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Title	**Virtual Education Strategies in the Context of Sustainable Healthcare and Medical Education: A Topic Modeling Analysis of Four Decades of Research**
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[Declaration]

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Virtual Education Strategies in the Context of Sustainable Healthcare and Medical Education: A Topic Modeling Analysis of Four Decades of Research

Abstract

Background:

The growing importance of sustainability has led to the current literature being saturated with studies on the necessity of, and suggested topics for, Education for Sustainable Healthcare (ESH). Even so, ESH implementation has been hindered by educator unpreparedness and resource scarcity. A potential resolution lies in virtual education. However, research on the strategies needed for successfully implementing virtual education in the context of sustainable healthcare and medical education is sparse; this study aims to fill the gap.

Methods:

Topic modeling, a computational text-mining method for analyzing recurring patterns of co-occurring word clusters to reveal key topics prevalent across the texts, was used to examine how sustainability was addressed in research in medicine, medical education, and virtual education. A total of 17,631 studies, retrieved from Web of Science, Scopus, and PubMed, were analyzed.

Results:

Sustainability-related topics within healthcare, medical education and virtual education provided systematic implications for Sustainable Virtual Medical Education (SVME) – ESH via virtual platforms in a sustainable way. Analyses of keywords, phrases, topics and their associated networks indicate that SVME should address the three pillars of environmental, social, and economic sustainability, and medical practices to uphold them; employ different technologies and methods including simulations, VR, AR, AI, cloud computing, online and distance learning, and MOOCs; and implement strategies for collaborative development, persuasive diffusion, and quality assurance.

Conclusions:

This research suggests that sustainable strategies in Virtual Education for ESH requires a systems approach, encompassing components such as learning content and objectives, evaluation, targeted learners, media, methods, and strategies. The advancement of SVME necessitates that medical educators and researchers play a central and bridging role, guiding both the fields of sustainable healthcare and medical education in the development and implementation of SVME. In this way, they can prepare future physicians to address sustainability issues that impact patient care.

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Introduction

In the last five decades, sustainability has been widely recognized as an essential tenet guiding innovation. The seminal 1972 report, *The Limits to Growth*,[1] simulated the interactions between economic and population growth, on one hand, and resource depletion and environmental degradation, on the other. Without immediate and decisive action, the authors argued, the existing trajectory would lead to global collapse in the near future. In the 30 years that followed, interest in sustainability grew, but it was not until the 2000s that the discourse moved beyond environmental concerns to social and economic issues.[2-4] Now, three accepted dimensions of sustainable development are: *environmental sustainability* (focusing on preserving natural resources, reducing environmental harm, and maintaining biodiversity), *social sustainability* (focusing on equitable access to basic needs, protection of human rights, social equality, and responsible community engagement), and *economic sustainability* (focusing on responsible use of economic resources and creating a stable and sustainable economy for present and future generations).[3]

A growing body of medical research has demonstrated the need for a paradigm shift toward medical practices and systems that promote environmental, social, and economic sustainability.[5-7] In recognizing the interdependence between human health and the health of the planet, a holistic planetary health approach can provide guidance at patient, service, and system levels by identifying, for example, such priorities as empowering patients and addressing social determinants of health.[8, 9] Despite ongoing challenges posed by societal and cultural attitudes, political obstacles, and economic limitations, increasing attention and investment are being directed towards advocacy, research, and education for more sustainable medical practices.

As an inevitable response to the movement towards sustainable medicine, organizations have called for education for sustainable healthcare (ESH)[10, 11]. The Association for Medical Education in Europe (AMEE) and the General Medical Council (GMC) have taken the position that medical school graduates should be equipped to promote sustainability in healthcare delivery, thus reducing negative environmental impacts, and promoting social and economic sustainability. [11-16] The UK Medical School Council has identified specific ESH topics that should be covered, including planetary health, the health impacts of the climate crisis, the impacts of healthcare on the environment, and professionalism and leadership for structural change.[17]

Although the current literature is saturated with studies advocating the incorporation of ESH in medical education, and also with studies on learning objectives and topics for ESH,[12-14, 16, 18] few

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universities have actually integrated ESH content into their curricula. A recent survey by the International Federation of Medical Students' Associations found that 31% of medical schools across 112 countries have no ESH content in their curriculum, and only 14% have dedicated any time to the topic.[19] In another international survey, only 11% of nearly 3000 medical schools were found to provide ESH content in their curriculum.[20] Similar findings have been found at Monash University in Australia, where 81% of instructors surveyed indicated they do not include ESH in their offerings, and 68% said they are uncertain how to teach it.[21] A number of studies point out the lack of faculty expertise and resources as factors impeding the development and implementation of high-quality ESH curricula. [7, 22]

Given the unpreparedness of medical educators to teach sustainability and the scarcity of physical resources for ESH curriculum development, virtual education (VE) can serve a feasible solution, both for acquainting curricular stakeholders with ESH, and for ultimately incorporating ESH into medical curricula. VE harnesses the potential of various technological advancements to overcome the constraints of expense, time, space and logistics traditionally inherent in education. Thus, VE can potentially facilitate the dissemination of ESH to a broader group of learners and also foster inter-institutional collaboration among medical educational institutions.[23]

To optimize VE's efficacy for ESH within the context of healthcare and medical education, an integrated strategy is crucial. This would mirror trends in public and professional discourses on sustainability. Both the seminal book "The Limits to Growth" (1972, updated in 2004) [1] and the UN's shift from Millennium Development Goals (MDGs) in 2000 to Sustainable Development Goals (SDGs) in 2015 underscore the importance of a holistic approach for effective policy-making towards sustainable development. Similarly, an effective approach to the development and implementation of ESH using VE requires a holistic approach that takes into account potential contradictions, inherent tensions, and trade-offs[3] arising from the different values and interests in healthcare and medical education. This necessitates more comprehensive strategies that reflect multifaceted systematic considerations, including educational objectives and content, targeted learners, media and technology, as well as integration strategies.[14] To date, research into such comprehensive strategies has been sparse, [12, 20] with some studies attributing the failure of widespread ESH curricular implementation on virtual platforms to vague concepts and constructs.[3] To bridge this gap, the authors constructed the following research questions (RQ):

RQ1. What are the prevalent topics represented in Sustainable Healthcare (SH) research;
RQ2. What are the prevalent topics represented in Sustainable Medical Education (SME) research;
RQ3. What are the prevalent topics represented in Sustainable Virtual Education (SVE) research;

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and

RQ4. What overarching dimensions and strategies for Sustainable Virtual Medical Education (SVME) can be derived from the analysis of SH, SME, and SVE research

Answering these questions was intended to yield nuanced, systematic SVME strategies intersecting healthcare, medical education, and virtual education. For a clear starting point, we define Sustainable Healthcare (SH) as medical practices and systems that promote environmental, social, and economic sustainability, Sustainable Medical Education (SME) as education for sustainable healthcare (ESH) with sustainable means, Sustainable Virtual Education (SVE) as education that utilizes digital technology in a way that is environmentally, socially, and economically sustainable, and Sustainable Virtual Medical Education (SVME) as the sustainable use of virtual education for ESH.

Methods

We conducted topic modeling, a computational text mining methodology to uncover hidden topics within a collection of texts. Topic modeling is guided by the assumptions that text documents are organized into *bags of words*, and that words can be clustered in a meaningful way by the patterns they co-occur across documents. Using a computer algorithm, topic modeling captures the substantially meaningful *aboutness* of documents, providing a bird's eye view of research in a field.[24, 25] Topic modeling is thus known as an optimal method for discovering thematic trends in a large volume of textual data and predicting future directions.[26]

In general, more traditional approaches to revealing major topics and trends within a field involve manual reviews of published literature, such as a systematic review, scoping review, or narrative review. These techniques require considerable effort when iteratively reviewing a large volume of full articles since they involve highlighting, coding, and grouping data into salient themes and manually extracting and updating topics. The scoping review method and topic modeling shares the same objective: exploring the scope of a body of literature on a given topic and giving its clear indications.[27]

The reason why we chose topic modeling over a manual review methodology is three-fold. First, we wished to examine how sustainability was addressed in publications on SH, SME and SVE that spanned an extended period of time. Manual review of such a large volume of studies would have been extremely labor intensive and time-consuming, making an automated approach vastly preferable. Second, we felt that topic modeling would provide a relatively unbiased overview of a broad research landscape[26] because it would not rely primarily on the researcher's own predefined concepts and categories.[28] In

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fact, though manual reviews seek to overcome systematic error in searching, selecting, and synthesizing studies, numerous sources of bias are possible, such as favoring older articles or impact measures, omitting recently published articles, or skewing selection through various predispositions toward particular themes.[26] Lastly, we believed that automating certain aspects of process of topic modeling would allow us to make implicit conceptual notions of discourse visible and zoom in on detailed specifics across texts, which extends human readers' analytic capacities.[24, 28] The methodological steps of topic modeling included: (1) data collection; (2) pre-processing; (3) keyword and phrase frequency analysis; (4) topic modeling; and (5) link analysis.

Data collection

In order to retrieve peer-reviewed journal articles containing the topics of (1) sustainable healthcare or medicine (SH), (2) sustainable medical education (SME), and (3) sustainable virtual education (SVE), we searched 3 databases: Web of Science (1996~), Scopus (1987~), and PubMed (1982~). We developed search strategies incorporating Medical Subject Headings (MeSH) and Major Topic of PubMed indexing systems. We chose studies containing "sustainable" or "sustainability" in the title, abstract, and keywords at the same time, in order to ensure the sole inclusion of papers with a fundamental focus on sustainability. All studies were written in English and published up to January 10, 2023, without any restricted start date. Analyzing this extensive set of studies was made possible only due to the capabilities of topic modeling. We restricted our analysis to journal articles and conference proceedings, as they are typically conducive to in-depth discussion of a subject. Conversely, other types of literature, such as editorials, letters, commentaries, and erratum, were excluded due to their propensity for superficial mention of a topic. The search queries and the glossary of methodological terms are provided in Appendix 1 and 2.

Pre-processing

We pre-processed raw textual data and created a term-by-document matrix (TDM) using the text mining software QDA Miner 6 with WordStat 9 (Montreal, QC, 2022). Preprocessing involved removing punctuation, numbers, and whitespaces as well as stop-words including articles (e.g., *a, an, the*), prepositions (e.g., *with, to, on*), conjunctions (e.g., *and, or, but*), and pronouns (e.g., *she, he, they*). We also carried out lemmatization, a procedure that converts a word's inflected forms into a single base form (e.g., *run* for *runs, ran* and *running*). We excluded terms commonly used in research literature (e.g., *introduction, method, results, findings*), because they have the potential to obscure central themes.

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Keyword and phrase frequency analysis

We examined the frequencies of keywords and phrases in each area. We looked at the TF-IDF (Term Frequency weighted by Inverse Document Frequency) index, which is based on two assumptions: (1) the frequency of a term in a document determines how well it characterizes its content, and (2) the number of documents in which a term appears indicates how discriminating the term is. In other words, as the frequency of occurrence of a term *within* a document increases, it becomes more representative of the document's content. Conversely, as the frequency of occurrence of a term *across* multiple and diverse document collections increases, its ability to differentiate between the content of those documents decreases. Consequently, as the frequency of a word within a document increases and the number of documents containing it decreases, the TF-IDF value of the word is heightened.

Topic modeling

A topic represents a cluster of words that frequently appear together and are centered on a set of key terms, similar to the way individuals create written works related to specific themes or concepts.[29] The analysis of recurring patterns of co-occurring words reveals clusters of words that are prevalent across the texts, and subsequently converts these clusters into discrete topics.[29, 30]

We employed the Non-Negative Matrix Factorization (NMF) method to decompose the original matrix V (consisting of n texts and m words) into two factors: W, comprised of n texts and k topics, and H, consisting of k topics and m words. This process resulted in the creation of final topic lists, represented by the matrices W and H, with the frequency of documents classified as utilizing each topic. NMF is more efficient in creating understandable and cohesive topics than other methods, such as Latent Dirichlet Allocation (LDA).[31-34]

Using relevant guiding studies[26,35] and preliminary examinations, we determined that the optimal number of topics for highly interpretable and diverse topics was 40, among which top 12 topics for each area were reported based on Normalized Point-wise Mutual Information (NPMI), which relies on the frequency of word co-occurrences, and correlates with topic interpretability.[36] The interpretation of identified topics in topic modelling usually relies on the context in which the word or words are embedded, the research questions, current literature, and researchers' expertise in the area.[28, 37, 38] In instances where the precise meaning and context of some terms were ambiguous to interpret or the

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interpretations of independent researchers did not coincide, we jointly consulted the original text using the *word-in-context* function of the software (Appendix 3), and also used a framework consisting of: (1) three interacting fields (SH, SME and SVE), (2) three pillars of sustainability (environmental, social and economic), and (3) the system components of VE (learning content and objectives, evaluation, targeted learners, media, methods, and strategies).

Link analysis

We performed link analyses by centering the most significant terms to discover contextual connections between extracted keywords and phrases, and associated network diagrams showing the textual elements (nodes) and their association strength (links with numerical values) based on co-occurrence. We used force-based multidimensional scaling (MDS) with a tolerance of 0.000001 and a maximum iteration of 500. The co-occurrence measure between a pair of nodes served as an indicator of semantic proximity.[39] The more two items co-occurred in source documents, the higher their level of semantic proximity. The weight value ranged from 0 to 1, where 0 indicates no possibility that the two items could occur together in a source document.

Results

Research Overview

We retrieved and analyzed a total of 17,631 articles containing the terms *sustainability* or *sustainable development* in the fields of medicine, medical education (ME), and virtual education (VE) after removing duplicates from the initial search result of 19,321 articles. Table 1 shows the quantity of articles by field, the frequency of *sustainability* and *sustainable*, and the ratio of term occurrence per 10,000 words (the intensity of the discussion). The medicine field had the highest number of articles, followed by the VE field, with the lowest number of articles in the ME field. VE articles had the greatest intensity of the use of sustainability-related terms while ME articles containing the terms had relatively less emphasis on sustainability issues.

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The earliest journal article across the three fields was published in 1982 by Loraine (1982). A consistent rise in the number of sustainability-related articles has continued through 2022 (Figure 1). A marked growth in the number of such articles has occurred since 2015. Notably, half of the total number of articles published in the last 41 years were published in the last 8 years (n=8508, 50%).

INSERT Figure 1. HERE

RQ1. Prevalent Sustainability Topics Explored in Healthcare Research

Our first research question concerned the prevalence of topics related to Sustainable Healthcare (SH) research. The most frequently occurring keywords, phrases, topics and their interconnections in the field of SH are as shown in Tables 2 and Figure 2. The results highlight the central theme of sustainability at environmental, social, and economic dimensions, and the medical practices to achieve them, particularly in relation to healthcare service and systems, patient empowerment, preventive measures, and workforce training. In terms of environmental sustainability (32.7%), *climate change* was most frequently mentioned, with a particular emphasis on *waste* and *waste management*.[40, 41] This leads to a practical movement towards low carbon alternatives and operational resource use (minimizing waste, energy and travel). Phrases related to the social sustainability reveal frequent references to equitable access to healthcare services and the social determinants of health, with a particular emphasis on vulnerable patient groups such as *children, women, pregnant women*, and *infants* (11.5%), along with populations in *low-income countries* (11.5%). These phrases also point to social responsibility issues among medical professionals, institutions, and health systems (23.1%).[8, 10] In terms of economic sustainability (5.8%), phrases such as *cost effectiveness* and *long-ter*m suggest a focus on the efficiency and effectiveness of healthcare in ways of prevention (3.8%) and patient empowerment (11.5%), which ultimately aim to reduce healthcare costs. Reducing medical activity and educating and encouraging patients, particularly those with chronic diseases (reflected in phrases such as *blood pressure, weight loss*, and *physical activity*) and streamlining clinical pathways are examples of SH practices that are both economically and socially sustainable.[42] The topics of training of medical workforce (3.8%) also were present, which leads to sustainability topics in the field of ME.

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RQ2. Prevalent Sustainability Topics Explored in Medical Education Research

Tables 3 and Figure 3 display the most frequently occurring keywords, phrases, topics and their interlinkages in SME articles. The three pillars of sustainability and upholding medical practices were recurrent topics in SME but with different emphases. The first cluster of topics encompasses concepts related to environmental (9.6%), social (7.7%), and economic (5.8%) sustainability. The second cluster includes topics in the medical field, including healthcare services and systems (19.2%), patient empowerment (7.7%), and prevention (1.9%). Words related to public health appeared more frequently (7.7%) than in SH. The third cluster shows words related to education (30.8%), including such common terms as *curriculum, clinical training*, and *medical workforce*. The topic of *evaluation* indicates both the assessment of learner acquisition of knowledge, skills, and attitudes, and the evaluation of program effectiveness. Of the phrases notable as SME strategies, the following four emerged as most prominent: *standard; evaluating effectiveness; training with simulations;* and *collaborative training for global health*. In the link analysis, a central cluster of *knowledge, clinical skills,* and *reasoning skills* was noted along with a cluster of words related to social sustainability, including *value, responsibility,* and *rural practice* at the bottom.

INSERT Table 3. HERE

INSERT Figure 3. HERE

RQ3. Prevalent Sustainability Topics Explored in Virtual Education Research

As shown in Table 4 and Figure 4, the analysis of keywords, phrases, topics, and their networks in SVE articles also yielded topics related to environmental sustainability (13.5%) and social sustainability (5.8%). Words related to social sustainability, like *equity* and *social responsibility,* were more explicit than words from medicine and ME articles. The most frequently appearing terms were those associated with technology, such as virtual reality (VR), augmented reality (AR), information and communication technology (ICT), and cloud computing (28.8%), which can be used to raise learners' awareness of environmental issues and promote their pro-environmental attitudes and behaviors with immersive, hands-on learning experiences—without a need to travel.[43]. We observed a substantial presence of words related to the form of VE, such as the conventional forms *e-learning, online and distance learning*, as well as the more recent emergence of terms like *massive open online courses* (MOOCS) (9.6%). Terms surrounding the advantages of VE, such as *traditional, face-to-face, competitive advantage over traditional classroom lecture,* and *COVID pandemic*, were observed as well (9.6%).
The presence of terms relating to macro- and micro- strategies was notable, both among institutions and

within institutions implying collaborative strategies for developing and implementing VE. This finding was exemplified by phrases such as *funded cooperation, stakeholders*, and *collaboration* (3.8%) along with phrases on educational institutions, such as *university, higher education institutions* and *postgraduate education* (9.6%). The strategies involve minimizing resource consumption, encompassing not only tangible resources such as travel and administrative burden but also intangible resources, including human capital, which would not have been incurred if traditional resource-intensive methods had been employed[12, 21]. The use of keywords related to innovation, such as *behavioral change* and *digital transformation*, also was observed (3.8%).

INSERT Table 4. HERT

INSERT Figure 4. HERE

RQ4. The Synthesis of SVME Dimensions and Strategies

The keywords, phrases, topics, and networks extracted from the SH, SME, and SVE studies provided dimensions and strategies of SVME in regard to learning content, media and methods, and strategies. Figure 5 illustrates how the implications of topics derived from SH, SME, and SVE studies constitute SVME system elements. SH-derived topics provide the broader context of SVME, influencing the learning content and objectives of SVME. These topics encompass the three pillars of sustainability and the medical practices for achieving them, serving as the goals and means of SH. Through the SME aspect, these topics become the learning content, and the acquisition of related knowledge, skills, and attitudes becomes the learning objectives. The SME research topics provide insights into learners and their evaluation. They imply that the target learners of SVME should encompass not only medical students but also healthcare professionals and staff within the entire workforce. The topic *workforce training* emerges towards the end of the SH field, linked to the SME topic. This finding not only situates SVME within the context of SH but also denotes the intended learners of SVME. The topic *technology* from SME studies overlaps with SVE research topics, which contributes to the shaping of SVME tools, methods, and strategies. The resulting SVME guidelines and strategies are summarized in Table 5.

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Discussion

The primary purpose of this study was to identify sustainability topics in a large volume of studies in order to explore strategies for implementing ESH via virtual platforms in medical education. We extracted keywords, phrases, topics, and their networks from studies on sustainability in the fields of healthcare, medical education, and virtual education. This process revealed relevant concepts with practical implications within each area. Grounded in the results of each research questions, we discerned new definitions of sustainability within each field, consequently leading to the extrapolation of virtual education strategies in the context of Sustainable Healthcare and Medical Education.

Sustainable Healthcare Redefined

In the healthcare area, three major topics emerged: (1) environmental sustainability within a medical context (supporting human and planetary health by reducing the carbon intensity of services), social sustainability (providing equitable access to healthcare services), and economic sustainability (ensuring the long-term cost-effectiveness of healthcare services); (2) the means to achieve these three pillars of sustainability, including the transformation of healthcare services and systems, patient empowerment, and prevention; and (3) non-medical means for sustainable healthcare, which is, essentially, workforce training. Based on the topics we identified, we can redefine sustainable healthcare as:

> *A holistic strategy that supports environmental responsibility (both human and planet-friendly), social equity (accessibility for all), and economic viability (cost-effectiveness in the long run) by reducing the carbon intensity of services, increasing patient empowerment, emphasizing prevention, transforming healthcare services and systems, and training a healthcare workforce equipped to understand and implement these priorities*

This definition redefines the original three pillars of sustainability within the context of healthcare, incorporating enabling medical practices. Compared to previous definitions that primarily focused on environmental sustainability in healthcare (e.g., Gandhi et al., 2020[11]), this is a more balanced and integrated definition. It stresses the necessity of cultivating a healthcare workforce trained to proficiently implement and advance such a sustainability paradigm. In essence, this feature introduces a new perspective that extends and shapes a nexus between sustainable healthcare and medical education (Figure 5)

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Sustainable Medical Education Defined

In the medical education area, three groups of topics emerged: (1) three pillars of sustainability and their enabling medical practices directly aligned with topics from sustainable healthcare, which can constitute ESH content and learning objectives; (2) educational interventions to implement the content and objectives in curriculum intended for a specific learning population (e.g. *healthcare professionals, workforce, staff*); and (3) strategies to enhance the effectiveness of ESH such as program evaluation (e.g. *effectiveness, knowledge, clinical skills, reasoning skills, values*), including the use of technology as a potential medium for delivery. Sustainable Medical Education could therefore be defined as:

> *A pedagogical approach designed to educate the entire healthcare-related workforce on sustainable healthcare priorities, including environmental responsibility (both human and planet-friendly), social equity (accessibility for all), and economic viability (cost-effectiveness in the long run), through the coordination of curricula, programs, technology, and the evaluation of program effectiveness*

In current medical education literature, approaches to sustainability predominantly focused on what medical educators should teach to promote sustainable healthcare; this is commonly referred to as Education for Sustainable Healthcare (ESH) (e.g., Bevan et al. 2022[20]; Hategan & Abdurrahman, 2021[9]; Thompson et al. 2014[16]). This definition reflects the finding that medical education researchers view teaching about sustainability as not only pertinent to the content of instruction but as a practice necessitating sustainable methods of education. The last group of medical education topics also implies that if ESH programs are to be genuinely sustainable, they must engage in quality assurance through program evaluation, as reflected in Goal 4 (Quality Education) of the UN Sustainable Development Goals (SDGs). As shown in Figure 5, the above definition also places technology at intersection point of ME and VE.

Sustainable Virtual Education Defined

The primary topics emerging from the Virtual Education (VE) studies we analyzed can be categorized into three groups: (1) VE's contributions to environmental and social sustainability, (2) The variety of technologies that can be used to enable VE, and (3) VE strategies, for collaboration between educational institutions, and for the diffusion of innovation. Sustainable Virtual Education can thus be defined as:

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An pedagogical approach in which learning programs employ virtual platforms with advanced technologies that provide unique affordances overcoming the limitations of current training methods, and which is enhanced by institutional collaboration and diffusion strategies

This definition augments the existing concepts of sustainability discussed in virtual education, namely, its utility from a sustainability perspective. For example, VE reduces the need for student travel to physical campuses and improving access to quality education for students in remote or underserved areas (e.g. Alonso-Garciaet et al., 2019 [51]). Sustainable Virtual Education also encompasses the strategies required for its own sustainability. This includes judicious selection of technology that aligns learning objectives and relives institutions of economic and logistic burdens. It also stresses cross-functional collaborations to effect development, adoption, implementation, and to engage stakeholder who can help drive diffusion of innovation.

Sustainable Virtual Medical Education: Definition and Strategies

The redefined concepts of Sustainable Healthcare (SH), Sustainable Medical Education (SME), and Sustainable Virtual Education (SVE) yield implications for a definition of Sustainable Virtual Medical Education (SVME) and the strategies by which to promote it, as depicted in Table 5. First, SVME content should encompass three widely-accepted principles of environmental responsibility, social equity, economic viability actualized through such means as reducing the carbon intensity of services, supporting patient empowerment, and prevention, and advocating the transformation of healthcare services and systems Secondly, one objective of SVME should be to provide the entire healthcare workforce, at all levels, with the requisite knowledge, skills, and attitudes necessary to comprehend and operationalize these principles and facilitating practices. Thirdly, SVME should be leveraged by a variety of media and methods, including simulations, VR, AR, AI, cloud computing, online and distance learning, and MOOCs, whilst bearing in mind the unique affordance of each medium. Finally, those implementing SVME should utilize collaborative institutional development, engage with the process of innovation diffusion, and evaluate the effectiveness of SVME programs based on learning objectives and outcomes. Accordingly, we can define Sustainable Virtual Medical Education (SVME) as:

A systematic integrated approach for educating sustainable healthcare that employs virtual platforms to embed environmental responsibility, social equity, and economic viability within medical education content and practices, empower the healthcare workforce with pertinent

sustainability-based knowledge, skills, and attitudes, utilize diverse media and innovative methods, and promote sustainability through collaborative development, innovation diffusion, and quality assurance of program effectiveness based on learning objectives and outcomes.

The study advances understandings of the role of SVME in sustainable healthcare and medical education both in providing the first clear definition of SVME and in proposing a systematic approach to making SVME methods themselves sustainable. *A systems (or systematic) approach* to teaching and learning addresses educational challenges by examining the various components of an educational system as interconnected and interdependent parts.[44, 45] Instead of focusing on curriculum or instruction in isolation, for example, a systems approach views these elements as part of a larger, integrated whole. The topics and new definitions identified in this study reflect such a systematic approach to SVME, which includes careful planning and development of learning content based on sustainability principles, the utilization of sustainable technologies and practices, and the evaluation of the effectiveness and sustainability of these educational experiences. The overarching purpose in this process is to ensure that SVME not only teaches about sustainability but also embodies sustainability in its methodologies and practices.

Another significant implication of our findings is that the discourse on SVME should be primarily driven by the field of medical education. Although a considerably smaller quantity of sustainability research was identified in studies on ME (n=626, 3.6%) versus medicine (n=15,082, 85.5%) or VE (n=1,923, 10.9%), the critical SVME strategies pertain to the ME strategies for quality assurance and innovation diffusion, which provide practical guidance for curriculum developers, educators, researchers, and other stakeholders.

Achieving integrated sustainability in the field of medicine and medical education may involve tensions between different dimensions of sustainability[3] and lead to conflicts related to quality assurance. For example, sustainable healthcare may require the provision of cost-effective medical services, challenging both economic sustainability and social sustainability goals for economically-challenged individuals—potentially leading to a decline in service quality. Similar conflicts can arise in SME and SVME when trying to provide cost-effective learning to a large number of learners, as seen in the emergency remote medical learning required by the COVID pandemic. The quality of healthcare, medical education, and virtual education should not be compromised over sustainability values, but quality assurance should be a guiding principle for SVME.[3, 9, 46] High-quality education has been shown to positively impact individual and community development and serve not only as an end goal in itself, but as a means for promoting sustainability.[47] Instructional design, stakeholder needs, and accessibility

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are all criteria that can be used to evaluate the quality of SVME. In fact, advanced technology alone cannot ensure successful learning outcomes without proper curricular design and instructional strategies, as argued by Clark[48, 49] in historical instructional media debates. A recent systematic review also found that effective virtual patient programs for medical communication training were distinguished by their instructional design, not technical quality.[50] Thus, the needs and expectations of learners, educators, and society, including the accessibility of programs, must be taken into account when defining quality in virtual education.[46]

This study has methodological limitations, however, in terms of identifying detailed subtopics within each topic and understanding their precise meanings and implications, despite efforts to explore documents using the keyword-in-context function. In acknowledging this limitation, we recommend further validation through in-depth investigations employing other quantitative and qualitative research methodologies. Nevertheless, grounded on the topic analysis of over 17,000 research spanning more than 40 years in the domains of SH, SME and SVE, this study redefined the notions of sustainable healthcare, sustainable medical education, and sustainable virtual education and created a definition and strategies for SVME, a substantial contribution to the field of medical education. It is our intention to contribute to the refinement of SVME concepts and strategies by measuring and enhancing the effectiveness of SVME and facilitating its continuous improvement. In this way we hope to quantify, optimize, and incrementally advance the efficacy of SVME.

Conclusion

The emergent topics underscore that SVME requires a comprehensive systems approach that takes the following into account: learning content and objectives, evaluation, target learners, media/technologies, and strategies to ensure development, diffusion of innovation and stringent quality assurance. Among these, quality assurance is a critical and non-negotiable guiding principle. The advancement of SVME necessitates that medical educators and researchers play a central and bridging role, guiding both the fields of sustainable healthcare and medical education in the development and implementation of SVME. In this way, they can prepare future physicians to address sustainability issues that impact patient care. It is hoped that this research will encourage further investigation in this area that will lead to actionable steps to deliver ESH to future generations of physicians, who will certainly find this learning increasingly important to the health of their patients.

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