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Searching for Sustainability in Health Systems: Toward a Multidisciplinary Evaluation of Mobile Health Innovations

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Abstract: Mobile health (mHealth) innovations are considered by governments as game changers toward more sustainable health systems. The existing literature focuses on the clinical aspects of mHealth but lacks an integrated framework on its sustainability. The foundational idea for this paper is to include disciplinary complementarities into a multi-dimensional vision to evaluate the non-clinical aspects of mHealth innovations. We performed a targeted literature review to find how the sustainability of mHealth innovations was appraised in each discipline. We found that each discipline considers a different outcome of interest and adopts different time horizons and perspectives for the evaluation. This article reflects on how the sustainability of mHealth innovation can be assessed at both the level of the device itself as well as the level of the health system. We identify some of the challenges ahead of researchers working on mobile health innovations in contributing to shaping a more sustainable health system.

Keywords: mobile health; sustainable health system; health technology assessment; life-cycle assessment; eco-design; transformative innovation

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1. Introduction

Mobile health (mHealth) is defined as a "medical and public health practice supported by mobile devices, such as mobile phones, patient monitoring devices, personal digital assistants, and other wireless devices" [1] (p. 14). Mobile health relies on information and communication technology. Apps, smart watches, glasses and activity trackers are purely wearable and wireless electronic devices composed of a set of sensors (sometimes integrated into fibers, textiles or garments) for acquiring and measuring body information and signals for health monitoring and diagnosis, used for sending messages to clinicians when emergency situations are detected [2,3]. A wearable medical device typically consists of three blocks: (i) a sensor or a sensor array to sense vital signals or some biomarkers, (ii) a rigid read-out (and communication) platform and (iii) a power source. A reliable energy source is essential for portable medical applications, either a battery or a supercapacitor. In more advanced settings, additional energy harvesters can ensure an autonomous operation of the device (Dahiya et al., 2019). Mobile health is also characterized by its means as it is thought to improve the quality of healthcare as well as the quality of life of patients through more personalized individual-centered care, to empower patients and enable them to self-manage their condition [2]. Given the context of rapid aging and a shrinking workforce, especially in Western contexts [4,5], technology supporting (elderly) care and health from a distance constitutes an asset for patients in need of complex care wanting to stay at home [6]. Despite the fear of care "turning cold" with the elderly surrounded by technology instead of caring people [7], the overall evaluation of mobile health (mHealth) reflects an attitude of optimism. It raises hope for increasing efficiency measured through the optimization of resources (in terms of reducing costs and improving the use of the workforce capacity) and indirect benefits from more appropriate care [8]. Furthermore, the Internet-of-Medical-Things (IoMT) revolution adapted for the medical sector has supported research into developing mHealth and many other wearable devices to facilitate the patient–doctor communication on one side and offer personalized healthcare solutions on the other side. Research efforts have been allocated to develop wearable devices embedded into clothing, wrist bands and electronic skin [9]. Additionally, the pandemic setting has promoted the benefits of the IoMT in orthopedics [10] and as a point-of-care for infectious diseases [11]. With recent virus outbreaks, innovations in mHealth have gained momentum and are seen as a major instrument for enhancing sustainability in health systems [3,12].

Current mHealth evaluations measured in terms of the quality of care or impact on health and cost savings mainly focus on clinical efficacy and often neglect other relevant dimensions of sustainability, namely those where social and environmental issues are at stake [11,13]. The healthcare sector itself generates a significant environment burden, including greenhouse-gas (GHG) emissions and plastic and pharmaceutical waste, which in turn have effects on people's health [11,14,15]. This sector is responsible for up to 4.6% of the global GHG emissions emerging directly from healthcare facilities and indirectly from the global supply chains feeding the health sector [16,17]. For example, GHG emissions in the US healthcare sector are estimated to cause 123,000 to 381,000 disability adjusted-life years (DALYs) annually [18,19]. Additionally, fine particles, especially particle matters, are responsible for the loss of 405,000 DALYs per year in the US and 14,700 DALYs per year in Canada [20]. To truly improve healthcare while addressing the finite nature of resources as well as targets of reduced GHG emission and waste in general [11,21], mHealth innovations should substantially differ from mainstream (technical and product-driven) innovations [13]. Accordingly, the evaluation of mHealth innovations should be sensitive to these multidimensional challenges, look beyond the clinical efficiency and assess their potential to be cost saving. To date, very few authors have investigated these issues. The question if and to what extent current mHealth innovations are positioning care and health systems on a more sustainable trajectory has never been addressed, and the dimensions that define sustainable mHealth innovations remain unclear [22]. An in-depth understanding and evaluation of the sustainability of m-Health innovations is essential to unleash their ability to provide a systemic solution for charting a sustainable path forward.

This paper reflects on the evaluation of mHealth solutions, primarily targeting their sustainability. We follow the definition of sustainability as proposed by the World Commission on Environment and Development, according to which sustainability is seen as "*meeting the needs of the present without compromising the ability of future generation to meet their own needs*" [23] and "*entails protection of the environment and natural resources as well as to provide social and economic welfare to the present and to subsequent generations*" [24]. Therefore, sustainability rests on three components: social, economic and environmental. In the mHealth sector, this translates into assessing the social, economic and environmental effects of mHealth innovations. The cost-effectiveness of these innovations is assessed through Health Economics (HE). Since the environmental effects are technology-related, an Information and Communication Technology (ICT) perspective is introduced to evaluate the environmental footprint through life-cycle analysis. Additionally, a human–computer interaction (HCI) perspective allows to bridge the gap between technology and social aspects encompassing the long-term behaviors and attitudes of end-users (i.e., patients and/or caregivers). Finally, a transformative social innovation (TSI) perspective that connects innovation to systemic change facilitates a global sustainability assessment. This paper examines these four specific dimensions of mHealth innovations within a multi-disciplinary dialogue. We first pin down the meaning of sustainability in each of these disciplines' perspectives using a targeted literature review. We then provocatively discuss how the current discipline-specific evaluations are limited and do not individually grasp the essence of sustainable transitions in health systems. The paper takes the first step toward a more holistic evaluative framework that considers sustainability in mHealth through a multidimensional perspective.

2. Positioning the Problem

Digitalization is part of the EU's Green Deal [25]. It is thought to improve the potential of policies to deal with climate change and to better monitor and optimize the use of resources [26]. Even if the EU and national governments tend to praise digitalization as part of a cleaner and greener economy, it is not clear whether it is a real driver for sustainability. Digitalization is often described as reducing the environmental impact of current healthcare pathways through a reduction in greenhouse gas emissions while circumventing aging costs and the shortage in workers [5]. However, the EU itself stresses the overall risk that digital technologies pose on the environment. As for mHealth, the current literature tends "to oversell" its sustainability potential [27,28]. Beyond the clinical interest and the benefits associated with access to information, the production of mHealth devices and the related data center activity and networks engage with resource depletion (land, water, biodiversity) and have direct and indirect environmental impacts [26]. For example, mHealth (wearable) devices "*embedded in non-ICT products (in this case: textiles) create difficulties for local waste management processes and often require specific recycling procedures*" [26]. Not only are environmental issues associated with the production and use of mHealth but social issues are as well. Mobile health encompasses different stakeholders, such as direct users (patients, professional and informal carers), caregivers, producers, as well as decision makers. Weak stakeholders among them, such as patients or informal caregivers, are not part of the decision or evaluation process for using new technologies, making it difficult for them to envision the real benefit brought by mHealth and for whom [7]. Production processes (including workers' own health and well-being), business models (including modes of governance and ownership) and the way producers deal with their externalities remain largely unquestioned: "*Successful enterprise is the basis for implementation, not public consideration of what defines good care or a good life for individual patients, not knowledge about the workings of telecare*." [7]. Yet, mHealth innovations are linked to surveillance technologies targeting the cared-for with consequences for caregivers whose consent is overlooked [29]. Other ethic-related problems such as breaches of privacy, iatrogenesis, disinformation and misinformation, or "fake news", and cyber-attacks are insufficiently considered [30]. These can have unintended environmental effects, such as lowering the interest for existing technologies and accelerating their obsolescence. Similarly, problems of equity of access should be considered: the use of mHealth tools requires an ease of use of the technology or internet access and stakeholders that do not always have the appropriate level of technological literacy to use them. At present, the literature helps list the pros and cons but lacks an assessment framework on mHealth sustainability and the role of digital health technologies in enhancing health systems' sustainability.

Measuring sustainability at the level of technological devices differs from looking at systems, structures or devices as they have different scales and objectives [31]. A sustainable health system is defined as a "*system (that) improves, maintains or restores health, while minimizing negative impacts on the environment and leveraging opportunities to restore and improve it, to the benefit of the health and well-being of current and future generations*" [32]. A sustainable structure "*is a structure that can be easily maintained and that can be functional from the environmental, social and economic point of view, in order to comply with the diverse interests and needs of all the stakeholders*" [31]. At present, no definition is available for mHealth sustainability at the level of a device. As a trigger, we will endorse the following definition: "*the ability to meet current needs without compromising the ability of future generations* *to meet their own needs*" [8]. Sustainability reconciles economical, societal and environmental dimensions and involves an ethical responsibility regarding humans and nature [33]. There is a need to rethink evaluation practices of mHealth innovation toward multidimensional sustainability to provide health policy makers with clear directions. That means, in the first place, to advance our understanding of mHealth and its many stakeholders and consider case studies in accordance with what is considered sustainable at the various stages of production, distribution, usage and end-of-life. It also means looking under which conditions we can improve the way mHealth innovations are evaluated in terms of environmental and social or ethical sustainability. Yet, few researchers on mHealth have identified the issue of sustainability. Therefore, other research fields and disciplines where sustainability issues are core can bring new insights. There is an interest in putting these approaches together and adopting a multidisciplinary perspective.

3. Methodology

This article is part of a research process that started in 2019. Each author was interested in sustainability within health systems issues and felt they detained sparse knowledge to assess transition processes toward sustainability in the health sector. Prior to the research collaboration, the team initiated a dialogue in successive steps. Aware of epistemological differences, the team started at a basic level and built a common research environment sharing their respective definitions of the meaning of sustainability. This led to compare theorization levels (micro/meso/macro, individual/societal) and identify common ground and specialism. To strengthen reciprocal understanding, an exercise was planned where each disciplinary approach was considered to analyze three mobile health devices (namely an electronic thermometer, a connected pill-distributor and an interactive robot) and was subsequently challenged by the other disciplines. To produce a robust multidisciplinary approach, methodological tools were shared and discussed to identify which respective disciplinary perspective could best occur at what stage of the research process. A targeted literature review (TLR) on sustainable mHealth assessment followed these initial steps where relevant papers were identified within each of the respective four disciplines, namely HE, ICT, IHM and TSI.

We chose to run a TLR because: (1) translating our multidimensional perspective into a single inclusive query was complicated, if not impossible; (2) the set of relevant references obtained through TLR was quite limited and stemmed from a knowledgeable selection of high-quality, easy-to-identify references, as opposed to an all-encompassing list of irrelevant references; (3) a TLR allowed us to keep only the references maximizing rigorousness while minimizing selection bias; (4) a TLR was better suited at describing and understanding sustainability in each discipline separately.

The flow diagrams in Figure 1 depict the TLR process for each discipline. We used a set of independent queries, several per discipline and tailored to the respective disciplines (see Table A1 Appendix A). We performed the searches in June 2021 on the following databases: Google Scholar, PubMed, Scopus and Isidor and the Connected Papers research tool. We then analyzed papers by screening their title and abstract. In total, 66 were included.

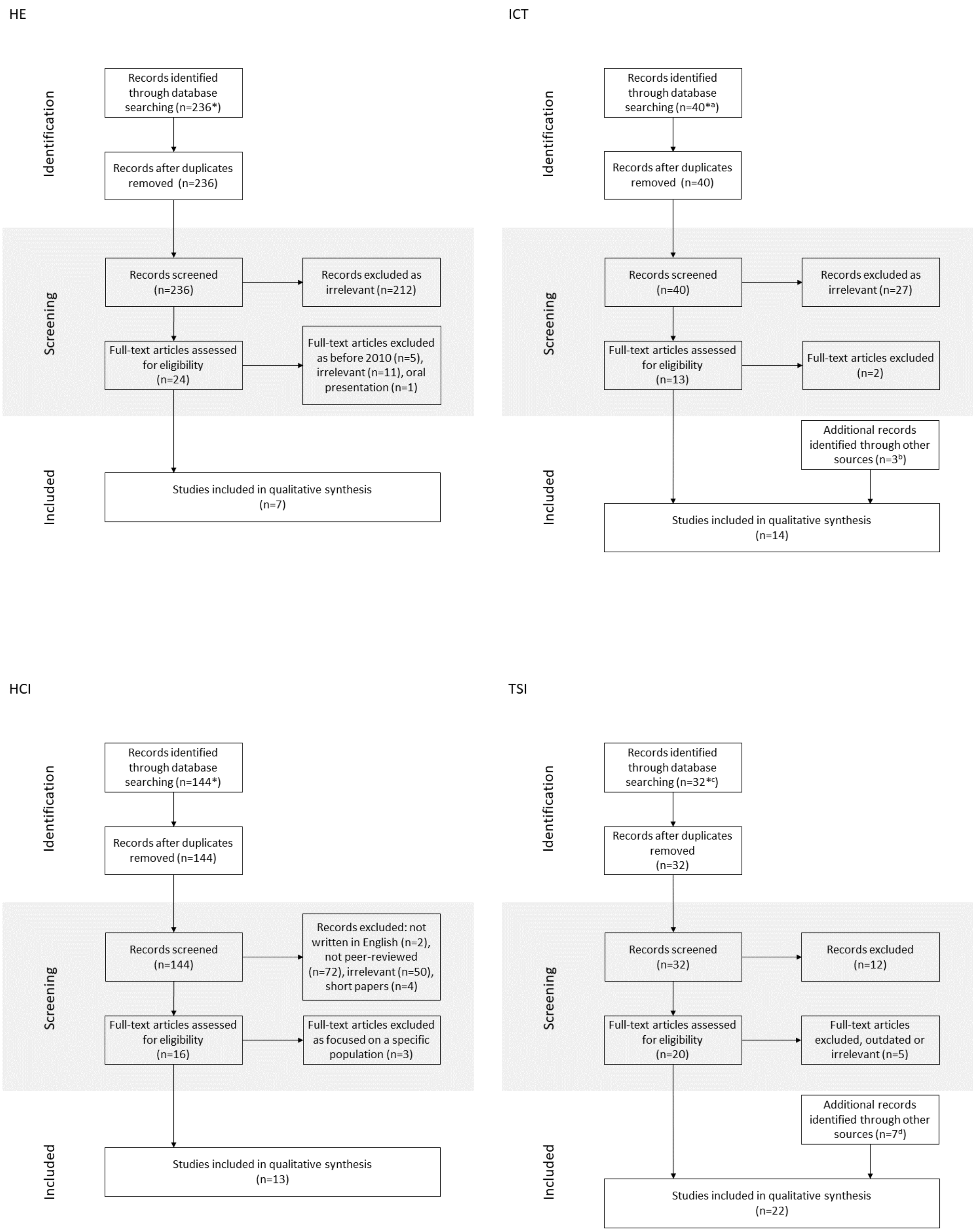

Figure 1. Flow diagrams describing the TLR process for each discipline. * indicates records identified based on the queries presented in Table A1. ICT: ([a]) inclusion of journals articles in English covering ICT (computer science, engineering, material science . . .); ([b]) exclusion of articles that do not comply with selection criteria but are relevant to the discussion. TSI: ([c]) inclusion of papers in English and French as TSI literature is well developed both in Québec and France and use of the connected papers tool for relevant papers (n = 4); ([d]) inclusion of research reports, EU policy and local government's strategy papers on health-related social innovations.

4. A Multidisciplinary Evaluation of the Sustainability of mHealth

In this section, we discuss how the four previously identified disciplines offer resources to evaluate mHealth beyond purely medical and financial viewpoints. We summarize the sustainability dimension in each of the disciplines with the aim to emphasize their complementarity and enhance their potential to provide a broader vision of the sustainability of mHealth.

4.1. Economic Sustainability

The cost-effectiveness analysis is the gold standard to guide healthcare resource allocation. A health technology assessment (HTA) is a long- and well-established framework that jointly evaluates the effects, benefits, impacts of innovative healthcare technologies or interventions along with their costs and impact on the healthcare budget. An HTA supports decision makers to ensure the best health technologies are provided to patients within the healthcare system and is extensively used in national health authorities (e.g., the UK NICE, the French HAS, the Belgium KCE, etc.). So far, mHealth interventions appear to be cost-saving and efficient solutions for the healthcare system; however, it is increasingly required to undertake a comparative economic evaluation of mHealth strategies in comparison with standard strategies to help the uptake and large-scale adoption of such health innovations within the healthcare systems [34]. Yet, "*guidance does not exist on which analytic approaches are most appropriate*" for the evaluation of mHealth tools and as such they are not appropriately evaluated [35] (p. 2), [36]. Economic evaluation distinguishes cost-effectiveness analyses (CEA) which "*generate evidence on which programs represent the best value for money*" from the cost-benefit analyses (CBA) or return on investment studies used "*to demonstrate affordability and estimate resource requirements for scale-up and sustainability*" [35] (p. 13). The choice of the proper economic evaluation method depends on the targeted outcome measures (i.e., survival gains, quality of life gains, quality-adjusted life years (QALYs), usability, prevention of events or costs savings) as well as on the aim of mHealth and the stage of development. CEAs seemed to be the most commonly used tool to undertake an economic evaluation and are also relevant to assess mHealth technologies [34,35,37,38].

There are different frameworks available to assess mHealth technologies from a health economic perspective. An HTA of a healthcare device usually assesses effectiveness and costs; however, mHealth technology also requires assessing other dimensions, such as clinical safety, data protection, security, usability and accessibility, interoperability and technical stability [37,39]. Evaluating the cost-effectiveness of mHealth technologies may also differ according to whose perspective is considered (individual or organizational) or whether the mHealth service is evaluated at a specific life-cycles phase (development, implementation, etc.) [38]. The cost-effectiveness of mHealth is often limited to evaluating the economic viability and business models for mHealth more than the health outcomes themselves [38].

However, since mHealth technologies are characterized as complex interventions in a complex system, they can have an impact on dimensions beyond the users themselves. For example, a few studies conducted an economic evaluation including the impacts of the mHealth technologies beyond the users themselves (e.g., caregivers, family members) or beyond the health sector (e.g., the education or labor sectors) [36–38,40]. Still, the standard HTA evaluation frameworks do not mention whether and how the environmental impacts should be considered. An explanation to this oversight is that pollution is generally ignored because it does not have a market value and the "*lack of means and metrics available to support sustainability as an important component in the delivery of health-related services (that) is currently the main constraint*" [8] (p. 106).

4.2. Environmental Sustainability

An environmental footprint assessment is a key aspect of sustainability, but for many reasons, it is difficult to apply to mHealth devices. From a technical standpoint, wearable and mHealth devices have many restrictions due to their portability requirements. These restrictions include constraints related to physical dimensions, size, shape, appearance, materials, weight and biocompatibility which impose specific design and technical specifications. In responding to these requirements, most studies devoted to ICT have considered sustainability mostly from an environment-centered angle. It is noteworthy that this sector has been slow to adopt sustainability principles or embed sustainable practices in their operations [41].

Among the tools that support sustainable design, life-cycle assessment (LCA) emerges as the most comprehensive tool to assess the environmental credentials of the device across its life cycle. This standardized framework, included in the ISO 14040, evaluates the "*environmental aspects and potential impacts throughout a product's life cycle (i.e., cradle-to-grave) from raw materials acquisition through production, use and disposal*" [42]. While not particularly developed for the medical sector, the LCA methodology is backed by a rich literature stream and provides quantitative estimations of environmental and social impacts for a specific product configuration, assuming access to reliable data. The LCA works by comparison and has already been used in the medical sector to compare the effects of single-use vs. reprocessed medical devices [43] or how to make sure we reap the benefits of bioplastics when replacing petroleum-based medical plastics [44].

Identified barriers to implementing more widely environment-conscious design in the medical industry include increased design time and cost, a higher priority to other design factors, a lack of demand, legal regulations and inappropriate business models [41]. Additionally, like all the electronic devices, the LCA of mHealth devices also suffers from the lack of reliable data inventory from the outsourced manufacturing or the (hidden) actors involved in the global supply chain. Furthermore, skin-worn devices require biocompatible materials and may necessitate the adoption of complex manufacturing techniques to render the device flexible or stretchable [45,46]. Those non-conventional electronic materials are particularly problematic because their complex manufacturing and end-of-life treatment may add significant environmental impacts, while further amplifying the lack of data for the LCA.

To overcome those limitations, design tools and frameworks have been proposed to help the innovators adopt a holistic perspective on their medical product life cycle and expose the complex trade-offs and their impacts at the life-cycle stages. Eco-design, for example, offers a simpler framework that can help define a slow, material flow loop that includes material scarcity, promotes the reduction in the material range and associations, additive manufacturing techniques and avoids energy-intensive processing [41]. It also refers to the end-of-life phases, including the disassembling facility, recycling potential and toxicity of the transformation processes. Furthermore, the environmental burden of electronic waste should require special end-of-life considerations to facilitate the disposal of the device. To some extent, biodegradable electronics [47] can reduce electronic waste generation but they are still in their infancy at this point to consider them a viable solution.

Beyond the life-cycle impacts covered by the LCA, mHealth devices may have indirect effects on the environment. According to the Life cycle, Enabling, Structural framework (LES) [48], indirect effects are enabling impacts that are induced using ICT equipment. These effects happening at the micro-level can be positive, such as optimization and substitution of resources, or negative, such as obsolescence mechanisms. The indirect impacts of a single innovation are much more difficult to analyze as they require looking at the whole system. The few studies that have tackled those issues have mainly focused on positive impacts, such as the reduction in emissions linked to tele-medicine due to reduced transportation [49]. It is interesting to note here that the LES framework also includes macro changes at a structural level that need to be looked at from a multidisciplinary perspective.

Many papers have worked on frameworks to include sustainability in the design process of devices, some of them specifically targeting medical devices. However, there is still a divide between papers helping with the design process and papers undertaking an impact assessment of the devices. There are two main dimensions regarding the environmental impact assessment with the LCA. On the one hand, the LCA is a quantitative and detailed tool but time-consuming and therefore not the most useful during the design phase. On the other hand, design guidelines are far more qualitative but easier to follow at the very beginning of the design stage. Regarding mHealth, some recent works tried to tackle the quantification of environmental impacts due to the introduction of electronics, e.g., cardiac monitoring, smart wearables, etc. Nevertheless, the literature on LCAs for wearable electronics is very limited. Data access and expertise with the LCA for electronics is often the main bottleneck. Mobile health and smart wearables make extensive use of unconventional electronics, such as flexible and stretchable electronics. However, this is very poorly covered by the current LCA, and consequently, prospective evaluations are not straightforward.

4.3. Behavioral Sustainability

Sustainability within an HCI faces the dilemma to have to propose an HCI-made definition of sustainability and to broaden its contribution outside an HCI. Despite the interest aroused by this young discipline, there is, to the best of our knowledge, no standardized framework, method nor tool within an HCI to evaluate the sustainability of technologies or projects. The earliest acknowledged advances related to sustainability in an HCI date from the 2007 conference on human factors in computing systems [50]. Blevis (2007) argued that "*sustainability can and should be a central focus of interaction design–a perspective that* [he called] *sustainable interaction design (SID)*" [51] (p. 503). Meanwhile, Mankoff et al. (2007) organized a sustainable HCI (SHCI), a special interest group aimed to raise awareness of sustainability in an HCI [52]. These breakthroughs led to the growth of the field, although the community rapidly faced a lack of consensus while attempting to define, scope and broaden an SHCI [53]. The closest the community has come to a consensus is a publication resulting from a CHI 2014 workshop on an SHCI, which urged the community to engage in sustainability-oriented work outside an HCI and move beyond simplistic silo models to address sustainability issues [54]. While there is still a disagreement as to whether an SHCI is a process or an endpoint [55], the community rapidly acknowledged the need for a holistic, multidisciplinary approach to assess technologies. For example, Dillahunt et al. (2010) framed a checklist of sustainability criteria, such as "use of alternative energy", "all materials can be replaced", "all materials are reusable" or "device is recyclable" [56]. Further, Dillahunt (2014) proposed to integrate environmental, social and economic sustainability into technology assessments [57]. Likewise, Remy et al. (2017) urged the HCI community to broaden its evaluation methods to other disciplines to demonstrate why a specific technology sustainably works in the real world [58]. In addition, Remy et al. (2018) elicited five key elements that can provide guidance to conduct evaluations for (S)HCI research: goal, mechanics, metrics, methods and scope [53]. The goals of a given evaluation are achieved through the choice of mechanisms, metrics, method and scope. The authors did not enumerate any specific metrics or methods. Rather, they highlighted potential assessment constructs such as quantifiable amounts of resources, practices of people affected by the artefact and long-term impact or behavior change. They also recommended using life-cycle assessment (LCA) data as a starting point to build a reliable repository or database for SHCI metrics. An LCA provides a range of environmental metrics regarding the entire life cycle of a product. Finally, Lundström and Pargman (2017) proposed a taxonomy for classifying computing projects as sustainable or unsustainable ones by assessing three dimensions of sustainability, namely the credibility of intentions, impact of the project and likelihood of the impact [59]. The authors also pointed out that any assessment depends on judgement calls (e.g., the definition of system boundaries) and argued for a specific method for assessing each dimension.

The landscape of an SHCI is contrasted and extensive, ranging from persuasive technologies to sustainable interaction design. For example, Mankoff et al. (2007) distinguish contributions to sustainability in design, which consists of including environmental sustainability considerations (e.g., energy footprint) into the material design of products, from contributions to sustainability through design, which consists of supporting sustainable lifestyles and decision making through technologies [52]. DiSalvo et al. (2010) break down the SHCI into five genres: (1) persuasive technologies, which attempt to convince users to behave more sustainably; (2) ambient awareness, which intends to make users aware of the sustainability of their behavior; (3) sustainable interaction design, which refers sustainability to rethink the role and outcomes of design; (4) formative user studies, which aim to understand users' attitudes to the environment; and (5) pervasive and participatory sensing, which uses sensors to monitor and report on environmental conditions, with the implicit goal of using the data collected to change these conditions [60]. Attempts to convince users to behave more sustainably have long been the focus of most publications within an SHCI [27,60].

We argue that an HCI can mostly contribute to mHealth technologies for behavior change by involving patients and caregivers in the design process and by supporting the integration of usability, technology adoption and behavior change in the evaluation process of such systems. Usability, technology adoption and behavior change have all been identified as key success factors of mHealth technologies [27,61–63]. Yet, only a few works measure mHealth usability [64]; definitions and measurements of technology acceptability, acceptance or adoption of mHealth technology lack consistency and standardization [63] and evaluations hardly ever assess behavior change rigorously [27]. We explain this lack of publications as follows. Evaluating mHealth technologies for behavior change is resource-intensive, spreads over a long period of time and requires a functional mHealth system [65]. These constraints comply neither with academic publication requirements [54] nor with eligibility criteria established by the funders of research projects. In addition, while behavior change seems to be acknowledged as a relevant construct of the sustainability of mHealth systems, its measurement is still a work in progress. Among the few publications dealing with behavior change within an HCI that we identified, only one proposes to use engagement as a measure for behavior change [66]; the other three deal with usability [64,65] or adoption [63]. However, designers and developers define what engagement means. A similar problem arises when designers and developers define what (un)sustainable behavior entails [58].

4.4. Social Sustainability

Social innovations (SIs) are context-specific innovations that occur at the level of social relations using specific new technologies, embedded in services or products. They shape social sustainability through answering needs that are presently unmet, enhancing democratic governance and improving work relations and/or work organization. [67,68]. SIs are also increasingly considered in ecological terms to reduce waste and resource intensity while transforming existing practices or production processes toward low-carbon societies [69,70]. Mehmood et al. [71] have drawn two guiding principles for environmentally sustainable SIs: (i) to find socially innovative solutions to environmental problems and (ii) to follow a social innovation approach to the governance of sustainable development so that institutional arrangements facilitate participation and engagement of social groups that are usually left out of the solution-finding process. The EU considers social enterprises (SEs) as the "natural vector" for sustainability transitions [72]. SEs are suited to boost sustainability innovations in society as their missions are aligned with societal challenges and follow bottom-up dynamics [73]. The specific organizational set-up (participative and democratic governance) of SIs emerging from SEs enables them to address the social bottom-line of sustainable development [71] as well as to involve multiple stakeholders [73]. Lately, reflections on SIs from a sustainable transitions studies' approach (STS) [74,75] have contributed to better envision the challenges of SIs regarding their transformative potential within bigger socio-technical systems. The STS is interested in system innovations, i.e., innovations that are radical in relation to the dominant socio-technical system. The changes involved do not only concern technology but also science, market, politics, culture, etc., and refer to a multitude of actors. Transformative SIs [70,76] are then innovations that bring about systemic change in incumbent regimes (agro-food, transports, energy or health) in terms of social relations, rules and directionality. Transformative SIs put systems on a more sustainable path and empower actors that intend to do so. In this perspective, they are inclusive solutions to address inequalities in healthcare delivery that meet the needs of end-users through a multi-stakeholder and community-engaged process. Alongside low-cost technologies, collaborative learning empowering patients [77], SIs addressing health literacy problems through on-line education, peer-support, etc., [78] or healthy buildings [79] can have systemic impacts. In this transformative perspective, sustainable mHealth-related innovations compensate for economic shocks and failures in the welfare state, respond to increasing social inequities and also bring structural reforms in health policies [80,81]. To gain substantial sustainability, Lehoux et al. (2016) suggest that the 4A scheme of the WHO (availability, accessibility, appropriateness, affordability) serves as a direction for future innovations [82]. Principles of subsidiarity (innovations that enable the most decentralized unit in the system—the patient or the primary carer—to provide the service), self-care (innovations that extend patients' capacity for self-care) and reduced labour-intensity (innovations that simultaneously improve outcomes and reduce labour intensity) should also be encouraged. The degree of institutionalization of mHealth innovations (in terms of funding, supporting legislation, etc.) as well as their number are considered key for transformation: neither of them is the solution, it is their collaboration and incorporation into the (sustainable) "fabric of society" that matter [83].

5. Discussion: Toward a Broader Vision on mHealth's Sustainability

Going beyond safety in functioning, effectiveness and costs when evaluating the potentials of healthcare solutions such as mHealth is not a simple task [84]. We advocate that a first step toward a broader evaluation of the sustainability in mHealth systems is to initiate a multidisciplinary dialogue. We inaugurate this dialogue relying on the four relevant disciplines we identified to be major when dealing with the sustainability of mHealth innovations. This section shows how these four disciplines complete each other in terms of gold standard, scope and time horizon of the sustainability assessment and how their complementarity sheds light on yet unsolved challenges related to the assessment of the sustainability of mHealth innovations.

5.1. What Does Each Discipline Bring to Each Other's Perspective on Sustainability?

The key dimensions considered by the four disciplines are summarized in Table 1. Each discipline does not focus on the same outcome of interest nor use the same time horizon and perspective for the evaluation and, hence, has different gold standards.

Table 1. Sustainability assessment of mobile health in the four approaches.

Discipline	Gold Standard	Scope	Time Horizon
Health Economics (HE)	QALYs, a generic measure of health gains, combining the quality and the quantity of life gained	Individual	Short/Long term
Information and Communication Technology (ICT)	Environmental footprint	Device	Short term
Human–Computer Interaction (HCI)	Usability, technology acceptance, behaviour change	Individual or group of individuals	Short/Long term
Transformative Social Innovations (TSI)	Systemic change	Social	Long term

HE has developed techniques to perform health technology assessments but discards environmental issues and potential long-term health and monetary benefits beyond patients' health status. So, while environmental sustainability issues remain out of the scope of the process that leads to the validation of mHealth innovations using an HTA, the environmental footprint of any mobile device is an objective of life-cycle assessments. However, such an assessment offers no insight on if and how patients use devices or on their social agency. While the LCA focuses on environmental issues, it does not investigate variables that are involved in social sustainability, namely long-term use and meeting the unmet social needs of patients. An HCI proposes to evaluate mHealth technologies beyond usability and technology acceptance and for this purpose focuses on users' behavior change but not on systemic change through innovations. The transformative social innovation approach highlights how mHealth tackles social issues and connects innovation to the perspective of systemic change.

These are a few examples as to how a dialogue between the four disciplines can function and bring up useful complementarities. In the next section, we will briefly illustrate how these complementarities help better envision the sustainability challenges of mHealth innovations at the level of their construction and at a more systemic level.

5.2. Assessing Sustainability in the Health Sector: Challenges and Proposed Solutions from a Digital Innovation Point of View

Challenge 1: As it is important to evaluate whether mHealth contributes to the overarching goals of a sustainable health system in an optimal way, assessments should be performed at both the level of the digital health device that is being delivered and at the health system's level itself [85]. In other words, both intrinsic and systemic sustainability are at stake. **Proposed solution:** We suggest that a combination of the perspectives of the previous four disciplines would allow a broader evaluation of the sustainability of mHealth innovations that equally assess their design and the benefits and changes they bring into the medical sector.

Challenge 2: At the level of the device itself, and from a construction viewpoint, sustainable technologies may be embroiled in environmental and humanitarian conflicts (BBC: future, 2015. http://www.bbc.com/future/story/20150402-the-worst-place-on-earth, accessed on 29 December 2021) [86] and, as such, be recognized as a threat to sustainable development (https://master-iesc-angers.com/le-transfert-technologique-une-force-du-modele-israelien/, accessed on 29 December 2021). It is not clear at what point of the innovation process material choices become locked-in and hence more difficult to reverse. Such understanding would be vital for a timely identification of the sustainability challenge associated with the use of certain materials in emerging technologies and the development of ethical and responsible research and innovation [87,88]. The socio-economic models chosen for producing or running mHealth devices (for example, for-profit or not-for-profit) is also a construction issue: how do those models engage with ownership structure and internal governance; how do they address the issue of work and well-being? **Proposed solution:** The construction process of mHealth innovations could gain from being confronted by the notion of "good care" [7] which comes with diversity in definition but brings the issues of users to the forefront. It is not clear what role users (be it the cared-for or carers) can play in the construction process of mHealth innovations but they might bring in the necessary vision on what practices are transferable into technology and whether existing practices lose or gain from the technology transfer.

Challenge 3: The design of mHealth innovations as well as their usability and scalability require a systemic perspective to capture and assess the associated externalities to contribute to sustainable health systems as "*the driving force for pursuing environmental sustainability in health systems stems from a recognition of the synergies that exist between health and environmental sustainability*" [32] (p. 1). An important challenge relates to the identification and measurements of the multi-level benefits that come with fostering sustainability in health systems. Decisions to adopt innovative mHealth devices are ideally based on evidence. A large set of outcomes at different levels can be considered; this includes performance and efficiency but also health and quality of life gains. The attainment of these broad health system goals are objectives against which to judge new digital health services [85]. Nevertheless, we lack unique and agreed metrics on how to measure each of those outcomes and we are unable to aggregate them on comparable grounds. **Proposed solution:** In addition to a measurement consensus, one may suggest that some outcomes may matter more than others for the health system goals and therefore we may need to weight outcomes according to their relevance for the general sustainability of the system.

6. Conclusions

Due to its critical nature, the medical sector is known for its high innovation rate and, consequently, a short life span for devices, which in turn contributes greatly to what is already a huge environmental-burden sector. Following the call "*for a concerted European response to maximize the benefits of the digital revolution while minimizing the harms, arguably one of the greatest challenges facing the public health community today*" [88] (p. 1), this article offers a multidisciplinary vision of the sustainability issues underlying mHealth innovations. Sustainability in mHealth solutions taken as a synergistic contribution between social, environmental and technical forces is timely with the call for a greener healthcare system and focus on sustainable development goals [30,89]. We argue that if we want to put the medical sector on a more sustainable path, we need to include and consider within the decision-making process both the direct and indirect effects of digital medical products, whether they are social or environmental. Such a multidisciplinary dialogue to foster sustainability transitions remains fragile. It must go beyond an "add disciplines and stir" perspective and this is what we attempted in this paper. To the best of our knowledge, there exists no published work that addresses sustainability from a similar multidisciplinary perspective.

The relatively unprecedented characteristics of contemporary social change from a historical viewpoint and the irreversibility of certain environmental and inequality problems have mobilized the authors of the article in what they feel is an urgent matter. The paper takes the hypothesis that sustainability transitions could and should occur in the health sector. Yet, there is still no consensus. Instead, there are many barriers to including more stringent sustainability considerations for medical devices. It is an industry that is largely regulated with a strong emphasis on safety, efficiency and hygiene. Sustainability, when considered, is considered as a last step (often too late). Some initiatives were started to include it in the global strategies (e.g., carbon-free NHS), but it is still a bit blurry and often remains limited to individual initiatives or company strategy, and thus they are far from global. Some environment-related regulations exist for devices, as with any other product (electronic waste regulations, use of toxic materials, etc.). Though, medical devices can sometimes be exempted from them—for justified reasons—when it is necessary to perform their function.

Our approach presents some limitations. First, our dialogue considered four disciplines that were brought together by an opportunistic context, and we are aware that we could have included additional disciplines, such as physics, philosophy or ethics, also relevant to sustainability.

Second, the paper does not rely on a systematic review nor a meta-analysis. Our targeted literature review does not provide an exhaustive analysis of existing research on the sustainability of mHealth innovations in each of the four disciplines but focuses on identified critical dimensions when evaluating mHealth innovations.

Third, there are difficulties inherent to multidisciplinary research where not only the vocabulary differs but also the metrics and methodologies. This article initiates a dialogue but does not offer an operational frame: measuring the potential role of mHealth innovations in sustainable transitions is still—in pure quantitative terms—out of reach, as it lacks the methodology to assess and aggregate the different dimensions of sustainability. The lack of common grounds slows down the realization of the research and requires a high level of adaptability and willingness to accept trade-offs. For example, in an interdisciplinary dialogue, one often must trade discipline-specific accuracy for the use of broad and global terms. Such dialogue should thus be continued to trigger further dimensions that are relevant for sustainability.

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Appendix A

Table A1. Searches used to perform the TLR sorted per discipline. HCI query 1 aimed to identify the challenges associated with sustainable HCI, HCI query 2 aimed to describe how mHealth technologies are evaluated within HCI and how sustainability is considered in such evaluations.

Discipline	Database	Keywords or Queries
HE	Google Scholar, PubMed	Mobile Health (mHealth), eHealth, wearable devices, (sustainable) Health Technology Assessment, cost-effectiveness analysis, cost-utility analysis, cost-benefit analysis, utility, effectiveness, cost, benefit Queries: (“Mobile Health” OR “mHealth” OR “eHealth” OR “wearable” OR “wearable devices”) AND (“Health Technology Assessment” OR “cost-effectiveness analysis” OR “cost-utility analysis” OR “cost-benefit analysis” OR “utility” OR “effectiveness” OR “cost” OR “benefit”) AND (“Sustainable” OR “Sustainability” OR “Environment”).
ICT	Scopus	Sustainable (medical) device, mHealth (m-Health), sustainability, wearable medical device, eco-design, life cycle assessment Queries: (“mHealth” AND “sustainability”), “sustainable medical device”, “eco-design”
HCI	Google Scholar	Sustainable HCI (SHCI), sustainable interaction design, sustainability within/in HCI, definition of sustainability, defining sustainability, assessment/evaluation framework, mHealth, mobile health Query 1: (“sustainable HCI” OR “SHCI” OR “sustainable interaction design” OR “sustainability in HCI”) AND (“definition of sustainability” OR “defining sustainability”) Query 2: (“assessment framework” OR “evaluation framework”) AND (“mHealth” OR “mobile health”) AND (“within HCI” OR “in HCI”)
TSI	Google Scholar, Isidor and www.connectedpapers.com	(sustainable) Mobile Health (mHealth), (sustainable) wearables, (tele-)care, (sustainable) social innovation, (sustainable) transformative social innovation

HE Health Economics, ICT Information and Communication Technology, HCI Human Computer Interaction, TSI Transformative Social Innovation

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