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RESEARCH AND ANALYSIS

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Potential for industrial ecology to support healthcare sustainability

Scoping review of a fragmented literature and conceptual framework for future research

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Summary

Healthcare is a critical service sector with a sizable environmental footprint from both direct activities and the indirect emissions of related products and infrastructure. As in all other sectors, the "inside-out" environmental impacts of healthcare (e.g., from greenhouse gas emissions, smog-forming emissions, and acidifying emissions) are harmful to public health. The environmental footprint of healthcare is subject to upward pressure from several factors, including the expansion of healthcare services in developing economies, global population growth, and aging demographics. These factors are compounded by the deployment of increasingly sophisticated medical procedures, equipment, and technologies that are energy- and resource-intensive. From an "outside-in" perspective, on the other hand, healthcare systems are increasingly susceptible to the effects of climate change, limited resource access, and other external influences. We conducted a comprehensive scoping review of the existing literature on environmental issues and other sustainability aspects in healthcare, based on a representative sample from over 1,700 articles published between 1987 and 2017. To guide our review of this fragmented literature, and to build a conceptual foundation for future research, we developed an industrial ecology framework for healthcare sustainability. Our framework conceptualizes the healthcare sector as comprising "foreground systems" of healthcare service delivery that are dependent on "background product systems." By mapping the existing literature onto our framework, we highlight largely untapped opportunities for the industrial ecology community to use "top-down" and "bottom-up" approaches to build an evidence base for healthcare sustainability.

KEYWORDS

healthcare sector, healthcare sustainability, industrial ecology, literature review, medical activities, scoping review

1 | INTRODUCTION

Healthcare is a critical service sector, typically representing a large portion of spending in developed economies, with a sizable environmental footprint from both direct activities and the indirect emissions of related products and infrastructure. The combined direct and indirect greenhouse gas emissions from healthcare have been estimated at 10% of the national total in the United States (Eckelman & Sherman, 2016), 7% in Australia (Malik, Lenzen, McAlister, & McGain, 2018), 5% in the United Kingdom (NHS Sustainable Development Unit, 2016), and 4.6% in Canada (Eckelman, Sherman, & MacNeill, 2018).

Using terminology from influential business management scholars (Porter & Kramer, 2006), we conceptualize the environmental impacts of healthcare (e.g., from greenhouse gas emissions, smog-forming emissions, and acidifying emissions) as "inside-out" impacts. As in all other sectors, these "inside-out" impacts are harmful to public health. According to the aforementioned study by Eckelman and Sherman (2016), the environmental emissions from the US healthcare sector are responsible for the loss of up to 470,000 disability-adjusted life years (DALYs) annually (405,000 DALYs when adjusted for reductions in the carbon intensity of electricity generation). These figures are on par with the number of deaths from preventable medical errors in the US healthcare sector (Eckelman & Sherman, 2016). The environmental footprint of healthcare is subject to upward pressure from several factors. These include the expansion of healthcare services in developing economies, global population growth (the United Nations Department of Economic and Social Affairs, 2017 projects a global population of almost 10 billion by 2050), and aging demographics (according to the same UN report). These factors are compounded by the deployment of increasingly sophisticated medical procedures, equipment, and technologies that are energy- and resource-intensive.

On the other hand, healthcare systems are increasingly susceptible to the effects of climate change (e.g., property damage from extreme weather events and growing demand for treatment of heat-related illnesses), limited resource access (e.g., due to supply disruptions of "critical raw materials" like specialized metals and alloys used in complex medical devices and equipment), and other external influences. Based on the terminology from Porter and Kramer (2006), we conceptualize these external influences as "outside-in" impacts *on* healthcare.

There is a growing research and policy interest regarding environmental issues and other sustainability aspects in healthcare (e.g., in the World Health Organization, 2017; the World Bank, 2017; and the Lancet Commission on Climate Change and Health, Watts et al., 2017). In April 2018, the Workshop on Environmental Sustainability in Clinical Care, co-hosted by Yale University and New York University (henceforth referred to as "the Yale Workshop"), brought together experts from around the world, including three of the authors[1], to discuss the state of the art and highlight future research directions (Thiel et al., 2018). At the Yale Workshop, we presented preliminary results from the work contributed in this article—a comprehensive scoping review of the existing literature on healthcare sustainability, based on a representative sample from over 1,700 articles published between 1987 and 2017. Although most of the literature we collected is focused on environmental and resource-related issues, we aimed at capturing a wide range of sustainability aspects, including economic and social dimensions to a limited extent.

This article is structured as follows. We begin by explaining the methodology of our *scoping review*—a relatively new type of literature review that is similar to, but not the same as, a systematic review—including the literature search protocol, inclusion criteria, and content analysis. In a departure from the conventional scoping review methodology, we incorporate a novel application of a basic statistical inference technique—stratified random sampling—to obtain a representative sample of 157 articles for review. To guide content analysis of the existing literature, and to build a conceptual foundation for future research, we developed an industrial ecology framework for healthcare sustainability. Our framework conceptualizes the healthcare sector as comprising "foreground systems" of healthcare service delivery that are dependent on "background product systems." By mapping the existing literature onto our framework, we highlight largely untapped opportunities for the industrial ecology community to use "top-down" and "bottom-up" approaches to build an evidence base for healthcare sustainability.

2 | METHODS

To build a comprehensive overview of the existing literature on healthcare sustainability, we applied a variation of a relatively new literature review methodology—the *scoping review*. Scoping reviews are similar to, but not the same as, systematic reviews. Although both methods follow a systematic protocol for collecting and analyzing relevant literature, they serve different purposes. Systematic reviews aim to synthesize the collective body of evidence regarding a specific question(s)—for example, the efficacy of a particular medical intervention (Peters et al., 2015) or the life cycle environmental impacts of a specific product type (Zumsteg, Cooper, & Noon, 2012). Scoping reviews are more exploratory in nature, with the aim of "mapping" broad fields of literature, highlighting gaps in the existing knowledge base, and prioritizing directions for future research (Peters et al., 2015). This was precisely our aim with respect to the burgeoning field of healthcare sustainability.

Following the scoping review methodology developed by Peters et al. (2015) and outlined in Figure 1, we conducted systematic literature searches via two large international databases: Scopus and PubMed. Although most of the literature we collected is focused on environmental and resource-related issues, we aimed at capturing a wide range of sustainability aspects, including economic and social dimensions to a limited extent (see Supporting Information S1 on the Journal's website). We excluded broader considerations of wellbeing, social equity, access to healthcare, and financial sustainability. These topics are important, but beyond the scope of our industrial ecology framework. Search phrases were constructed by combining "sustainability-related" keywords with "healthcare-related" keywords. "Sustainability-related" keywords included generic terms like *environment*, *sustainability*, and *social responsibility*, along with more specific keywords like *carbon footprint*, *energy efficiency*, *environmental management*, *waste management*, *life cycle assessment*, and *material flow analysis*. Boolean operators were used to capture synonyms (e.g., *carbon footprint* OR *greenhouse gas** OR *climate change* OR *global warming*) and related words (e.g., *sustainab** captures terms like *sustainable*, *sustainability*, and *sustainable development*). Similarly, "healthcare-related" keywords included generic terms (e.g., *healthcare* OR *health care*, *medic**, *clinic**, *surger** OR *surgical*)

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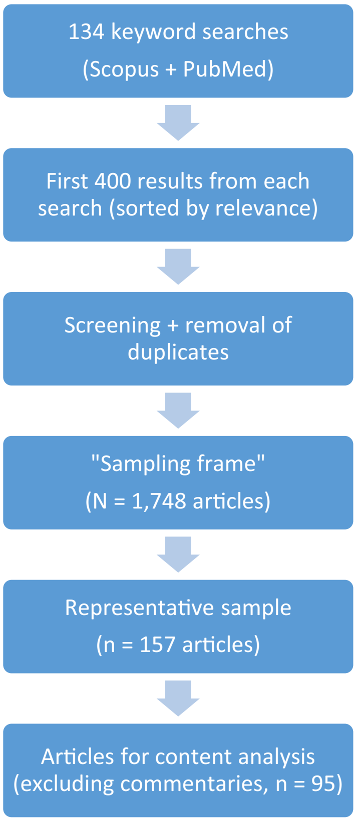

FIGURE 1 Scoping review flow diagram

and specific keywords (e.g., *X-ray*, *ultrasound*, *magnetic resonance imaging*, *medical device**, *long-term care*, *prevent** *care*, and *pharmaceutical**). When searching the PubMed database, which is oriented toward the health sciences and medicine, only "sustainability-related" keywords were used. Using the PubMed database helped capture any relevant literature we may have missed when searching the Scopus database. In all, we conducted 134 literature searches between September 29 and November 17, 2017 (details in Supporting Information S2).

We screened the first 400 results from each search (sorted by relevance) according to the following inclusion criteria. First, our review was limited to academic journal articles published from 1987 onward (i.e., corresponding to the landmark "Brundtland report" and available in English (World Commission on Environment and Development [WCED], 1987). Although the lack of "grey literature" in our review is a limitation, restricting our scope to academic journal articles provided us with a "sampling frame" comprising documents of similar format (i.e., every article we reviewed has an academic journal title attached to it). This enabled us to analyze basic characteristics of the *academic* literature on healthcare sustainability (e.g., the distribution of publications between journal titles and between the subject matter classifications in the Scopus database). It also facilitated a novel application of a basic statistical inference technique—stratified random sampling—to our scoping review methodology (as further explained in the following paragraphs). To keep our scope limited to healthcare services provided for *human* patients, we excluded literature on veterinary care. We included editorials and commentary articles, as these are part of the healthcare sustainability discourse—especially in medical and health science journals. We did not, however, conduct full content analysis on these documents, as they do not make substantive contributions to healthcare sustainability research.

Screening of search results based on our inclusion criteria, along with removal of duplicates, yielded a list of 1,748 articles. Although conventional systematic and scoping review protocols include separate steps for screening and removal of duplicates, given the broad coverage of literature we aimed for, and the large number of literature searches we conducted (134 in total), we conducted these steps in parallel. We imported search results from the Scopus and PubMed databases into a spreadsheet, in which we removed duplicates along with search results that did not meet our inclusion criteria (e.g., book chapters, non-academic articles, articles not available in English, and articles published before 1987). We do not see the lack of separate steps as a limitation, as duplicates must be removed in any case, and they have no bearing on our inclusion criteria or on the final results of our scoping review. Moreover, our literature search protocol (see details of keyword searches in Supporting Information S2) and inclusion criteria (as outlined above, with further details on "sustainability aspects" in Supporting Information S1) are described in sufficient detail to be replicable by an independent researcher.

As mentioned earlier, our biggest departure from the conventional scoping review methodology was our novel application of a basic statistical inference technique—stratified random sampling—to representatively understand the content of the literature we collected based on a relatively small subset of this literature. It is impractical to read over 1,700 articles—especially given the time-sensitive nature of a systematic or scoping review (i.e., new literature continues to be published while the review is conducted, thus diminishing the timeliness and value of the review). The conventional approach is to limit the scope of the review through the inclusion and exclusion criteria (Peters et al., 2015). For example, Godfrey et al. (2013) conducted a scoping review of "homecare safety and medication management with older adults." The scope of the review was limited by participant characteristics (i.e., "older adults," defined as individuals aged 65 and older), key concepts (i.e., medication management), and contextual factors (i.e., in-home care). Following the initial screening of search results based on the *inclusion* criteria, the conventional scoping review methodology described by Peters et al. (2015) also includes a step in which additional *exclusion* criteria are applied to narrow the collected literature down to a manageable selection of relevant articles for review.

Our review was significantly broader than a conventional systematic review, or even a conventional scoping review. The 1,748 articles we collected through our search protocol comprised our literature "sampling frame." Theoretically, the "population" for our review would have comprised *all* relevant literature on healthcare sustainability. Our sampling frame is an imperfect, but reasonably robust, representation of this literature population, subject to the limitations of our search protocol—including the coverage of the databases searched, the keyword search phrases used, and the inclusion criteria applied.

Within our literature sampling frame, we applied a stratified random sampling approach using journal "subject clusters" in the Scopus database: life sciences, social sciences, physical sciences, and health sciences. To ensure that each article was classified into only one subject cluster, we created a fifth subject cluster, termed "cross-disciplinary," to capture journals classified under more than one of the first four subject clusters. We assigned each of the 1,748 articles a random number, and then sorted the articles by these numbers (in ascending order). We obtained a representative sample of 157 articles by selecting articles (in the randomized order) from each subject cluster (serving as a "stratum" in sampling terminology) such that the distribution of articles between subject clusters reflected that of our "sampling frame" of 1,748 articles.

Although it cannot overcome the limitations of our literature sampling frame as discussed in the preceding paragraphs, random sampling is a well-established, scientifically sound technique (as described in statistics textbooks such as DeVeaux, Velleman, Bock, Vukov, & Wong, 2015) that supports statistical *inference* about the sampling frame without the need to review all the literature contained within it. Randomization avoids sampling bias and ensures that, to a specified degree of uncertainty, the sample is representative of the sampling frame from which it is drawn. *Stratifying* the sample according to identifiable "sub-populations" (e.g., journal "subject clusters" in our case) improves upon simple random sampling by ensuring that these "sub-populations" are proportionally represented in the sample (DeVeaux et al., 2015). Supporting Information S3 describes our literature sampling frame in terms of the distribution of publications over time and between the subject matter classifications in the Scopus database. It can be seen that the existing healthcare sustainability literature is highly fragmented—being spread out over hundreds of academic journals in a wide variety of fields. Over 700 articles were published in journals with fewer than three relevant articles each. As discussed in the Yale Workshop, this fragmentation makes it difficult to target appropriate audiences for the dissemination of healthcare sustainability research. It can also complicate the publishing process, as reviewers and journal editors—particularly in medicine—may not be familiar with this burgeoning field.

To guide content analysis on our literature sample of 157 articles, and to build a conceptual foundation for future research, we developed an industrial ecology framework for healthcare sustainability. We refined our framework based on feedback from participants at the Yale Workshop, as well as discussions with colleagues in the fields of medicine and healthcare management. As illustrated in Figure 2, our framework conceptualizes the healthcare sector as comprising "foreground systems" of healthcare service delivery (e.g., hospital campuses, ambulatory surgery centers, clinics, and laboratories) in which medical activities (e.g., diagnostic imaging and operating room procedures) and "supporting" activities (e.g., building maintenance, hospital food services, and healthcare waste management) take place (details in Supporting Information S1).

The "foreground systems" have physical exchanges with "background product systems." On the input side, background product systems supply energy (in the form of electricity and fuels), materials, chemicals (including active pharmaceutical ingredients and compounds), devices, equipment, and infrastructure used to provide healthcare services. On the output side, background product systems facilitate "end-of-life" management (e.g., through contracted waste management services and reprocessing of used medical devices).

Our framework incorporates the "inside-out" impacts *of* foreground and background systems (e.g., from greenhouse gas emissions, smog-forming emissions, and acidifying emissions), along with the "outside-in" impacts of external influences *on* these systems (e.g., property damage from extreme weather events, growing demand for treatment of heat-related illnesses, and supply disruptions of critical raw materials like specialized metals and alloys used in complex medical devices and equipment).

Finally, our framework recognizes that foreground and background systems are subject to the legal and regulatory contexts of the jurisdictions in which they operate. Healthcare-related laws and regulations (e.g., pertaining to critical issues like healthcare waste management, environmental protection, workplace health and safety, and infection control) vary from country to country (as well as within countries), and are a key influence on physical flows associated with healthcare (as seen, e.g., in the literature on healthcare waste management and the trend toward single-use medical devices and supplies).

As illustrated in Figure 3, and further discussed in the next section, we mapped the existing healthcare sustainability literature onto our framework by coding each of the 95 research articles (i.e., excluding the 62 articles we coded as "commentaries") in our literature sample according to categories of medical activities, supporting activities, and background product systems. We also coded the articles based on the "inside-out" and/or "outside-in" sustainability aspects addressed. Coding the articles in this way enabled us to analyze the distribution of literature in relation to our

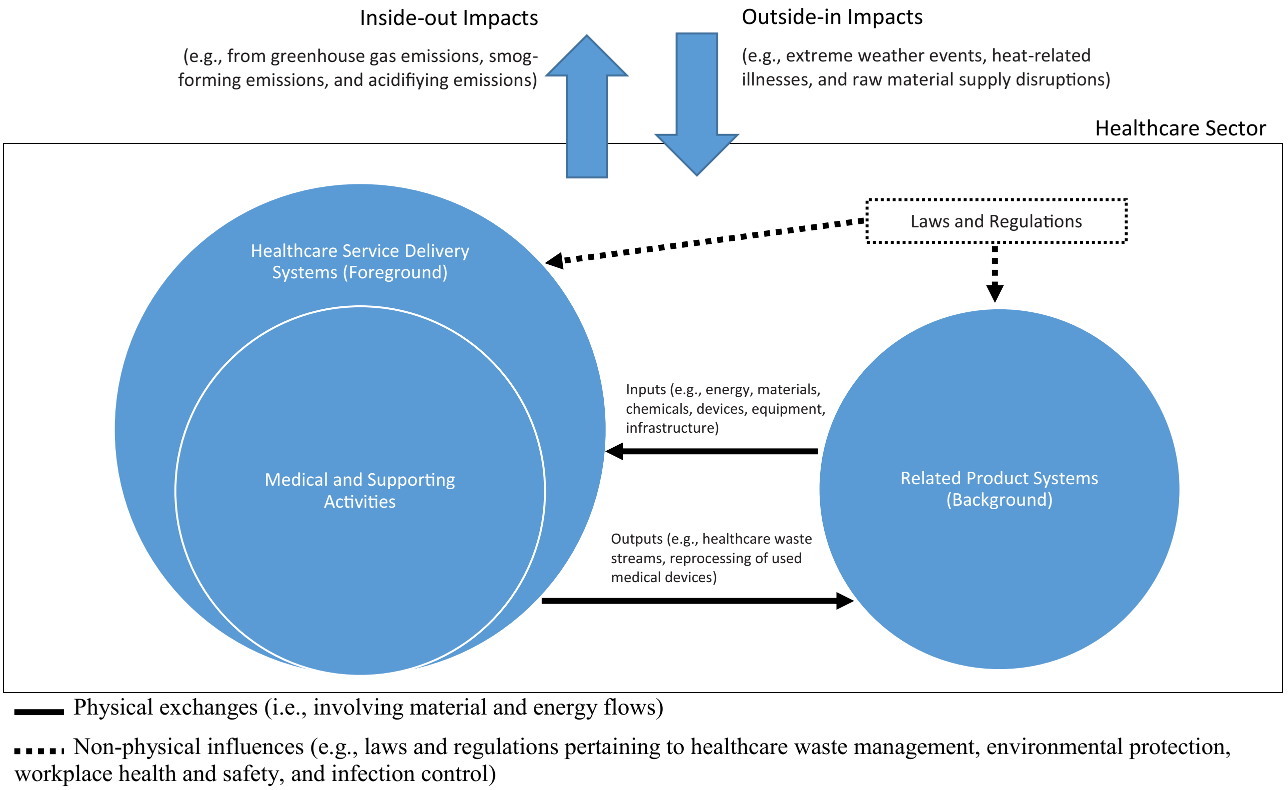

FIGURE 2 Industrial ecology framework for healthcare sustainability

framework (i.e., the percentage of articles coded in each category). As explained earlier, our literature sample was designed to be representative of our full "sampling frame" of 1,748 articles collected through our literature search protocol. We therefore *inferred* the "true" distribution of literature based on our sample. As described in Supporting Information S4, we constructed 95% confidence intervals for the percentages. Precise descriptions of our coding categories are provided in Supporting Information S1. A complete list of the 157 articles analyzed, with bibliographic information and coding, is provided in Supporting Information S5.

3 | RESULTS

Through the lens of our industrial ecology framework, two major gaps are evident in the existing healthcare sustainability literature. First, many components of our framework, including important medical activities, supporting activities, and background product systems, are understudied from a sustainability perspective. Second, the existing literature is limited by the narrow scope of sustainability aspects addressed.

As can be seen in Figure 3, there is relatively little literature that explicitly examines sustainability aspects of specific medical activities. Exceptions include studies of energy use in diagnostic imaging (Burke & Stowe, 2015; Esmaeili et al., 2015), which constitute about 1.3% (±1.8 percentage points[2]) of the 1,748 articles we collected, along with a growing interest in LCA studies of operating room procedures (e.g., a study of hysterectomies by Thiel et al., 2015 and a study of birthing procedures by Campion et al., 2012), which constitute about 2.5% (±2.5 percentage points). There is a paucity of literature regarding sustainability aspects of consults, pharmacy services, hospitalization, ambulance services, and medical research. These activities may not be equally important from a sustainability perspective (e.g., consults are likely to be less resource- and energy-intensive than operating room procedures), but without further study, this is difficult to gauge. Indeed, part of the purpose of industrial ecology tools, like LCA and economic input–output analysis, is to highlight "hotspots" of resource use and environmental impacts. Based on the existing literature, the "hotspots" of healthcare are not well understood. Of particular concern is the lack of literature on pharmacy services, inpatient hospitalization (particularly in emergency rooms and intensive care units), and ambulance services. These are important medical activities, and their sustainability aspects are probably not trivial.

[2] In this case, the margin of error is larger than the estimated percentage of articles in this category. With 95% confidence, the "true" percentage (i.e., of all 1,748 articles in our literature sampling frame) could be as large as 3.1% (i.e., 1.3% + 1.8%), or it could be close to 0%).

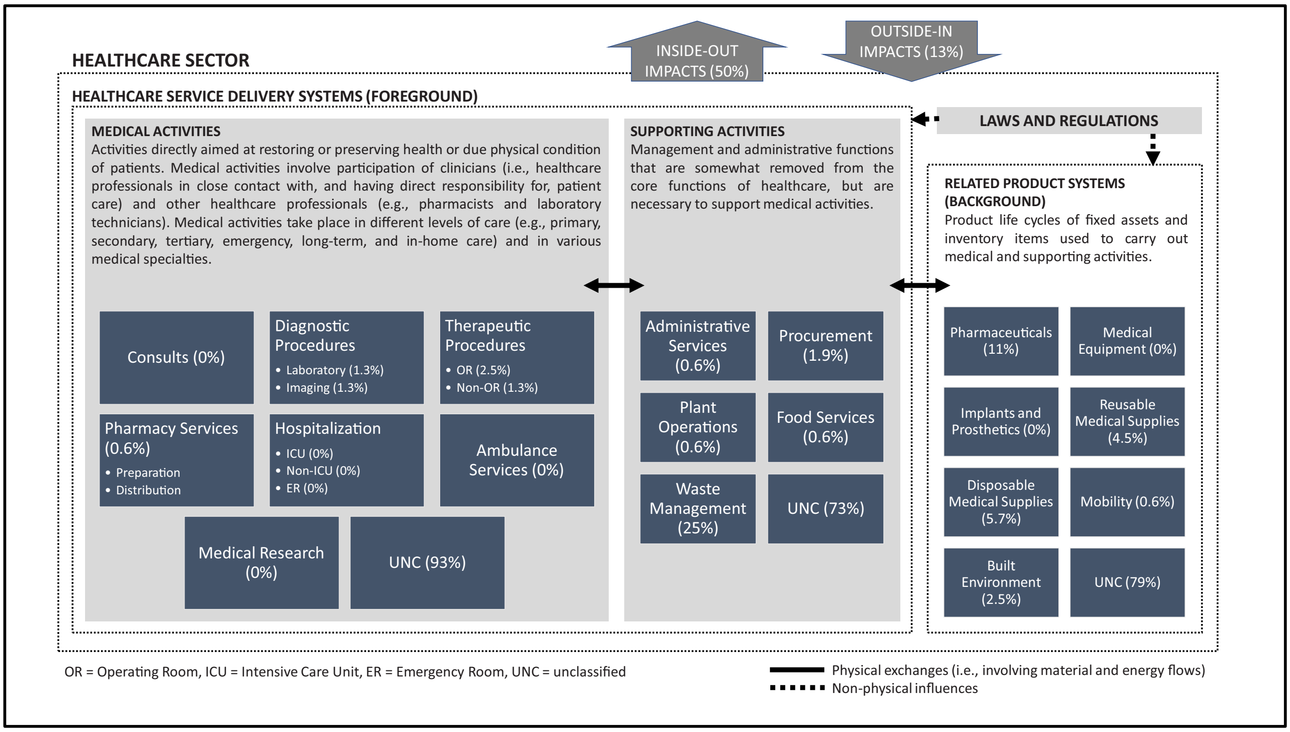

FIGURE 3 Distribution of healthcare sustainability literature ($n = 157$ articles) in relation to our industrial ecology framework. The "true" distribution of literature (i.e., the actual percentages [of $N = 1{,}748$ articles] in each category) was inferred from the sample. For simplicity, margins of error (provided in Supporting Information S4) are omitted from this figure. For several reasons, the percentages do not sum to 100%. First, coding categories (including categories of medical activities, supporting activities, background product systems, and "inside-out" vs. "outside-in" impacts) are not mutually exclusive (i.e., the same article may be coded under multiple categories). Second, the percentages of "inside-out" and "outside-in" impacts shown here are totals out of our sample of 157 articles; they are not tied to any categories of medical activities, supporting activities, or background product systems. Finally, 62 articles were coded as "commentaries" and excluded from content analysis; therefore, these articles are not captured in the "inside-out" and "outside-in" percentages. A value of 0% does not necessarily mean that there is no literature in that category (although that is a possibility); it means that there is no such literature in our sample

With the notable exception of healthcare waste management (25% ± 6.8 percentage points), "supporting" activities are also understudied. The literature on healthcare waste management includes, but is not limited to, reviews of legal and regulatory requirements (Takatsuki, 2000; Haylamicheal & Desalegne, 2012; Botelho, 2013), surveys and case studies of healthcare waste management attitudes and practices (Idowu, Alo, Atherton, & Al Khaddar, 2013; Ul Rahman, Hameed, Shahjehan, Ayyaz, & Kha et al., 2017; Askarian, Vakili, & Kabir, 2004; Aseweh Abor & Bouwer, 2008; Saad, 2013; Thiel, Duncan, & Woods, 2017; Jovanović, Manojlović, Jovanović, Matić, & Đonović, 2016; Gupta et al., 2014), waste audits (Patwary et al., 2009; Voudrias, Goudakou, Kermenidou, & Softa, 2012; Suwannee, 2002; Komilis, Brat, Makary, 2011; Saad, 2013; Majid & Umrani, 2006; Patil & Pokhrel, 2005), and toxicological studies of healthcare wastes (Gupta, Mathur, Bhatnagar, Nagar, & Srivastava, 2009). The evident focus on waste management probably reflects the visibility of this issue, the large volumes of waste generated in healthcare services (e.g., the US healthcare sector generates about 1.7 million tons of solid waste annually [United States Environmental Protection Agency, 2005]), and the complex legal and regulatory aspects related to medical waste.

With regard to "background product systems," the categories with the most coverage in the literature include pharmaceuticals (11% ± 4.9 percentage points), reusable medical supplies (4.5% ± 3.2 percentage points), and disposable medical supplies (5.7% ± 3.6 percentage points). Sustainability aspects of active pharmaceutical ingredients and compounds are related to production of these chemical products (Raymond, Slater, & Savelski, 2010; Van der Vorst, Dewulf, Aelterman, De Witte, & Van Langenhove, 2011; Van der Vorst et al., 2010) and their effects when released into the environment (Derksen, Rijs, & Jongbloed, 2004; Straub, 2016). The literature on reusable and disposable medical supplies includes comparative LCAs, for example, of disposable and reusable laryngeal mask airways (Eckelman, Mosher, Gonzalez, & Sherman, 2012) and of metered dose inhalers and electric nebulizers (Goulet, Olson, & Mayer, 2017). There is a paucity of literature on production of medical equipment, materials and manufacturing of implants and prosthetics, and mobility of patients and staff.

The existing literature on healthcare sustainability is also limited by its narrow coverage of sustainability aspects. As can be seen in Figure 3, the "inside-out" impacts *of* healthcare (50% ± 7.8 percentage points) have received significantly more coverage than "outside-in" impacts *on* healthcare (13% ± 5.2 percentage points). Supporting Information S4 provides a more detailed analysis of the sustainability aspects addressed in relation to medical activities, supporting activities, and background product systems. Most of these sustainability aspects (e.g., common environmental LCA impact categories like acidification, eutrophication, and ecotoxicity) can be considered "inside-out," though some aspects, like climate change, can be either "inside-out" (i.e., greenhouse gas emissions from healthcare) or "outside-in" (i.e., effects of climate change like extreme weather events and heat-related illnesses). Overall, energy use (11% ± 4.9 percentage points) and climate change (18% ± 6.0 percentage points) have received the most coverage of all sustainability aspects considered in our review. While energy use and climate change are important issues, other environmental and social aspects, like smog-forming emissions, acidifying emissions, and labor practices in healthcare supply chains, are often overlooked. "Outside-in" impacts, particularly in terms of resource-related issues like supply disruption risks of critical raw materials, are also underexplored.

4 | DISCUSSION AND CONCLUSIONS

We have conducted a timely and comprehensive scoping review of the existing literature on healthcare sustainability. Previous limited reviews have been conducted in this space—for example, a review of recycling and waste management practices by Kwakye et al. (2011), a review of environmental sustainability in hospitals (mostly focused on what are considered "foreground" activities in our framework) by McGain and Naylor (2014), a review of pharmaceutical sustainability by De Soete, Jiménez-González, Dahlin, & Dewulf (2017), and a review of environmental considerations in health technology assessment by Polisena, De Angelis, Kaunelis, & Gutierrez-Ibarluzea (2018). Nonetheless, to the best of our knowledge, our review is the broadest survey to date—using a wide range of keyword searches—of this fragmented literature.

There are limitations to our review. First, our "sampling frame" of 1,748 articles is an imperfect representation of the existing literature on healthcare sustainability, subject to the limitations of the databases searched (no database is fully comprehensive) and the keyword search phrases used (which reflect our limited perspective, knowledge, and understanding). Given that we limited our scope to academic journal articles, "grey literature," such as the carbon footprinting reports of the UK NHS Sustainable Development Unit, was not covered. Our review was also limited to a static snapshot of literature published between 1987 and 2017, with the last search conducted on November 17, 2017. Consequently, our review does not cover the most recent advancements in this burgeoning field.

Second, our review does not provide complete coverage of our literature sampling frame. Content analysis was conducted on only a relatively small subset of the 1,748 articles we collected through our literature search protocol. When interpreting the results of our literature "mapping" analysis (i.e., the category percentages in Figure 3), a value of 0% does not necessarily mean that there is no literature in that category (although that is a possibility); it means that there is no such literature *in our sample*. Nonetheless, our stratified random sampling design avoids sampling bias and ensures that the 157 articles we reviewed are *representative* of the 1,748 articles in our sampling frame. Therefore, the "true" distribution of literature (i.e., the actual percentages of articles in each category) can be *inferred* from the sample (subject to the margins of error).

Limitations notwithstanding, our review highlights largely untapped opportunities for the industrial ecology community to use "top-down" and "bottom-up" approaches to build an evidence base for healthcare sustainability. "Top-down" approaches can begin with a high-level overview of national or regional healthcare sectors to prioritize "hotspots" for deeper investigation. In their economic input–output analysis of the US healthcare sector, Eckelman and Sherman (2016) assessed the contributions of greenhouse gas emissions by National Health Expenditure (NHE) categories and economic sectors. The largest contributors by NHE category were Hospital Care (36%), Physician and Clinical Services (12%), and Prescription Drugs (10%). Contribution analysis by sector revealed that only 2.5% of greenhouse gas emissions were directly attributable to the activities of healthcare facilities (e.g., from onsite boilers). The overwhelming majority of healthcare's "carbon footprint" was attributed to the "embodied" emissions of purchased energy, goods, and services—termed "background product systems" in our framework. Similar observations were made for other environmental impact categories, and for the Canadian healthcare sector (Eckelman et al., 2018). Starting from this highly aggregated analysis, other industrial ecology tools, like material flow analysis and LCA, could be used to "zoom in" on healthcare service delivery systems (e.g., hospital campuses), and the activities conducted therein (many of which are evidently understudied based on our review). There is also considerable scope for further investigation of background product systems (e.g., LCAs of medical equipment, implants, and prosthetics).

Using "bottom-up" approaches, relatively granular LCAs of medical activities, supporting activities, and background product systems can be scaled up to "feed" into large-scale sector overviews like those conducted by Eckelman and Sherman (2016) and Eckelman et al. (2018). To our knowledge, large-scale healthcare "footprinting" studies have only been conducted for a limited number of developed countries—the United States (Eckelman & Sherman, 2016), the United Kingdom (NHS Sustainable Development Unit, 2016), Australia (Malik et al., 2018), and Canada (Eckelman et al., 2018)—and are often limited to "carbon footprints" rather than a wide range of environmental impact categories. It would be valuable to conduct similar studies in other parts of the world (e.g., in the EU, Japan, and developing countries), to broaden the scope of sustainability aspects addressed (including "inside-out" and "outside-in" impacts), and to update the analyses as new data become available.

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REFERENCES

Abor, P. A., & Bouwer A. (2008). Medical waste management practices in a Southern African hospital. *International Journal of Health Care Quality Assurance*, *21*(4), 356–364.

Askarian, M., Vakili, M., & Kabir G. (2004). Results of a hospital waste survey in private hospitals in Fars province, Iran. *Waste Management*, *24*(4), 347–352.

Botelho, A. (2013). The impact of regulatory compliance behavior on hazardous waste generation in European private healthcare facilities. *Waste Management and Research*, *31*(10), 996–1001.

Burke, N. P., & Stowe, J. (2015). Energy efficiency in the radiography department: An Irish perspective. *Radiography*, *21*(2), 150–153.

Campion, N., Thiel, C. L., DeBlois, J., Woods, N. C., Landis, A. E., & Bilec, M. M. (2012). Life cycle assessment perspectives on delivering an infant in the US. *Science of the Total Environment*, *425*, 191–198.

De Soete, W., Jiménez-González, C., Dahlin, P., & Dewulf, J. (2017). Challenges and recommendations for environmental sustainability assessments of pharmaceutical products in the healthcare sector. *Green Chemistry*, *19*(15), 3493–3509.

Derksen, J. G. M., Rijs, G. B. J., & Jongbloed, R. H. (2004). Diffuse pollution of surface water by pharmaceutical products. *Water Science and Technology*, *49*(3), 213–221.

DeVeaux, R. D., Velleman, P. F., Bock, D. E., Vukov, A. M., & Wong, A. C. M. (2015). *Stats: Data and models* (2nd Canadian ed). Toronto, ON, Canada: Pearson.

Eckelman, M. J., Mosher, M., Gonzalez, A., & Sherman, J. D. (2012). Comparative life cycle assessment of disposable and reusable laryngeal mask airways. *Anesthesia and Analgesia*, *114*(5), 1067–1072.

Eckelman, M. J., & Sherman, J. D. (2016). Environmental impacts of the U.S. health care system and effects on public health. *PLOS One*, *11*(6), e0157014.

Eckelman, M. J., Sherman, J. D., & MacNeill, A. J. (2018). Life cycle environmental emissions and health damages from the Canadian healthcare system: An economic-environmental-epidemiological analysis. *PLOS Medicine*, *15*(7), e1002623.

Esmaeili, A., Twomey, J. M., Overcash, M. R., Soltani, S. A., McGuire, C., & Ali, K. (2015). Scope for energy improvement for hospital imaging services in the USA. *Journal of Health Services Research and Policy*, *20*(2), 67–73.

Godfrey, C. M., Harrison, M. B., Lang, A., Macdonald, M., Leung, T., & Swab, M. (2013). Homecare safety and medication management with older adults: A scoping review of the quantitative and qualitative evidence. *JBI Database of Systematic Reviews and Implementation Reports*, *11*(7), 82–130.

Goulet, B., Olson, L., & Mayer, B. (2017). A comparative life cycle assessment between a metered dose inhaler and electric nebulizer. *Sustainability*, *9*(10), 1725.

Gupta, P., Mathur, N., Bhatnagar, P., Nagar, P., & Srivastava, S. (2009). Genotoxicity evaluation of hospital wastewaters. *Ecotoxicology and Environmental Safety*, *72*(7), 1925–1932.

Gupta, S. C., Gupta, O. P., Verma, Y. S., Ahmad, I., Kumar, D. P., & Srivastava, S. P. (2014). Knowledge, attitude and practices of health care professionals regarding biomedical waste management in Indian oral pathology laboratories. *Research Journal of Pharmaceutical, Biological and Chemical Sciences*, *5*(4), 40–49.

Haylamicheal, I. D., & Desalegne, S. A. (2012). A review of legal framework applicable for the management of healthcare waste and current management practices in Ethiopia. *Waste Management and Research*, *30*(6), 607–618.

Idowu, I., Alo, B., Atherton, W., & Al Khaddar, R. (2013). Profile of medical waste management in two healthcare facilities in Lagos, Nigeria: A case study. *Waste Management and Research*, *31*(5), 494–501.

Jovanović, V., Manojlović, J. M., Jovanović, D., Matić, B., & Đonović, N. (2016). Management of pharmaceutical waste in hospitals in Serbia: Challenges and the potential for improvement. *Indian Journal of Pharmaceutical Education and Research*, *50*(4), 695–702.

Komilis, D., Katsafaros, N., & Vassilopoulos, P. (2011). Hazardous medical waste generation in Greece: Case studies from medical facilities in Attica and from a small insular hospital. *Waste Management and Research*, *29*(8), 807–814.

Kwakye, G., Brat, G. A., & Makary, M. A. (2011). Green surgical practices for health care. *JAMA Archives of Surgery*, *146*(2), 131–136.

Majid, R. & Umrani, T. (2006). Hospital waste generation and management in a tertiary care hospital in Quetta. *Medical Forum Monthly*, *17*(5), 2–7.

Malik, A., Lenzen, M., McAlister, S., & McGain, F. (2018). The carbon footprint of Australian health care. *The Lancet Planetary Health*, *2*(1), e27–e35.

McGain, F., & Naylor, C. (2014). Environmental sustainability in hospitals: A systematic review and research agenda. *Journal of Health Services Research and Policy*, *19*(4), 245–252.

NHS Sustainable Development Unit. (2016). Carbon footprint update for NHS in England 2015. https://www.sduhealth.org.uk/policy-strategy/reporting/nhs-carbon-footprint.aspx

Patil, G. V., & Pokhrel, K. (2005). Biomedical solid waste management in an Indian hospital: A case study. *Waste Management*, *25*(6), 592–599.

Patwary, M. A., O'Hare, W. T., Street, G., Maudood Elahi, K., Hossain, S. S., & Sarker, M. H. (2009). Quantitative assessment of medical waste generation in the capital city of Bangladesh. *Waste Management*, *29*(8), 2392–2397.

Peters, M. D. J., Godfrey, C. M., Khalil, H., McInerney, P., Parker, D., & Soares, C. B. (2015). Guidance for conducting systematic scoping reviews. *International Journal of Evidence-Based Healthcare*, *13*(3), 141–146.

Polisena, J., De Angelis, G., Kaunelis, D., & Gutierrez-Ibarluzea, I. (2018). Environmental impact assessment of a health technology: a scoping review. *International Journal of Technology Assessment in Health Care*, *34*(3), 317–326.

Porter, M. E., & Kramer, M. R. (2006). Strategy & society: The link between competitive advantage and corporate social responsibility. *Harvard Business Review*, *84*(12), 78–92.

Raymond, M. J., Slater, C. S., & Savelski, M. J. (2010). LCA approach to the analysis of solvent waste issues in the pharmaceutical industry. *Green Chemistry*, *12*(10), 1826–1834.

Saad, S. A. G. (2013). Management of hospitals solid waste in Khartoum State. *Environmental Monitoring and Assessment*, *185*(10), 8567–8582.

Straub, J. O. (2016). Reduction in the environmental exposure of pharmaceuticals through diagnostics, personalised healthcare and other approaches: A mini review and discussion paper. *Sustainable Chemistry and Pharmacy*, *3*, 1–7.

Suwannee, A. (2002). Study on waste from hospital and clinics in Phitsanulok. *Online Journal of Health and Allied Sciences*, *1*(3), 6–14.

Takatsuki, H. (2000). Appropriate disposal of medical wastes—According to the manual on disposal of infectious wastes. *Rinsho Byori: The Japanese Journal of Clinical Pathology S*, *112*, 1–5.

Thiel, C. L., Duncan, P., & Woods, N. C. (2017). Attitude of US obstetricians and gynaecologists to global warming and medical waste. *Journal of Health Services Research and Policy*, *22*(3), 162–167.

Thiel, C. L., Eckelman, M., Guido, R., Huddleston, M., Landis, A. E., Sherman, J., Shrake, S. O., Copley-Woods, N., & Bilec, M. M. (2015). Environmental impacts of surgical procedures: Life cycle assessment of hysterectomy in the United States. *Environmental Science and Technology*, *49*(3), 1779–1786.

Thiel, C. L., MacNeill, A. J., Bialowitz, J., Bilec, M. M., Costello, A., Dubrow, R., Eckelman, M., et al. (2018). *The Green Print: Agenda for the advancement of environmental sustainability in healthcare*. New Haven, CT: Yale University.

Ul Rahman, T., Hameed, S., Shahjehan Ayyaz, S., & Khan, R. M. A. (2017). Knowledge and attitude of nurses regarding healthcare waste management practices in a tertiary care hospitals of Lahore. *Pakistan Journal of Medical and Health Sciences*, *11*(2), 739–741.

United Nations Department of Economic and Social Affairs. (2017). World population prospects. https://esa.un.org/unpd/wpp/Publications/Files/WPP2017_KeyFindings.pdf

United States Environmental Protection Agency. (2005). *Profile of the healthcare industry*. Washington, DC: United States Environmental Protection Agency.

Van der Vorst, G., Dewulf, J., Aelterman, W., De Witte, B., & Van Langenhove, H. (2011). A systematic evaluation of the resource consumption of active pharmaceutical ingredient production at three different levels. *Environmental Science and Technology*, *45*(7), 3040–3046.

Van der Vorst, G., Swart, P., Aelterman, W., Van Brecht, A., Graauwmans, E., Van Langenhove, H., & Dewulf, J. (2010). Resource consumption of pharmaceutical waste solvent valorization alternatives. *Resources, Conservation and Recycling*, *54*(12), 1386–1392.

Voudrias, E., Goudakou, L., Kermenidou, M., & Softa, A. (2012). Composition and production rate of pharmaceutical and chemical waste from Xanthi General Hospital in Greece. *Waste Management*, *32*(7), 1442–1452.

Watts, N., Adger, W. N., Ayeb-Karlsson, S., Bai, Y., Byass, P., Campbell-Lendrum, D., … Costello, A. (2017). The Lancet Countdown: Tracking progress on health and climate change. *The Lancet*, *389*(10074), 1151–1164.

World Commission on Environment and Development (WCED). (1987). Our common future. Oxford, UK: Oxford University Press.

World Bank. (2017). *Climate-smart healthcare: Low-carbon and resilience strategies for the health sector*. Washington, DC: World Bank.

World Health Organization. (2017). *Environmentally sustainable health systems: Strategic document*. Copenhagen, Denmark: World Health Organization.

Zumsteg, J. M., Cooper, J. S., & Noon, M. S. (2012). Systematic review checklist: A standardized technique for assessing and reporting reviews of life cycle assessment data. *Journal of Industrial Ecology 16*, S12–S21.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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