitalization process, eHealth and mHealth also have indirect impacts, such as the reduction of travel thanks to telemedicine or the reduction of the paper consumption with electronic records. Overall, these considerations have been mostly optimistic, under the commonly shared assumption that digital solutions provide opportunities to reduce the environmental impacts [15, 16]. However, the evidence on the actual impacts of these technologies remains limited and the balance between positive and negative impacts is still hard to evaluate [17].

By extending the work presented in [14] on the ICT aspects and the environmental sustainability, this work aims at reviewing and commenting on the current state of environmental considerations around mHealth solutions in the scientific literature. This review shows that several critical characteristics of mHealth technologies are poorly taken into account, especially regarding their indirect impacts. The LES model proposed by Hilty and Aebischer [18] is therefore used as a framework to address these limitations and discuss the larger systemic impacts of mHealth technologies. This work is organized as follows. First, in Section 2, a systematic literature review evaluates which aspects of the environmental sustainability of mHealth and medical devices have been the most explored by the scientific community. Section 3 discusses the shortcomings of these studies with a focus on the specificities of mHealth technologies compared to traditional medical devices. In particular, the lack of an approach that takes into account their systemic impacts is highlighted. Finally, Section 4 leverages the LES framework originating from the field of ICT to highlight and sort the potential systemic impacts which are currently under-evaluated in the literature. Examples of presumptive effects of mHealth drawn from the literature are used to illustrate the proposed framework.

2. Literature Review

In this section, we highlight how environmental impacts have been considered for mHealth technologies in the scientific literature. Evaluating the environmental sustainability of mHealth technologies is a challenging task that involves direct and indirect levels of impacts, different scopes (components, devices and systems) and many indicators of environmental harm. The analysis of the selected articles aims at understanding from which perspectives sustainability has been looked at and what aspects have been most studied.

2.1. Methodology

In order to provide a detailed account on how environmental sustainability is considered in the scientific literature, we conducted a systematic literature review. The PRISMA methodology [19] was used to sort and report the results, as detailed in Section 2.2. The selection of relevant abstracts and articles was performed by the author. Three databases were searched to extract relevant studies: Scopus (multidisciplinary), PubMed (biomedical and life sciences) and IEEE Xplore (engineering and technology). The searched phrase was built as a combination of a keyword linked to mobile health and another linked to environmental sustainability. Due to the limited number of papers focusing specifically on mHealth, the search was expanded to the related fields of medical devices and telemedicine. The complete list of keywords used is as follows:

- Mobile health
  - eHealth
  - mHealth / m-health / mobile health
  - wearable device / wearable electronics / wearables
  - medical device
  - telemedicine / telehealth
- Environmental sustainability
  - environmental sustainability
  - environmental impact / ecological impact
  - ecological footprint
  - life-cycle analysis / life-cycle assessment / LCA
  - eco design / ecodesign
  - carbon footprint / GHG / greenhouse gas
  - climate change

Section 2.3 provides an overall description of the articles selected in this review. Given the wide variety of topics covered in the articles, their presentation is structured in several clusters, which were defined in a bottom-up fashion based on the similarity of the presented topics and research approaches. The description of the articles focuses on how environmental sustainability is considered in the articles and which research approach is used to address it. The exhaustive list of the selected papers and associated topic clusters are listed in Appendix A.

A content analysis was then performed in Section 2.4 to assess quantitatively which themes are the most present in the articles. This analysis consisted in counting how many articles mentioned given themes. The targeted topics for this analysis are the scope of the environmental study, the level of impacts considered and the environmental indicators. The scope indicates which parts of the healthcare system is evaluated, i.e., either the medical device, its internal components or the broader system. The level of impacts relates to the direct life cycle impacts or indirect induced effects of the technology. The environmental indicators list the types of impacts which are considered, e.g., carbon footprint, ecosystem pollution, or resource depletion. The papers included in the analysis were each reviewed individually and linked to the themes that they mention. To avoid any subjective appreciation when assessing the significance of a theme mention, all theme references are counted as a single hit per article, regardless of their importance in the text.

2.2. Search results

The database search resulted in a total of 537 unique articles. The titles and abstracts were screened to exclude those that do not fit the research question. More specifically, the articles whose scope do not include healthcare systems, medical or ICT devices, or environmental sustainability were rejected. After retrieval of the full texts, a second assessment for relevance was made based on the same criteria, which returned 59 results. In addition, 4 documents from the grey literature that were not in the searched databases were added: the NHS zero-carbon strategy [20], the *Plan de transformation de l'économie française* report from the Shift Project [17], a Master thesis on wearable cardiac monitoring devices [21] and a publication from the H2020 UBORA project [22]. A total of 63 studies are therefore included in the following analyses, as reported in Fig. 2.

2.3. Structured presentation of the selected articles

In this section, the main ideas presented in the selected articles are described. Given the large variety of subjects and research domains present in the list of articles, this description focuses on discussing how environmental impacts are considered and from which perspective they are being addressed. The articles are structured in different clusters which correspond to the main topics and research approaches, that were built in a bottom-up fashion during the review of the articles. The number of clusters and their boundaries were decided arbitrarily to balance the level of details and the ease of understanding. The main clusters are the environmental assessment of medical devices, the design of new components for wearable devices, the reduction of travel-related emissions with telemedicine, methodologies for environmentally-conscious design, sustainable business models, top-down healthcare system assessment and environmental considerations of stakeholders. When necessary, subcategories in the clusters are also presented to highlight specific differences. The exhaustive list of articles and their classification of articles in the different clusters can be found in Table A1 in Appendix A.

Medical device assessment The most represented topic in the selected articles (n=18, 29%) is the assessment of impacts of medical devices. Those articles generally aim at understanding the absolute or relative impacts of medical devices. The precision of the assessment ranges from a general analysis of the environmental impacts and the associated design challenges [23], to a more specific and quantitative impact evaluation for a given device [24, 25]. The reference method for the quantification of environmental impacts of a device is the life-cycle assessment (LCA), defined in the ISO14044 standard [26], which relies on a precise material inventory and information

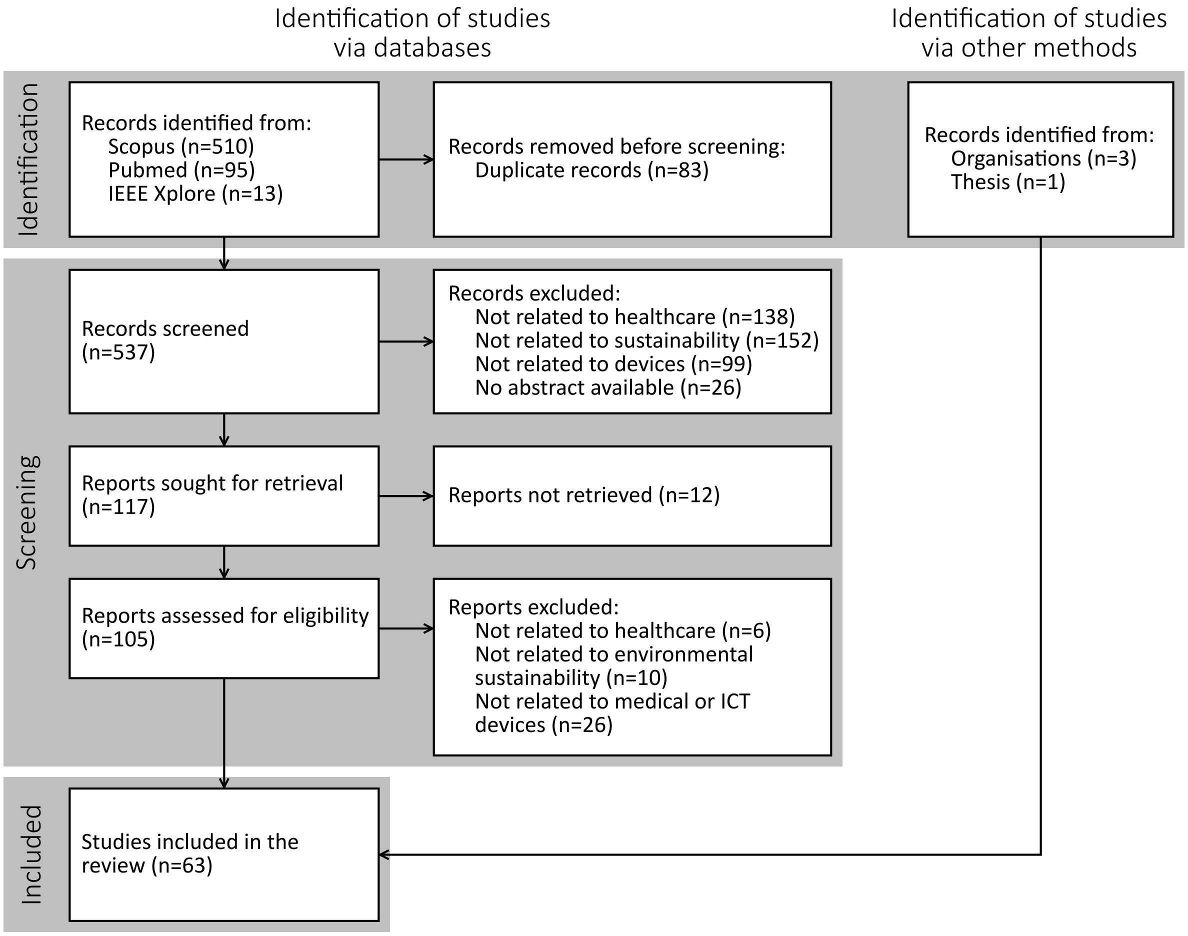

Figure 2. Identification of relevant studies with the PRISMA methodology [19]. The articles identified in the database search were iteratively sorted according to the exclusion criteria to provide the final list of studies for the following analyses (cfr. Appendix A). The number of papers excluded and related criteria are specified in the chart.

from databases to evaluate several impact categories (e.g., global warming, ozone depletion, ecotoxicity, human toxicity). This analysis is however tedious to apply and suffers from a lack of data on environmental impacts and significant variability in the results. It is therefore still rarely applied and only a handful of examples exist in the literature. The types of devices assessed in those studies vary largely, but focus mainly on devices used in the hospitals, such as dialysis equipment [27] or catheters [25]. A more general review of LCA and eco-design studies for medical devices is provided by Sousa *et al.* [28]. They conclude that despite the growing importance of sustainability in the medical device industry, the number of studies is still quite limited.

Within the assessment of medical devices, some categories are more represented. For instance, single-use devices, or their reusable alternative, have received more attention. Some examples include laryngoscopes [23, 29, 30], dialyzer cartridges [31], dental burs [24], biopolymer-based devices [32], catheters [33], or other surgery equipment [34]. The interest for reusable alternatives can be explained by the large quantities of medical waste generated annually by the medical sector and the associated concerns with its sustainability.

Wearable devices for mobile health are however assessed in only 6 of the selected studies. This number is quite low given that mHealth is the focus of this study. The subjects of these studies include a wearable computer [35], a cardiac monitoring device [21], a smartwatch [36], and e-textiles [37, 38, 39]. Three of these studies include precise evaluation of the direct impacts with LCA: Ma *et al.* [36] on a smartwatch, Kokare [21] on rigid and flexible cardiac monitoring devices, and van der Velden *et al.* [39] on a garment with embedded electronics. Lankey *et al.* [35] propose qualitative guidelines and a list of criteria for the design of a wearable computer, i.e., equivalent to a personal digital assistant. Gurova *et al.* [37] discuss the general impacts of e-textiles by merging insights from the fashion and ICT industries. Finally, Köhler *et al.* [38] focus on the issues that arise with the end of life and disposal of e-textiles, due to the combination of electronic and textile waste streams.

Component design Among selected articles, another significant group focused on designing subparts of the device (n=16, 25%), e.g., power supply, flexible substrate or electronic components, with the goal of improving their sustainability thanks to new materials or designs. Even though they are presented in the articles as components of wearable devices, they can also belong to other types of electronic devices.

In the selected studies, 6 aim at providing a sustainable source of energy thanks to the use of energy harvesting. In the case of wearable devices, several sources of energy are available for supplying the device, if a suitable conversion circuit is present. In most studies, energy is harvested from the human body, either in the form of mechanical energy from motion [40, 41, 42] or chemical energy from fluids [43, 44]. In the work of Mukherjee and Dahiya [45], the energy is harvested from the ambient light using photovoltaic cells. In most cases, the amount of energy that can be harvested often remains limited and requires strong reduction in the device power consumption.

Other studies have proposed new materials or fabrication techniques for the design of the components, usually to reduce the end-of-life impacts, or to enable sustainable sourcing and avoid resource depletion. Some of these solutions rely on bio-inspired materials such as silk for piezoelectric sensors or actuators [46, 47], protein-nanowire humidity sensors [48], flexible substrates made of biopolymers [49], or DNA-based memories [50]. Other synthetic materials have been studied for their biodegradability [51, 52], Earth abundance [53], or flexibility [52, 54]. Finally, Rahman *et al.* [55] evaluated additive manufacturing to design touch sensors in order to reduce waste in production.

Travel reduction with telemedicine As mentioned in the methodology in Section 2.1, the search includes articles on telemedicine, whose applications are often related to mHealth. Due to the exclusion criteria, only those that discussed the equipment used were selected, which resulted in a list of 10 articles (n=10, 16%). Within those articles, the modalities for remote consultation varied: videoconferencing [56, 57, 58, 59], telephone [60], or either of them [61, 62, 63, 64, 65]. From an environmental perspective, the focus of all these papers stands on the indirect reduction of the carbon footprint thanks to the reduction of travel. Regardless of the modalities used, all papers concluded that the savings from travel reduction largely exceeded the direct impacts of the infrastructure. The amplitude of the savings depends however significantly on several factors such as the type of consultations (general or specialized medicine), the country, the settings (urban or rural), or the modes of transportation.

Environmentally-conscious design methodologies In-depth environmental assessment is time-consuming and data-intensive. It is thus impractical to iteratively perform such evaluation during the design of a medical device. To bypass this issue, some authors have worked on tools to guide the design process and take environmental considerations into account at each step (n=3, 5%). The information provided by those design tools is often less comprehensive than LCA, but they can be directly applied by the designer.

Alternative assessment methods have been proposed to replace LCA during the design for faster iteration. Moultrie *et al.* [66] developed an evaluation grid specifically tailored for medical devices, in which several indicators are qualitatively evaluated to identify the main bottlenecks in the design. Another common tool is the checklist, as discussed by Unger *et al.* [67], that allows to quickly verify that some environmental criteria are met in hospitals, such as encouraging recycling programs or sustainable device sourcing.

One of the main difficulties in the design of medical devices is the large number of constraints that apply such as regulations, safety, medical efficacy or cost. Mak and Kritchanchai [68] investigated those different constraints, ranked them according to their importance and provided design recommendations. Hede *et al.* [69] proposed to incorporate sustainability in a decision-making framework, in order to help prioritize sustainability criteria with other constraints.

Business models Maintenance, repair, recycling or reconditioning are practices that enhance the sustainability of devices by prolonging their life cycle or giving them a second life. Those are however not straightforward to apply in a cost-conscious healthcare industry, in addition to the conflicting constraints of safety and medical efficacy. Circular business models that incentivize sustainable practices have been studied and adapted for this particular sector. While business models impact primarily the economic aspects of sustainability, they have consequences for the environmental dimension as well, which is why they are included in this review (n=5, 8%).

As the medical device ecosystem is quite diverse and different devices often have distinct characteristics and specifications, several types of alternative business models exist to fit each use case. Guzzo *et al.* [70] reviewed different types of circular business models, such as rental, end-of-life equipment collection, reprocessed devices or equipment as a service, and mapped them to different device characteristics. Other authors studied how some models apply to specific healthcare use cases and how they improve sustainability. For example, product-as-a-service systems [71, 72], in which the client pays for the use of a product rather than its property, usually encourage the provider to maximize the life cycle of the device by improving maintenance and reconditioning. Zlamparet *et al.* [73] studied the technological and economic advantages of recycling and remanufacturing imaging equipment and servers. Finally, the UBORA project [22] evaluated the potential for open-source devices in the medical industry, as well as their impacts on environmental sustainability.

Top-down healthcare system assessment While most works look at sustainability in a bottom-up approach by starting from selected use cases, five studies included in the analysis proceed in a top-down approach by taking a macroscopic view at healthcare systems (n=5, 8%). The aggregate results that are provided are usually coarser, but they allow to understand the global picture of environmental impacts in healthcare and come up with practical guidelines to mitigate those impacts. Among the most urgent objectives regarding environmental sustainability, the reduction of GHG emissions is necessary in the healthcare sectors to comply with the Paris agreement which aims at limiting global warming well below 2 °C above pre-industrial levels [74]. Sector-wide GHG emission reduction strategies have therefore been proposed for the healthcare system. Sherman *et al.* [75] reviewed the healthcare emissions research and summarized the main emission reduction strategies and research gaps. Plans at the national level have also been proposed by organizations in different countries. In the selected articles, two of those plans are included, for England [20] and France [17], respectively. These plans consist in an overview of the current annual emissions divided by sources as well as propositions, usually at the political and regulatory level, to reduce those emissions. The interest of these documents in this review is twofold. First, the potential savings enabled by telemedicine and mHealth for different emission sources can be compared with their respective share in the overview of the total emissions, illustrated in Fig. 3. Second, digitalization, which usually includes telemedicine and mHealth, is recognized as an important driver for sustainability, e.g., by using virtual procedures instead of those currently taking place in physical settings, such as remote consultations or electronic records. In these documents, the importance of taking into account the footprint due to the direct impacts of this increasing digital infrastructure is also highlighted.

In two studies, the authors specifically tackled the evaluation of the environmental impacts of eHealth, including the impacts of several applications. Holmner *et al.* [15] evaluated qualitatively the potential environmental benefits of several applications that are part of a larger eHealth system, such as remote consultations, remote health education, electronic prescriptions or remote diagnosis. Di Giacomo and Håkansson [16] quantitatively assessed the GHG reduction following the implementation of an eHealth network for electronic prescription and referral. Both studies mentioned the reduction in travel as the main environmental benefit from eHealth, compared to paperwork reduction for instance, while direct impacts from ICT infrastructure were negligible

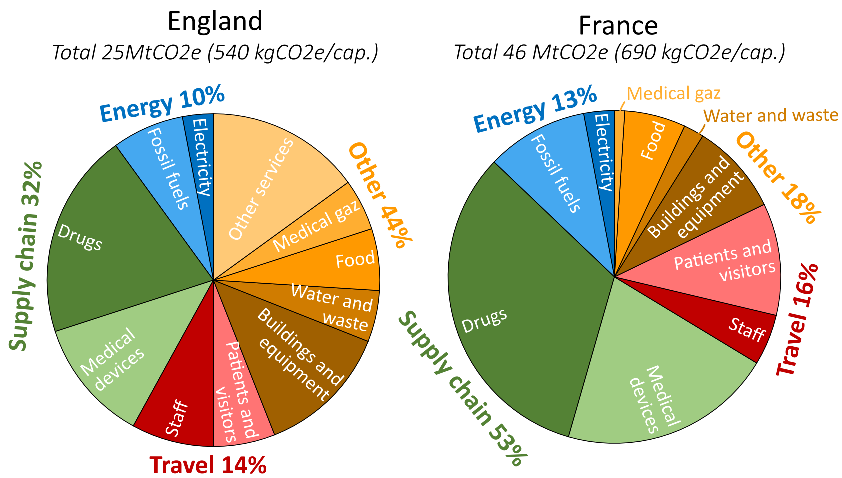

Figure 3. National carbon footprints for the healthcare sector (adapted from [17] and [20], with supplementary data from [76]). The main emission source categories are represented with similar colors, with shades to distinguish subcategories. The scopes for the emission sources each chart may not be exactly similar and they cannot be compared directly.

in the studied applications.

Stakeholders environmental considerations In order to understand how environmentally-friendly practices are considered in the healthcare sector, some authors performed interviews directly with stakeholders (n=2, 3%). Moultrie *et al.* [77] interviewed designers from medical device manufacturers to assess the extent of environmental measures in their design work, and the drivers and barriers to their implementation. Ordway *et al.* [78] investigated hospital practices to reduce waste by interviewing hospital staff. While stakeholders are generally willing to improve the environmental impact of the sector, they face significant constraints to do so. From a design point of view, the medical industry is seen as risk-averse, cost-conscious and subject to a lot of stringent regulations. The environmental issues are therefore much lower in the list of priorities. In both studies, the lack of information or education was also designated as a barrier to the implementation of more sustainable practices.

Other A few studies (n=3, 5%) appeared as outliers in the pool of selected papers in the sense that their scope was not deemed similar to other studies. For instance, Cosgrove *et al.* [79] proposed a framework to evaluate the energy reduction in medical devices production facilities. Alshqaqeeq *et al.* [80] performed a literature review of the carbon footprint assessment of patient care alternatives in hospital services. Finally, McGain *et al.* [81] discussed qualitatively the environmental impacts of a catherization laboratory and an operating room, with a focus on the opportunities and barriers for improvement.

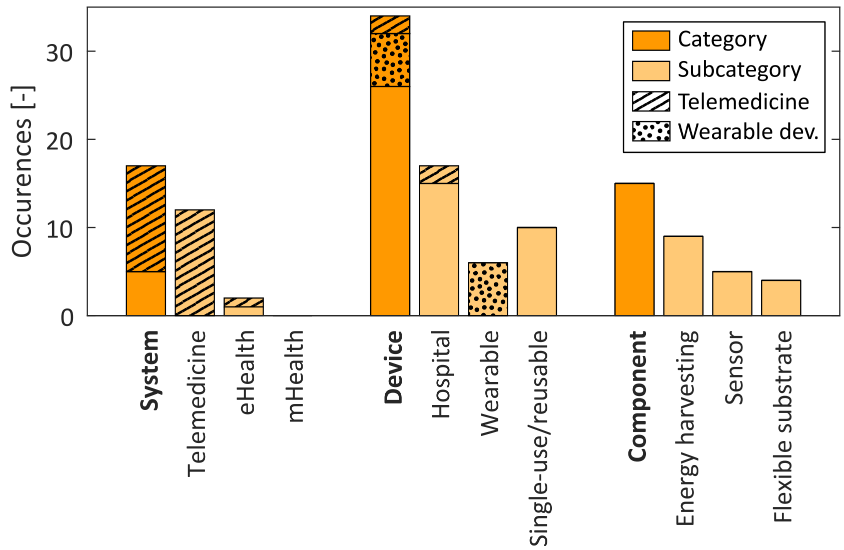

Figure 4. Occurences of scopes in selected articles. The scopes correspond to healthcare system components whose environmental impacts are considered. Relevant subcategories are displayed to highlight significant groups. Studies on telemedicine and wearable device are highlighted.

2.4. Quantitative content analysis

In order to get a clearer understanding of what aspects of sustainability are mostly considered in the literature, and hence also identify those that are under-studied, a quantitative content analysis is performed. This analysis aims at classifying the selected articles in three dimensions: the scope, the level of impacts and the environmental indicators. Along each dimension, categories have been created and associated with the articles, with possibly one additional level of hierarchy to highlight important subcategories. For a given dimension, each study is linked to at least one category, and possibly more than one if several corresponding themes are discussed in the article. The extracted themes and corresponding occurrences are reported respectively in Figs. 4, 5 and 6. The exhaustive association of themes and articles is provided in Table A1 in Appendix A.

Scope of the environmental considerations The scope of the environmental considerations corresponds to the part of the healthcare system whose environmental impacts are discussed, and has been divided in three categories. Firstly, the *device* category corresponds to the studies that look at the impacts of whole individual medical devices, such as a laryngoscope or a smartwatch. Secondly, the *system* category corresponds to the aggregated impacts of several devices, usually in the context of an application. Thirdly, the *component* category includes studies that focus on subparts of a device, such as the sensor or power supply.

It can be seen in Fig. 4 that most of the selected articles belong to the *device* category, which is the focus of the review. However, only 6 of these correspond to

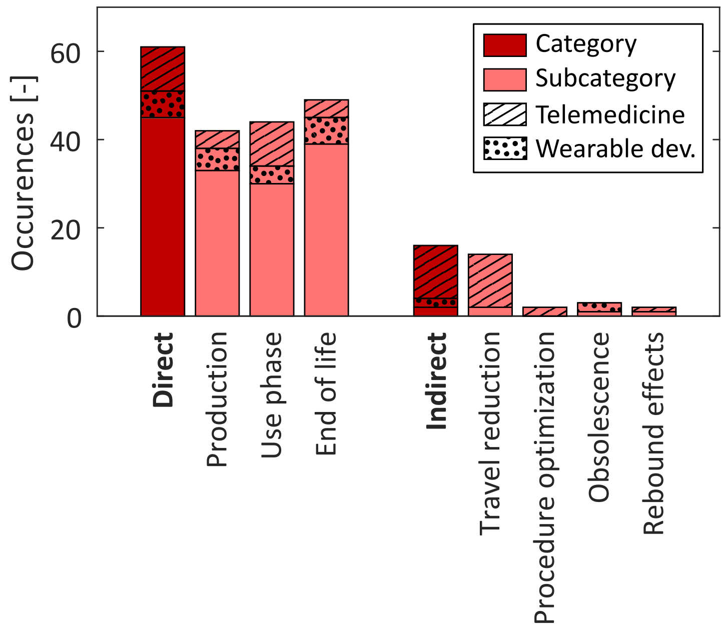

Figure 5. Occurences of impact levels in selected articles. The impact levels indicate in what ways the devices generate effects on the environment, either directly through their life cycle or indirectly through their use. Relevant subcategories are displayed to highlight significant groups. Studies on telemedicine and wearable device are highlighted.

wearable devices and, when specified, a larger proportion focuses on hospital equipment and single-use devices for medical intervention. The *system* category mainly consists in articles on telemedicine. A few papers discussed the global impacts of eHealth, but none focused on the impacts of mHealth as a system. In the *component* category, the energy harvesting circuits, sensors and flexible substrate are the most represented.

Level of environmental impacts The level of environmental impacts is here divided in two categories. The *direct* impacts are related to the life cycle of the devices, which includes the impacts of their production (material extraction, manufacturing, transport), use phase (energy consumption, maintenance) and end of life (disposal, recycling, reconditioning). The *indirect* impacts are the changes in other impact sources enabled by the use of the devices. In the selected articles, those consist mainly in positive impacts such as the reduction of emissions from transportation and optimization of healthcare procedures.

Fig. 5 shows that a majority of the papers analyze the *direct* impacts of the medical devices. All life cycle stages are discussed, with a slightly higher proportion for the end of life stage. The articles associated with the *indirect* impacts are predominantly focused on telemedicine and the induced reduction in travel. Two studies [60, 62] also discuss the optimization of healthcare procedures thanks to remote triage of the patients. Finally, four articles briefly discussed potential negative indirect impacts due to obsolescence [37, 17, 38] or rebound effects [61, 17].

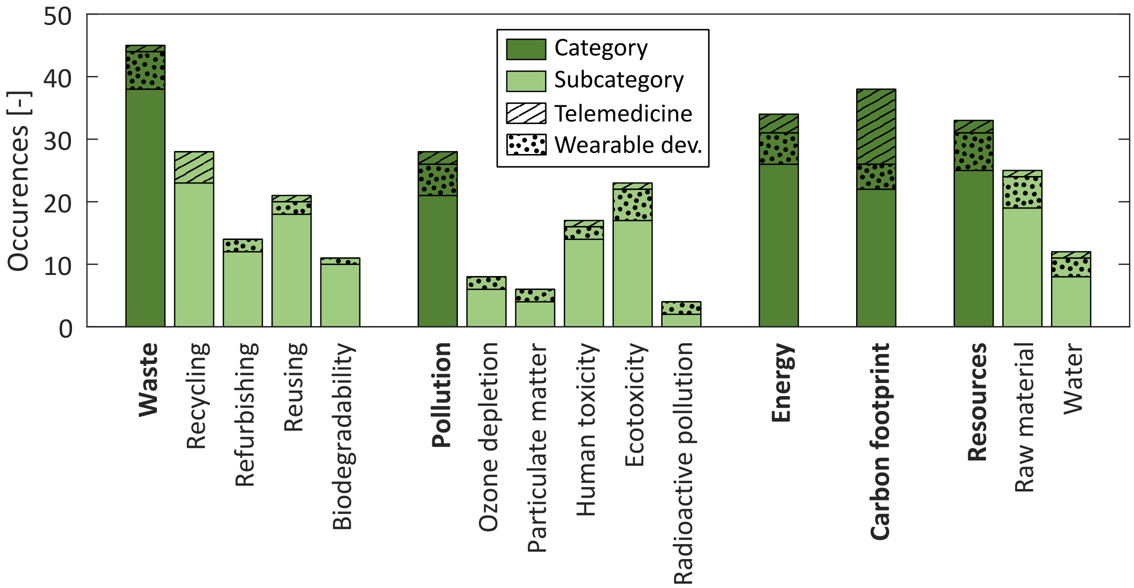

Figure 6. Occurences of environmental indicators in selected articles. The environmental indicators correspond to the aspects of the environment that are impacted and how they are quantified. Relevant subcategories are displayed to highlight significant groups. Studies on telemedicine and wearable device are highlighted.

Environmental indicators The environmental impacts of healthcare are multifold and require several indicators to be fully evaluated. This is reflected by the following categories of indicators. *Waste* relates to the amount of discarded devices at their end of life and includes the alternative ways to reduce its impact such as recycling, refurbishing, reusing or using biodegradable materials. The *pollution* can be of different forms depending on the types of emissions and impacts on the humans or ecosystem. The *energy* category includes the energy consumption at all stages of the life cycle, as well as the attempts to reduce it. The *carbon footprint* corresponds to all emissions of GHG that contribute to climate change. Finally, the depletion of non-renewable resources and the usage of water are included in the *resources* category.

As shown in Fig. 6, the waste category is the most represented one with 71% of the selected articles mentioning it. The generation of waste has indeed been reported as one of the main concerns in the medical device industry. It is also likely the most visible one for the different stakeholders compared to other categories of impacts that are more difficult to visualize. The other categories are all significantly present in the studies, with between 44 and 60% of the articles. The carbon footprint is slightly overrepresented in the studies on telemedicine that evaluate the emission savings due to transportation. Within each category, different qualitative or quantitative evaluation methods may be used for a given indicator.

2.5. Limitations

The systematic literature review suffers from a few limitations. First, the review of the abstracts and articles could only be performed by a single reader due to practical reasons. Additional reviewers would likely reduce the risk of subjective bias in the assessment of the selection criteria. Second, in the selection and analysis of the articles, all studies were considered equal and included in the analysis, regardless of their scientific quality and the amount of evidence presented. Because of the large variety of research areas present in the articles, an evaluation of research quality would have required expertise in all those different domains. Finally, it is possible that some studies were missed due the limited selection of the search key-words. Indeed, as the research question was purposefully broad to include as many view points as possible, it is difficult to frame the issue with a reasonable number of key-words. For example, as only a single generic term “medical device” to complement the search on mHealth, other studies using more specific terms may have been missed. However, the selection of the articles returned 63 individual items, which already provides an extensive and representative account of the literature.

Regarding the content analysis, a first limitation is the choice and definition of the classification dimensions (scopes, levels and indicators) which were chosen arbitrarily and thus subject to bias. Secondly, as mentioned in the methodology, all mentions of the themes were counted equally, with exactly zero or one hit per article. While this avoids a subjective assessment of the importance of each theme, it represents less accurately the weight of a given theme in the literature. Indeed, this counting method does not take into account whether a theme is the focus of the study or only a small part of the discussion. Finally, similarly to the article selection, the content analysis could only be performed by one researcher, which increases the risk of bias when associating words in the texts to themes.

3. Shortcomings of mHealth Environmental Impact Assessment

Based on the description of the articles in Section 2.3 and the observations from the content analysis in Section 2.4, some conclusions can be made with regards to the current considerations for environmental sustainability of mHealth. Section 2.3 showed that environmental sustainability for mHealth, and more largely telemedicine and medical devices, has been looked at from many different perspectives. While the multiplicity of research approaches is beneficial with regards to the complexity of the question, all these perspectives often seem rather disconnected and do not provide a consistent understanding of the impacts of these new technologies. In Section 2.4, we discussed some specific aspects of environmental impacts assessment, i.e., the scopes, levels and indicators, and highlighted the distribution of studies along these axes. This division helps emphasize that some characteristics of environmental impacts have been more studied than others.

The research on sustainability in the healthcare sector is still relatively new and it is therefore normal that significant research questions remain unanswered. However, this lack of research is even more pronounced for mHealth, which can be seen as an issue for two reasons. Firstly, regarding the devices themselves, wearable devices differ in many respects from traditional medical devices. Indeed, their composition relies primarily on electronics whose production and end of life have significant impacts. For instance, the LCA of an e-textile by van der Velden *et al.* [39] showed that electronic components are responsible for 71% of the device production impacts. Due to their portability requirements, they are also subject to additional constraints such as their power consumption or size, which requires more tightly integrated components. Compared to traditional medical devices that are mostly prescribed or used by doctors, there are many devices associated to mHealth, such as fitness trackers, smartwatches, or simple monitoring devices for sleep or stress, that are currently mostly bought on the patient's own initiative. Finally, they operate outside usual medical settings and procedures, which means that they are not subject to the same medical and regulatory oversight. Similarly to other electronic devices, the wide variety of mHealth devices should be reflected in the evaluations, as their respective bottlenecks may differ [82]. Secondly, regarding the mHealth system, the current drive towards a more sustainable healthcare system is expected to rely partly on eHealth. When discussing the environmental impacts at the system level, most authors focus on the positive effects and often consider all new technologies indiscriminately, without discerning the different devices, applications and contexts. As mentioned in the national strategic plans [17, 20], the sustainability potential of digitalization can only occur if it is explicitly taken into account to avoid adverse effects. As these technologies are only currently emerging, the opportunity can be seized to implement sustainable practices and regulations from the start, but first require understanding the use case in which they can actually bring benefits.

Within direct impacts, the previous analyses showed that sustainability in the healthcare sector is largely centered around the issues of waste and end of life. This may be due to the frequent use of single-use devices and plastics to avoid contaminations, and the higher visibility of waste for hospital staff compared to other indicators. However, the relative importance of each life cycle stage in terms of impacts can significantly vary from one device to another. For instance, due to their technological complexity, the production of electronics often accounts for a significant part of the total impacts in sensor devices [82, 83]. The evaluation of mHealth solutions therefore needs to take into account all life cycle stages, looking at the various indicators of environmental harm. Additionally, direct impacts due to the devices life cycle are not the only effects that a new technological solution can have on the environment. Indirect effects induced by the use of a technology can, in some cases, be larger than the direct impacts. In the literature, the discussion around these indirect impacts are largely dominated by the travel reduction obtained thanks to telemedicine. They are therefore mostly focused on positive impacts and revolve around the issues of carbon footprint. However, indirect impacts can also be negative, e.g., when they induce an increase in the demand for another resource, and involve different indicators than GHG emissions. In our review, only four article included negative indirect impacts. Three mentioned the increased obsolescence for e-textiles [37, 38] or digital devices [17]. Purohit *et al.* and the Shift Project report also succinctly discussed the possibility of rebound effects [61, 17].

Due to the shift in paradigm enabled by these technologies, eHealth and mHealth can induce deep transformations in the healthcare system. In order to anticipate the sustainability aspects of these emerging technologies, their effects at the macroscopic systemic level must be taken into account. An exhaustive sustainability evaluation should therefore consider the direct life-cycle impacts of a technology and the positive and negative effects induced by the use of the technology, but also the broader structural changes to the healthcare infrastructure, usage, institutions and economy.

4. Systemic Approach to mHealth Sustainability

As discussed in Section 3, when considering the long-term global impacts of a new technology, it is important to consider both its direct and indirect impacts, whose relative proportion varies from one application to another. Indirect impacts are especially important for ICT-based solutions which have the potential to indirectly influence the consumption of other related resources through, e.g., behavior modification, process optimization or virtualization. A commonly cited example is the reduction in the amount of resources for paper consumption thanks to the use of electronic communication and archiving. The nature of these indirect impacts varies in their direction, either improving or degrading the overall environmental footprint, and their action scale, at the level of an individual or society. Hilty and Aebischer [18] have proposed the LES model to conceptualize these impacts along multiple levels. In their model, the *Life-cycle (LC)* impacts relate to the direct impacts that occur during the production, use or disposal of ICT devices, similarly to the definition used in the previous sections. Indirect impacts are divided in two separate levels. The *Enabling (E)* impacts are the changes induced by the usage of the devices at the micro level, with technological, behavioral or organizational modifications. These modifications may have a positive impact, through substitution (ICT replaces another resource) or optimization (ICT enables the reduction of another related resource), or a negative impact, through induction (ICT stimulates the use of another resource) or obsolescence (ICT reduces the lifespan of another resource). For mHealth, this relates for example to the reduction of patient travel, the optimization of health procedures, or the increased healthcare demand due to medicalization. The *Structural (S)* impacts correspond to macroscopic changes in the economic structures and institutions, enabled by the ICT devices. Long-term modifications in the healthcare infrastructure or in the role of doctors are examples of these dynamics due to mHealth. Like enabling impacts, structural impacts can also go in either positive or negative directions regarding the overall footprint evolution. The different impact categories of the LES model are usually conveniently displayed in a grid as the one in Table 1.

Building on the limitations drawn from the literature review presented in Section 3, this section relies on the LES framework to evaluate more extensively the impacts of mHealth. To do so, the different levels of the framework are illustrated with presumptive examples of positive and negative effects that mHealth may have on the environment, all listed in Table 1. For a few of the proposed examples (in blue in the table), the link between mHealth systems and environmental impacts has already been explicitly mentioned in the literature. For the others (in black), the link from mHealth to environmental impacts has not been discussed explicitly and is therefore extrapolated in this work from the wider literature on mHealth. The intentionally normative distinction between positive and negative impacts present in the original framework has been kept as it highlights the balance between the optimistic expectations and possible downsides. All items in Table 1 are detailed in the rest of this section. While the discussion aims at providing a large overview of the possible impacts, it cannot be completely exhaustive due to the wide range of possible impacts, especially as we progress towards complex system-level consequences of mHealth technologies.

4.1. Life-cycle Impacts

As observed in the literature review, *Life-cycle* impacts, i.e., direct impacts, are by far the main point of attention for medical devices. However, the evaluations that are provided often remain only qualitative or incomplete. For a thorough evaluation of the direct impacts of a technology, life-cycle assessment (LCA) studies, as described in the ISO14040 standard, provide the most extensive results. In the review, only 11 studies reported LCA results for medical devices [21, 36, 24, 25, 28, 29, 32, 34, 39, 42, 67]. Within these, two of them focused on wearable devices: the article by Ma and Chan on a smartwatch [36] and the thesis of Kokare on cardiac monitoring devices [21]. Despite the increasing efforts, LCA studies remain difficult to perform due to the length of the process, the required expertise and the lack of available data, especially for electronic devices.

Several characteristics of mHealth devices point towards an increase of their direct impacts compared to traditional medical devices. **[LC1$^-$]** At the unit scale, mHealth devices often consist in complex devices: flexible and biocompatible materials for skin-worn electronics, devices seamlessly integrated into garments, advanced technologies for small form factor, etc. These technologies all involve complex material streams that make their fabrication and disposal increasingly difficult to handle. For instance, Köhler *et al.* [38] highlighted future issues with the disposal schemes of e-textiles due to the tight integration of electronics into the fabrics. **[LC2$^-$]** In some cases, these issues with more complex streams might be further amplified by the safety precautions required for devices that have been contaminated though contact with tissues or biological fluids. Those hinder the implementation of circular business models that reduce end-of-life impacts by enhancing recycling or refurbishing rates [70].

Table 1. Life cycle-Enabling-Structural impact model applied to mHealth, based on the model by Hilty and Aebischer [18]. Presumptive examples of environmental effects from mHealth illustrate the categories. For examples highlighted in blue, the link between mHealth and environmental impacts has been explicitly mentioned in the literature, while it is extrapolated for examples in black.

<table>
<tr><th></th><th>Positive</th><th>Negative</th></tr>
<tr><td>Life cycle</td><td>Not applicable by definition</td><td>[LC1$^-$] More integrated devices require more advanced technologies with potentially higher impacts.
[LC2$^-$] Contamination risks makes circular end of life options difficult.
[LC3$^-$] mHealth is expected to be deployed at a large scale.
[LC4$^-$] More ICT infrastructure will be required to support eHealth.</td></tr>
<tr><td>Enabling</td><td>[E1$^+$] Telehealth reduces travel and use of other resources.
[E2$^+$] Remote monitoring can reduce the frequency and duration of hospital stays.
[E3$^+$] Prevention and early diagnosis could reduce the amount of procedures.
[E4$^+$] More targeted, personalized and possibly more efficient evidence-based medicine optimizes medical procedures and reduces drugs, procedures, etc.</td><td>[E5$^-$] Demand for healthcare increases due to medicalization and adverse effects.
[E6$^-$] Lifetime of electronic and wearable devices is shortened by obsolescence (hardware, software or psychological) and fast innovation cycles.</td></tr>
<tr><td rowspan="2">Structural</td><td>[S1$^+$] ICT helps promote more sustainable business models in the healthcare sector.</td><td>[S2$^-$] Rebound effects of energy/carbon savings countervail the potential efficiency improvements.</td></tr>
<tr><td colspan="2">[S3] Remote health services lead to the centralization of specialized medical infrastructure.
[S4] Practices and regulations are transferred between healthcare and ICT sectors.
[S5] Changing care paradigm restructures the healthcare institutions.</td></tr>
</table>

While the previous effects refer to the relative impacts of individual devices, the overall environmental impacts depend on the absolute footprint of the devices, which is proportional to the scale of the deployment. As mHealth is built as a distributed infrastructure, the amount of electronic equipment for mHealth is likely to increase by design. [**LC3**$^-$] While applications for smartphones mainly rely on existing devices, mHealth also includes a large number of wearable connected sensors that will add to the existing ICT infrastructure. This market, often referred to the Internet of Medical Things (IoMT) in reference to the global Internet of Things (IoT), is expected to grow very rapidly with millions of new connected devices [84]. This growth in the number of devices is not only due to economic reasons, but is also sometimes required by design. Indeed, for instance, lots of devices are necessary to justify the shared networks and infrastructure which must be installed to connect them. Similarly, the artificial intelligence algorithms often used in combination with these devices require lots of data originating from many devices, in order to improve their own accuracy. [**LC4**$^-$] Wearable devices usually require additional infrastructure in order to store, transmit and process the huge quantities of data generated. As the ICT infrastructure of healthcare, including dedicated computers or datacenters, has not been designed to manage all this data, it will also need to grow in the future. In telemedicine-related studies, this impact of the ICT infrastructure has often shown to be negligible, but the scope was usually only limited to videoconference or telephone call during the time of the remote consultation, at a limited scale. Those conclusions will likely therefore change if telehealth becomes more mainstream and other uses start to emerge.

4.2. Enabling Impacts

In the scientific literature, indirect *Enabling* impacts have been mostly studied from the perspective of reduced travel thanks to telehealth. [**E1**$^+$] In the review of Section 2, 11 studies that discussed telemedicine reported a decrease in the carbon footprint obtained by substituting face-to-face appointments with remote consultations [61, 56, 57, 58, 59, 60, 62, 63, 64, 65, 80]. While most of these studies focus on specialized medicine associated with longer travel distances, the carbon break-even point between indirect travel emissions and direct ICT footprint has been estimated at only a few kilometers (16 km [64], 7.2 km [57]).

Other reductions have also been reported in those studies, though less frequently. [**E2**$^+$] One example is the information obtained through ICT devices which can be used to optimize the use of healthcare resources. Audebert *et al.* [62] mentioned that telehealth and telemonitoring could be used as a basis to reduce unnecessary hospital admissions. Indeed, on top of the reduced travel, large amounts of resources and energy are consumed at the hospital, which can be avoided by relying on data obtained remotely. Similarly, Wang *et al.* [60] proposed using preoperative triage remotely to assess whether the patient is fit for surgery travelling to the hospital. Thanks to telemedicine, additional savings are obtained from the reduced use of physical resources such as personal protective equipment [64] or paper [63] associated with physical consultations.

To the best of our knowledge, other positive indirect effects of mHealth have not been discussed in the literature, yet present a high potential for reducing environmental impacts. Indeed, when considering the carbon footprint, as shown in Fig. 3, many emission sources contribute to the global footprint. Among those, travel which receives most of the attention only accounts for 14 to 16% of the total [17, 20]. Relying on mHealth to optimize specifically the other emission sources such as the supply chain or hospital resources may prove equally or more effective in reducing the sector impacts. [**E3**$^+$] One way to do so is to increase preventive medicine. It has been mentioned as a lever to reduce the healthcare footprint, thanks to the reduction of resource-hungry curative medical procedures [17, 20]. By making it possible to interact more frequently with the patients, telehealth has been considered as an interesting tool to promote healthy behaviors and prevent medical issues [85, 86, 87]. [**E4**$^{+}$] It has also been reported that up to 40% of care is either useless or even harmful [88]. In addition to the effects on the health, cost and comfort for the patient, this also induces additional environmental impacts. Artificial intelligence, relying in part on mHealth sensor data, could be used to pave the way towards a more evidence-based and personalized medicine in order to bridge this gap [89]. Given the large proportion of environmental impacts originating from the supply chain (Fig. 3), this data-driven optimization could induce significant savings.

Enabling impacts can however also be negative when they cause an increase in the environmental footprint. Induction effects are an example of such negative indirect impact which occur when the use of a technology stimulates the consumption of similar or different resources. [**E5**$^{-}$] For mHealth, induction effects could appear as an increase in the demand for healthcare. For instance, adverse health effects may occur due to the use of eHealth applications. Behne and Teuteberg [90] reviewed some of the negative health impacts of these technologies such as increased stress, reduced quality of sleep, or overcompensation behaviours. Additionally, even in the absence of actual health issues, the demand in healthcare may increase due to the medicalization of previously non-medical aspects of the patients life. Baker [91] hypothesized that the feedback obtained from a wearable device would encourage the wearer to self-correct toward a norm that may not be well defined. While the ensuing actions could be beneficial, e.g., exercising more or improving their diet, it could also lead to unnecessary medical consultations.

[**E6**$^{-}$] Finally, connected objects with embedded electronics tend to be subject from shorter innovation cycles, which leads to increased obsolescence [92, 93]. Obsolescence can occur in multiple ways: components of the system failing prematurely (hardware obsolescence), software updates not being provided for older systems (software obsolescence), or features from new devices lessening the appeal for previous versions (psychological obsolescence). This effect has also been reported for wearable devices such as hearing aids [94], e-textiles [37, 38] or handheld assistant devices for nurses [95]. This shortened life-cycle increases the quantities of devices that must be replaced, along with the associated fabrication and end-of-life impact overhead.

4.3. Structural Impacts

The level of *Structural* impacts refers to macroscopic, systemic and long-term changes to institutions or economic structures. Due to their more complex nature, they are often more difficult to describe and predict. This part is therefore more of a prospective exercise. [**S1**$^{+}$] At the business level, ICT has been shown to be a key component in the transition towards more sustainable production and consumption patterns, by using the connectivity properties to enhance material circularity. In a healthcare industry that is still very reliant on disposable single-use devices, more circular business models could emerge to reduce the amounts of waste, with the support of digital devices and mHealth [70, 96]. However, digital systems are not necessarily associated with these more sustainable patterns, for example as they have also contributed to increase consumption in some contexts.

[S2⁻] Rebound effects, also know as the Jevons paradox, take place at the macro-level when the resources (energy, time, money, etc.) saved by improving efficiency are respent and increase the demand for similar or different services, i.e. direct or indirect rebound effects. Overall, this effect curbs the gains that would be expected from the efficiency improvement alone and, in some cases, even leads to an increase in the absolute amount of resources spent [97], which are called backfire cases. Purohit *et al.* mention the possibility of such rebound effect in the context of telemedicine, whose time and cost savings may be reinvested in other activities [61]. More generally, due to the behavioral and societal factors, it is difficult to predict if and how the energy, time and cost savings from mHealth and telemedicine will be reinvested in other areas and thus reduce potential abatement [98].

Regarding some other systemic effects, it can be extremely difficult to assess whether the global impact will end up as positive or negative. **[S3]** For example, Cornaggia *et al.* showed that telemedicine puts a financial strain on rural hospital due to the redistribution of services towards more specialized urban hospitals [99]. This financial hardship may cause bankruptcy for smaller hospitals and lead to centralization of care in larger facilities. On the one hand, this could lead to economies of scale and improved energy performance in the hospitals. On the other hand, as telemedicine cannot fully replace face-to-face appointments, typically for physical examination or treatment, this centralization could increase the length of individual journeys, which is a form of rebound effect as telemedicine is intended to limit these journeys.

Structural effects also include changes at the institutional level, for example by inducing changes in the laws. **[S4]** Regulation has often been reported as both a barrier [27, 71, 75, 81] or a driver [23, 77, 78] for implementing more sustainable healthcare solutions. For instance, in the European Union, some directives such as the ones on Waste Electrical and Electronic Equipment Directive (WEEE), Restriction of Hazardous Substances Directive (RoHS) or Ecodesign already encourage more sustainable practices, including for mHealth devices [77]. Given the current concerns for the environment, these are likely to become increasingly stringent. At the same time, other regulatory constraints regarding, e.g., safety or privacy put an additional, although necessary, burden on the design of the devices, thus shifting the focus away from environmental sustainability.

Given their impact on the healthcare paradigm, eHealth has the potential to deeply modify the way healthcare currently operates in the long-run [100], ultimately having implications for the environmental footprint. **[S5]** Some examples of the potential profound changes are the modification of the role of doctors through the patient empowerment [101], the increasing importance of technology in healthcare services [102] or the overall improvements in the health outcomes. The amplitude of these effects are still very much unknown and their future environmental impacts would be very difficult to estimate.

5. Conclusion

mHealth and eHealth are on the verge of profoundly transforming the healthcare system. This transformation is likely to have significant impacts on environmental sustainability, but they are still difficult to evaluate due to the limited knowledge on these issues. This work aimed at providing a better understanding of the global environmental impacts of mHealth using the LES framework, and highlighting the lack of a systemic vision. This has been done by first evaluating how environmental impacts are considered in the scientific literature, then highlighting the current limitations in the evaluation of these impacts, and finally proposing a systemic framework that takes into consideration a macroscopic view of the mHealth system. By looking at the potential evolutions of the mHealth system and its impacts, some prospective examples were used to illustrate these larger impacts. This is a first step towards an approach that looks further than usual considerations in the literature, which remain limited to life-cycle impacts of individual devices and travel reduction.

The more comprehensive LES framework also highlights the complexity of evaluating the overall impact of design directions. When a design choice has multiple effects on the environmental sustainability, these effects can be synergistic or antagonistic, i.e., acting in similar or opposite directions, respectively. For instance, the implementation of smart wearable devices which embed local processing of the data to reducing the wireless transmission data rates can reduce the average power consumption of the device, while at the same time reducing the need for additional infrastructure to transfer, store and process large quantities of data. On the other hand, antagonistic effects may occur, such as the more complex and integrated devices with higher production impacts, or increased obsolescence due to specialization of the device if upgradability is not included. Evaluating the balance of these choices is not straightforward, especially when the effects span multiple levels.

Research around those larger impacts of mHealth is required in order to design future guidelines and policies, and to ensure that mHealth leads the healthcare sector on a path towards increased sustainability. As concerns regarding environmental footprint are currently rising, the priority given to sustainability in the design and choice of new technologies is likely to rise, but requires the proper methodologies and tools. While the proposed framework provides a way to characterize and categorize the potential effects of these technologies, there is still a long road to providing actionable guidelines for their development. As the effects discussed in Section 4 remain hypothetical, future steps consist in their study, and quantification when possible, in relevant use cases to evaluate their relative importance. The balance between positive and negative impacts could then be assessed for different mHealth technologies and in different contexts. Indeed, while wearable technologies could provide valuable benefits in some situations, the outcomes could change in other cases due to differences in cultures, geographical and political contexts, or needs for the healthcare system. Further research into these questions would be valuable for both designers in order to optimize the impacts of their devices, and for policy-makers and institutions to properly regulate the development of these emerging technologies.

As described in Section 4, the environmental effects of mHealth involve changes in the healthcare system as a whole. The study of these changes involves medical, economic, social, psychological, political or behavioral questions that are beyond the traditional scope of engineering. In the LES model that is used to structure the impact categories, the life cycle level is usually limited to technical considerations and is easier to quantify, which also likely explains why it has been the focal point of previous research. Enabling and structural changes are less well-defined, depend on user behavior and institutional response, and they are less prone to precise quantification. An interdisciplinary dialogue therefore seems necessary to reconcile these different characteristics and fully grasp those systemic impacts. It is also worth remembering that environmental issues are only a part of the overall sustainability question, in parallel with economic and social considerations. This multi-sided vision ensures that mHealth has the least detrimental impact on the environment, but is also socially acceptable, e.g., with fair treatment of the workforce and respect of the local and global communities, and economically viable, i.e., thanks to cost effectiveness and proper governance. These considerations further highlight the need for interdisciplinary research, in order to provide the proper tools and education to the stakeholders [14].

Finally, while improving efficiency and minimizing environmental impacts of the individual devices are necessary strategies, they alone will not address the systemic impacts and potential rebound effects. The concept of digital sufficiency described by Santarius *et al.* [103] provides clues on how to identify ICT solutions that foster a reduction in the absolute environmental footprint. Applied to mHealth, sufficiency consists in ensuring that new technological developments actually answer the medical needs, that their deployment and use fits the intended purpose, or that they provide low-impact alternatives to existing services. Considering that we only have finite resources at our disposal, this question of selecting only the most valuable outcomes can be seen as a sensitive issue, especially in the context of health which is often seen as a primary concern. These issues call for a wider societal reflection on our health objectives and how technology will contribute to them.

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Appendix A. Selected Articles in Literature Review

Table A1 lists all the articles selected with the PRISMA methodology in Section 2. The papers are sorted according to the topic clusters described in Section 2.3. A short description and the themes (scope, level, and indicators) associated to each item are provided.

Table A1: List of articles

Reference	**Description**	**Scope**	**Level**	**Indicator**
Medical device assessment				
– Hospital devices				
Barbero, 2017 [27]	Sustainability analysis of haemodialysis equipment based on systemic design	Dev (Hosp)	Dir (Use, EoL)	Waste; Pollution (ET, RP)
Stripple, 2008 [25]	Environmental evaluation of plastic materials for catheters using LCA	Dev (Hosp)	Dir (Prod, Use, EoL)	Pollution (OD, P, HT, ET); Energy; Carbon footprint; Resources (Raw)
Sousa, 2021 [28]	Review of LCA and eco-design studies of medical devices	Dev (Hosp)	Dir (Prod, Use, EoL)	Waste (Rec); Pollution (HT, ET); Energy; Carbon footprint; Resources (Raw, Water)
– Single-use or reusable devices				
Agrawal, 2021 [23]	Review of environmental, economic and social sustainability of single-use endoscopes	Dev (Hosp, SU)	Dir (Prod, Use, EoL)	Waste (Rec); Pollution (PM, HT, ET); Carbon footprint
Hanson, 2009 [31]	LCA and functional analysis of a dialyzer cartridge	Dev (Hosp, SU)	Dir (Prod, Use, EoL)	Waste (Rec, Reu, Bio); Pollution (ET); Energy; Resources (Raw)
Unger, 2014 [24]	LCA comparison of dental burs	Dev (Hosp, SU)	Dir (Prod, Use, EoL)	Waste (Rec, Reu); Pollution (OD, HT, ET); Energy; Carbon footprint; Resources (Water)
Unger, 2017 [32]	LCA of plastics and biopolymers for surgery equipment	Dev (Hosp, SU)	Dir (Prod, Use, EoL)	Waste (Bio); Pollution (OD, HT, ET); Energy; Carbon footprint; Resources (Raw)
Unger, 2016 [34]	LCA and cost assessment of reprocessed medical devices	Dev (Hosp, SU)	Dir (Prod, Use, EoL)	Waste; Pollution (HT); Carbon footprint
Sherman, 2018 [29]	LCA and cost assessment of laryngoscopes	Dev (Hosp, SU)	Dir (Prod, Use, EoL)	Waste (Rec, Ref, Reu); Pollution (OD, PM, HT, ET); Energy; Carbon footprint; Resources (Water)
McGain, 2012 [33]	LCA of venous catheter insertion kits	Dev (Hosp, SU)	Dir (Prod, Use, EoL)	Waste (Rec); Pollution (ET); Energy; Carbon footprint; Resources (Raw, Water)
Viani, 2016 [30]	End of life value recovery from used laryngoscopes	Dev (Hosp, SU)	Dir (EoL)	Waste (Rec, Reu); Energy
– Wearable devices				
Lankey, 1997 [35]	Eco-design of a wearable computer	Dev (Wear)	Dir (Prod, Use, EoL)	Waste (Rec, Ref, Reu); Pollution (ET); Energy; Resources (Raw)
Kokare, 2020 [21]	LCA of wearable cardiac monitoring devices	Dev (Wear)	Dir (Prod, Use, EoL)	Waste (Rec); Pollution (OD, PM, HT, ET, RP); Energy; Carbon footprint; Resources (Raw, Water)
Ma, 2017 [36]	LCA of a smartwatch	Dev (Wear)	Dir (Prod, EoL)	Waste; Pollution (OD, PM, HT, ET, RP); Energy; Carbon footprint; Resources (Raw, Water)
– E-textiles				
Gurova, 2020 [37]	Review of environmental impacts of e-textiles from the fashion and ICT standpoints	Dev (Wear)	Dir (Prod, EoL); Ind (Obs)	Waste (Rec, Ref, Reu, Bio); Pollution (ET); Energy; Carbon footprint; Resources (Raw, Water)
Köhler, 2011 [38]	Impacts of e-textiles on device end of life	Dev (Wear)	Dir (EoL); Ind (Obs)	Waste (Rec); Pollution (ET); Resources (Raw)
van der Velden, 2015 [39]	LCA of an e-textile garment	Dev (Wear)	Dir (Prod, Use, EoL)	Waste (Rec); Energy; Carbon footprint; Resources

Table A1: List of articles (continued)

Reference	Description	Scope	Level	Indicator
– Other				
Mirkouei, 2017 [104]	Eco-design of an ankle foot orthosis	Dev	Dir (Prod)	Energy; Carbon footprint; Resources (Raw)
Component design				
– Energy harvesting				
Abdi, 2014 [40]	Design of a piezoelectric energy harvester from abdominal motion	Comp (EH)	Dir (Use)	Energy
Liu, 2021 [41]	Review of mechanical energy harvesters	Comp (EH)	Dir (Use)	Energy
Mahmud, 2021 [42]	LCA of PET and PMMA used in triboelectric energy harvesters of	Comp (EH)	Dir (Prod, EoL)	Waste; Pollution (OD, PM, HT, ET, RP); Energy; Carbon footprint; Resources (Raw, Water)
Wu, 2021 [43]	Review of wearable biofuel cells to harvest energy from bodily fluids	Comp (EH)	Dir (EoL)	Waste (Bio); Energy
Manjakkal, 2021 [44]	Review of sweat-based energy harvesting and storage	Comp (EH, Sens)	Dir (Use, EoL)	Waste; Energy
Mukherjee, 2021 [45]	Evaluation of environmental impacts of electronic skin with photovoltaic energy harvesting	Comp (EH)	Dir (Use, EoL)	Waste (Rec, Ref, Bio); Pollution (ET)
– New material				
Cocchi, 2021 [49]	Design of organic LEDs and flexible biopolymer substrate	Comp (Disp, Flex)	Dir (Prod, EoL)	Waste (Rec, Bio); Resources (Raw)
Dong, 2021 [54]	Review of aqueous rechargeable zinc-ion batteries	Comp (Supp)	Dir (Prod, EoL)	Waste (Rec); Energy
Lam, 2020 [50]	Design of a DNA-based memory device	Comp (Mem)	Dir (Prod, EoL)	Waste (Bio); Resources (Raw)
Liu, 2020 [48]	Design of a humidity sensor with protein nanowires	Comp (Sens)	Dir (Prod, EoL)	Waste; Energy; Resources (Raw)
Yu, 2022 [51]	Design of a biodegradable transparent conductive film	Comp (Flex)	Dir (Prod, EoL)	Waste (Rec); Resources (Raw)
Yang, 2017 [53]	Design of a biodegradable transparent conductive film with sustainable materials	Comp (Flex)	Dir (Prod, EoL)	Waste (Rec, Bio); Resources (Raw)
Wang, 2018 [52]	Review of skin-inspired electronic substrates	Comp (Flex)	Dir (Use, EoL)	Waste (Ref, Bio)
Veronica, 2021 [46]	Review of silk-based piezoelectric devices	Comp (EH, Sens, Act)	Dir (Prod, Use, EoL)	Waste (Bio); Energy; Resources (Raw)
Strassburg, 2021 [47]	Review of silk-based electronic devices	Comp (EH, Sens)	Dir (Prod, Use, EoL)	Waste (Bio); Carbon footprint; Resources (Raw)
Rahman, 2016 [55]	Design of capacitive touch sensors with additive manufacturing	Comp (Sens)	Dir (Prod)	Waste; Pollution (HT)
Telemedicine				
Audebert, 2010 [62]	Qualitative environmental impact analysis of telemedicine in neurology	Syst (TM)	Ind (Travel, Opti)	Energy; Carbon footprint
Yellowlees, 2010 [63]	Qualitative environmental impact analysis of telemedicine and eHealth in the US	Syst (TM, eH)	Dir (Use, EoL); Ind (Travel)	Waste (Rec, Reu); Pollution (HT); Energy; Carbon footprint; Resources (Raw)

Table A1: List of articles (continued)

Reference	Description	Scope	Level	Indicator
Bartlett, 2022 [64]	Carbon footprint assessment of virtual geriatry consultations	Dev (Hosp); Syst (TM)	Dir (Prod,Use, EoL); Ind (Travel)	Carbon footprint
Blenkinsop, 2021 [56]	Carbon footprint assessment of virtual consultations in epilepsy services	Syst (TM)	Ind (Travel)	Waste; Pollution (ET); Carbon footprint; Resources (Water)
Edison, 2020 [65]	Review of telemedicine in urology	Syst (TM)	Ind (Travel)	Carbon footprint
Holmner, 2014 [57]	Carbon footprint assessment of virtual consultations in different specialized services	Syst (TM)	Dir (Prod,Use, EoL); Ind (Travel)	Carbon footprint
Whetten, 2019 [58]	Carbon footprint assessment of virtual consultations in neurology	Syst (TM)	Dir (Use); Ind (Travel)	Carbon footprint
Wang, 2021 [60]	Carbon footprint assessment of telehealth for preoperative screening	Syst (TM)	Dir (Use); Ind (Travel, Opti)	Carbon footprint
Purohit, 2021 [61]	Review of carbon footprint assessment in telemedicine applications	Syst (TM)	Dir (Use); Ind (Travel, Reb)	Carbon footprint
Masino, 2010 [59]	Carbon footprint assessment of virtual consultations in different specialized services	Syst (TM)	Dir (Use); Ind (Travel)	Carbon footprint
Design methodologies				
Hede, 2013 [69]	Implementation of a multicriteria hierarchical decision model for medical device design	Dev	Dir (Prod, Use, EoL)	Waste (Rec, Ref, Reu); Pollution; Resources (Raw)
Mak, 2019 [68]	Analysis of the factors influencing medical device design using analytical hierarchy process	Dev	Dir (Prod, Use, EoL)	Waste (Rec, Ref, Reu); Pollution (OD, HT, ET); Energy; Carbon footprint
Unger, 2016 [67]	Evaluation of green practices checklists in hospitals	Dev (Hosp); Syst	Dir (Prod, Use, EoL)	Waste (Reu); Energy; Carbon footprint; Resources (Water)
Moultrie, 2016 [66]	Implementation of a qualitative assessment grid for environmental impacts of medical devices	Dev	Dir (Prod, Use, EoL)	Waste (Rec, Ref, Reu); Pollution (HT, ET); Energy; Carbon footprint; Resources (Raw)
Business models				
Fargnoli, 2018 [71]	Implementation of a product-service system business model for haemodialysis equipment	Dev (Hosp)	Dir (Prod, Use, EoL)	Waste (Ref, Reu)
Haber, 2021 [72]	Implementation of a product-service system business model for molecular diagnosis equipment	Dev (Hosp)	Dir (EoL)	Waste (Rec, Ref, Reu)
Guzzo, 2020 [70]	Review of circular business models in the medical device industry	Dev (Hosp)	Dir (Use, EoL)	Waste (Rec, Ref, Reu); Pollution (ET); Energy; Resources
Zlamparet, 2018 [73]	Evaluation of upgrade and remanufacturing business model for used electronic products	Dev (Hosp)	Dir (EoL)	Waste (Rec, Reu); Energy; Carbon footprint; Resources (Raw)
Ahluwalia, 2022 [22]	Environmental impact assessment of open-source medical devices	Dev (Hosp)	Dir (Prod, Use, EoL)	Waste (Rec, Ref, Reu); Carbon footprint; Resources (Raw)

Table A1: List of articles (continued)

Reference	Description	Scope	Level	Indicator
Top-down healthcare system assessment				
Sherman, 2020 [75]	Review of environmental sustainability research in the healthcare sector	Dev (Hosp); Syst	Dir (Prod, Use, EoL)	Waste (Rec, Ref, Reu); Pollution (HT, ET); Carbon footprint
NHS, 2020 [20]	Decarbonization propositions for the English National Health Service	Syst	Dir (Prod, Use, EoL); Ind (Travel)	Waste (Ref, Reu); Energy; Carbon footprint
Shift Project, 2021 [17]	Decarbonization propositions for the French healthcare sector	Syst	Dir (Prod, Use, EoL); Ind (Travel, Obs, Reb)	Waste (Rec, Reu); Energy; Carbon footprint; Resources (Water)
Di Giacomo, 2011 [16]	Assessment of carbon emission reduction in eHealth applications	Syst (TM, eH)	Dir (Prod, Use); Ind (Travel)	Waste (Rec, Reu); Pollution (ET); Carbon footprint
Holmner, 2012 [15]	Review of climate change mitigation and adaptation eHealth strategies in the healthcare sector	Syst (eH)	Dir (Prod, Use, EoL)	Energy, Carbon footprint; Resources
Stakeholders environmental considerations				
Ordway, 2018 [78]	Interviews of healthcare staff regarding opportunities for reuse and recycling of medical equipment	Dev	Dir (EoL)	Energy; Carbon footprint
Moultrie, 2015 [77]	Interviews of medical device designers regarding eco-design	Dev	Dir (Prod, Use, EoL)	Waste; Pollution (HT, ET)
Other				
Cosgrove, 2018 [79]	Evaluation of energy savings in medical device production facilities	Dev	Dir (Prod)	Energy
Alshqaqeeq, 2020 [80]	Review of GHG emission reduction alternatives for medical services and equipments	Dev (Hosp); Syst (TM)	Dir (Prod, Use, EoL); Ind (Travel)	Carbon footprint
McGain, 2012 [81]	Analysis of environmental sustainability improvement opportunities in paediatric cath lab and operating room	Dev (Hosp);	Dir (Prod, Use, EoL)	Waste (Rec, Reu); Pollution (HT); Energy; Carbon footprint; Resources (Raw, Water)

Dev: Device - Hosp: Hospital - Wear: Wearable - Comp: Component - EH: Energy harvesting - Sens: Sensor - Disp: Display - Flex: Flexible substrate - Supp: Power supply - Mem: Memories - Act: Actuator - Syst: System - TM: Telemedicine - eH: eHealth

Dir: Direct impacts - Prod: Production - Use: Use phase - EoL: End of life - Ind: Indirect impacts - Travel: Travel reduction - Opti: Care optimization - Obs: Obsolescence - Reb: Rebound effects

Rec: Recycling - Ref: Refurbishing - Reu: Reusing - Bio: Biodegradability - OD: Ozone depletion - PM: Particulate matter - HT: Human toxicity - ET: Ecotoxicity - RP: Radioactive pollution - Raw: Raw material