Strategies and tactics to reduce the impact of healthcare on climate change: systematic review

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ABSTRACT

OBJECTIVE
To review the international literature and assess the ways healthcare systems are mitigating and can mitigate their carbon footprint, which is currently estimated to be more than 4.4% of global emissions.

DESIGN
Systematic review of empirical studies and grey literature to examine how healthcare services and institutions are limiting their greenhouse gas (GHG) emissions.

DATA SOURCES
Eight databases and authoritative reports were searched from inception dates to November 2023.

ELIGIBILITY CRITERIA FOR SELECTING STUDIES
Teams of investigators screened relevant publications against the inclusion criteria (eg, in English; discussed impact of healthcare systems on climate change), applying four quality appraisal tools, and results are reported in accordance with PRISMA (preferred reporting items for systematic reviews and meta-analyses).

RESULTS
Of 33 737 publications identified, 32 998 (97.8%) were excluded after title and abstract screening; 536 (72.5%) of the remaining publications were excluded after full text review. Two additional papers were identified, screened, and included through backward citation tracking. The 205 included studies applied empirical (n=88, 42.9%), review (n=60, 29.3%), narrative descriptive (n=53, 25.9%), and multiple (n=4, 2.0%) methods. More than half of the publications (51.5%) addressed the macro level of the healthcare system. Nine themes were identified using inductive analysis: changing clinical and surgical practices (n=107); enacting policies and governance (n=97); managing physical waste (n=83); changing organisational behaviour (n=76); actions of individuals and groups (eg, advocacy, community involvement; n=74); minimising travel and transportation (n=70); using tools for measuring GHG emissions (n=70); reducing emissions related to infrastructure (n=63); and decarbonising the supply chain (n=48).

CONCLUSIONS
Publications presented various strategies and tactics to reduce GHG emissions. These included changing clinical and surgical practices; using policies such as benchmarking and reporting at a facility level, and financial levers to reduce emissions from procurement; reducing physical waste; changing organisational culture through workforce training; supporting education on the benefits of decarbonisation; and involving patients in care planning. Numerous tools and frameworks were presented for measuring GHG emissions, but implementation and evaluation of the sustainability of initiatives were largely missing. At the macro level, decarbonisation approaches focused on energy grid emissions, infrastructure efficiency, and reducing supply chain emissions, including those from agriculture and supply of food products. Decarbonisation mechanisms at the micro and meso system levels ranged from reducing low value care, to choosing lower GHG options (eg, anaesthetic gases, rescue inhalers), to reducing travel. Based on these strategies and tactics, this study provides a framework to support the decarbonisation of healthcare systems.

SYSTEMATIC REVIEW REGISTRATION
PROSPERO: CRD42022383719.

WHAT IS ALREADY KNOWN ON THIS TOPIC
The carbon footprint of healthcare systems has been estimated at about 4.4% of global emissions, but comprehensive reviews investigating mitigation are lacking

One review took a global approach when examining the environmental impact of healthcare systems; however, this study was not peer reviewed and data were limited to one year

Another study discussed the sustainability of healthcare at a global level, however it was not conducted as a systematic review, and the methods used to evaluate and collate data were unclear

WHAT THIS STUDY ADDS
This review includes 18 years of studies, frameworks, and tools assessing the carbon footprint of healthcare systems, and the steps taken to measure and reduce these impacts

Overarching strategies and specific tactics, models, and tools were identified that could be used to decarbonise healthcare systems, aiming to reach net zero emissions by 2050

Introduction
The direct and indirect human health impacts of climate change have been well documented over the past two decades. The 2015 Paris Agreement and subsequent research have painstakingly established the association between planetary and human health.[1-4] However, until recently, less attention has been directed towards

the impact healthcare systems have on climate change. This issue is gaining momentum, spurred on by the implementation of the Paris Agreement and the introduction of the UK National Health Service (NHS) net zero carbon strategy.[5 6]

In essence, healthcare systems occupy a special place; although they are on the frontlines in dealing with climate induced demand for healthcare, they are also major emitters.[7 8] Healthcare systems must therefore address a predicament: maintenance of high quality care with the resilience and capacity to respond to escalating climate induced demands; and mitigation of their own, substantial contributions to the climate crisis. The action required to manage the complexities of the environmental and societal costs of delivering health services is not trivial. Healthcare systems, notably hospital facilities, are energy intensive, high consumption organisations that produce considerable quantities of waste.[8-11] Although there is an irrefutable duty of care to patients and a fundamental commitment to do no harm at the point of delivery, healthcare systems have until recently remained largely unrecognised contributors to the climate crisis.[12] However, healthcare systems are well positioned as environmental stewards to get their own house in order and promote benefits—lowering the collective carbon footprint while simultaneously improving long term health by reducing low value care.

That said, healthcare systems currently lag behind other service sectors in reducing carbon emissions.[6 13] To be compliant with the Paris Agreement and contribute to the Intergovernmental Panel on Climate Change's target of limiting global warming to 1.5°C above preindustrial levels, healthcare must play its part, aiming for net zero carbon emissions by 2050.[13-15] There is a need to act in a swift and decisive manner because humanity has a limited window to achieve significant progress in reducing carbon emissions or irreversible changes will exceed the boundaries of the planet.[16]

Most estimates place average global emissions from healthcare at about 4.4%, with a country range of 4-8.5%.[15] As confronting as these numbers are, it is possible they will get worse before they get better.[17] More frequent large scale events stimulated by climate change (eg, bushfires, floods, cyclones, heatwaves, and other weather sequelae) will require more carbon inducing care, placing additional, often overwhelming loads on overstretched healthcare systems grappling to contend with the current high burden of chronic diseases, non-communicable diseases (such as cardiovascular diseases), communicable diseases, constant introduction of new interventions and technologies as we discover new ways to manage disease, and ageing populations.[10-19] With slow progress on reduction strategies, increased demand on healthcare systems in turn generates further environmental impacts in a vicious cycle (fig 1).

Against that backdrop, we sought to examine the quality and quantity of global evidence on ways in which healthcare systems contribute to climate change and the proposed and implemented ways of reducing the effects of healthcare systems on the climate. Table 1 presents our key terms.

Methods

Search strategy and selection criteria

In this review, we assessed the quality and quantity of evidence on ways in which healthcare systems contribute to climate change and the approaches, models, and tools available to decarbonise healthcare systems. The review was prospectively registered on PROSPERO (CRD42022383719) and reported in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines (supplementary materials 1 and 2).[35]

The search strategy was designed by the review team in conjunction with a research librarian, and run across eight electronic databases. Seven of these databases were searched from their respective inception dates to November 2023: Business Source Premier, CINAHL, Cochrane Reviews, Embase, Health Business (EBSCO), Medline, and Web of Science. Scopus was searched from 1990 to November 2023. Supplementary material 3 gives more details on the search terms.

Publications were eligible if they were full text articles in peer reviewed journals. All study designs (eg, case studies, reviews) were included. Reports from authoritative international agencies (eg, World Health Organization, World Bank, United Nations, and Organisation for Economic Co-operation and Development) or government reports at a federal or national level were also eligible if assessed to be of suitable quality. A primary focus on the effects of human healthcare systems on climate change was required. Articles were excluded if they were not available in English, were not published as full papers, or did not have a primary focus on healthcare systems' effects on or contribution to climate change. Supplementary material 4 presents full inclusion and exclusion criteria.

Records identified in the database search were imported into Rayyan, a screening software tool,[36] and

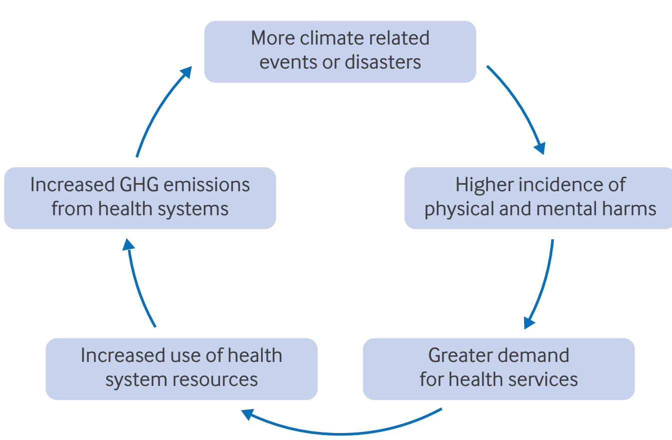

Fig 1 | Positive feedback loop reflecting current association between the healthcare system and climate change. GHG=greenhouse gas

Table 1 | Glossary of terms

Term	Definition
Climate change	Change in global climate patterns and events, particularly in response to human activity resulting in increased carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions produced primarily through use of fossil fuels.[20]
Healthcare system	Organisations, people, infrastructure, and resources involved in promoting, restoring, or maintaining health for individuals, groups, populations, and communities[21]; this includes but is not limited to delivery of healthcare by public and private health services and also healthcare quality, governance, the health workforce, and medical technologies and products.
Low value care	Care that is of little or no benefit to the patient, such as unnecessary tests or procedures; according to some accounts, currently estimated at 30% of care.[22]
Micro level of the system	Healthcare system on frontlines where clinicians interface with patients, involving healthcare delivery such as at a clinic, general practice, or hospital department through to an entire hospital or provider facility.[23 24]
Meso level of the system	Healthcare system at regional or network level; this can range from a health district or hospital network to a provincial or state jurisdiction. Examples include carbon footprint of an entire United States hospital network; an NHS England region; the New South Wales healthcare system[25]; or an emergency medical services network.[26]
Macro level of the system	Whole health sector, eg, a national system or collection of national healthcare systems in a World Health Organization region. Examples include emissions attributed to surgery reported at the national level[27]; carbon budget of the entire Chinese healthcare system[11]; total carbon footprint of asthma exacerbation across the UK[28]; or WHO's Eastern Mediterranean region.
Carbon footprint	GHGs attributed directly or indirectly to an entity, individual, or product, which is expressed as carbon dioxide equivalents (CO_2e)[29]; measurement of total GHG emissions (including CO_2, methane, and nitrous oxide) along supply chains[11]; estimates of level of emissions in CO_2e for which a country, business, institution, individual, or another entity is responsible.[30]
Decarbonisation	Process of reducing CO_2 and other GHG emissions from a specific activity, process, or procedure.[31]
CO_2 equivalent	Unit used for comparing different GHGs (eg, methane) based on global warming potential (GWP) through conversion to equivalent amounts of CO_2 with the same GWP—usually expressed as million metric tonnes of carbon dioxide (MMTCDE). CO_2e for a gas is calculated by multiplying tonnes of the gas by its GWP,[32] eg, methane has a GWP of 21, therefore one million metric tonnes of methane is equivalent to 21 MMTCDE. Essentially, CO_2e are a measure of GHGs created by an identifiable set of activities; this includes emissions under the control of an emitter and indirect GHG generation from supplied electricity.[33]
Carbon neutral	Balancing CO_2e released into the atmosphere by removing corresponding amount of CO_2.[34]
Net zero	Point at which there is a balance between GHG equivalent emissions and removal of GHG equivalent emissions.[34] Balance can be achieved at the product, individual, country, region, or global level.[30]

duplicates removed. For inter-rater reliability, pilot screening of titles and abstracts was conducted on a set of 200 randomly selected publications and any resulting discrepancies were resolved by the group. In our original review protocol, it was planned that six investigators would screen records in pairs. However, given the large volume of literature identified in the search, 15 investigators screened records in pairs. The full set of titles and abstracts retrieved from searches were then independently double screened for inclusion by investigators working in teams of two or three (EL, LE, EM, GD, CLS, AC, KB-C, SW, GF, RP, LP, HRA, SS, CR, AP). The full texts of the remaining publications were then duplicate screened against the inclusion criteria to ensure consistency in the final set of included texts. Supplementary material 5 presents reasons for exclusion during the full text review. Regular meetings took place to resolve any disagreements by consensus at each step of the process, with JB available as arbiter.

Data analysis

Data extraction and quality appraisal were conducted independently by investigators, and verified during synthesis processes. Four quality appraisal tools were applied to assess the quality of included publications: Joanna Briggs Institute critical appraisal checklist for systematic reviews and research synthesis[37]; Mixed-Methods Appraisal Tool (MMAT)[38]; Scale for the quality Assessment of Narrative Reviews (SANRA)[39]; and Authority, Accuracy, Coverage, Objectivity, Date, Significance (AACODS) tool for evaluation and critical appraisal of grey literature.[40] After initial appraisal, the quality of each article was assigned to one of four categories: critically low, low, moderate, high. Articles determined to be of critically low quality were excluded from analysis; supplementary materials 6-10 provide further details.

A purpose built data extraction workbook was developed in Microsoft Excel. Data extraction variables included publication details (author, title, year, country of publication), healthcare system level (micro, meso, macro), healthcare system sector (eg, primary care, surgery, mental health), and measurement of climate impact (eg, carbon footprint). A thematic analysis of the extracted data was performed using an inductive approach to identify themes emerging from the literature.[41] One reviewer (SW) first familiarised themselves with all extracted data, and then created a set of six initial broad themes and 24 subthemes using inductive thematic analysis.[41] A subgroup of five reviewers (CLS, KBC, GD, SW, EL) discussed and revised the initial coding of themes to 12 themes. The whole authorship team conducted a review of these broad themes for content and accuracy, and the final nine themes were then reviewed by the senior author (JB). Once the nine broad themes had been developed, a subgroup of reviewers (CLS, KBC, GD, SW, EL, EM) met to code the data within each broad theme into appropriate subthemes, again using an inductive thematic analysis. Two broad categories were also developed to frame the themes as avenues of enacting change (overarching strategies), or specific approaches for reducing GHG emissions in healthcare systems (decarbonisation tactics). The whole authorship team reviewed and approved all categories and subthemes, which were finalised by the senior author (JB). Supplementary materials 11-13 provide details.

Patient and public involvement

This research did not focus on any specific patient population. Although no patients were directly involved in setting the research question or conducting the review, we ensure we have healthcare consumers' input, expertise and advice on the progress of our research at the intersection of climate change, health, and healthcare, which feeds into and shapes all our work in this area. Healthcare consumers are an integral part of our results dissemination strategy.

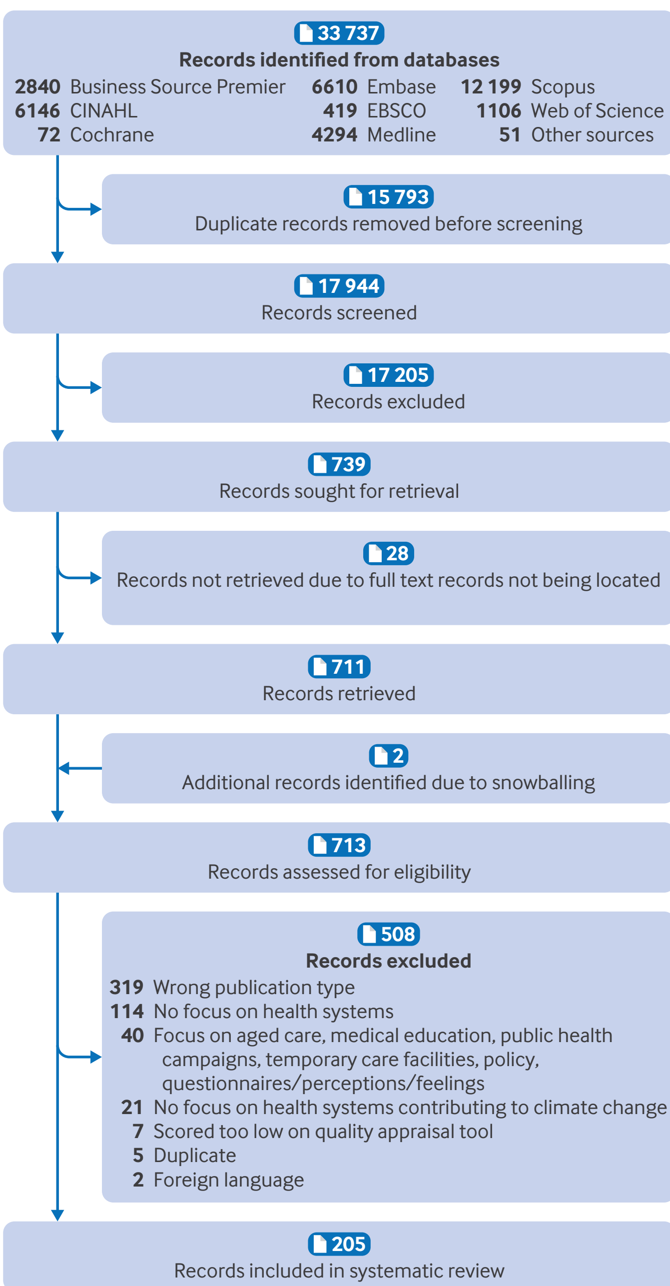

Fig 2 | Preferred reporting items for systematic reviews and meta-analyses (PRISMA) diagram

Results

Study selection and quality assessment

Electronic database searches identified 33 737 publications, 15 793 of which were duplicates, leaving 17 944 publications for title and abstract screening; 739 studies met the inclusion criteria for full text screening. Of these, 28 were excluded because they could not be retrieved, leaving 711 texts to be screened (fig 2). Two additional papers were identified, screened, and included through backward citation tracking.

Most of the articles in this review were appraised as high (n=112, 54.6%) or moderate (n=80, 39.0%) quality. Only 13 articles (6.3%) were identified as lower quality but were included because they provided valuable information for the review. Seven studies were considered ineligible based on critically low quality appraisal ratings (supplementary materials 6-10). After full text screening and quality appraisal, 205 publications were included (fig 2).

Study characteristics

Types of studies

Included publications were categorised by study design (table 2): empirical studies; reviews including narrative, scoping, and systematic; non-empirical "narrative descriptive" publications (eg, case studies, reports); and those applying multiple methods. Studies were also categorised based on the level of the healthcare system to which they pertained: micro, meso, or macro (table 2; see table 1 for full definitions).

Geographical focus

High income countries were over-represented in the included publications (n=101, 69.2%, excluding reviews). The most commonly discussed country was the United States (n=27, 13.2%), followed by the UK (n=21, 10.2%), Australia (n=17, 8.3%), and Canada (n=14, 6.8%). Figure 3 depicts the study setting by country. Many publications (n=30, 14.6%) focused on the macro level without discussing a specific country or region.[6 42-70]

Publication dates

Most included records were published in recent years (fig 4), with 85.4% (n=175) from 2019 onwards, indicating the growing interest in this topic.

Topics covered

A wide range of healthcare related topics were discussed, including surgery (n=36)[24 27 51 54 71-102]; internal medicine specialties (ie, renal services, gynaecological services; n=18)[23 57 75 103-117]; digital health (n=15)[59 66 71 118-129]; primary care (n=15)[53 56 63 75 130-140]; hospitals (n=14)[82 92 141-152]; supply chains (eg, procurement; n=10)[42 44 153-160]; oncology (n=8)[48 58 161-166]; pharmaceuticals (n=7)[45 47 167-171]; diagnostics (n=6)[52 172-176]; chronic condition treatment (n=5)[28 61 177-179]; workforce (n=5)[180-184]; pathology services (n=5)[75 174 185-187]; dentistry (n=4)[60 188-190]; critical care (n=3)[90 191 192]; clinical trials (n=2)[67 193]; emergency medical services

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Table 2 | Overview of key characteristics of included publications (n=205)

Classification	Publications, n (%)
Study designs	
Empirical	88 (42.9)
Review	60 (29.3)
Narrative descriptive	53 (25.9)
Multiple methods	4 (2.0)
Healthcare system level*	
Micro (eg, frontline clinician level, including healthcare delivery at a clinic or department level to whole hospital or facility level)	83 (35.3)
Meso (regional or network level, eg, health district, hospital network)	31 (13.2)
Macro (whole healthcare system level, including national or global systems)	121 (51.5)

*If applicable, publications were categorised into more than one category; therefore, the healthcare system level total does not add up to 100%.

(n=2)[26 194]; mental health services (n=2)[195 196]; outpatient care (n=2)[197 198]; screening (n=2)[199 200]; travel related to doctors' medical education (n=1)[201]; and palliative care (n=1).[202] Fifty papers examined the system as a whole, taking a macro perspective.[6 7 11 19 25 43 46 49 50 55 62 64 65 68-70 203-236]

Scope

Twenty nine (14.1%) publications specifically used terminology that refers to GHG emissions according to three emission scopes defined by the Greenhouse Gas Protocol[237] (direct emissions, indirect emissions from energy use, indirect supply chain emissions).[7 27 44 45 47 48 50 55 65 68 69 81 85 125 142 152 166 172 184 193 197 200 202 207 209 219 224 229 232] Table 3 presents definitions of the three scopes.

Measurement of healthcare emissions

Forty eight publications developed or applied specific models or tools to measure healthcare emissions; some publications used several models or tools (table 4). Models included life cycle assessment (LCA; n=27),[60 76 84 104 107 111 119 122 128 130 141 142 155 162 173 174 175 179 186 190 193 200 209 212 213 223 231] economic input-output LCA (n=2),[197 212] LCA multiregion input-output models (n=1),[25] environmentally extended input-output models (n=6),[7 11 24 77 213 232] environmentally extended multiregional input-output model (n=4),[43 44 231 232] and the Bilan Carbone model (n=1).[166] Tools used in the literature included carbon calculators (n=6),[52 101 115 121 165 176] Carbon Trust recommendations (n=1),[26] the Eyefficiency tool (n=1),[89] the Pollard model (n=1),[188] the Ringelmann smoke chart (n=1),[157] and the US Environmental Protection Agency's waste reduction model (n=1).[144] Other studies (n=16) used publicly available datasets (eg, UK Department of Business, Energy, and Industrial Strategy conversion factor data; environmental impact data provided by the German Federal Environment Agency), or previously published literature to quantify GHG emissions in their facilities.[74 83 94 99 110 113 123 126 129 148 161-163 168 178 202]

Key themes emerging from the literature

From the thematic analysis, nine themes emerged across the included publications, which were then grouped into one of two categories: overarching strategies (table 5) or decarbonisation tactics (table 6). The most frequently discussed overarching strategy was the need for effective policies and governance surrounding healthcare sustainability (n=97) and the most common decarbonisation tactic was changing clinical and surgical practices (n=107). Papers discussing numerous themes or subthemes were included in several categories.

Overarching strategies

Policy and governance level initiatives

The need for policies and incentives to promote, guide, monitor, or evaluate changes at the country, state, and facility level was discussed in 97 publications[6 7 11 19 23 25 42-51 55-59 61 63-70 71 73 76 79 88 89 95 96 103-105 109 111 112 114 115 117 120 123-125 127 128 130 133 136 138 142 143 151 152 154 159 162 166 168 170 171 173 179 180 184 188 191-193 200 201 203 205-210 212 213 216-234]; 39.2% of the

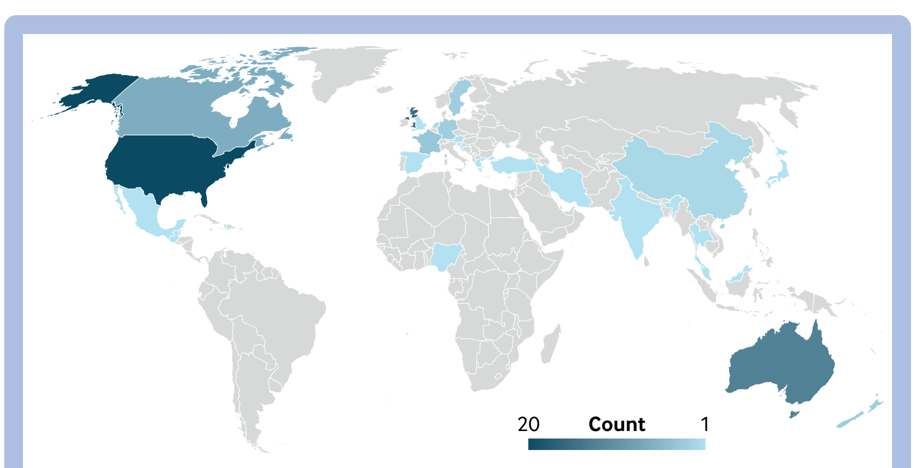

Fig 3 | Setting of included empirical publications by country. Some publications refer to more than one country. Countries were counted for all empirical publications

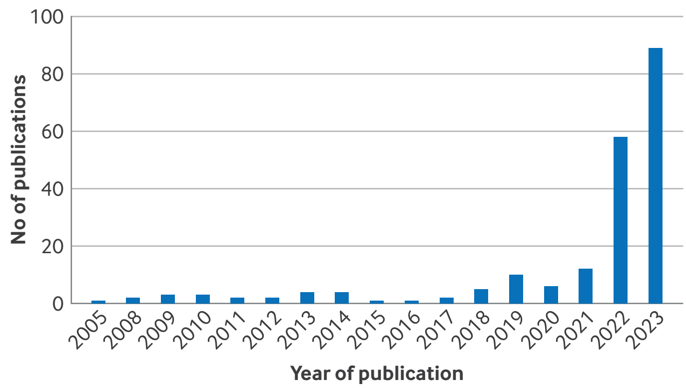

Fig 4 | Included publications by year

publications discussing this theme were empirical studies. The most common strategy focused on priority setting and leadership from national and international bodies (n=51), such as integrating sustainability into policy or setting long term sustainability goals across organisations.[6,7,11,19,43,46,50,51,56,57,59,63-65,67,70,76,79,95,96,104,105,109,111,114,115,120,125,127,128,130,133,138,143,152,154,166,170,184,188,206,209,210,216-218,220221,231,232,234] This was followed by publications (n=27) that suggested mandating evaluations, benchmarking, and reporting of the carbon footprint for healthcare organisations to strengthen the evidence base for future decision making.[6,7,23,45,55,58,61,68,70,73,88,124,136,142,151,159,168,173,179,205,207,208,212,213,216,219,221] An equal number of publications (n=21 each) highlighted using financial policy and incentives for sustainable healthcare processes[6,42,43,44,48,49,70,73,89,96,123,133,138,143,162,171,180,200,221,224,233] and the need for a multisectoral approach to mitigate the carbon footprint of healthcare,[7,23,56,69,73,89,96,103,112,117,162,191,192,201,203,205,210,217,220,221,233] such as collaborations between large healthcare organisations. Fifteen publications recommended setting targeted emissions reductions.[7,11,19,25,45-47,58,70,71,89,136,193,218,219]

Organisational behaviour change

Organisational change to develop a future ready workforce was dealt with in 76 publications.[24,25,27,46,48-50,57,58,63,65,68,69,70,71,73,75,77,79-81,83,86,91,93,99,102,103,105,110,112,114,116,127,130,133,135-138,142,143,150-152,154,165,166,171,172,174,178-182,185,187,191,192,195,196,199,202,205-207,210,212,216,220,221,228,233,234,235] Roughly 30.3% of the publications discussing this theme were empirical studies. Ongoing education and training within healthcare organisations and tertiary institutions was identified in 59 publications as a way of ensuring the workforce is aware of and equipped for sustainability challenges.[24,25,48-50,57,63,65,68,69,73,75,77,79,81,83,86,91,99,102,103,110,112,114,116,127,130,133,135,137,138,142,143,150-152,165,166,171,172,174,178-180,185,187,192,195,196,202,205-207,210,212,220,228,233,235] Publications discussing organisational leadership focused on implementing multidisciplinary teams, "green champions," and other organisational role models to manage sustainability at different levels of the healthcare system and empower employee decision making (n=26).[27,46,58,63,70,71,77,80,93,105,127,133,135,136,152,154,165,181,182,185,191,196,199,216,221,234]

Individual and group action

The literature outlined several important roles for individuals and groups in reducing healthcare's carbon footprint (n=74)[7,19,28,43,48-51,53,56,57-59,61,63-67,69,71,73,81,85,86,88-91,96,98,102,103,107,108,112,114,116,117,127,130,133-135,137,139,142,143,151,160,162,168,171,177,180,181,183,184,192,195,196,210,212,215,216,218,219-221,226,229,232,233,236]; 20.3% of the publications discussing this theme were empirical studies. Promoting change through advocacy, lobbying, and open support of sustainability initiatives was the focus of 45 publications,[7,48-51,53,58,61,64-67,71,81,85,86,88-90,96,98,103,107,114,116,117,127,133-135,139,142,151,171,180,181,183,184,192,195,196,216,218,232,233] including the need for community involvement and education when enhancing the sustainability of healthcare practices (n=21).[43,53,56,81,90,103,112,130,133,151,160,168,192,210,212,218,221,229,232,233,236] Several publications emphasised individual responsibility as a key factor in making change (n=15), particularly through engaging with low carbon healthcare and living an active lifestyle.[57,59,63,73,81,89,91,96,103,143,160,162,192,220,233] Additionally, 15 articles identified benefits of reducing GHGs in the health system, which included financial savings and reducing disease burden.[19,28,50,69,96,102,107,108,112,137,177,212,215,219,226]

Using tools for measuring and monitoring GHG emissions

The impetus to develop, use, and standardise tools for measuring and monitoring GHG emissions was a prominent theme (n=70 publications).[6,7,11,19,26,43-45,47,48,51,58,59,61,62,66,68,69,71,73,75,77,79,84,88,96,103-105,107,109,112,114,124,125,137,139,142,146,148,149,154,163,164,171,177,188,192,193,194,200,205,207,208,209,211,212,216,217-219,221,222,224,225,227,228,230,231,234] Nearly 37.1% of the publications discussing this theme were empirical studies. Evaluative tools, along with existing models such as LCA, can be used to improve decision making on procurement and services, and was a feature of 43 publications.[6,43,47,58,59,62,66,68,73,75,77,79,84,88,96,104,105,107,109,112,124,137,139,142,146,149,154,164,192,200,205,208,211,212,216,217,218,224,225,227,230,231,234]

Developing tools to measure GHG emissions and monitor the movement of materials was discussed in 25 publications.[7,11,19,26,43,44,69,103,124,125,146,171,177,188,193,194,207,209,211,219,221,222,225,227,228]

Several publications (n=17) emphasised the need for standardised platforms for reporting and comparing the sustainability of products

Table 3 | Three scopes of carbon footprint

Scope	Definition
1	Direct emissions from healthcare facilities and healthcare owned vehicles.
2	Indirect emissions from purchased energy sources, including electricity grids, and energy used for steam, cooling, and heating.
3	Indirect emissions from healthcare supply chain, including emissions related to transportation, production, and disposal of medical goods and services.

Source: Definitions derived from Greenhouse Gas Protocol.[237]

Table 4 | Tools for measuring healthcare emissions from empirical studies

Method	Description	References
Model*		
Life cycle assessment (LCA)	Method used to assess environmental impacts of product or service throughout its entire life cycle, from extraction of raw materials to final disposal of product or service, with goal of identifying stages of life cycle that have greatest environmental impact, and to suggest ways to reduce environmental impact of product or service. In practice, boundaries are placed on sources of emissions to facilitate analysis. Studies also used other LCA related models, such as life cycle impact assessments (LCIA), life cycle costs (LCC), and organisational LCA (O-LCA).	60, 76, 84, 104, 107, 111, 119, 122, 128, 130, 141, 142, 155, 162, 173-175, 179, 186, 190, 193, 200, 209, 212, 213, 223, 231
Bilan Carbone	Method of carbon footprint analysis that accounts for all sources of GHG emissions, such as carbon dioxide, methane, nitrous oxide, and other GHGs, from direct and indirect sources.	166
Economic input-output LCA (EIOLCA)	Monetary flows across economic sectors are compiled as part of input-output models. These input-output models are then linked to sector specific environmental data, which form part of a life cycle inventory for evaluating carbon impact of a system.	197, 212
LCA multiregion input-output (LCA-MRIO)	Model that considers economic and environmental interactions between different regions or countries to assess environmental impact of product or service. Applying input-output analysis, interrelations between different economic sectors and their environmental impacts are assessed to estimate total environmental impact of product or service across entire supply chain.	25
Environmentally extended input output (EEIO)	Method that combines economic input-output data of industrial sectors with environmental information to provide comprehensive picture of environmental impacts of economic activities in a country. Examples include national EEIOs, such as the United States EEIO.	7, 11, 24, 77, 213, 232
Environmentally extended multiregional input-output (EE-MRIO)	Model that tracks the flow of economic expenditure and associated carbon emissions between regions and countries. Carbon emission calculations are derived from economic activity.	43, 44, 231, 232
Tools		
Carbon calculator (online software)	Software tools that enable individuals, businesses, and organisations to calculate their carbon footprint generated over given period of time. Software uses data inputs provided by user and then applies calculations based on established methods to provide estimated total carbon footprint; this includes calculators developed by US EPA.	52, 101, 115, 121, 165, 176
Carbon Trust recommendations	Data collection tool based on recommendations from the Carbon Trust used to assess energy consumption of emergency medical services systems. The tool uses reports on energy consumption associated with ambulances, vehicles, on site energy usage, and aviation fuel to determine overall carbon footprint.	26
Eyefficiency tool (environmental LCA)	Sustainability benchmarking tool used to estimate GHG emissions and efficiency of surgical processes using data from consumption, travel, and waste. Process involves determining scope, measuring emission sources, and applying emissions factors to determine overall GHG emissions footprint.	89
Pollard model (decision support tool)	Using detailed care pathway approach, this model simulates carbon footprint of service reconfigurations and accurately calculates bottom line implications and associated resource consequences of changes in health sector.	188
Ringelmann smoke chart	Graphical tool used to visually assess density of smoke from combustion source.	157
US EPA's waste reduction model (WARM V15)	Tool developed by US EPA that provides high level estimates of GHG emissions produced by materials and material management practices; allows comparison of practices for industry and researchers.	144

Models are general method used to measure GHG emissions at a certain level, whereas tools were developed to measure emissions using one or more models.
GHG=greenhouse gas; US EPA=United States Environmental Protection Agency.
* Some publications used several models.

or processes to enable healthcare organisations to make informed decisions about their current practices.[7,26,45,47,48,51,61,71,107,114,148,154,163,177,207,211,219]

Decarbonisation tactics

Changing clinical and surgical practices

Changing clinical and surgical practices as a solution for reducing healthcare's carbon footprint was advocated in 107 publications[6,7,11,23,24,25,27,28,42,43,48,50-52,54,55,57,61,63,66,68,69,71,73-75,77-79,81-87,90,91,93,94,96,97-103,106-109,112-114,116,120,126,128-130,133,135,138,139,142,143,148,149,151,152,159,161,163,165-171,173-175,177-179,183,185,186,189-192,196,205,212,214,217,224,227,229,230,232-234,236]; 37.4% of the publications discussing this theme were empirical studies. This solution included replacing high GHG practices with lower GHG options (n=80),[11,23,27,28,43,48,54,57,61,63,68,71,73-75,77-79,81-87,90,91,93,94,96-98,100,102,103,106,107,112-114,120,126,128,129,133,135,138,139,148,149,152,159,161,163,165-168,170,171,173,174,177-179,183,189,190,192,196,214,217,224,227,229,230,232-234,236] such as choosing anaesthetic gas types and systems with lower carbon footprints.[54,71,73,81,83,85,86,96,100,229] This advocation was also seen in primary care settings (n=6).[63,130,133,135,138,139] As a way of minimising healthcare usage, and thus reducing healthcare's carbon footprint, 41 publications reinforced the need to assess clinical practices for low value care.[6,7,24,28,42,51,52,55,66,68,69,75,77,79,93,97,99,101,109,116,130,142,149,151,152,169,174,175,177,179,185,186,190,191,192,205,212,214,224,229,233] This included identifying and reducing unnecessary processes or procedures, minimising drug overprescription, or encouraging a preventative care approach to reduce the need for health services. Reducing water usage during procedures, disinfection and sterilisations, laundry, recycling water, and practising water efficiency were also suggested in six publications.[23,25,50,108,143,189]

Managing physical waste

Dealing with waste was a focus of 83 publications[11,25,43,47-50,51,54,55,57,60,61,63,67,72,73,77,78,80,81,82,84-86,88,89,91,93,95-98,100,101,102,104,105,107,110,112,114,116,135,138,142-144,149-155,157,159,160,169,171,177,183,189,190-192,198,199,206,210,211,217-219,222-224,228

Table 5 | Publications in the overarching strategies category, grouped into themes

Theme	Examples	Subtheme and definition		References
Enacting policies and governance (n=97)	Existing sustainability targets include the UK National Health Service's net zero by 2040 policy,[224] and the Paris Agreement to achieve net zero emissions by 2050.[58] The Healthier Hospital Initiative was organised collaboratively with Health Care Without Harm, Practice Greenhealth, and the Centre for Health Design, and has since engaged over 1000 hospitals to improve healthcare sustainability in the United States.[212] Tax incentives for investment into renewable energy are available through the US Inflation Reduction Act 2022.[224]	Priority setting and leadership (n=51)	Policy making and priority setting from governments and regulatory bodies relating to climate change in healthcare systems	6, 7, 11, 19, 43, 46, 50, 51, 56, 57, 59, 63-65, 67, 70, 76, 79, 95, 96, 104, 105, 109, 111, 114, 115, 120, 125, 127, 128, 130, 133, 138, 143, 152, 154, 166, 170, 184, 188, 206, 209, 210, 216-218, 220, 221, 231, 232, 234
		Require auditing, evaluation of processes, reporting of progress, and benchmarking across facilities (n=27)	Mandatory reporting of sustainability processes based on standardised metrics	6, 7, 23, 45, 55, 58, 61, 68, 70, 73, 88, 124, 136, 142, 151, 159, 168, 173, 179, 205, 207, 208, 212, 213, 216, 219, 221
		Financial policy (including procurement; n=21)	Incentivisation of sustainable practice through payment models	6, 42-44, 48, 49, 70, 73, 89, 96, 123, 133, 138, 143, 162, 171, 180, 200, 221, 224, 233
		Multisectoral approach including dedicated organisations (n=21)	Collaboration between stakeholders from different sectors and industries to instigate change	7, 23, 56, 69, 73, 89, 96, 103, 112, 117, 162, 191, 192, 201, 203, 205, 210, 217, 220, 221, 233
		Selecting targeted emissions reductions including required use of tools (n=15)	Setting quantifiable and mandatory targets for reducing emissions with required use of standardised tools and metrics	7, 11, 19, 25, 45-47, 58, 70, 71, 89, 136, 193, 218, 219
Changing organisational behaviour (n=76)	Establishment of an Environmental Sustainability Special Interest Group within an Australian renal clinical network. This group surveyed dialysis facilities, and found only 21% had formal sustainability education within their organisation.[105] After surveying 11 hospitals in Turkey regarding their sustainability practices, recommendations for organisational change were identified including creating an "environment friendly team" to lead sustainability initiatives, and providing training to all hospital staff related to sustainable practice.[80]	Education and training (n=59)	Formal education and training programmes or informal knowledge sharing for professional healthcare clinicians and staff	24, 25, 48-50, 57, 63, 65, 68, 69, 73, 75, 77, 79, 81, 83, 86, 91, 99, 102, 103, 110, 112, 114, 116, 127, 130, 133, 135, 137, 138, 142, 143, 150-152, 165, 166, 171, 172, 174, 178-180, 185, 187, 192, 195, 196, 202, 205-207, 210, 212, 220, 228, 233, 235
		Leadership and empowerment (n=26)	Leadership groups and committees supporting decarbonisation actions and empowering change within healthcare organisations	27, 46, 58, 63, 70, 71, 77, 80, 93, 105, 127, 133, 135, 136, 152, 154, 165, 181, 182, 185, 191, 196, 199, 216, 221, 234
Actions of individuals and groups (n=74)	Medical organisations specifically promoting sustainable or low carbon practice, eg, the British Thoracic Society promoting low carbon inhaled therapies.[139] Healthcare professionals championing sustainability efforts within their institutions, and also connecting with local communities to share ideas and advocate for change.[151] Encouraging patients to work towards improving their health and the health of those around them to reduce health risks and unnecessary use of health services.[236]	Advocacy (n=45)	Open promotion and systemic advocacy towards addressing climate change in healthcare systems	7, 48-51, 53, 58, 61, 64-67, 71, 81, 85, 86, 88-90, 96, 98, 103, 107, 114, 116, 117, 127, 133-135, 139, 142, 151, 171, 180, 181, 183, 184, 192, 195, 196, 216, 218, 232, 233
		Community involvement and education (n=21)	Educating, empowering, and uniting communities to take action on climate change issues related to the healthcare system	43, 53, 56, 81, 90, 103, 112, 130, 133, 151, 160, 168, 192, 210, 212, 218, 221, 229, 232, 233, 236
		Individual responsibility (n=15)	Individuals, including patients and health professionals, acting independently to minimise their carbon footprint	57, 59, 63, 73, 81, 89, 91, 96, 103, 143, 160, 162, 192, 220, 233
		Benefits of reducing GHG emissions (n=15)	The flow-on effects of reducing GHG emissions, such as reduced disease burden and cost savings	19, 28, 50, 69, 96, 102, 107, 108, 112, 137, 177, 212, 215, 219, 226
Using tools for measuring and monitoring GHG emissions (n=70)	The ENERGY STAR Portfolio Manager is a standardised benchmarking tool for the energy efficiency of buildings. Its development and use has enabled measurement and reporting of over 50 000 metric tons of GHG savings.[207] Tools such as life cycle analysis should be used to measure and monitor GHG emissions, and could be incorporated into health technology assessment and metrics for measuring quality of care.[58 59 114 164 227] (More detailed examples of tools and methods are in table 4.)	Using tools to improve decision making on procurement and services (n=43)	Using established tools and databases to quantify GHG emissions and inform sustainable improvements	6, 43, 47, 58, 59, 62, 66, 68, 73, 75, 77, 79, 84, 88, 96, 104, 105, 107, 109, 112, 124, 137, 139, 142, 146, 149, 154, 164, 192, 200, 205, 208, 211, 212, 216-218, 224, 225, 227, 230, 231, 234
		Develop tools to assess GHG emissions from different levels (n=25)	Developing new tools that quantify GHG emissions from several sources, and in different contexts	7, 11, 19, 26, 43, 44, 69, 103, 124, 125, 146, 171, 177, 188, 193, 194, 207, 209, 211, 219, 221, 222, 225, 227, 228
		Standardise platforms for reporting or decision making (n=17)	Consolidation of standard and systematic ways of reporting GHG emissions across health and other industries	7, 26, 45, 47, 48, 51, 61, 71, 107, 114, 148, 154, 163, 177, 207, 211, 219

Overarching strategies definition: mechanisms for healthcare system improvement relating to climate change.
GHG=greenhouse gas.

Table 6 | Publications in the decarbonisation tactics category, grouped into themes

Theme	Examples	Subtheme and definition		References
Changing clinical and surgical practices (n=107)	In 2019, an Australian tertiary hospital reported replacing desflurane with low flow sevoflurane, which resulted in carbon emission savings of 270 474 kg carbon dioxide equivalent.[83] Wide-awake, local anaesthesia, no tourniquet (WALANT) hand surgery has been found to be more environmentally friendly than traditional hand surgery with sedation owing to reduced waste and use of equipment.[78]	Replacing identified high GHG practices with lower GHG options (n=80)	Using sustainable or low GHG options when applicable, including healthcare products and processes	11, 23, 27, 28, 43, 48, 54, 57, 61, 63, 68, 71, 73-75, 77-79, 81-87, 90, 91, 93, 94, 96-98, 100, 102, 103, 106, 107, 112-114, 120, 126, 128, 129, 133, 135, 138, 139, 148, 149, 152, 159, 161, 163, 165-168, 170, 171, 173, 174, 177-179, 183, 189, 190, 192, 196, 214, 217, 224, 227, 229, 230, 232-234, 236
		Reducing the amount of low value care (n=41)	Reduction of unnecessary or inefficient tests, procedures, and products	6, 7, 24, 28, 42, 51, 52, 55, 66, 68, 69, 75, 77, 79, 93, 97, 99, 101, 109, 116, 130, 142, 149, 151, 152, 169, 174, 175, 177, 179, 185, 186, 190-192, 205, 212, 214, 224, 229, 233
		Reducing water usage (n=6)	Reduction of water used in clinical and surgical practice	23, 25, 50, 108, 143, 189
Managing physical waste (n=83)	By incorporating the 5R principles (reduce, reuse, recycle, rethink, and research), hospitals can reduce the amount of waste generated in operating theatres.[88] Three primary hip operational rooms at a large NHS hospital in the UK were audited and revealed nearly 15% of clinical waste disposal contained clean recyclable items such as cardboard and plastics.[95]	Waste minimisation approaches (n=71)	Methods related to reducing, reusing, recycling, and repurposing waste	11, 25, 43, 47-51, 54, 55, 57, 60, 61, 63, 67, 72, 73, 77, 78, 80, 82, 84, 85, 88, 91, 95-98, 100-102, 104, 105, 107, 110, 112, 116, 135, 138, 142-144, 149, 151, 152, 154, 155, 159, 160, 169, 171, 177, 183, 189-192, 198, 206, 211, 217-219, 222, 224, 228, 229, 232-234
		Waste disposal (n=29)	Choosing appropriate and low carbon methods of segregating and disposing of healthcare waste	50, 57, 73, 77, 80-82, 86, 88, 89, 93, 95, 107, 114, 143, 144, 150, 151, 153, 157, 160, 177, 183, 199, 206, 210, 223, 232, 236
Minimising travel and transportation (n=70)	Fractionated treatments of radiotherapy might potentially reduce distance travelled by patients because a substantial portion of carbon footprint produced by radiotherapy is from patient travel.[161] A prospective randomised control trial investigating follow-up care through digital health app video consultations compared with in-person clinic consultations concluded that telemedicine decreases 11.248 kg of travel related GHG emissions per patient (based on car estimates).[94]	Using models of care that reduce travel (n=41)	Use of telemedicine, integrated models, or more local services that minimise patient travel	6, 24, 43, 47, 48, 51, 59, 63, 71, 73, 74, 79, 84, 94-96, 105, 109, 119, 121, 122, 124-126, 128, 132, 135, 148, 161, 163, 165, 171, 172, 176, 188, 191, 195, 196, 217, 228, 229
		Access to alternative forms of transportation (n=25)	Promotion and access to shared or active transport options for patients and clinicians	7, 47, 55, 69, 79, 105, 114, 121, 131, 137, 140, 142, 152, 161, 166, 174, 176, 190, 192, 197, 202, 224, 226, 232, 233
		Streamlining medical services (n=14)	Organising medical services and consultations to maximise efficiency and minimise patient travel	61, 79, 86, 93, 127, 131, 132, 148, 156, 161, 166, 176, 188, 193
		Reducing professionals' travel for conferences and education (n=13)	Reduction of business travel for health professionals and other stakeholders	43, 47, 51, 63, 85, 117, 120, 171, 191, 195, 201, 224, 228
Strengthening infrastructure (n=63)	Carbon emissions produced by diagnostic imaging can be reduced by limiting unnecessary imaging, optimising use of equipment on needs basis (ie, turning off scanners when not in use) and considering standby power usage when obtaining new equipment.[175] By adding piping and insulating boiler plant equipment, upgrading lighting and building controls, St Joseph Hospital in Canada was able to avoid 15% of overall GHG emissions and captured this using energy benchmarking.[207]	Energy efficient buildings (n=40)	Prioritising energy efficiency in the design and infrastructure of healthcare facilities	47, 50, 55, 57, 61, 63, 69, 72, 73, 80, 81, 92, 93, 97, 98, 109, 112, 135, 141-143, 146, 147, 152, 160, 171, 192-194, 207, 210-212, 218, 221, 224, 229, 232, 234, 235
		Energy conservation processes (n=34)	Conserving energy through optimising equipment use and efficiency	26, 27, 43, 57-59, 61, 63, 73, 84, 88, 96, 97, 108, 114, 117, 118, 135, 143, 145, 151, 152, 161, 174, 175, 184, 194, 195, 202, 206, 221, 226, 228, 229
Decarbonising the supply chain (n=48)	Decreasing procurement emissions requires understanding sustainability and the lifecycles a product can go through, in addition to developing a relation with suppliers.[89] A large tertiary hospital based in Victoria, Australia has produced a consensus of priorities actions for procurement, including a commitment from suppliers to achieve carbon neutrality, incorporating sustainability clauses in procurement contracts, implementation of reusable equipment when possible and policy changes so that companies provide life cycle assessment of products before purchasing.[142]	Sustainable production and procurement (n=43)	Considering sustainability in the manufacturing and procurement of healthcare products	7, 25, 42-44, 47, 50, 54-56, 59, 65, 73, 84, 85, 98, 104, 105, 110, 112, 114, 127, 136, 139, 142, 143, 151, 152, 158, 171, 175, 183, 193, 197, 210, 212, 215, 218, 224, 229, 232, 234, 235
		Decreasing energy grid emissions (n=10)	Reduce reliance on non-renewable forms of energy grid supply	7, 26, 50, 87, 89, 158, 194, 204, 212, 232

Decarbonisation tactics definition: tactics for reducing greenhouse gas emissions within healthcare systems.
GHG=greenhouse gas.

[229 232-234 236]; 32.5% of the publications discussing this theme were empirical studies. This theme included waste minimisation methods (n=71),[11 25 43 47-51 54 55 57 60 61 63 67 72 73 77 78 80 82 84 85 88 91 95 96-98 100-102 104 105 107 110 112 116 135 138 142-144 149 151 152 154 155 159 160 169 171 177 183 189 190-192 198 206 211 217-219 222 224 228 229 232 233 234] such as reducing, reusing, and recycling medical equipment, and using reusable alternatives over disposable items. Several publications highlighted the need for effective segregation and disposal of waste (n=29),[50 57 73 77 80-82 86 88 89 93 95 107 143 144 150 151 153 157 160 177 183 199 206 210 223 232 236] including choosing disposal methods such as incineration that help minimise carbon emissions.

Minimising travel and transportation

Patient or clinical travel and transportation was emphasised as an important and addressable source of carbon emissions in 70 publications.[6 7 24 43 47 48 51 55 59 61 63 69 71 73 74 79 84 85 86 93-96 105 109 114 117 119-122 124-128 131 132 135 137 140 142 148 152 156 161 163 165 166 171 172 174 176 188 190-193 195-197 201 202 217 224 226 228 229 232 233] Some 42.9% of the publications discussing this theme were empirical studies. Using carbon efficient models of care was seen as a method to reduce emissions (n=41), for example, telemedicine or home based treatment options.[6 24 43 47 48 51 59 63 71 73 74 79 84 94-96 105 109 119 121 122 124-126 128 132 135 148 161 163 165 171 172 176 188 191 195 196 217 228 229] A further 25 publications discussed alternative forms of transportation (eg, car sharing, buses, trains, and active travel such as cycling) for patients and clinicians.[7 47 55 69 79 105 114 121 131 137 140 142 152 161 166 174 176 190 192 197 202 224 226 232 233] Streamlining medical services, such as emergency service coordination, redesigning schedules for clinicians to enhance ride share and closing sites with lower use, was discussed in 14 publications.[61 79 86 93 127 131 132 148 156 161 166 176 188 193] Several papers (n=13) also highlighted reducing professionals' travel (eg, clinicians, researchers, industry partners) for conferences and education as a decarbonisation method.[43 47 51 63 85 117 120 171 191 195 201 224 228]

This theme had the most implementation evaluations. These studies often highlighted reductions in carbon emissions resulting from teleconferencing or telemedicine,[122 163 176] and they also tended to be of high quality.

Strengthening infrastructure

Sixty three papers recommended improvements to healthcare infrastructure[26 27 43 47 50 55 57-59 61 63 69 72 73 80 81 84 88 92 93 96-98 108 109 112 114 117 118 135 141-143 145-147 151 152 160 161 171 174 175 184 192-195 202 206 207 210 211 212 218 221 224 226 228229 232 234 235]; 33.3% of the publications discussing this theme were empirical studies. Improving the energy efficiency of healthcare facilities such as hospitals was a feature of 40 publications.[47 50 55 57 61 63 69 72 73 80 81 92 93 97 98 109 112 135 141-143 146 147 152 160 171 192-194 207 210 211 212 218 221 224 229 232 234 235] For example, consideration of design features such as insulation and passive shading options can help reduce reliance on electrical heating and cooling, and therefore reduce GHG emissions. Thirty four publications advocated for using energy conservation measures—such as turning off appliances when not in use—to help minimise carbon emissions at a facility level.[26 27 43 57-59 61 63 73 84 88 96 97 108 114 117 118 135 143 145 151 152 161 174 175 184 194 195 202 206 221 226 228 229]

Decarbonising healthcare supply chains

Forty eight papers proposed decarbonising the supply chains as a way of reducing GHG emissions.[7 25 26 42 43 44 47 50 54-56 59 65 73 84 85 87 89 98 104 105 110 112 114 127 136 139 142 143 151 152 158 171 175 183 193 194 197 204 210 212 215 218 224 229 232 234 235] Roughly 39.6% of the publications discussing this theme were empirical studies. Numerous publications (n=43) focused on ways to reduce the carbon footprint by deploying sustainable production and procurement mechanisms within supply chains, such as using sustainable or local sources of food supply, or using supply chains with low emissions.[7 25 42 43 44 47 50 54-56 59 65 73 84 85 98 104 105 110 112 114 127 136 139 142 143 151 152 158 171 175 183 193 197 210 212 215 218 224 229 232 234 235] Decarbonising the sources of energy for healthcare by using renewable sources rather than fossil fuel sources and monitoring energy grid consumption was noted in 10 publications.[7 26 50 87 89 158 194 204 212 232]

Discussion

Key areas for policy and practice

From our findings we developed a rich picture of the strategies and tactics for reducing the emissions produced by healthcare systems (fig 5). This schematic figure is not an exhaustive example, but rather illustrates how these strategies and tactics to reduce emissions produced by healthcare systems are interconnected and affect flow within and outside of the healthcare system. Authorisation to proceed starts at the top, with effective policies, governance, and high level leadership. Measurement of GHGs through recognised and increasingly sophisticated tools is necessary, and now more pronounced, as is the use of tools and frameworks to report on progress, and make decisions about alternative, greener options. Tools and frameworks for use at micro, meso, and macro levels are now more widely available. Several options for individuals and groups to orchestrate change and improvement, typically targeted at organisations such as hospitals, care facilities for older people, and general practices, have been generated.

On decarbonisation specifically, attention was focused on modifying medical, surgical, and other clinical practices, reducing physical waste, and minimising transportation costs or eliminating travel altogether through new clinical models such as virtual care, telehealth, or telemedicine.[24 59 63 81 94 97 120 121 126 165 172 196] When enacting decarbonisation tactics that affect patient care, it is vital that lower carbon alternatives provide equal or improved patient outcomes compared with current practices and be acceptable to and supported by patients.[105] Other specific activities for reducing carbon emissions and greening healthcare, directly or in those services indirectly controlled by healthcare systems, include building new or remediating existing healthcare infrastructure and reducing the carbon footprint along healthcare supply chains. Given the large contribution of supply chain emissions and the high potential for reducing emissions,[238] it is surprising

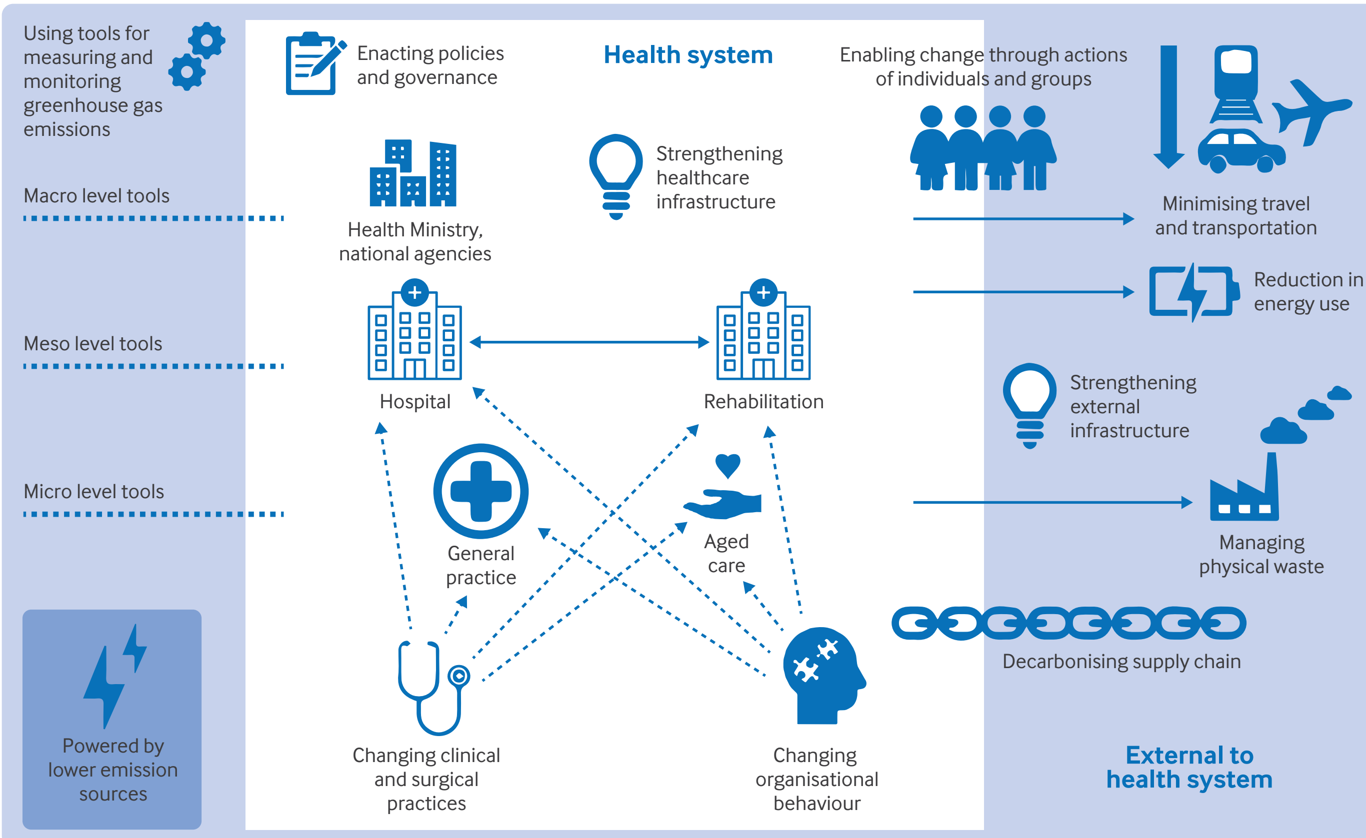

Fig 5 | Strategies and tactics for reducing healthcare system greenhouse gas (GHG) emissions according to healthcare system level: micro (eg, frontline clinician, including healthcare delivery at a clinic, department, whole hospital, or facility), meso (regional or network level, eg, health district, hospital network), macro (whole healthcare system, including national or global systems)

that supply chain decarbonisation approaches, including those related to food supply, were less frequently discussed than others. Another surprising lack of attention was discussion at the intersection of universal health coverage and healthcare system decarbonisation because reducing the need for care through primary prevention would have a direct impact on carbon emissions by lowering demand.[49 140]

A way forward

Overall, a framework of useful activities to substantially reduce the carbon budget of healthcare is now available, and represented in figure 5. Although this framework provides a platform to assess these activities, determining which elements would be most effective, and under what conditions, will partly depend on the characteristics of the individual healthcare system.[96] Barriers to implementing sustainable practice into healthcare systems might also exist, including patients accepting changes, cost and funding mechanisms, attitudes towards change, and workforce capacity in an already overburdened system. As these decarbonisation approaches are put into practice, any barriers and potential enablers should be explored further.

The included literature was mainly from high income countries. However, we found some examples of lower-middle income country healthcare systems and organisations taking the lead in advancing the overarching strategies identified, such as developing tools to measure emissions (eg, the Aga Khan Health Services (AKHS) freely available tool),[44] and the decarbonisation tactics, such as reducing physical waste and emissions from waste disposal (eg, Snigdha and colleagues),[158] and improving the environmental sustainability of clinical practices.[111 156 199] Some of the decarbonisation tactics might be more challenging to implement in lower-middle income country healthcare systems, such as strengthening infrastructure.[96]

Regardless of the setting, having an overarching set of mechanisms and approaches might be useful and highlights the need for a multipronged approach, including how we measure emissions and progress, especially given the range of measuring tools that have emerged. The actions include effective governance and supportive policies, appropriate financing, and strengthening infrastructure and service delivery.[20] Collaborative, international, multisectoral leadership is needed to learn from progress elsewhere and to localise and prioritise strategies and support direct actions.

Achieving a step change reduction in emissions is a socially and ethically responsible imperative. In principle, it is feasible and beneficial to roll out these strategies and tactics at scale to achieve systemic change—this is central to the mission of healthcare providers: to do no or less harm, to alleviate suffering, and to improve the health status of the population. Healthcare can set an example for other industries and sectors as responsible environmental stewards. This review suggests that healthcare systems and professionals have recognised their duty and are embracing the necessary changes, but there is a long way to go.

Strengths and limitations

The comprehensive analysis of 18 years of studies, frameworks, and tools that assess and quantify the carbon footprint of healthcare is a key strength of the paper, as is the development of a new framework. Previous reviews did not appear to focus sufficiently on mitigation strategies or use the systematic review methodology.

Our review was limited to papers and authoritative reports written in English, and so some papers might have been missed. However, eight databases were searched, therefore the likelihood of new themes being identified is low. Most of the included literature discussed healthcare systems in high income countries, which is a well known bias. This bias can create challenges when extrapolating identified strategies to low-middle income countries. However, the included papers revealed that healthcare systems in low-middle income countries are undertaking similar strategies to high income countries. A review specifically focused on healthcare systems in low-middle income countries, and the ethical implications of climate change and decarbonisation tactics, is warranted. Inductive approaches, as in this study, allow flexibility and deeper understanding of the data, but introduce issues of inter-rater reliability and bias. Our review used 19 investigators for screening, extraction, synthesis, and interpretation to minimise bias.

Conclusions

We reviewed the literature to generate strategies and tactics for reducing the impact of healthcare systems on climate change. Implementing these strategies should enable substantial progress towards reducing healthcare's carbon footprint and support a greener health sector powered by renewable sources. However, healthcare systems would need to adapt these approaches to their context and needs to maximise their effects. Healthcare can lead the way in shifting to net zero by 2050, and by doing so we can reduce the burden of patients who would otherwise need more care as a consequence of a warming world.

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Contributors: JB conceived the project and led the work. CLS and YZ co-conceived the project. LE, EL, GD, CLS, AC, KB-C, EM, SW, GF, RP, LP, HRA, SS, CR, and AP screened the publications. CLS, SW, KB-C, EM, GD, EL, RP, GF, LP, HRA, SS, CR, and AP extracted data from the publications. CLS, SW, KB-C, EM, GD, EL, and RP synthesised the findings from the review. JB directly accessed and verified the underlying data reported in the manuscript. JB drafted the manuscript with input from CLS, EL, SW, KB-C, GF, RP, EM, GD, and AC. EC, JW, and YZ made critical comments on the emerging draft. All authors critically reviewed the final manuscript and take responsibility for its accuracy and presentation. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted. JB is the study guarantor.

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Ethical approval: No individual participant data are included in this manuscript. All data are aggregated from existing publications. Ethics approval was therefore not required. We attest that we have obtained appropriate permissions and paid any required fees for use of copyright protected materials.

Data sharing: All datasets generated and analysed for this study, including the search strategy, list of the included and excluded studies, data extracted, analysis plans, and quality assessment are available in the article or supplementary material and upon request from the corresponding author. No individual participant data were used for this study.

Transparency: The lead author and guarantor affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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Dissemination to participants and related patient and public communities: Results will be disseminated using social media such as X, and LinkedIn, at international conferences, and to relevant stakeholders within healthcare in conjunction with our healthcare consumers, advisors and experts, partners and stakeholders.

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1 United Nations. Climate Change. The Paris Agreement. UNFCCC. 2016. https://unfccc.int/process-and-meetings/the-paris-agreement
2 Romanello M, Napoli CD, Green C, et al. The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. *Lancet* 2023;402:2346-94. doi:10.1016/S0140-6736(23)01859-7
3 United Nations. Climate Change. COP28 Declaration on Climate and Health. 2023. https://www.cop28.com/en/cop28-uae-declaration-on-climate-and-health
4 Burki T. Health at COP26. *Lancet* 2021;398:1472-3. doi:10.1016/S0140-6736(21)02308-4
5 Roelfsema M, van Soest HL, Harmsen M, et al. Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nat Commun* 2020;11:2096. doi:10.1038/s41467-020-15414-6
6 Bhopal A, Norheim OF. Priority setting and net zero healthcare: how much health can a tonne of carbon buy?*BMJ* 2021;375:e067199. doi:10.1136/bmj-2021-067199
7 Eckelman MJ, Huang K, Lagasse R, Senay E, Dubrow R, Sherman JD. Health care pollution and public health damage in the United States: an update. *Health Aff (Millwood)* 2020;39:2071-9. doi:10.1377/hlthaff.2020.01247
8 Pichler P-P, Jaccard IS, Weisz U, et al. International comparison of health care carbon footprints. *Environ Res Lett* 2019;14:064004. doi:10.1088/1748-9326/ab19e1
9 Malik A, Lenzen M, McAlister S, McGain F. The carbon footprint of Australian health care. *Lancet Planet Health* 2018;2:e27-35. doi:10.1016/S2542-5196(17)30180-8
10 Bi P, Hansen A. Carbon emissions and public health: an inverse association?*Lancet Planet Health* 2018;2:e8-9. doi:10.1016/S2542-5196(17)30177-8
11 Wu R. The carbon footprint of the Chinese health-care system: an environmentally extended input-output and structural path analysis study. *Lancet Planet Health* 2019;3:e413-9. doi:10.1016/S2542-5196(19)30192-5
12 Miller FA. Mitigating Health Care's Contribution to the Climate Crisis. *Jt Comm J Qual Patient Saf* 2021;47:609-11. doi:10.1016/j.jcjq.2021.08.005
13 Salas RN, Maibach E, Pencheon D, Watts N, Frumkin H. A pathway to net zero emissions for healthcare. *BMJ* 2020;371:m3785. doi:10.1136/bmj.m3785
14 Chen L, Msigwa G, Yang M, et al. Strategies to achieve a carbon neutral society: a review. *Environ Chem Lett* 2022;20:2277-310. doi:10.1007/s10311-022-01435-8
15 Karliner J, Slotterback S, Boyd R, et al. Health care's climate footprint: how the health sector contributes to the global climate crisis and opportunities for action. 2019. https://noharm-global.org/sites/default/files/documents-files/5961/HealthCaresClimateFootprint_092319.pdf
16 Rockström J, Gupta J, Qin D, et al. Safe and just Earth system boundaries. *Nature* 2023;619:102-11. doi:10.1038/s41586-023-06083-8
17 Hough E. Lowering Carbon Emissions Through Redesigned Health Care. 2023. https://www.commonwealthfund.org/blog/2023/lowering-carbon-emissions-through-redesigned-health-care
18 Bishop-Williams KE, Berrang-Ford L, Sargeant JM, et al, IHACC Research TeamBwindi Community Hospital. Understanding weather and hospital admissions patterns to inform climate change adaptation strategies in the healthcare sector in Uganda. *Int J Environ Res Public Health* 2018;15:2402. doi:10.3390/ijerph15112402
19 Eckelman MJ, Sherman JD. Estimated global disease burden from US health care sector greenhouse gas emissions. *Am J Public Health* 2018;108(S2):S120-2. doi:10.2105/AJPH.2017.303846
20 World Health Organization. *Operational framework for building climate resilient health systems.* World Health Organization, 2015.
21 World Health Organization. Everybody's business: strengthening health systems to improve health outcomes: WHO's framework for action. 2007. https://www.who.int/publications/i/item/everybody-s-business----strengthening-health-systems-to-improve-health-outcomes
22 Braithwaite J, Glasziou P, Westbrook J. The three numbers you need to know about healthcare: the 60-30-10 Challenge. *BMC Med* 2020;18:102. doi:10.1186/s12916-020-01563-4
23 Lim AEK, Perkins A, Agar JWM. The carbon footprint of an Australian satellite haemodialysis unit. *Aust Health Rev* 2013;37:369-74. doi:10.1071/AH13022
24 Wang EY, Zafar JE, Lawrence CM, et al. Environmental emissions reduction of a preoperative evaluation center utilizing telehealth screening and standardized preoperative testing guidelines. *Resour Conserv Recycling* 2021;171. doi:10.1016/j.resconrec.2021.105652
25 Malik A, Padget M, Carter S, et al. Environmental impacts of Australia's largest health system. *Resour Conserv Recycl* 2021:169:105556. doi:10.1016/j.resconrec.2021.105556
26 Blanchard I, Brown LH. Carbon footprinting of emergency medical services systems: a proof-of-concept study. *Prehosp Emerg Care* 2009;13:546-9. doi:10.1080/10903120903144973
27 MacNeill AJ, Lillywhite R, Brown CJ. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. *Lancet Planet Health* 2017;1:e381-8. doi:10.1016/S2542-5196(17)30162-6
28 Kponee-Shovein K, Marvel J, Ishikawa R, et al. Carbon footprint and associated costs of asthma exacerbation care among UK adults. *J Med Econ* 2022;25:524-31. doi:10.1080/13696998.2022.2063603
29 The Carbon Trust. Carbon footprinting. An introduction for organisations. 2007. https://www.carbontrust.com/our-work-and-impact/guides-reports-and-tools/a-guide-to-carbon-footprinting-for-businesses
30 United Nations Framework Convention on Climate Change. Climate Neutral Now: Guidelines for Participation. United Nations. 2021. https://unfccc.int/sites/default/files/resource/CNN%20Guidelines.pdf
31 Butler T, Lode B, Parker A, Mar KA, Schmidt F, Lawrence MG. Long-term climate goals. Decarbonization, carbon neutrality, and climate neutrality. 2015. doi:10.2312/iass.2015.029
32 eurostat. Glossary: carbon dioxide equivalent. 2017. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent
33 East AJ. What is a carbon footprint? An overview of definitions and methodologies. Horticulture Australia, 2008. https://www.daf.qld.gov.au/__data/assets/pdf_file/0003/59025/Hort-Fruit-Drought-Carbon-Report1.pdf
34 Bernoville T. What is the difference between carbon-neutral, net-zero and climate positive? A non-misleading guide to carbon-neutrality. planA; 2022. https://plana.earth/academy/what-is-difference-between-carbon-neutral-net-zero-climate-positive
35 Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 2021;372:n71. doi:10.1136/bmj.n71
36 Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan-a web and mobile app for systematic reviews. *Syst Rev* 2016;5:210. doi:10.1186/s13643-016-0384-4
37 Aromataris E, Fernandez R, Godfrey CM, Holly C, Khalil H, Tungpunkom P. Summarizing systematic reviews: methodological development, conduct and reporting of an umbrella review approach. *Int J Evid Based Healthc* 2015;13:132-40. doi:10.1097/XEB.0000000000000055
38 Hong QN, Fàbregues S, Bartlett G, et al. The Mixed Methods Appraisal Tool (MMAT) version 2018 for information professionals and researchers. *Educ Inf* 2018;34:285-91. doi:10.3233/EFI-180221
39 Baethge C, Goldbeck-Wood S, Mertens S. SANRA—a scale for the quality assessment of narrative review articles. *Res Integr Peer Rev* 2019;4:5. doi:10.1186/s41073-019-0064-8
40 Tyndall J. Authority, Accuracy, Coverage, Objectivity, Date, Significance (AACODS) Checklist. 2010. https://fac.flinders.edu.au/dspace/api/core/bitstreams/e94a96eb-0334-4300-8880-c836d4d9a676/content
41 Braun V, Clarke V. Using thematic analysis in psychology. *Qual Res Psychol* 2006;3:77-101. doi:10.1191/1478088706qp063oa.
42 Alami H, Lehoux P, Miller FA, Shaw SE, Fortin JP. An urgent call for the environmental sustainability of health systems: a 'sextuple aim' to care for patients, costs, providers, population equity and the planet. *Int J Health Plann Manage* 2023;38:289-95. doi:10.1002/hpm.3616
43 Andrieu B, Marrauld L, Vidal O, Egnell M, Boyer L, Fond G. Health-care systems' resource footprints and their access and quality in 49 regions between 1995 and 2015: an input-output analysis. *Lancet Planet Health* 2023;7:e747-58. doi:10.1016/S2542-5196(23)00169-9
44 Baddley J, Rasheed FN. The Aga Khan Development Network's (AKDN) approach to supply chain carbon foot printing for healthcare providers. *Clean Logist Supply Chain* 2023;7. doi:10.1016/j.clscn.2023.100109
45 Belkhir L, Elmeligi A. Carbon footprint of the global pharmaceutical industry and relative impact of its major players. *J Clean Prod* 2019;214:185-94. doi:10.1016/j.jclepro.2018.11.204
46 Bhopal A, Norheim OF. Fair pathways to net-zero healthcare. *Nat Med* 2023;29:1078-84. doi:10.1038/s41591-023-02351-2
47 Booth A, Jager A, Faulkner SD, Winchester CC, Shaw SE. Pharmaceutical company targets and strategies to address climate change: content analysis of public reports from 20 pharmaceutical companies. *Int J Environ Res Public Health* 2023;20:3206. doi:10.3390/ijerph20043206
48 Brown M, Schoen JH, Gross J, Omary RA, Hanneman K. Climate change and radiology: impetus for change and a toolkit for action. *Radiology* 2023;307:e230229. doi:10.1148/radiol.230229
49 Campbell-Lendrum D, Neville T, Schweizer C, Neira M. Climate change and health: three grand challenges. *Nat Med* 2023;29:1631-8. doi:10.1038/s41591-023-02438-w

50 Corvalan C, Villalobos Prats E, Sena A, et al. Towards climate resilient and environmentally sustainable health care facilities. *Int J Environ Res Public Health* 2020;17:8849. doi:10.3390/ijerph17238849
51 Cunha MF, Pellino G. Environmental effects of surgical procedures and strategies for sustainable surgery. *Nat Rev Gastroenterol Hepatol* 2023;20:399-410. doi:10.1038/s41575-022-00716-5
52 Furlan L, Di Francesco P, Tobaldini E, et al. The environmental cost of unwarranted variation in the use of magnetic resonance imaging and computed tomography scans. *Eur J Intern Med* 2023;111:47-53. doi:10.1016/j.ejim.2023.01.016
53 Gonzalez-Holguera J, Gaille M, Del Rio Carral M, et al. Translating planetary health principles into sustainable primary care services. *Front Public Health* 2022;10:931212. doi:10.3389/fpubh.2022.931212
54 Herr MM, Outterson RE, Aggarwal S. Lost in the Ether: The Environmental Impact of Anesthesia. *Oper Tech Orthop* 2022;32. doi:10.1016/j.oto.2022.100997
55 Iyer Y, Moorthy S, Al-Kindi S, Rajagopalan S. Climate change and healthcare organizations: a call to arms. *Eur Heart J* 2022;43:2435-7. doi:10.1093/eurheartj/ehac110
56 Kadandale S, Marten R, Dalglish SL, Rajan D, Hipgrave DB. Primary health care and the climate crisis. *Bull World Health Organ* 2020;98:818-20. doi:10.2471/BLT.20.252882
57 Lachkar S, Crombag LMM, Musani AI. How interventional pulmonologists can address climate change. *Respiration* 2023;102:207-10. doi:10.1159/000528764
58 Lichter KE, Bloom JR, Sheu RD, et al. Tracking and reducing SF_6 usage in radiation oncology: a step toward net-zero health care emissions. *Pract Radiat Oncol* 2023;13:e471-4. doi:10.1016/j.prro.2023.06.003
59 Lokmic-Tomkins Z, Borda A, Humphrey K. Designing digital health applications for climate change mitigation and adaptation. *Med J Aust* 2023;218:106-10. doi:10.5694/mja2.51826
60 Maloney B, McKerlie T, Nasir M, et al. The environmental footprint of single-use versus reusable cloths for clinical surface decontamination: a life cycle approach. *J Hosp Infect* 2022;130:7-19. doi:10.1016/j.jhin.2022.09.006
61 Martin MF, Maturen KE, Foster C, et al. Environmental stewardship and healthcare: global reflections for radiology. *Chin J Acad Radiol* 2022;5:244-8. doi:10.1007/s42058-022-00103-8
62 McAlister S, Morton RL, Barratt A. Incorporating carbon into health care: adding carbon emissions to health technology assessments. *Lancet Planet Health* 2022;6:e993-9. doi:10.1016/S2542-5196(22)00258-3
63 Pali-Schöll I, Hermuth-Kleinschmidt K, Dramburg S, et al. An EAACI review: Go green in health care and research. Practical suggestions for sustainability in clinical practice, laboratories, and scientific meetings. *Allergy* 2023;78:2606-22. doi:10.1111/all.15836
64 Pratt B. Expanding health justice to consider the environment: how can bioethics avoid reinforcing epistemic injustice?*J Med Ethics* 2023;49:642-8. doi:10.1136/jme-2022-108458
65 Priyan S, Banerjee S. An interactive optimization model for sustainable production scheduling in healthcare. *Healthc Anal (N Y)* 2022;2:100124. doi:10.1016/j.health.2022.100124
66 Richie C. Environmentally sustainable development and use of artificial intelligence in health care. *Bioethics* 2022;36:547-55. doi:10.1111/bioe.13018
67 Rublee C, Bikomeye J, Rao S, et al. Climate mitigation and adaptation is cancer prevention and control. *J Clim Change Health* 2023;10. doi:10.1016/j.joclim.2023.100209
68 Smith CL, Zurynski Y, Braithwaite J. We can't mitigate what we don't monitor: using informatics to measure and improve healthcare systems' climate impact and environmental footprint. *J Am Med Inform Assoc* 2022;29:2168-73. doi:10.1093/jamia/ocac113
69 Teshome M. The transformative role of adaptation strategies in designing climate-resilient and sustainable health systems. *J Prev (2022)* 2023;44:603-13. doi:10.1007/s10935-023-00740-4
70 Wolf T, Martinez GS, Cheong H-K, Williams E, Menne B. Protecting health from climate change in the WHO European Region. *Int J Environ Res Public Health* 2014;11:6265-80. doi:10.3390/ijerph110606265
71 Al Fannah J, Al Sabahi S, Al Harthi H, Al Bahrani M, Al Salmi Q. Towards a green hospital approach in Oman: A case study of quantifying an environmental impact. *Int J Health Plann Manage* 2023;38:1583-9. doi:10.1002/hpm.3662
72 Amato C, Yang C, Bernhard L, et al. Towards the OR of the future: introducing an adaptive and technology-embracing OR wing layout. *Int J Comput Assist Radiol Surg* 2023;18:401-8. doi:10.1007/s11548-022-02760-7
73 Anastasopoulos NA, Papalois V. How can we address the ever-pressing need to 'green up' surgical practice in the National Health Service?*J R Soc Med* 2022;115:213-9. doi:10.1177/01410768221095242
74 Arndt EM, Jansen TR, Bojko J, et al. COVID-19 measures as an opportunity to reduce the environmental footprint in orthopaedic and trauma surgery. *Front Surg* 2023;10:959639. doi:10.3389/fsurg.2023.959639
75 Batcup C, Breth-Petersen M, Dakin T, et al. Behavioural change interventions encouraging clinicians to reduce carbon emissions in clinical activity: a systematic review. *BMC Health Serv Res* 2023;23:384. doi:10.1186/s12913-023-09370-2
76 Boberg L, Singh J, Montgomery A, Bentzer P. Environmental impact of single-use, reusable, and mixed trocar systems used for laparoscopic cholecystectomies. *PLoS One* 2022;17:e0271601. doi:10.1371/journal.pone.0271601
77 Bravo D, Thiel C, Bello R, Moses A, Paksima N, Melamed E. What a waste! The impact of unused surgical supplies in hand surgery and how we can improve. *Hand (N Y)* 2023;18:1215-21. doi:10.1177/15589447221084011
78 Bravo D, Townsend CB, Tulipan J, Ilyas AM. Economic and environmental impacts of the Wide-Awake, Local Anesthesia, No Tourniquet (WALANT) technique in hand surgery: a review of the literature. *J Hand Surg Glob Online* 2022;4:456-63. doi:10.1016/j.jhsg.2022.05.009
79 Buchan JC, Thiel CL, Steyn A, et al. Addressing the environmental sustainability of eye health-care delivery: a scoping review. *Lancet Planet Health* 2022;6:e524-34. doi:10.1016/S2542-5196(22)00074-2
80 Candan Dönmez Y, Aslan A, Yavuz VAN Giersbergen M. Environment-friendly practices in operating rooms in Turkey. *J Nurs Res* 2019;27:e18. doi:10.1097/jnr.0000000000000296
81 Cockrell HC, Hansen EE, Gow K, Fecteau A, Greenberg SLM. The intersection of pediatric surgery, climate change, and equity. *J Pediatr Surg* 2023;58:943-8. doi:10.1016/j.jpedsurg.2023.01.017
82 Conti CB, Cereatti F, Salerno R, et al. Disposable duodenoscopes: evidence and open issues. *Life (Basel)* 2023;13:1694. doi:10.3390/life13081694
83 Davies JF, Trajceska L, Weinberg L. The financial and environmental impact of purchased anaesthetic agents in an Australian tertiary hospital. *Anaesth Intensive Care* 2023;51:141-8. doi:10.1177/0310057X221129291
84 Delaie C, Cerlier A, Argenson JN, et al. Ecological burden of modern surgery: an analysis of total knee replacement's life cycle. *Arthroplast Today* 2023;23:101187. doi:10.1016/j.artd.2023.101187
85 Dilger AE, Bergmark RW. Environmental sustainability in otolaryngologic surgery. *Curr Opin Otolaryngol Head Neck Surg* 2023;31:238-43. doi:10.1097/MOO.0000000000000888
86 Engler ID, Curley AJ, Fu FH, Bilec MM. Environmental sustainability in orthopaedic surgery. *J Am Acad Orthop Surg* 2022;30:504-11. doi:10.5435/JAAOS-D-21-01254
87 Hu X, Pierce JT, Taylor T, et al. The carbon footprint of general anaesthetics: A case study in the UK. *Resour Conserv Recycling* 2021;167. doi:10.1016/j.resconrec.2021.105411
88 Kagoma YK, Stall N, Rubinstein E, Naudie D. People, planet and profits: the case for greening operating rooms. *CMAJ* 2012;184:1905-11. doi:10.1503/cmaj.112139
89 Latta M, Shaw C, Gale J. The carbon footprint of cataract surgery in Wellington. *N Z Med J* 2021;134:13-21
90 Liu Y, Lee-Archer P, Sheridan NM, Seglenieks R, McGain F, Eley VA. Nitrous oxide use in Australian health care: strategies to reduce the climate impact. *Anesth Analg* 2023;137:819-29. doi:10.1213/ANE.0000000000006620
91 Ma Y, Han S. Carbon neutral hand surgery: simple changes to reduce carbon footprint. *Plast Surg (Oakv)* 2024;32:108-12. doi:10.1177/22925503221088839
92 Ma Y, Zedan S, Liu A, et al. Impact of a warming climate on hospital energy use and decarbonization: an Australian building simulation study. *Buildings* 2022;12. doi:10.3390/buildings12081275
93 McGain F, Ma SCY, Burrell RH, et al. Why be sustainable? The Australian and New Zealand College of Anaesthetists Professional Document PS64: *Statement on Environmental Sustainability in Anaesthesia and Pain Medicine Practice* and its accompanying background paper. *Anaesth Intensive Care* 2019;47:413-22. doi:10.1177/0310057X19884075
94 Muschol J, Heinrich M, Heiss C, et al. Economic and environmental impact of digital health app video consultations in follow-up care for patients in orthopedic and trauma surgery in Germany: randomized controlled trial. *J Med Internet Res* 2022;24:e42839. doi:10.2196/42839
95 Pegg M, Rawson R, Okere U. Operating room waste management: a case study of primary hip operations at a leading National Health Service hospital in the United Kingdom. *J Health Serv Res Policy* 2022;27:255-60. doi:10.1177/13558196221094488
96 Qin RX, Velin L, Yates EF, et al. Building sustainable and resilient surgical systems: A narrative review of opportunities to integrate climate change into national surgical planning in the Western Pacific region. *Lancet Reg Health West Pac* 2022;22:100407. doi:10.1016/j.lanwpc.2022.100407

97 Shao C, Tsai S, Woo R, Dream S. Becoming a sustainable academic surgeon. *J Surg Res* 2023;283:606-10. doi:10.1016/j.jss.2022.10.091
98 Sherry B, Lee S, Ramos Cadena MLA, et al. How ophthalmologists can decarbonize eye care: a review of existing sustainability strategies and steps ophthalmologists can take. *Ophthalmology* 2023;130:702-14. doi:10.1016/j.ophtha.2023.02.028
99 Spoyalo K, Lalande A, Rizan C, et al. Patient, hospital and environmental costs of unnecessary bloodwork: capturing the triple bottom line of inappropriate care in general surgery patients. *BMJ Open Qual* 2023;12:e002316. doi:10.1136/bmjoq-2023-002316
100 Sulbaek Andersen MP, Nielsen OJ, Sherman JD. Assessing the potential climate impact of anaesthetic gases. *Lancet Planet Health* 2023;7:e622-9. doi:10.1016/S2542-5196(23)00084-0
101 Talibi SS, Scott T, Hussain RA. The environmental footprint of neurosurgery operations: an assessment of waste streams and the carbon footprint. *Int J Environ Res Public Health* 2022;19:5995. doi:10.3390/ijerph19105995
102 Wyssusek KH, Keys MT, van Zundert AAJ. Operating room greening initiatives - the old, the new, and the way forward: A narrative review. *Waste Manag Res* 2019;37:3-19. doi:10.1177/0734242X18793937
103 Al-Shihabi F, Moore A, Chowdhury TA. Diabetes and climate change. *Diabet Med* 2023;40:e14971. doi:10.1111/dme.14971
104 Baboudjian M, Pradere B, Martin N, et al. Life cycle assessment of reusable and disposable cystoscopes: a path to greener urological procedures. *Eur Urol Focus* 2023;9:681-7. doi:10.1016/j.euf.2022.12.006
105 Barraclough KA, Gleeson A, Holt SG, Agar JW. Green dialysis survey: establishing a baseline for environmental sustainability across dialysis facilities in Victoria, Australia. *Nephrology (Carlton)* 2019;24:88-93. doi:10.1111/nep.13191
106 Barratt AL, Li Y, Gooroovadoo I, et al. Environmental impact of cardiovascular healthcare. *Open Heart* 2023;10:05. doi:10.1136/openhrt-2023-002279
107 Campion N, Thiel CL, Woods NC, et al. Sustainable healthcare and environmental life-cycle impacts of disposable supplies: a focus on disposable custom packs. *J Clean Prod* 2015;94:46-55. doi:10.1016/j.jclepro.2015.01.076
108 Connor A, Milne S, Owen A, Boyle G, Mortimer F, Stevens P. Toward greener dialysis: a case study to illustrate and encourage the salvage of reject water. *J Ren Care* 2010;36:68-72. doi:10.1111/j.1755-6686.2010.00153.x
109 Connor A, Mortimer F, Tomson C. Clinical transformation: the key to green nephrology. *Nephron Clin Pract* 2010;116:c206. doi:10.1159/000317200
110 Ditac G, Cottinet PJ, Quyen Le M, et al. Carbon footprint of atrial fibrillation catheter ablation. *Europace* 2023;25:331-40. doi:10.1093/europace/euac160
111 Hernández-de-Anda MT, Taboada-González P, Aguilar-Virgen Q, et al. Environmental impacts of a Mexican hemodialysis unit through LCA. *J Clean Prod* 2023;384. doi:10.1016/j.jclepro.2022.135480
112 Jahan S, Barraclough K, Harber M. The climate crisis, sustainable kidney care and us. *J Kidney Care* 2023;8:211-5. doi:10.12968/jokc.2023.8.5.211
113 King J, Poo SX, El-Sayed A, et al, GLINT Research Network. Towards NHS Zero: greener gastroenterology and the impact of virtual clinics on carbon emissions and patient outcomes. A multisite, observational, cross-sectional study. *Frontline Gastroenterol* 2022;14:287-94. doi:10.1136/flgastro-2022-102215
114 Melnyk AI, Woods N, Moalli P. Going green in gynecology: a call to action. *Am J Obstet Gynecol* 2023;229:269-74. doi:10.1016/j.ajog.2023.04.025
115 Roy W, Hans B, Jannat RU, Reddy YK, Hadi Y, Gayam S. Tele-visits for GERD: "Ecofriendly, efficient and effective". *J Gastroenterol Hepatol* 2023;38:905-9. doi:10.1111/jgh.16148
116 Szirt R, Monjur MR, McGovern L, et al. Environmental sustainability in the cardiac catheter laboratory. *Heart Lung Circ* 2023;32:11-5. doi:10.1016/j.hlc.2022.06.694
117 Veitch AM. Greener gastroenterology and hepatology: the British Society of Gastroenterology Strategy for Climate Change and Sustainability. *Frontline Gastroenterol* 2022;13(e1):e3-6. doi:10.1136/flgastro-2022-102134
118 Bishoyi PK, Misra S. Towards energy-and cost-efficient sustainable MEC-assisted healthcare systems. *IEEE Trans Sustain Comput* 2022;7:958-69. doi:10.1109/TSUSC.2022.3170508
119 Di Giacomo P, Håkansson P. A method to measure the reduction of CO2 emissions in e-health applications. *Stud Health Technol Inform* 2011;169:970-4
120 Donald N, Irukulla S. Greenhouse gas emission savings in relation to telemedicine and associated patient benefits: a systematic review. *Telemed J E Health* 2022;28:1555-63. doi:10.1089/tmj.2022.0047
121 Ellis I, Cheek C, Jaffray L, Skinner T. Making a case for telehealth: measuring the carbon cost of health-related travel. *Rural Remote Health* 2013;13:2723
122 Holmner A, Ebi KL, Lazuardi L, Nilsson M. Carbon footprint of telemedicine solutions--unexplored opportunity for reducing carbon emissions in the health sector. *PLoS One* 2014;9:e105040. doi:10.1371/journal.pone.0105040
123 Iaccarino MA, Paganoni S, Tenforde A, et al. Environmental impact of telerehabilitation visits in an urban setting. *J Clim Change Health* 2022;8. doi:10.1016/j.joclim.2022.100150
124 Lange O, Plath J, Dziggel TF, et al. A transparency checklist for carbon footprint calculations applied within a systematic review of virtual care interventions. *Int J Environ Res Public Health* 2022;19:7474. doi:10.3390/ijerph19127474
125 Pickard Strange M, Booth A, Akiki M, Wieringa S, Shaw SE. The role of virtual consulting in developing environmentally sustainable health care: systematic literature review. *J Med Internet Res* 2023;25:e44823. doi:10.2196/44823
126 Sharma S, Yellowlees PM, Gotthardt CJ, Luce MS, Avdalovic MV, Marcin JP. Environmental impact of ambulatory telehealth use by a statewide university health system during COVID-19. *Telemed J E Health* 2023;29:1134-42. doi:10.1089/tmj.2022.0396
127 Sittig DF, Sherman JD, Eckelman MJ, Draper A, Singh H. i-CLIMATE: a "clinical climate informatics" action framework to reduce environmental pollution from healthcare. *J Am Med Inform Assoc* 2022;29:2153-60. doi:10.1093/jamia/ocac137
128 Thiel CL, Mehta N, Sejo CS, et al. Telemedicine and the environment: life cycle environmental emissions from in-person and virtual clinic visits. *NPJ Digit Med* 2023;6:87. doi:10.1038/s41746-023-00818-7
129 Tselapedi-Sekeitto B, Rocha T, Sowerby LJ, Rotenberg B, Biadsee A. Telemedicine as an environmental ally - The social, financial, and environmental impact of virtual care in the otolaryngology clinic. *Am J Otolaryngol* 2023;44:103791. doi:10.1016/j.amjoto.2023.103791
130 Alzaabi A, Bell JP, Montero-Arias F, et al. Greenhouse gas emissions from respiratory treatments: results from the SABA CARBON international study. *Adv Ther* 2023;40:4836-56. doi:10.1007/s12325-023-02663-2
131 Andrews E, Pearson D, Kelly C, Stroud L, Rivas Perez M. Carbon footprint of patient journeys through primary care: a mixed methods approach. *Br J Gen Pract* 2013;63:e595-603. doi:10.3399/bjgp13X671579
132 Saleh JR, Mehta N, Mitchell A. Travel in orthopaedics: getting where we need to be for the planet. *Oper Tech Orthop* 2022;32. doi:10.1016/j.oto.2022.100999
133 Spooner R, Glover Williams A, Roome C. Improving the environmental sustainability of paediatric care. *Arch Dis Child Educ Pract Ed* 2023;108:218-24. doi:10.1136/archdischild-2021-322933
134 Temte JL, Barrett B, Erickson R, Bell C. Developing a research agenda on climate change and health in primary care. *Fam Pract* 2023;40:519-21. doi:10.1093/fampra/cmac130
135 Tsagkaris C, Nikolakea M, Laskaratou ED, et al. Environmental sustainability in healthcare: time to make outpatient care in orthopaedics and rheumatology greener. *Int J Health Plann Manage* 2023;38:547-56. doi:10.1002/hpm.3617
136 Walker R. Climate change and primary health care intervention framework. *Aust J Prim Health* 2009;15:276-84. doi:10.1071/PY09041
137 Wicklum SC, Nuique K, Kelly MA, Nesbitt CC, Zhang JJ, Svrcek CP. Greening Family Medicine clinic operations and clinical care, where do we start? A scoping review of toolkits and aids. *Fam Pract* 2023;40:473-85. doi:10.1093/fampra/cmad006
138 Wilkinson A, Woodcock A. The environmental impact of inhalers for asthma: A green challenge and a golden opportunity. *Br J Clin Pharmacol* 2022;88:3016-22. doi:10.1111/bcp.15135
139 Woodcock A, Beeh KM, Sagara H, et al. The environmental impact of inhaled therapy: making informed treatment choices. *Eur Respir J* 2022;60:2102106. doi:10.1183/13993003.02106-2021
140 Zakrzewski-Fruer JK, Thackray AE. Enhancing cardiometabolic health through physical activity and breakfast manipulations in children and adolescents: good for humans, good for the planet. *Proc Nutr Soc* 2023;82:272-85. doi:10.1017/S0029665122002804
141 Botejara-Antúnez M, González Domínguez J, García-Sanz-Calcedo J. Life cycle analysis methodology for heating, ventilation and air conditioning ductwork in healthcare buildings. *Indoor Built Environ* 2023;32:1213-30. doi:10.1177/1420326X231155146
142 Davies JF, McGain F, Francis JJ. Consensus on prioritisation of actions for reducing the environmental impact of a large tertiary hospital: application of the nominal group technique. *Int J Environ Res Public Health* 2023;20:3978. doi:10.3390/ijerph20053978
143 Lattanzio S, Stefanizzi P, D'ambrosio M, et al. Waste management and the perspective of a green hospital—a systematic narrative review. *Int J Environ Res Public Health* 2022;19:15812. doi:10.3390/ijerph192315812

144 Lewandowski PA, Barker LA, Howard A, Collins J. Packaged hospital food appears safe and feasible to reuse. *Nutr Diet* 2023;80:173-82. doi:10.1111/1747-0080.12801
145 Ludin NA, Junedi MM, Affandi NAA, et al. Energy efficiency action plan for a public hospital in Malaysia. *Alam Cipta* 2019;12:73-9
146 Mui KW, Satheesan MK, Wong LT. Building cooling energy consumption prediction with a hybrid simulation approach: generalization beyond the training range. *Energy Build* 2022;276. doi:10.1016/j.enbuild.2022.112502
147 O'Hara AC, Miller AC, Spinks H, et al. The sustainable prescription: benefits of green roof implementation for urban hospitals. *Front Sustain Cities* 2022;4. doi:10.3389/frsc.2022.798012
148 Phull M, Begum H, John JB, et al. Potential carbon savings with day-case compared to inpatient transurethral resection of bladder tumour surgery in England: a retrospective observational study using administrative data. *Eur Urol Open Sci* 2023;52:44-50. doi:10.1016/j.euros.2023.03.007
149 Schmidt L, Bohnet-Joschko S. Planetary health and hospitals' contribution—a scoping review. *Int J Environ Res Public Health* 2022;19:13536. doi:10.3390/ijerph192013536
150 Sepetis A, Zaza PN, Rizos F, Bagos PG. Identifying and predicting healthcare waste management costs for an optimal sustainable management system: evidence from the Greek public sector. *Int J Environ Res Public Health* 2022;19:9821. doi:10.3390/ijerph19169821
151 Silva GS, Schimek CA, Lighter JL, Thiel CL. Addressing the climate impacts of healthcare. *J Hosp Med* 2022;17:661-4. doi:10.1002/jhm.12834
152 Soares AL, Buttigieg SC, Bak B, et al. A review of the applicability of current green practices in healthcare facilities. *Int J Health Policy Manag* 2023;12:6947. doi:10.34172/ijhpm.2023.6947
153 Chakraborty P, Kumar R, Karn S, Srivastava AK, Mondal P. The long-term impact of coronavirus disease 2019 on environmental health: a review study of the bi-directional effect. *Bull Natl Res Cent* 2023;47:33. doi:10.1186/s42269-023-01007-y
154 Desterbecq C, Tubeuf S. Inclusion of Environmental Spillovers in Applied Economic Evaluations of Healthcare Products. *Value Health* 2023;26:1270-81. doi:10.1016/j.jval.2023.03.008
155 Griffing E, Overcash M. Reusable and disposable incontinence underpads: environmental footprints as a route for decision making to decarbonize health care. *J Nurs Care Qual* 2023;38:278-85. doi:10.1097/NCQ.0000000000000697
156 Jalilvand S, Heidari S, Mohammadnazari Z, et al. A bi-objective organ transplant supply chain network with recipient priority considering carbon emission under uncertainty, a case study. *Process Integr Optim Sustain* 2023;7:709-27. doi:10.1007/s41660-023-00314-1
157 Raila EM, Anderson DO. Black carbon emission reduction strategies in healthcare industry for effective global climate change management. *Waste Manag Res* 2017;35:416-25. doi:10.1177/0734242X16678315
158 Snigdha HM, Hiloidhari M, Bandyopadhyay S. Environmental footprints of disposable and reusable personal protective equipment – a product life cycle approach for body coveralls. *J Clean Prod* 2023;394:136166. doi:10.1016/j.jclepro.2023.136166
159 Varangu L, Cowan K, Amin O, et al. Reusable personal protective equipment in Canadian healthcare: Safe, secure, and sustainable. *Healthc Manage Forum* 2023;36:207-16. doi:10.1177/08404704231168752
160 Zikhathile T, Atagana H, Bwapwa J, Sawtell D. A review of the impact that healthcare risk waste treatment technologies have on the environment. *Int J Environ Res Public Health* 2022;19:11967. doi:10.3390/ijerph191911967
161 Chuter R, Stanford-Edwards C, Cummings J, et al. Towards estimating the carbon footprint of external beam radiotherapy. *Phys Med* 2023;112:102652. doi:10.1016/j.ejmp.2023.102652
162 Jacobson SI, Kacew AJ, Knoebel RW, Hsieh PH, Ratain MJ, Strohbehn GW. Alternative trastuzumab dosing schedules are associated with reductions in health care greenhouse gas emissions. *JCO Oncol Pract* 2023;19:799-807. doi:10.1200/OP.23.00227
163 Lambert P, Musto G, Thiessen M, Czaykowski P, Decker K. Impact of cancer-related virtual visits on travel distance, travel time, and carbon dioxide (CO_2) emissions during the COVID-19 pandemic in Manitoba, Canada. *Curr Oncol* 2023;30:5973-83. doi:10.3390/curroncol30070446
164 Lichter KE, Charbonneau K, Sabbagh A, et al. Evaluating the environmental impact of radiation therapy using life cycle assessments: a critical review. *Int J Radiat Oncol Biol Phys* 2023;117:554-67. doi:10.1016/j.ijrobp.2023.04.036
165 Patel KB, Gonzalez BD, Turner K, et al. Estimated carbon emissions savings with shifts from in-person visits to telemedicine for patients with cancer. *JAMA Netw Open* 2023;6:e2253788. doi:10.1001/jamanetworkopen.2022.53788
166 Piffoux M, Delpon G, Ducrot C, et al. Insights on the carbon footprint of radiotherapy in France. *Cancer Radiother* 2023;27:487-90. doi:10.1016/j.canrad.2023.07.009
167 Chakma MS, Usmani OS. Inhalers and the environment: pollution, plastics and policy. *Pneumon* 2022;35:26. doi:10.18332/pne/154608
168 Nagasaki K, Kaji Y, Wada Y, Sasaki T. The environmental impact of inhaler replacement: A carbon footprint and economic calculation of the National Database of Health Insurance Claims in Japan. *J Gen Fam Med* 2023;24:207-14. doi:10.1002/jgf2.622
169 Richie C. Environmental sustainability and the carbon emissions of pharmaceuticals. *J Med Ethics* 2022;48:334-7. doi:10.1136/medethics-2020-106842
170 Tian J, McGrogan A, Jones MD. Temporal and geographical variation in low carbon inhaler dispensing in England, 2016 to 2021: an ecological study. *J R Soc Med* 2023;116:65-75. doi:10.1177/01410768221133566
171 Weadick CS, Keogh RJ, Carroll HK, et al. Climate toxicity: an increasingly relevant clinical issue in Cancer Care. *J Cancer Policy* 2023;35:100410. doi:10.1016/j.jcpo.2023.100410
172 Alshqaqeeq F, Amin Esmaeili M, Overcash M, et al. Quantifying hospital services by carbon footprint: a systematic literature review of patient care alternatives. *Resour Conserv Recycling* 2020;154. doi:10.1016/j.resconrec.2019.104560
173 Esmaeili A, McGuire C, Overcash M, Ali K, Soltani S, Twomey J. Environmental impact reduction as a new dimension for quality measurement of healthcare services. *Int J Health Care Qual Assur* 2018;31:910-22. doi:10.1108/IJHCQA-10-2016-0153
174 Leapman MS, Thiel CL, Gordon IO, et al. Environmental impact of prostate magnetic resonance imaging and transrectal ultrasound guided prostate biopsy. *Eur Urol* 2023;83:463-71. doi:10.1016/j.eururo.2022.12.008
175 McAlister S, McGain F, Petersen M, et al. The carbon footprint of hospital diagnostic imaging in Australia. *Lancet Reg Health West Pac* 2022;24:100459. doi:10.1016/j.lanwpc.2022.100459
176 Peters S, Burrows S, Jenkins P. The challenge of environmental sustainability in radiology training and potential solutions. *Postgrad Med J* 2021;97:755-9. doi:10.1136/postgradmedj-2020-138835
177 McKenzie BJ, Haas R, Ferreira GE, Maher CG, Buchbinder R. The environmental impact of health care for musculoskeletal conditions: a scoping review. *PLoS One* 2022;17:e0276685. doi:10.1371/journal.pone.0276685
178 Owens S, Morris K, Hurley E, et al. Estimating the national carbon footprint of inhalers in healthcare. *Ir J Med Sci* 2023;192:2251-3. doi:10.1007/s11845-022-03234-0
179 ten Have P, van Hal P, Wichers I, et al. Turning green: the impact of changing to more eco-friendly respiratory healthcare - a carbon and cost analysis of Dutch prescription data. *BMJ Open* 2022;12:e055546. doi:10.1136/bmjopen-2021-055546
180 Kangasniemi M, Kallio H, Pietilä AM. Towards environmentally responsible nursing: a critical interpretive synthesis. *J Adv Nurs* 2014;70:1465-78. doi:10.1111/jan.12347
181 Lilienfeld E, Nicholas PK, Breakey S, Corless IB. Addressing climate change through a nursing lens within the framework of the United Nations Sustainable Development Goals. *Nurs Outlook* 2018;66:482-94. doi:10.1016/j.outlook.2018.06.010
182 Pinzone M, Lettieri E, Masella C. Sustainability in healthcare: combining organizational and architectural levers. *Int J Eng Bus Manag* 2012;4:1-9. doi:10.5772/54841
183 Schenk EC, Johnson S, Kelley-Gustafson B, et al. Nursing waste reduction for a healthy environment. *J Radiol Nurs* 2023;42:57-61. doi:10.1016/j.jradnu.2022.12.008
184 Webster RJ. Climate action, staff engagement, and change management: a paediatric hospital case study. *Healthc Manage Forum* 2023;36:195-8. doi:10.1177/08404704231165482
185 Breth-Petersen M, Bell K, Pickles K, McGain F, McAlister S, Barratt A. Health, financial and environmental impacts of unnecessary vitamin D testing: a triple bottom line assessment adapted for healthcare. *BMJ Open* 2022;12:e056997. doi:10.1136/bmjopen-2021-056997
186 McAlister S, Barratt AL, Bell KJL, McGain F. The carbon footprint of pathology testing. *Med J Aust* 2020;212:377-82. doi:10.5694/mja2.50583
187 Dhara VR, Schramm PJ, Luber G. Climate change & infectious diseases in India: implications for health care providers. *Indian J Med Res* 2013;138:847-52.
188 Duane B, Taylor T, Stahl-Timmins W, Hyland J, Mackie P, Pollard A. Carbon mitigation, patient choice and cost reduction--triple bottom line optimisation for health care planning. *Public Health* 2014;128:920-4. doi:10.1016/j.puhe.2014.08.008
189 Khanna SS, Dhaimade PA. Green dentistry: a systematic review of ecological dental practices. *Environ Dev Sustain* 2019;21:2599-618. doi:10.1007/s10668-018-0156-5
190 Lyne A, Ashley P, Johnstone M, Duane B. The environmental impact of community caries prevention - part 1: fluoride varnish application. *Br Dent J* 2022;233:287-94. doi:10.1038/s41415-022-4901-7

191 Bein T, Koch S, Schulz C. What's new in intensive care: environmental sustainability. *Intensive Care Med* 2021;47:903-5. doi:10.1007/s00134-021-06455-6
192 Trent L, Law J, Grimaldi D. Create intensive care green teams, there is no time to waste. *Intensive Care Med* 2023;49:440-3. doi:10.1007/s00134-023-07015-w
193 Mackillop N, Shah J, Collins M, Costelloe T, Öhman D. Carbon footprint of industry-sponsored late-stage clinical trials. *BMJ Open* 2023;13:e072491. doi:10.1136/bmjopen-2023-072491
194 Blanchard IE, Brown LH,North American EMS Emissions Study Group. Carbon footprinting of North American emergency medical services systems. *Prehosp Emerg Care* 2011;15:23-9. doi:10.3109/10903127.2010.519818
195 Hwong AR, Kuhl EA, Compton WM, et al. Climate change and mental health: implications for the psychiatric workforce. *Psychiatr Serv* 2022;73:592-5. doi:10.1176/appi.ps.202100227
196 Yellowlees P. Climate change impacts on mental health will lead to increased digitization of mental health care. *Curr Psychiatry Rep* 2022;24:723-30. doi:10.1007/s11920-022-01377-6
197 Keil M, Grün L. Greenhouse gas emissions of an outpatient care service: a cost-based approach. *Z Evid Fortbild Qual Gesundhwes* 2022;175:90-5. doi:10.1016/j.zefq.2022.09.005
198 Wolstencroft PW, Zacher NC, Scotellaro K, Centkowski S, Kwong BY. Development of a framework for addressing skin biopsy tray waste in dermatology clinics: a quality improvement study. *JAMA Dermatol* 2023;159:541-4. doi:10.1001/jamadermatol.2023.0511
199 Oteri J, Bawa S, Christopher E, et al. Potential for improving routine immunisation waste management using measles vaccination campaign 2017 in Kebbi State, Nigeria. *Vaccine* 2021;39(Suppl 3):C60-5. doi:10.1016/j.vaccine.2020.12.060
200 Williams JTW, Bell KJL, Morton RL, Dieng M. Exploring the integration of environmental impacts in the cost analysis of the pilot MEL-SELF trial of patient-led melanoma surveillance. *Appl Health Econ Health Policy* 2023;21:23-30. doi:10.1007/s40258-022-00765-6
201 Singh A, Hadfield J, Gale J, Shaw C. Doctors' travel in the Anthropocene. *N Z Med J* 2022;135:88-93.
202 Dokal K, Morris M, Spooner R, Perkins P. The carbon footprint of a hospice. *BMJ Support Palliat Care* 2022:spcare-2022-003972. doi:10.1136/spcare-2022-003972
203 Achour N, Price ADF. Resilience strategies of healthcare facilities: present and future. *Int J Disaster Resil Built Environ* 2010;1:264-76. doi:10.1108/17595901011080869
204 Haghighi Bardineh Y, Mohamadian F, Ahmadi MH, et al. Medical and dental applications of renewable energy systems. *Int J Low Carbon Technol* 2018;13:320-6. doi:10.1093/ijlct/cty040
205 Barratt AL, Bell KJL, Charlesworth K, McGain F. High value health care is low carbon health care. *Med J Aust* 2022;216:67-8. doi:10.5694/mja2.51331
206 Berniak-Woźny J, Rataj M. Towards green and sustainable healthcare: a literature review and research agenda for green leadership in the healthcare sector. *Int J Environ Res Public Health* 2023;20:908. doi:10.3390/ijerph20020908
207 Butler K. How energy benchmarking in healthcare facilities supports greenhouse gas emission reduction. *Healthc Manage Forum* 2023;36:199-206. doi:10.1177/08404704231165887
208 Cimprich A, Santillán-Saldivar J, Thiel CL, et al. Potential for industrial ecology to support healthcare sustainability: scoping review of a fragmented literature and conceptual framework for future research. *J Ind Ecol* 2019;23:1344-52. doi:10.1111/jiec.12921
209 Cimprich A, Young SB. Environmental footprinting of hospitals: organizational life cycle assessment of a Canadian hospital. *J Ind Ecol* 2023;27:1335-53. doi:10.1111/jiec.13425
210 Dinar HHA. Global actions on climate change: the health system focus—a systematic review. *Saudi J Health Syst Res* 2023;3:1-9. doi:10.1159/000528427
211 Drew J, Christie SD, Rainham D, Rizan C. HealthcareLCA: an open-access living database of health-care environmental impact assessments. *Lancet Planet Health* 2022;6:e1000-12. doi:10.1016/S2542-5196(22)00257-1
212 Eckelman MJ, Sherman J. Environmental impacts of the U.S. health care system and effects on public health. *PLoS One* 2016;11:e0157014. doi:10.1371/journal.pone.0157014
213 Eckelman MJ, Sherman JD, MacNeill AJ. Life cycle environmental emissions and health damages from the Canadian healthcare system: an economic-environmental-epidemiological analysis. *PLoS Med* 2018;15:e1002623. doi:10.1371/journal.pmed.1002623
214 Fragão-Marques M, Ozben T. Digital transformation and sustainability in healthcare and clinical laboratories. *Clin Chem Lab Med* 2022;61:627-33. doi:10.1515/cclm-2022-1092
215 Francis D, Cohen G, Bhatt J, Brask C, Devnani M, Surgenor G. How healthcare can help heal communities and the planet. *BMJ* 2019;365:l2398. doi:10.1136/bmj.l2398
216 Frumkin H, Hess J, Luber G, Malilay J, McGeehin M. Climate change: the public health response. *Am J Public Health* 2008;98:435-45. doi:10.2105/AJPH.2007.119362
217 Greenwood Dufour B, Weeks L, De Angelis G, et al. How we might further integrate considerations of environmental impact when assessing the value of health technologies. *Int J Environ Res Public Health* 2022;19:12017. doi:10.3390/ijerph191912017
218 Hancock T. Beyond net-zero: toward a "One Planet" health system. *Healthc Manage Forum* 2023;36:184-9. doi:10.1177/08404704231162775
219 Hensher M, McGain F. Health care sustainability metrics: building a safer, low-carbon health system. *Health Aff (Millwood)* 2020;39:2080-7. doi:10.1377/hlthaff.2020.01103
220 Issa R, Baker C, Spooner R, et al. Mapping the movement for climate change and health in England: a descriptive review and theory of change analysis. *Perspect Public Health* 2021;141:328-37. doi:10.1177/17579139211058303
221 Jackson R, Shields KN. Preparing the U.S. health community for climate change. *Annu Rev Public Health* 2008;29:57-73. doi:10.1146/annurev.publhealth.29.020907.090755
222 Karlsson M, Pigretti Öhman D. Material consumption in the healthcare sector: Strategies to reduce its impact on climate change—the case of Region Scania in South Sweden. *J Clean Prod* 2005;13:1071-81. doi:10.1016/j.jclepro.2004.12.012
223 Kumar H, Azad A, Gupta A, et al. COVID-19 Creating another problem? Sustainable solution for PPE disposal through LCA approach. *Environ Dev Sustain* 2021;23:9418-32. doi:10.1007/s10668-020-01033-0
224 Lee VS, Gerwig K, Hough E, et al. Decarbonizing health care: engaging leaders in change. *NEJM Catal* 2023;4. doi:10.1056/CAT.22.0433
225 McGinnis S, Johnson-Privitera C, Nunziato JD, Wohlford S. Environmental life cycle assessment in medical practice: a user's guide. *Obstet Gynecol Surv* 2021;76:417-28. doi:10.1097/OGX.0000000000000906
226 Pencheon D, Rissel CE, Hadfield G, Madden DL. Health sector leadership in mitigating climate change: experience from the UK and NSW. *N S W Public Health Bull* 2009;20:173-6. doi:10.1071/NB09044
227 Pinho-Gomes AC, Yoo SH, Allen A, Maiden H, Shah K, Toolan M. Incorporating environmental and sustainability considerations into health technology assessment and clinical and public health guidelines: a scoping review. *Int J Technol Assess Health Care* 2022;38:e84. doi:10.1017/S0266462322003282
228 Rahimi-Ardabili H, Magrabi F, Coiera E. Digital health for climate change mitigation and response: a scoping review. *J Am Med Inform Assoc* 2022;29:2140-52. doi:10.1093/jamia/ocac134
229 Rodríguez-Jiménez L, Romero-Martín M, Spruell T, Steley Z, Gómez-Salgado J. The carbon footprint of healthcare settings: a systematic review. *J Adv Nurs* 2023;79:2830-44. doi:10.1111/jan.15671
230 Sijm-Eeken ME, Arkenaar W, Jaspers MW, Peute LW. Medical informatics and climate change: a framework for modeling green healthcare solutions. *J Am Med Inform Assoc* 2022;29:2083-8. doi:10.1093/jamia/ocac182
231 Steenmeijer MA, Rodrigues JFD, Zijp MC, Waaijers-van der Loop SL. The environmental impact of the Dutch health-care sector beyond climate change: an input-output analysis. *Lancet Planet Health* 2022;6:e949-57. doi:10.1016/S2542-5196(22)00244-3
232 Tennison I, Roschnik S, Ashby B, et al. Health care's response to climate change: a carbon footprint assessment of the NHS in England. *Lancet Planet Health* 2021;5:e84-92. doi:10.1016/S2542-5196(20)30271-0
233 Thiel C, Richie C. Carbon emissions from overuse of U.S. health care: medical and ethical problems. *Hastings Cent Rep* 2022;52:10-6. doi:10.1002/hast.1404
234 Thomson D, Varangu L, Webster RJ. A climate resilience maturity matrix for Canadian health systems. *Healthc Manage Forum* 2023;36:217-23. doi:10.1177/08404704231169037
235 Vaishnavi V, Suresh M. Modelling the factors in implementation of environmental sustainability in healthcare organisations. *Manag Environ Qual* 2023;34:137-58. doi:10.1108/MEQ-10-2021-0243
236 Walpole SC, Eii MN, Lyons T, Aldridge C. Improving antimicrobial use to protect the environment: what is the role of infection specialists?*Antibiotics (Basel)* 2023;12:640. doi:10.3390/antibiotics12040640
237 World Resources Institute, World Business Council for Sustainable Development. The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition). 2004. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf
238 Lenzen M, Malik A, Li M, et al. The environmental footprint of health care: a global assessment. *Lancet Planet Health* 2020;4:e271-9. doi:10.1016/S2542-5196(20)30121-2

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