Environmental Sustainability in the Healthcare Sector: A Systematic Review of Practices, Metrics, and Regulatory Frameworks

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Abstract: The healthcare sector encompasses all activities related to the provision of medical services and assistance, involving a complex network of key stakeholders, including patients, care providers, financiers, and policymakers, as well as several supporting actors such as medical suppliers, logistics services, and waste management companies. This complexity highlights the strong interconnections between healthcare and other sectors. Despite its primary goal of improving human health and well-being, healthcare presents a significant paradox in terms of sustainability. On one hand, it aims to deliver high-quality care while aligning with global commitments such as the UN 2030 Agenda. On the other hand, it has a substantial environmental impact, contributing significantly to greenhouse gas emissions and pollution. In fact, the healthcare industry would be one of the biggest pollutants in the world if viewed as a separate entity. A critical issue lies in the management of healthcare waste, particularly hazardous waste, which represents a smaller share of total waste but poses serious risks to both human health and the environment. Given the limited and fragmented literature on the intersection between healthcare and sustainability, this study aims to provide a systematic review of existing studies, focusing on practices, metrics, and regulatory frameworks. The analysis begins with an overview of the methodological approach, followed by an examination of current sustainability regulations in healthcare, including selected case studies at both local and international levels. The core of the study consists of a comparative systematic review of sustainability practices and performance metrics adopted by organizations within the sector. Finally, the study presents key findings and insights derived from the analysis, contributing to a clearer understanding of how sustainability can be effectively integrated into healthcare systems.

Keywords: Healthcare sector; Sustainable practices, Sustainability metrics; Systematic Literature Review.

1.Introduction

The mission of healthcare organizations, as defined by the World Health Organization (WHO), is to protect and improve people's health through prevention, diagnosis, treatment, care, and rehabilitation. However, paradoxically, these also generate substantial environmental impacts that can, in turn, negatively affect public health. For instance, hospitals alone are estimated to account for approximately 4.4% of global net greenhouse gas emissions, corresponding to around 2 gigatons of carbon (Doucet et al., 2025).

The need to regulate the healthcare sector in this regard—just like any other industrial sector—stems from WHO estimates, which project an additional 250,000 deaths per year between 2030 and 2050 due to causes linked to the environmental impact on health (WHO, 2023).

At the European level, to cite two examples, there are two clear, general-purpose directives that govern the operations of any sector: the Omnibus Regulation, which aims to steer a shift in perspectives and behaviors toward sustainability; and the Clean Industrial Deal, which creates an attractive environment for companies by introducing new "green" technologies and fostering the development of a secure circular economy. However, there is no specific, structured legislation in Europe on environmental sustainability in the healthcare sector. Therefore, the previously mentioned directives indirectly impact on the healthcare sector. For instance, the Green Deal as applied to the healthcare sector involves two key points that must be addressed. The first is the indirect impact that packaging regulations have on the sector. In fact, by 2030, there must be both the possibility and the obligation to recycle packaging, including plastic packaging, and consequently, this requirement extends to the healthcare sector as well. The only extension is granted to the pharmaceutical sector, where packaging is closely tied to medicines or medical devices and is therefore more difficult to replace given sterilization requirements. Even in the medical-surgical field, many single-use devices must be managed so that they can be reused. Second is the importance of transparency regarding an organization's environmental impact. Through the Corporate Sustainability Reporting Directive (CSRD), the aim is to obtain a consistent report on the activities and impacts that an organization has on the environment. Reporting has always been carried out primarily on data related to the social and care sectors, but the inclusion of environmental aspects is both desirable and necessary. As a general directive, it also applies to the healthcare sector.

Because the relationship between healthcare and environmental sustainability is both challenging and paradoxical, the body of literature on this topic is relatively scarce from all analytical perspectives, particularly regarding real-world practices successfully adopted in the healthcare sector to respect the environment. Moreover, the benefits of integrated decision-making, considering the link between health and environmental impact reduction, are not yet clear, nor well supported by healthcare organizations' monitoring systems (Cavicchi, 2017).

The main objective of this paper is to provide a systematic review of the literature on this topic, seeking to compare the issues addressed as clearly and coherently as possible. Practices, metrics, and regulations will therefore be the focus of the analysis. This will be addressed by answering the following questions: *What practices, methodological approach, and metrics are used to assess and promote environmental sustainability in healthcare systems?*

The study is structured as follows: Section 2 describes the methodology used for addressing the research aim; Section 3 presents the results of the systematic literature review; Section 4 discusses the results by highlighting research gaps and research agenda in the field; finally, Section 5 concludes the study, presenting the main contributions and limitations. For clarity, throughout the rest of this paper, the term "sustainability" refers to environmental sustainability unless otherwise specified.

2. Methodology

This study conducts a systematic literature review to provide a structured and comprehensive overview of the research field under investigation. The systematic review approach ensures methodological rigor and replicability by identifying, selecting, and critically evaluating relevant scientific contributions, thereby minimizing the biases typically associated with narrative reviews (Tranfield et al., 2003). The first step was to formulate a query consistent with the research objective, as shown in Table 1. The selected keywords included multiple synonyms to obtain a broad baseline sample, combined using Boolean operators to construct the search string.

Table 1: Keywords and search string

Environmental sustainability		Healthcare		Practices and metrics
Environment OR sustainability OR ecologic OR "circular economy" OR waste OR reuse OR recycling OR renewable OR green OR "zero waste"	AND	healthcare OR hospital OR clinic OR medical OR "outpatient clinic" OR "healthcare facility" OR "healthcare organization"	AND	(metric* OR kpi* OR indicator* OR measure*) AND ("case study)

The search was conducted using the Scopus database. Specifically, the search was restricted to journal articles in English published in the fields of engineering or business, management and accounting. The search yielded an initial selection of 314 articles. These documents were then examined through a two-step screening process: first, titles and abstracts were reviewed; subsequently, the full texts were assessed. Inclusion criteria were established to narrow the corpus, ensuring alignment with the research objectives and in line with guidelines for systematic reviews (Sauer and Seuring, 2023). Specifically, based on a review of the titles and abstracts, the papers had to focus on the management aspects of environmental sustainability and practices aimed at improving it. For example, papers centred on architectural design or clinical aspects were excluded from the selection. Furthermore, the papers had to present an application of sustainability practices; theoretical papers or those without references to cases and practices were excluded. The screening process was performed independently by the two researchers. Any discrepancies were resolved through discussion. This screening resulted in a selection of 29 papers, which were read in full and analysed. Furthermore, an a priori coding structure was defined to determine which data to extract from the paper to answer the RQ. Specifically, both descriptive information about the articles (e.g., year, source title, country) and contextual information relevant to the research question (i.e., regulations and standards, sustainability area and approach, methods, KPIs, environmental indices and criteria) have been recorded.

3. Results

3.1 Corpus descriptive analysis

Of the 29 articles analyzed, the time frame covered spans from 2013 to 2025, with an increase in publications from 2020 onwards. This trend can be associated with the increasing focus on sustainability, accompanied by growing institutional commitment and regulatory developments. Geographically, a thorough examination of the available data indicates that Iran has published the most articles, accounting for 34.5% of the corpus, followed by Italy with 4 articles, China with 3, and France with 2. Bosnia and Herzegovina, the Netherlands, Denmark, Spain, Portugal, Turkey, Thailand, Ghana, Australia, and India are each represented by a single publication. The temporal and geographical distribution of the selected corpus provides further insight when analyzed in the light of existing regulatory frameworks. Indeed, these frameworks help understand the potential relationship between scientific interest and the development and implementation of policies and regulations across different national contexts. In fact, 31% of the corpus cites or refers to a specific regulation as either a driving factor or a contextual condition for the research.

These references can be broadly grouped into three categories: technical standards, international guidelines, and national or local regulations. Technical standards include Italian (UNI11425) and international frameworks such as ISO14001/ISO26000, as well as ISO 7730:2005 and ASHRAE standards, mainly addressing environmental performance aspects such as thermal comfort (Shi et al., 2023), indoor air quality in operating

theatres (Cappiello, 2024), or more general standards, cited to identify environmental management guidelines that healthcare organizations should follow to adopt a 'proactive' approach to sustainability (Bentahar et al., 2023). In addition, several studies rely on international guidelines promoted by the WHO. These concern waste classification and vaccine guidelines (Amos et al., 2020; Babaei et al., 2023; Cavicchi, 2017). National regulatory frameworks are also mentioned, such as the US RCRA, for guidelines on packaging and waste management (Hadipour et al., 2014). Finally, some papers refer to local regulations (Mallick et al., 2022; Mishra and Rani, 2021).

In several cases, in the absence of specific health legislation explicitly addressing sustainability, technical standards such as ISO or ASHRAE are used as reference frameworks. Within this fragmented landscape, WHO guidelines appear to play a bridging role across different national contexts. A further relevant aspect concerns the scope of these standards, which predominantly focus on building performance, particularly in terms of safety and indoor environmental quality.

3.2 Environmental Sustainability Practices

Building on the descriptive and regulatory analyses presented above, this section examines the environmental sustainability practices identified in the literature to understand how theoretical and regulatory frameworks translate into operational actions within the healthcare sector.

The environmental sustainability practice most frequently addressed in the corpus (65.5%) concerns the treatment and management of clinical waste. More specifically, the analysed studies focus on several interrelated aspects. First, a significant body of work investigates the logistical optimization of waste management, with particular attention to minimizing costs and pollution during transport (Mishra and Rani, 2021; Mokhtari et al., 2023). In this context, the infectious nature of clinical waste imposes specific constraints on the logistics chain (Koohkan et al., 2025), distinguishing it from general waste management. This includes, for instance, the use of specific transport vehicles and strict time windows for waste handling. A second line of research concerns treatment technologies, which evaluate alternative solutions (e.g., sterilization, incineration) to reduce the environmental impact of waste, particularly hazardous waste. Some studies focus on volume forecasting (Yenisari and Seker, 2025), which enables the identification of future medical waste production, thereby allowing for the optimization of waste storage and related processes. Finally, safety and quality emerge as an additional field of investigation (de Ridder et al., 2022), highlighting the need to ensure compliance with health standards alongside environmental objectives. It is also worth noting that 21% of articles on waste explicitly incorporate the concept of resilience. In these cases, the objective is to ensure that material recovery and recycling processes are compatible with the need to maintain a robust and adaptable logistics network, capable of responding to uncertain market conditions (Yahyapour Ganji et al., 2025) or to systemic shocks such as the COVID-19 pandemic (Karimi et al., 2024).

The second most recurrent theme in the corpus (27.6%) is energy management in healthcare facilities. Healthcare facilities are major energy consumers because they require uninterrupted operation. It is therefore necessary to analyse their energy supply systems and the quantity and/or quality of the energy consumed. The literature examines energy resilience by studying the dependence of healthcare facilities on the national electricity grid (Peirow et al., 2022). Within this domain, technological innovation also plays a relevant role. (Calise et al., 2016) present a case of technological innovation, examining the adoption of combined heat, cooling, and power systems to reduce consumption costs.

Further topics included the administration of medicines and medical devices to reduce carbon dioxide emissions (Asghari and Mirzapour Al-e-hashem, 2020; Goodarzian et al., 2021).

Although the research was designed with a primary focus on the environmental dimension, the systematic analysis revealed that, alongside the environmental aspect, the economic aspect is also examined – for example, with a view to minimizing disposal and inventory costs (Amos et al., 2020; Babaei et al., 2023) – and the social aspect (Cavicchi, 2017).

3.3 Methodological approaches

To critically assess the robustness of the previously described sustainability practices, it is also necessary to consider the methodological approaches through which they were generated. Therefore, in this section, the objective is to investigate "how" these issues are examined—that is, to highlight which analytical tools and mathematical models the sample of literature under review employs.

The transition from theoretically developed practices to concrete actions requires methodological support that yields useful results for stakeholders, whether by quantifying impacts or optimizing resources. The methodological approaches and methods used in relation to the practices under investigation were grouped into five categories: optimization-based and simulation models (41.2%), conceptual and framework-based approaches (27.6%), multi-criteria decision making (MCDM) methods (20.7%), statistical and data-driven methods (6.9%), and mixed-methods approaches (3.4%), applied to waste and energy management in healthcare.

Not surprisingly, optimization, such as linear programming, routing problems, and simulation, are the most recurrent approaches in the corpus. They involve optimizing the supply chain or transportation management for waste management, thereby minimizing emissions, costs, risks, and improving logistics (Asghari and Mirzapour Al-e-hashem, 2020; Babaei et al., 2023; Goodarzian et al., 2021; Karimi et al., 2024; Koohkan et al., 2025; Ni et al., 2018; Peirov et al., 2022; Supsermpol and Chiadamrong, 2023; Yahyapour Ganji et al., 2025).

Simulation models are also used for performing energy and economic analysis of energy efficiency actions in hospitals (Calise et al., 2016; Cappiello, 2024).

Among the quantitative methods, statistical and data-driven approaches, such as AI, Machine Learning, and forecasting models, are present in the corpus of analyzed publications and are used to identify operational inefficiencies and predict waste generation, monitor systems in real time, and support decision-making under uncertainty (Jiménez-Lacarra et al., 2022; Yenisari and Seker, 2025).

MCDM methods are also very common. They use qualitative-quantitative methods, translating subjective evaluations of different criteria into quantitative values. From a sustainability perspective, they are used to evaluate medical waste treatment technologies by integrating environmental, economic, technical and, at times, social impacts (Liu et al., 2021), for supporting the selection of optimal waste disposal location (Mishra and Rani, 2021), and selection of sustainable suppliers (Stević et al., 2020).

The second most recurrent methodological approach is qualitative by nature: conceptual and framework-based approaches. These studies aim to structure decision-making at a strategic level, finding critical factors and risks of sustainability strategies in healthcare. Among these studies, strategic methods are used, such as the Balance Scorecard (Khalid et al., 2025), SWOT and strategic planning techniques (Mokhtari et al., 2023). More generic qualitative analyses of real cases are employed for understanding critical aspects of environmental sustainability in healthcare, such as the culture more oriented to the economic dimension of the TBL, and the systems used to monitor the sustainability performance (Bentahar et al., 2023; Cavicchi, 2017; Mallick et al., 2022). A risk-based, process-oriented sustainability assessment method, the Healthcare Sustainability Mode and Effect Analysis (HSMEA), adapted from the traditional Failure and Mode Effects Analysis, is also present and is aimed at identifying and mitigating environmental hotspots in healthcare processes (de Ridder et al., 2022).

Only one study employs a mixed-method approach, combining qualitative and quantitative data to understand the problem under analysis, which once again deals with waste management in hospitals (Amos et al., 2020)

3.4 Sustainability Metrics

The practices described in section 3.2 are quantitatively assessed using indicators. Some of these indicators are directly linked to practices, such as waste management and energy consumption. The corpus also includes other indicators that are not strictly related to the implemented practices but are included because they are useful for providing a comprehensive assessment of sustainability in healthcare. 65.5% of the articles provide a quantitative assessment of the study's impact on sustainability. This prevalence is linked to the nature of the methods used in the body of literature analyzed. In fact, most studies rely on data-driven approaches, simulation models, logistics optimization techniques, and quantitative-statistical analyses. Due to their intrinsic properties, these methods require numerical inputs and produce measurable outputs, thereby ensuring more technical and scientifically robust results. The metrics are primarily environmental (given the purpose of the analysis). However, consistently with the previous findings, economic and social impacts are often considered alongside the environmental dimension. Specifically, 17.3% of the analyzed articles include a combination of environmental and economic metrics, while 20.7% incorporate all three dimensions, i.e., environmental, economic, and social metrics.

Not surprisingly, waste volume or mass is mainly cited (de Ridder et al., 2022; Hadipour et al., 2014; Karimi et al., 2024), also dived into infectious-hazardous and pseudo-household wastes (Hadipour et al., 2014), or only infected (Supsermpol and Chiadamrong, 2023). This is also expressed in the ratio between total common healthcare waste and the total healthcare waste, or the ratio between the cost of healthcare waste removal (bed) and the cost of healthcare waste removal (liters), as well as, ratio between the recyclable healthcare waste (kg) and the common healthcare waste (kg), as other indicators used for quantify hospital waste supply chains performance (Ferreira et al., 2025).

Primary energy consumption is also present in the studies of (Calise et al., 2016; Cappiello, 2024; Peirow et al., 2022), primarily addressing the second main sustainability practice found in the corpus.

CO_2 Equivalent Emissions are also present in the analysis of the metrics in different studies (Asghari and Mirzapour Al-e-hashem, 2020; de Ridder et al., 2022; Ni et al., 2018; Yahyapour Ganji et al., 2025). (Ni et al., 2018) uses this indicator as an aggregate index that quantifies the environmental impact in carbon-equivalent emissions from water, electricity, and gas consumption, as well as from reagent waste generated during diagnostic activities. In this case, the calculation is performed by multiplying collected data (e.g., kg of materials/resources/waste) by specific emission factors. This approach is also used for total carbon emissions computation related to the kilometers traveled by transport vehicles (Asghari and Mirzapour Al-e-hashem, 2020; Goodarzian et al., 2021; Yahyapour Ganji et al., 2025). This use of this indicator highlights its role as a standardized and comparable metric, enabling the aggregation of heterogeneous environmental impacts into a single indicator. However, its accuracy strongly depends on the selection of emission factors, which may vary across geographical contexts, energy mixes, and data sources, potentially affecting the comparability of results across studies.

Another single indicator is proposed as a global sustainability performance metric for hospitals, i.e., the Environmental Efficiency Index (EEI), which is computed by dividing the endpoint impacts in each impact category typical of LCA studies (calculated with ReCiPe) for the hospital complexity unit (HCU), which is a measure of healthcare activity (Jiménez-Lacarra et al., 2022).

Also interesting metric found in the analysis is the Pollution Risk index (Koohkan et al., 2025), which is used to quantify environmental and health risks as done for the Risk Priority Number (RPN) in failure and mode effects analysis (FMEA) studies. Therefore, it is computed based on the possible failure probability/number of operating days (occurrence), failure detectability, and their effects. Pollution Risk is used to identify criticalities of waste management networks. This metric shifts the focus from purely impact-based assessment (e.g., emissions) to a risk-oriented evaluation, capturing not only the magnitude of environmental damage. This makes it particularly valuable for operational decision-making, as it supports prioritizing interventions in the system's most critical areas. Although it may be influenced by a degree of subjectivity.

Economic and social impacts are also addressed in several studies, typically through the following metrics:

- Total costs are the most mentioned economic metric. Costs are usually used in combination with environmental metrics to find optimal solutions that can minimize both of them (Asghari and Mirzapour Al-e-hashem, 2020; Babaei et al., 2023; Calise et al., 2016; Goodarzian et al., 2021; Karimi et al., 2024; Koohkan et al., 2025; Peirow et al., 2022; Supsermpol and Chiadamrong, 2023; Yahyapour Ganji et al., 2025). Other financial indicators, as the Net Present Value, the dynamic investment payback period, and the Benefit-Cost Ratio are cited by (Shi et al., 2023). Emissions penalty is also present (Peirow et al., 2022).
- The number of fixed job opportunities (which is independent of the production capacity, such as managerial positions) is also used, specifically in waste management studies (Goodarzian et al., 2021; Karimi et al., 2024; Koohkan et al., 2025).
- Risks, such as exposure risks, and generally speaking, risks associated with waste management (Karimi et al., 2024; Supsermpol and Chiadamrong, 2023).
- Service level and service quality (built upon service response time, service reliability, professional approach, and responsiveness to problems), mainly used in waste management performance assessment and optimization (Amos et al., 2020; Babaei et al., 2023; Koohkan et al., 2025).

Other metrics are cited, classified into responsive and resilience indicators (Yahyapour Ganji et al., 2025).

The criteria used in MCDM studies show a high degree of consistency with the metrics employed in quantitative analyses, indicating that similar sustainability dimensions are captured across different methodological approaches. However, MCDM studies also tend to include additional indicators related to the social dimension, which are often not considered in quantitative studies and are not always easily quantifiable.

Overall, the analysis reveals a quantitatively driven research landscape, where standardized metrics enable comparability and robustness, and are not only descriptive but increasingly used as decision-support tools (optimization, simulations, etc.), but where the integration of social dimensions and more holistic sustainability assessments remains limited and fragmented.

4.Discussion

The analyses presented in the previous section highlight that the integration of sustainability strategies within the healthcare sector is a relatively recent process, still evolving and fragmented in both the practices adopted and the regulatory framework. Firstly, in operational terms, there is no holistic approach to sustainability; instead, individual practices are implemented to address the specific challenges faced by the analysed healthcare settings. Furthermore, the prevalence of practices primarily linked to waste management and energy efficiency in buildings suggests that the literature focuses on operational areas where the impact is more immediately apparent and easier to manage. However, such practices are often limited to specific stages of the process and are not integrated into a broader approach to sustainability. Regulatory fragmentation is also a contributing factor. Organizations primarily refer to technical standards, but these do not guarantee uniform application. WHO guidelines are important references, but their non-binding nature limits their ability to generate systemic change. In this context, institutions and hospitals' top managers should play a more proactive role by fostering shared decision-making processes through which professionals are made aware of: (a) how sustainability affects the overall performance of the health system; (b) how they can actively contribute to the sustainable provision of care services; and (c) how sustainability in service delivery is closely linked to the sustainable management of technologies. From a metrics perspective, it is considered fundamental to incorporate metrics that display and monitor environmental practices, as well as measures that can assist the organization in adjusting to mitigate the impacts of climate change and natural disasters. All of these enable an assessment of how sustainability can be integrated into healthcare organizations, addressing the RQ.

A further point for consideration concerns the integration of environmental sustainability with the other dimensions of sustainability, namely economic and social sustainability. In the corpus analysed, many studies integrate environmental sustainability with economic sustainability, for example, by linking reductions in operating costs to reductions in emissions; however, the social dimension appears to receive less consideration. Some reasons for this may be that this aspect is difficult to monitor and measure, and that its effects on social sustainability are usually evident only in the long term. Nevertheless, in the healthcare sector, social sustainability is particularly relevant, as it is closely linked to issues such as equity of access, quality of care, and the well-being of healthcare workers (Piffari et al., 2023).

In light of these considerations, it is possible to draw up a research agenda for the future. Firstly, it is necessary to assess the implementation of a more holistic approach to

sustainability within the healthcare sector. Future research could explore how to move beyond the current compartmentalized approach to examine practices applied simultaneously across the entire healthcare system, rather than in specific areas alone. It is also becoming clear that the scope of the investigation needs to be broadened to include other areas beyond waste management and energy efficiency, such as sustainable procurement, the proper use of medical devices and medicines, and the impact of innovative healthcare delivery approaches (e.g., telemedicine) on sustainability. Secondly, it is essential to investigate the role of public policies and regulatory instruments in promoting a more systematic uptake of sustainable practices, including through incentive mechanisms or more specific regulatory requirements. Finally, a further area for development concerns the integration of the social dimension, both in terms of defining practices and in their overall evaluation. This entails developing metrics, tools, and data infrastructure to enable the simultaneous assessment of clinical, economic, environmental, and social performance. In this regard, future research should aim to bridge the gap between quantitative modeling robustness and the complexity of real-world organizational practices. The summary of research gaps and consequent research agenda for academics and practitioners is reported in Table 2.

Table 2: Discussion summary

Research gaps	Future Research Directions
Lack of holistic implementation across healthcare systems	Develop and evaluate system-wide, integrated sustainability frameworks
Predominance of isolated practices rather than integrated strategies	Study cross-functional sustainability practices leveraging established operations and supply chain frameworks
Concentration on waste management and energy efficiency	Expand to other domains: procurement, pharmaceuticals, medical devices, telemedicine
Regulatory fragmentation and reliance on non-binding guidelines (e.g., WHO)	Analyze the role of policies, incentives, and binding regulations
Limited involvement of top management in sustainability integration	Promote shared decision-making models and leadership-driven sustainability governance
Environmental and economic dimensions dominate; social dimension underrepresented	Strengthen inclusion of social sustainability (equity, quality of care, workforce well-being)
Disconnect between quantitative models and real-world organizational complexity	Bridge modeling approaches with organizational behavior and implementation science

5. Conclusion

The relationship between healthcare and sustainability is challenging and has recently been explored in both the literature and real-world settings. This study deep-dives into the literature regarding real-world practices in the healthcare sector and contributes by summarizing existing practices, regulatory frameworks, methodological approaches, and metrics and KPIs, thereby answering the RQ, while highlighting gaps and proposing a research agenda for the topic. These insights provide actionable guidance for managers to make informed decisions about the implementation and evaluation of sustainability initiatives, and for policymakers to design evidence-based guidelines.

This study is subject to several limitations that should be acknowledged, mainly related to the intrinsic nature of SLR. First, the analysis is based on a selected sample of articles, which, although representative of the current state of the literature, may not fully capture all relevant contributions in the field. The use of specific databases and keywords may have led to the exclusion of potentially relevant studies, particularly those published in adjacent disciplines or using alternative terminology. Second, the content analysis and classification of methods and metrics involve a degree of interpretation.

References

Amos, D., Musa, Z.N., Au-Yong, C.P., 2020. Modelling the performance of waste management services in Ghana's public hospitals: A facilities management perspective. Facilities 38, 715–738.

Asghari, M., Mirzapour Al-e-hashem, S.M.J., 2020. A green delivery-pickup problem for home hemodialysis machines; sharing economy in distributing scarce resources. Transp. Res. Part E Logist. Transp. Rev. 134, 101815.

Babaei, Y.S., Malekkhouyan, S., Aghsami, A., Rabbani, M., 2023. A multi-objective multi-criteria decision-making approach for sustainable vaccine distribution, inventory control (R,s,S policy), and waste management considering risk assessment, a case study. Sustain. Cities Soc. 96, 104670.

Bentahar, O., Benzidia, S., Bourlakis, M., 2023. A green supply chain taxonomy in healthcare: critical factors for a proactive approach. Int. J. Logist. Manag. 34, 60–83.

Calise, F., dâ TMAccadia, M.D., Libertini, L., Quiriti, E., Vicidomini, M., 2016. Dynamic Simulation and Optimum Operation Strategy of a Trigeneration System Serving a Hospital. Am. J. Eng. Appl. Sci. 9, 854–867.

Cappiello, F.L., 2024. Energy and economic analysis of energy efficiency actions in surgery rooms: A dynamic analysis. Appl. Energy 373, 123887.

Cavicchi, C., 2017. Healthcare sustainability and the role of intellectual capital: Evidence from an Italian Regional Health Service. J. Intellect. Cap. 18, 00–00.

de Ridder, E.F., Friedericy, H.J., van der Eijk, A.C., Dankelman, J., Jansen, F.W., 2022. A New Method to Improve the Environmental Sustainability of the

Operating Room: Healthcare Sustainability Mode and Effect Analysis (HSMEA). Sustainability 14, 13957.

Doucet, C., Lioussis, M., Yamano, N., Mueller, M., 2025. Measuring greenhouse gas emissions in the health sector: A new approach to model GHG emissions combining (JHAQ) health expenditure data and the multi-regional inter-country input-output (ICIO) tables (OECD Health Working Papers), OECD Health Working Papers.

Ferreira, A., Ramos, A., Ferreira, J., Ferreira, L., 2025. Mapping key performance indicators for sustainable hospital waste management. Acta Logist. 12, 43–52.

Goodarzian, F., Taleizadeh, A.A., Ghasemi, P., Abraham, A., 2021. An integrated sustainable medical supply chain network during COVID-19. Eng. Appl. Artif. Intell. 100, 104188.

Hadipour, M., Saffarian, S., Shafiee, M., Tahmasebi, S., 2014. Measurement and management of hospital waste in southern Iran: a case study. J. Mater. Cycles Waste Manag. 16, 747–752.

Jiménez-Lacarra, V., Martínez-Cámara, E., Santamaría-Peña, J., Jiménez-Macías, E., Bruzzone, A., Blanco-Fernández, J., 2022. Environmental Efficiency Indices in the Public Hospital Sector: A Proposal. Appl. Sci. 12, 8120.

Karimi, H., Wassan, N., Ehsani, B., Tavakkoli-Moghaddam, R., Ghodratnama, A., 2024. Optimizing COVID-19 medical waste management using goal and robust possibilistic programming. Eng. Appl. Artif. Intell. 131, 107838.

Khalid, S.K., Beattie, C., Sands, J., Jones, G., 2025. Environmental Risk Planning and Performance: A Public Healthcare Sustainability Balanced Scorecard Case Study 19.

Koohkan, P., Asadi-Gangraj, E., Nayeri, S., 2025. A comprehensive decision-making framework to configure a viable healthcare waste management system considering pollution risk: a case study. Clean Technol. Environ. Policy 27, 1271–1295.

Liu, P., Rani, P., Mishra, A.R., 2021. A novel Pythagorean fuzzy combined compromise solution framework for the assessment of medical waste treatment technology. J. Clean. Prod. 292, 126047.

Mallick, P.K., Salling, K.B., Pigosso, D.C.A., McAloone, T.C., 2022. Designing Take-Back for Single Use Medical Devices: The Case of ReturpenTM. J. Diabetes Sci. Technol. 16, 1363–1369.

Mishra, A.R., Rani, P., 2021. Multi-criteria healthcare waste disposal location selection based on Fermatean fuzzy WASPAS method. Complex Intell. Syst. 7, 2469–2484.

Mokhtari, M., Pourkosari, F., Koupal, R., Askari, R., 2023. Design and Development of Hospital Waste Management Strategies Using Quantitative Strategic Planning Matrix Technique: A Case Study in Iran. J. Environ. Health Sustain. Dev.

Ni, K., Hu, Y., Ye, X., AlZubi, H.S., Goddard, P., Alkahtani, M., 2018. Carbon Footprint Modeling of a Clinical Lab. Energies 11, 3105.

Peirov, S., Razi Astaraei, F., Saifoddin, A., Yousefi, H., 2022. Sustainable Backup Power Supply of a Hospital by Designing a Hybrid Renewable Energy System. J. Renew. Energy Environ. 9.

Peirow, S., Razi Astaraei, F., Saifoddin, A.A., Yousefi, H., 2022. Sustainable Backup Power Supply of a Hospital by Designing a Hybrid Renewable Energy System. J. Renew. Energy Environ. 9, 48–63.

Piffari, C., Lagorio, A., Pinto, R., 2023. Toward Homecare Logistics 5.0: A Systematic Literature Review, in: Borgianni, Y., Matt, D.T., Molinaro, M., Orzes, G. (Eds.), Towards a Smart, Resilient and Sustainable Industry. Springer Nature Switzerland, Cham, pp. 235–246.

Shi, Y., Wang, R., Chen, P., 2023. Multi-criteria decision-making approach for energy-efficient renovation strategies in hospital wards: Balancing energy, economic, and thermal comfort. Energy Build. 298, 113575.

Stević, Ž., Pamučar, D., Puška, A., Chatterjee, P., 2020. Sustainable supplier selection in healthcare industries using a new MCDM method: Measurement of alternatives and ranking according to COmpromise solution (MARCOS). Comput. Ind. Eng. 140, 106231.

Supsermpol, P., Chiadamrong, N., 2023. Reverse Logistics Network Design with a 3-Phase Interactive Intuitionistic Fuzzy Goal Programming Approach: A Case Study of Covid-19 in Pathum Thani, Thailand. Eng. J. 27, 27–51.

Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Br. J. Manag. 14, 207–222.

WHO, 2023. Climate Change [WWW Document]. URL https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health (accessed 5.4.26).

Yahyapour Ganji, V., Hozan, E., Babolhavaeji, P., Tajally, A., Ghanavati-Nejad, M., 2025. A robust design of a circular supply chain network based on the resilience and responsiveness dimensions: A data-driven model. Socioecon. Plann. Sci. 101, 102294.

Yenisari, B., Seker, S., 2025. Feasibility of a Hybrid ANFIS-PSO Model to Predict Medical Waste: Case Study for Istanbul. IEEE Access 13, 148330–148352.