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TOPICAL REVIEW

Recent progress on carbon footprint assessment of healthcare services

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Abstract

As a result of the carbon-intensive nature of health care, hospital facilities are contributors to global warming. Health care's contributions to global warming and greenhouse gas emissions include those associated with carbon emissions, energy consumption, pharmaceuticals, travel-related emissions and procurement. This article presents a review of environmental impact of different medical services. The published research articles focused on estimating the carbon footprint of healthcare services are investigated here. This review also discusses methods used for determining greenhouse gas emissions. Life cycle assessment and component analysis are the two most used methods for calculating emissions. This study also highlights the existing challenges related to estimation of carbon emission of different healthcare services and ways to overcome these challenges associated with carbon emission. The findings reveal substantial variability in carbon footprint estimates depending on region, settings, and usage patterns, with energy consumption identified as the primary source of greenhouse gas emissions. The review also addresses challenges in data availability, the accuracy of estimations, and the exclusion of critical factors like the environmental impact of medical equipment manufacturing. To mitigate healthcare's carbon footprint, the study underscores the importance of transitioning from fossil fuels to renewable energy, minimizing unnecessary medical procedures, and promoting the use of reusable instruments. These insights are essential for developing more accurate and comprehensive strategies to reduce the carbon footprint of healthcare services globally.

1. Introduction

In the 21st century, climate change is a major threat to human health (Costello *et al* 2009, Watts *et al* 2015). It is imperative that all industries develop strategies to reduce greenhouse gas emissions to prevent a rise in global temperatures above 2 °C and the resulting climate disruption. Greenhouse gas emissions from healthcare are significant, accounting for approximately 4.4% of global emissions (ARUP 2022). Sustainability is a concept that seeks to cover our present needs without compromising future generations' resources by protecting our planet, stopping climate change, and promoting social development. In the past, literature reviews have been conducted on different aspects of healthcare sustainability. A systematic literature review, referencing publications prior to March 2011, was conducted to map the energy and greenhouse gas emissions of healthcare services (Brown *et al* 2012). Another review of sustainability in hospitals covers articles prior to October 2013 (McGain and Naylor 2014). In a recent article, the medical devices and services were quantified by carbon footprint and the articles from the year 2000 to 2016 were reviewed but did not assess the relative quality of information about reported life cycle methodologies (Alshqaqeeq *et al* 2020). Considering the recent articles on carbon footprint for different sectors of hospitals, there is no review paper published to date. Based on the analysis of previous research works, this review paper will discuss about the amount, sources, approaches, and challenges of carbon footprint for various aspects of healthcare.

This paper reviews the recent works related to the carbon footprinting of different sectors in healthcare services such as—diagnostic services, pathology testing, surgeries, treatment in the intensive care unit, renal service, dialysis, anaesthesia etc Estimating the carbon footprint can help to think of some changes in them to reduce the total greenhouse gas emission. In 2020–21, many major economies targeted to reduce carbon emissions by 2030, while becoming carbon neutral between 2050 and 2060 (House 2021). Within healthcare system, greenhouse gases emit from various sources, such as—electricity use, different materials used by patients and staffs, energy use for heating and cooling system, use of different anaesthetic gases, wase disposal etc By knowing the responsible sources and the amount of greenhouse gas emission, healthcare organizers can take necessary steps for reducing the total emission.

The content is organized as follows: section 2 describes the current scenario of carbon footprint in hospital. Sections 3 and 4 reviews the used methods and contributions in carbon footprinting of hospital. Section 5 discusses about the challenges of estimating carbon footprint and the ways to overcome these challenges. In the last, section 6 presents the conclusion.

2. Current scenario of carbon footprint in hospital

Global warming is a result of greenhouse gas that accumulates in the atmosphere, absorbs, and re-emits heat. The term Carbon Footprint is defined as the total greenhouse gases (GHG) (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PCFs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) (Wright *et al* 2011)) emissions including the emissions caused by individual, events, organizations, services, places, or products and is expressed in carbon dioxide equivalent (CO_2e). In accordance with the Greenhouse Gas Protocol (GHGP), an international standard for accounting and reporting emissions, emissions are classified according to their source into Scope 1, Scope 2, and Scope 3. As a consequence of the organisation’s activities, scope 1 represents direct emissions from within the organisational boundary, Scope 2 represents indirect emissions caused by electricity consumption and Scope 3 includes all indirect emissions caused by activities that are not directly within the organisational boundary.

It has been estimated that the healthcare industry, companies that provide clinical services, manufacture drugs and medical equipment, and are also involved in the diagnosis, treatment, nursing and management of illness, disease and injury; generates between 8%–10% of all greenhouse gas emissions in the U.S. (Chung and Meltzer 2009, Eckelman and Sherman 2016), and in the UK, 25% of all public sector emissions come from the National Health Service (NHS) (Commission 2009). In the UK, maintaining buildings are estimated to contribute only about 12% to the NHS’s overall carbon footprint, while pharmaceuticals and procurement contribute approximately 50% (Tennison *et al* 2021). Healthcare sector emissions account for 7% of Australia’s total greenhouse gas emissions, with hospitals and pharmaceuticals contributing greatly (Malik *et al* 2018). In 2014–15, Australia’s total CO_2e emissions were 494 930 kilotonnes, and health care emissions accounted for 35 772 of those emissions (Malik *et al* 2018). Within health care, the five most important sectors in terms of total CO_2e emissions ranged from: public hospitals (12 295 [34%] of 35 772 kilotonnes), private hospitals (3635 kilotonnes [10%]), other medications (3347 kilotonnes [9%]), and benefit-paid medications (3257 kilotonnes [9%]), and capital expenditure for buildings (2776 kilotonnes [8%]) (Malik *et al* 2018).

Depending on the medical services, the greenhouse gas emission occurs from different sources (table 1). Emission scopes were classified into few categories based on the boundaries of each study: travel related, energy consumption, procurement, waste and water. As much as 38% of healthcare greenhouse gas emissions are generated by transportation to and from healthcare facilities, excluding direct healthcare services (Subaiya *et al* 2011, Pollard *et al* 2013). However, healthcare industry’s environmental impact is primarily due to energy consumption and landfill waste production (Wong *et al* 1994, Hu *et al* 2004, DiConsiglio 2008, Sutherland 2008, Esaki *et al* 2009, Kwakye *et al* 2011, Power *et al* 2012, Organization 2013). The most frequently considered source of emission is energy usage for individual services. It is important to note that energy consumption is the largest source of greenhouse gas emission. After energy consumption, the second and third important source of emissions are consumables and pharmaceuticals. Other considerable sources are anaesthetic gases, transportation, waste management and water. A summary of all emission sources is shown in table 1.

3. Approaches to assess the carbon footprints in hospital

In this review article, the authors noted the kind of methodologies were used and list in table 3. The two most common approaches for calculating greenhouse gas emissions were component analysis and life cycle assessment (LCA).

Table 1. Emission sources for various medical services from previous research works.

References no.	Year	Healthcare sector	Service	Source of emission	Key findings
(McAlister *et al* 2022)	2022	Hospital diagnostic imaging	Chest x-ray (CXR), Mobile chest x-ray (MCXR), Computerised Tomography (CT), Magnetic, Resonance Imaging (MRI) and Ultrasound (US)	Electrical power, materials used by patients and staff such as sheets, gloves, gowns, contrast, needles, and syringes.	Electricity consumption is the most responsible source for greenhouse gas emissions.
(Janson *et al* 2022)	2022	Respiratory treatments		Short-acting β2-agonist (SABA), Controller medication.	Greenhouse gas emission is less for controller medication than SABA.
(McGain *et al* 2018)	2018	Intensive Care Unit (ICU)	Patients with septic shock	Electricity, gas use, energy consumption by gas boiler and chiller, consumables used - gloves, gowns, syringes, airway circuits and humidifiers, renal support equipment, paper towels, dressings, invasive vascular devices, bed linen, patient clothing, and laryngoscopes.	From energy consumption the maximum CO_2-e emissions occurs.
(McAlister *et al* 2020)	2020	Pathology testing	Full blood examination; coagulation profile; urea and electrolyte levels (U&E); C-reactive protein concentration (CRP); and arterial blood gas testing (ABG)	Materials used- nitrile, gloves, cotton swabs, alcohol swabs, BD vacutainers (plastic tubes and needles), syringes and adjuncts (serum separators, syringes, and sealable plastic specimen bags. aliquot tubes and reagents and their packaging, including glass and plastic bottles, plastic cartridges, printed instructions, and cardboard boxes, the power required to undertake each test.	The main sources of CO_2e emissions are sample collection consumables (swabs, gloves, vacutainer holders and collection tubes, specimen bags).
(MacNeill *et al* 2017)	2017	Operating theatres	Surgical suites	Anaesthetic gases; electricity use, energy for space heating, surgical supply chain, waste disposal	Anaesthetic gas is the largest source of CO_2e emission.
(Siau *et al* 2021)	2021	Endoscopy	Endoscopy	Carbon emissions from energy consumption; waste disposal.	Waste disposal is the main source of CO_2e Emissions for endoscopy.
(Tan and Lim 2021)	2020	Dermatologic surgery	Skin cancer excision	Transportation, Electricity, Surgical instruments, Plastic, Cotton gauze, Latex glove, waste.	Transportation and Electricity are the main sources for CO_2e emission.
(Connor *et al* 2010)	2010	Renal Service	Dorset Renal Service	Building Energy Use, Travel, Pharmaceuticals, Medical equipment, Radiology, Pathology, paper, Food, Laundry services,	Pharmaceutical is the largest source of greenhouse gas emission for renal service.

Table 1. (Continued.)

References no.	Year	Healthcare sector	Service	Source of emission	Key findings
				Construction, IT, Water, Sanitation products, Waste.	
(McGain *et al* 2021)	2021	Anaesthesia	Anaesthesia for Knee replacement	Sevoflurane, Oxygen, CO_2 absorbent, Drugs, Single use—plastics, cotton, glass etc, electricity for cleaning reusables- plastics, gowns etc, electricity for warmer, scavenging and anaesthesia machine	Electricity use plays a vital role for CO_2e emission.
(Morris *et al* 2013)	2013	Eye surgery	Cataract surgery	Building energy use, Travel, Pharmaceuticals, Medical equipment, paper and ink, Food, Laundry services, Information technology, Water, Waste	Medical equipment is the main source of CO_2e emission for cataract surgery.
(Balkenhol *et al* 2018)	2018	Regional hospital		Diesel, LPG, Electricity, Water, Plain paper, Nitrous oxide, Sevoflorane, Deflowering, Carbon dioxide, Waste generation, Wood pellet	Almost half of the total CO_2e emission comes from electricity use.
(Prasad *et al* 2022)	2021	Regular and intensive inpatient care		Energy consumption, water, waste, consumables, medical gases, equipment, food, staff travel.	Energy consumption is the main source of emission for regular inpatient and for intensive inpatient its consumables.
(Brown, Canyon, *et al* 2012)	2012	Ambulance operation	Air ambulance and ground ambulance	For ground ambulance—electricity, diesel, petrol. For air ambulance—aviation fuel, electricity, diesel, petrol.	Diesel and petrol consumption is the main source of emission for ground ambulance in both countries.
(Gatenby 2011)	2010	Reflux control	Surgical and medical treatment of gastro-oesophageal reflux	Endoscopy, pH tests, Manometry, Operation time, Consumables, Inpatient care/day, ICU, HDU, Visit to GP, Visit from GP, Outpatient appointment, Day case, Inpatient care, non-randomised surgery, Medication costs.	Non-randomised surgery is the main source.
(Chen *et al* 2017)	2016	Peritoneal dialysis		Transportation, Energy, paper (office), Packaging, paper (towel), Laundry, Waste disposal, Transportation	Packaging is the largest source of emission.
(Lim *et al* 2013)	2013	Haemodialysis (HD)		Energy use, Water, Travel, Waste, Pharmaceuticals, Medical equipment, Food, Sanitation products, Laundry services, paper, Diagnostics,	Pharmaceutical is the biggest source of emission along with medical equipment and energy usage.
(Connor *et al* 2011)	2011			Building energy use, Staff travel, Patient travel, Consumables, Packaging, Water	Consumables contributes the most, more than 36% of total emission.

Table 1. (Continued.)

References no.	Year	Healthcare sector	Service	Source of emission	Key findings
		Home and in-center maintenance hemodialysis		Consumption, paper Consumption, Laundry, Construction, Sanitation, Waste Management, Dialysis Access Surgery, Outpatient Appointments	
(Power *et al* 2012)	2012	Minimally Invasive Surgery		Industrial gas manufacturing, Power generation and supply, Gas extraction, CO_2 transportation, biomedical waste	Industrial gas manufacturing process contributes the most in emission.
(Woods *et al* 2015)	2015	Robotically assisted laparoscopy, laparoscopy and laparotomy		Energy, waste	From energy consumption the maximum CO_2-e emissions occurs.
(Maughan *et al* 2016)	2016	Long-acting injections		Medication, Needle and syringe, Appointment, Travel.	Appointment is the main source of emission.

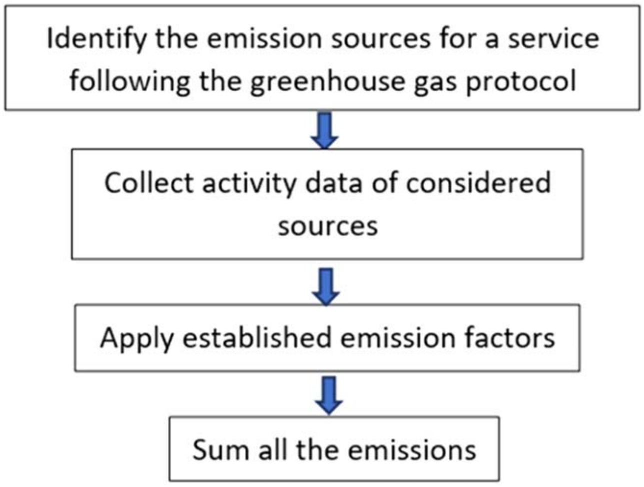

Figure 1. Steps of component analysis.

3.1. Component analysis

Component analysis was used mostly for calculating the carbon footprint in different services such as - renal service, cataract surgery, peritoneal dialysis, haemodialysis, minimally invasive surgery, robotically assisted laparoscopy, laparoscopy, and laparotomy and surgical suites. The result of component analysis comes from the summation of the multiplication of activity data and established emission factors for a considered field. In case of renal service (Connor *et al* 2010), cataract surgery (Morris *et al* 2013) and peritoneal dialysis (Chen *et al* 2017) analysis, the activity data were collected from three major sources such as building energy use, travel, and procurement. In both of the haemodialysis analysis (Connor *et al* 2011, Lim *et al* 2013), the activity data were collected from travel, electricity use and water use, waste disposal and recycling, procurement. For estimating the carbon footprint of surgical suites in operating theatres (MacNeill *et al* 2017) and the comparison of carbon emission of robotically assisted laparoscopy, laparoscopy and laparotomy (Woods *et al* 2015), energy consumption and waste disposal data were considered. The data of anaesthetic agents was also considered in surgical suites study. The steps of component analysis can be categorized as in figure 1. Component analysis is less complex as it only depends on the activity data and the considered emission factors. It is actually the multiplication of these two components. In component analysis, background data is not considered, which can lack its accuracy than other methods.

3.2. Life cycle assessment (LCA)

It is important to note that Life Cycle Assessment (LCA) is the most used approach in recent articles. A life cycle assessment evaluates environmental impacts across all the stages of a product or service's life cycle (Wikipedia 2022). According to ISO 14040, a life cycle assessment consists of four major phases: goal and scope definition, inventory analysis, impact assessment, and interpretation, as shown in figure 2. In goal and scope definition, the objectives, functional units and system boundaries are defined. Inventory Analysis phase involves collecting all data relating to the whole life cycle, including inputs, processes, emissions, etc Inventory analysis is used to quantify environmental impacts and input resources in Impact Assessment phase. In the last Interpretation phase, the results of the Impact Assessment phase are interpreted, and improvement measures are recommended.

Based on the Society of Environmental Toxicology and Chemistry definition, the following components are to be analysed as part of the LCA-

1. Acquisition of raw materials,
2. Manufacturing and processing,
3. Transportation and distribution,
4. Use, maintenance, and reuse,
5. Recycling and waste management. (Klöpffer 2006)

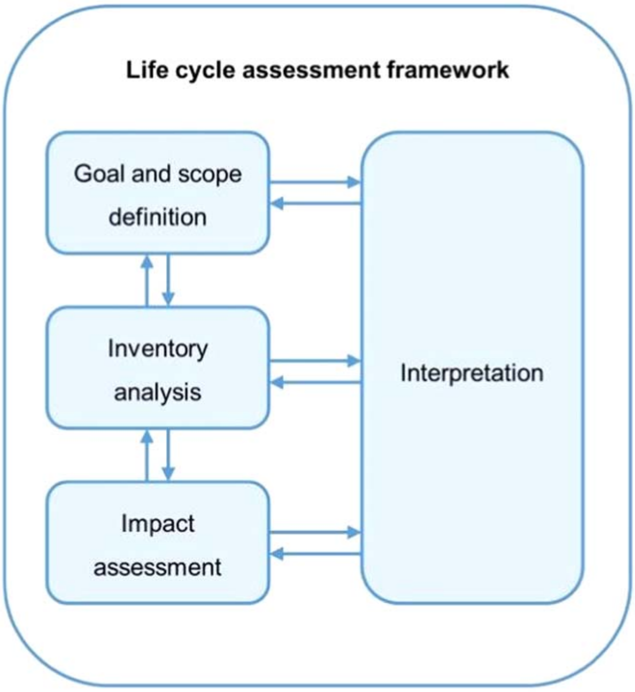

Figure 2. Phases of Life Cycle Assessment (LCA), as described in ISO 14040.

In (McAlister *et al* 2022), process based LCA was used to undertake both attributional (ALCA) and consequential (CLCA) analyses. An ALCA in imaging analyses the share of total impact from a single scan that can be attributed to a given modality, identifying the sources and magnitude of diagnostic imaging and its impact (McAlister *et al* 2022). CLCAs, on the other hand, only model changes to an operating system that result from a single additional scan (Weidema 2003).

In (McGain *et al* 2018), a combination of, a process-based LCA, and an economic input-output (EIO) LCA was performed to determine the carbon footprint of treating Patients with septic shock in ICU. In processes-based LCAs, direct environmental data is used to quantify impacts on the environment (for example, using electricity to drive ventilators or plastic to make syringes leads to GHG emissions and pollutants) (McGain *et al* 2018). In this study, the cost of pharmaceuticals, intravenous fluids, and pathology were analysed using an EIO-LCA - no publicly available LCA databases are available. A hybrid LCA is also used in (Prasad *et al* 2022) to study the carbon footprint of regular and intensive inpatient care.

Prospective life cycle assessment is used by the authors of (McAlister *et al* 2020) and (McGain *et al* 2021). In both studies, hospital heating/ventilating/air conditioning (HVAC) system was not included in the defined system boundary of LCA.

Recent research works mostly use life cycle assessment for determining carbon footprint, since it considers background data, making it more precise when compared to other approaches. The summary of used databases, methods and software are described in table 2.

In case of studying carbon footprinting of ambulance operation (Brown *et al* 2012), reflux control (Gatenby 2011) and long-acting injections (Maughan *et al* 2016); the considered data were operational and financial data, data from the costs of care of patients and NHS England carbon emissions carbon footprinting report and prescription data followed by economic and carbon cost projections using local and national data, respectively.

4. Recent estimations of the carbon footprints in hospital

The figure 3 illustrates the carbon footprint of various medical procedures, services, and treatments, highlighting significant disparities in CO2 emissions across healthcare activities. The vertical axis uses a logarithmic scale, revealing that high-emission procedures such as respiratory treatments and hemodialysis exhibit markedly higher carbon footprints compared to diagnostic services like blood tests and imaging modalities. Table 3 summarizes the used methodology and actual carbon footprint for the medical services.

Table 2. Life cycle assessment approaches from previous works.

Study	LCA type	Functional unit	System boundary	Input Data	Data from manufacturer	Life cycle inventories (LCI)	Software	Method	Study outcome
Diagnostic imaging	Attributional LCA (ALCA) and consequential LCA (CLCA)	CT, MRI, US, CXR or MCXR	Defined	Energy consumption (active power and standby power), Consumables	Power consumption of computers and monitors in the imaging control rooms	Ecoinvent 3.5 database	SimaPro	ReCiPe 2016 (H) impact assessment	CO_2e in kg
Pathology testing (full blood examination, coagulation profile, U&E, CRP, or ABG)	Consequential process-based LCA	The collection of a sample in a plastic vacutainer tube holder and collection tube and the analysis of a single blood sample in a hospital	Defined	Consumables, required power, Transport from place of manufacture		Consequential version of Ecoinvent 3.5	SimaPro	European Commission International Reference, Life Cycle Data system (ILCD; version 1.10) impact assessment method	CO_2e in grams
Treating septic shock patient in ICU	Hybrid LCA, a process-based LCA, and an economic input–output (EIO) LCA	The treatment of one ICU patient with septic shock	Defined	Energy consumption, consumables, waste		Ecoinvent version 2.		ReCiPe, 2016 version	CO_2e in kg
Regular and intensive inpatient care	Hybrid LCA, economic input output LCA and process-based LCA	1 year of inpatient care in both a high- and low-intensity unit	Defined	Production and disposal of all physical resources, Energy consumption, consumables, waste		Ecoinvent 3.4 unit process database.	SimaPro, OpenLCA	For EIOLCA- 2013 US Environmentally Extended Input Output (EEIO), LCA model.	CO_2e in kg
General, Regional, and Combined Anaesthesia for Total Knee Replacements	Prospective life cycle assessment	All anaesthesia for a total knee replacement in a hospital	Defined	Anaesthetic items, gases, and drugs, and electricity for patient warming and anaesthetic machine	Electricity consumption for anaesthesia devices	Ecoinvent, Switzerland, and the Australian Life Cycle Inventory	SimaPro	Monte Carlo methods	CO_2e in kg

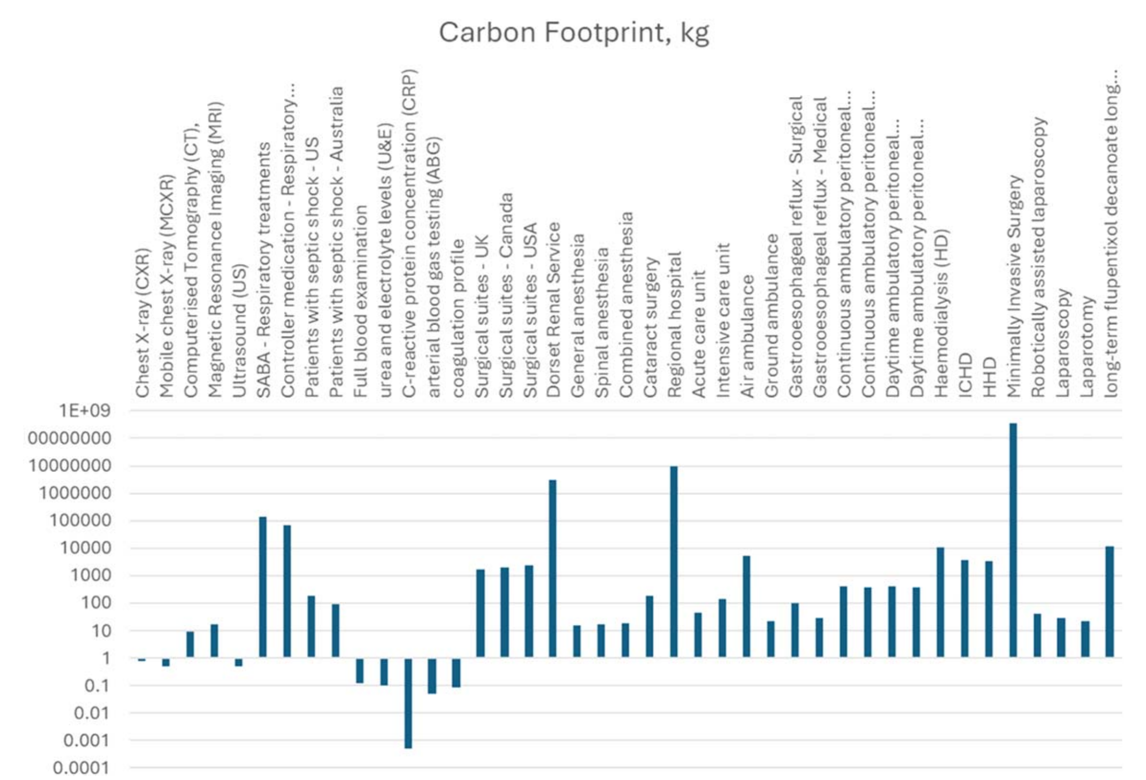

Figure 3. Carbon footprint of different healthcare services.

4.1. Diagnostic imaging

Scott McAlister, in (McAlister *et al* 2022) described all major diagnostic imaging modalities' life cycle carbon footprints. According to their finding, Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI) had greater carbon footprints than x-rays and ultrasounds, which are the traditional imaging modalities. According to their calculation, greenhouse gas emission per scan were 17.5 kg CO_2e for MRI, 9.2 kg for CT, 0.8 for chest x-ray and 0.53 kg for ultrasound. In consequential analysis, emissions per additional scan for MRI were 1.1 kg; 1.1 kg for CT; 0.6 kg for CXR; 0.1 kg for MCXR; and 0.1 kg for US, since standby power emissions were excluded. Due to differences in scanners as well as in usage patterns, large differences have been reported in scanner energy consumption (Sheppy *et al* 2014, Heye *et al* 2020).

4.2. Respiratory treatments

In (Janson *et al* 2022), a observational study was done to calculate the carbon footprint of respiratory treatment in Europe and Canada. Among respiratory treatments, a lot of attention has been paid to the environmental impact of controller inhalers because MDIs use hydrofluorocarbon propellants that contribute to global warming (Janson *et al* 2022). The United Kingdom (UK) has set targets for reducing total emissions by 80% by 2036–2039 (England and Improvement 2020), including those from medical devices, when MDIs accounted for 3% of health and social care system (England 2018) and 13.1% related to delivering care of greenhouse gas emissions in 2019 (Tennison *et al* 2021). In comparison to SABA, which produces 12 to 134 tonnes of CO_2e per 10 000 persons per year in Sweden and the United Kingdom, controller medication use produces 4 to 65 tonnes of CO_2e per 10 000 persons per year in Romania and the United Kingdom.

4.3. Treatment of patients with septic shock in ICU

The carbon footprint of treating septic shock patient in US-ICU and Aus-ICU were measured by Forbes McGain in (McGain *et al* 2018). There was an average of 178 kg carbon dioxide equivalent (CO_2-e) emissions per day in the US-ICU (range, 165–228 kg CO_2-e), while the carbon footprint in the Aus-ICU was 88 kg (range, 77–107 kg CO_2-e). It was estimated that 155 kg CO_2-e came from energy in the US-ICU (87%) and 67 kg CO_2-e from the Aus-ICU (76%) during the study. For the US-ICU, the average energy use per patient was 272 kWh per day, while for the Aus-ICU, it was 143 kWh per day. Single-use materials averaged 3.4 kg for the US-ICU and 3.4 kg for the Aus-ICU per patient on a daily basis. There was a consideration that variations in ICU HVAC energy consumption owing to energy efficiency and/or geography might considerably impact carbon footprint.

Table 3. Summary of used methodology and estimated carbon footprint.

Healthcare service			Methodology	Carbon footprint (CO_2e)	Functional unit	Country
Hospital diagnostic imaging	Chest x-ray (CXR)		Life Cycle Assessment (LCA)	0.8 kg	Per scan	Australia
	Mobile chest x-ray (MCXR)			0.5 kg	Per scan	
	Computerised Tomography (CT),			9.2 kg	Per scan	
	Magnetic Resonance Imaging (MRI)			17.5 kg	Per scan	
	Ultrasound (US)			0.5 kg	Per scan	
Respiratory treatments	SABA		Observational study	134 tonnes	CO_2e per 10 000 persons per year per capita	UK
	Controller medication			65 tonnes	CO_2e per 10 000 persons per year per capita	
Intensive Care Unit (ICU)	Patients with septic shock		Life Cycle Assessment (LCA)	178 kg	Treatment per patient	US
				88 kg	Treatment per patient	Australia
Pathology testing	Full blood examination		Life Cycle Assessment (LCA)	116 g	Per test	Australia
	urea and electrolyte levels (U&E)			99 g	Per test	
	C-reactive protein concentration (CRP)			0.5 g	Per test	
	arterial blood gas testing (ABG)			49 g	Per test	
	coagulation profile			82 g	Per test	
Operating theatres	Surgical suites		Component analysis	1702 kg	per unit area	UK
				1951 kg	per unit area	Canada
				2284 kg	per unit area	USA
Renal Service	Dorset Renal Service		Component analysis	3006 tonnes	Per annum	UK
Anaesthesia for Knee replacement	General anesthesia		Life Cycle Assessment (LCA)	14.9 kg	Per patient	Australia
	Spinal anesthesia			16.9 kg	Per patient	
	Combined anesthesia			18.5 kg	Per patient	
Eye surgery	Cataract surgery		Component analysis	181.8 kg	Per operation	UK
Regional hospital			Descriptive study	9,660.3 tons	One year	Chile
Regular and intensive inpatient care	Acute care unit		Life Cycle Assessment (LCA)	45 kg	Per hospitalization day	US
	Intensive care unit			138 kg	Per bed day	
Ambulance operation	Air ambulance		Two-phase study of operational and financial data	5.3 t	Per air ambulance mission	Australia
	Ground ambulance			22 kg	Per ambulance response	
Reflux control	Gastro- oesophageal reflux	Surgical	Used data from the costs of care of patients and NHS England Carbon Emissions Carbon Footprinting Report	100 kg	Per annum	UK
		Medical		30 kg	Per annum	
Peritoneal dialysis	Continuous ambulatory peritoneal dialysis (CAPD)	Home	Component analysis	407.1 kg	Per patient	China

Table 3. (Continued.)

Healthcare service			Methodology	Carbon footprint (CO_2e)	Functional unit	Country
		PD center		363.5 kg	Per patient	
	Daytime ambulatory peritoneal dialysis (DAPD)	Home		409.5 kg	Per patient	
		PD center		365 kg	Per patient	
Haemodialysis (HD)			Component analysis	10.2 t	Per patient per year	Australia
Home and in-center maintenance hemodialysis	ICHD		Component analysis	3818 kg	4 h sessions of HD, thrice/week	UK
	HHD			3308 kg	4 h sessions of HD, thrice/week	
Minimally Invasive Surgery			Component analysis	355,924 tonnes	Per year	US
Robotically assisted laparoscopy, laparoscopy, and laparotomy	Robotically assisted laparoscopy		Component analysis	40.3 kg	Per patient	USA
	Laparoscopy			29.2 kg	Per patient	
	Laparotomy			22.7 kg	Per patient	
Long-acting injections	long-term flupentixol decanoate long acting injections		Used prescription data followed by economic and carbon cost projections using local and national data	11 519 kg	Per year	UK

However, within the intensive care unit, nurses can implement innovative and efficient solutions for managing medical waste, reducing energy and medication use, and fostering both personal and institutional changes in behaviour to support environmental sustainability (ga PhD 2024).

4.4. Pathology testing

A substantial percentage of all Medicare expenditures ($3.0 billion) went toward pathology services during 2018–19 (Services 2020). In (McAlister *et al* 2020), the carbon footprint of five common hospital pathology tests was estimated by Scott McAlister. Two categories of tests were considered in this study such as haematology tests (coagulation profile, full blood examination) and biochemical tests (C-reactive protein, arterial blood gas assessment, urea and electrolyte assessment). Greenhouse gas emissions for coagulation profile was 82 g/test (range 73–91 g $test^{-1}$) and 116 g $test^{-1}$ (range 101–135 g $test^{-1}$) for full blood examination, 0.5 g $test^{-1}$ CO_2e (range 0.4–0.6 g $test^{-1}$) for C-reactive protein, 49 g $test^{-1}$ (range 45–53 g $test^{-1}$) for arterial blood gas assessment, and 99 g $test^{-1}$ (range 84–113 g $test^{-1}$) for urea and electrolyte assessment. Due to the fact that the C-reactive protein is usually ordered along with urea and electrolyte assessments, the C-reactive protein is low.

4.5. Surgical suites in operating theatres

There is a high demand for energy, consumables, and waste in operating theatres, one of the most resource-intensive subsectors of health care. In (MacNeill *et al* 2017), authors studied Surgical suites at three hospitals in Canada, USA and UK. In the study, UK's surgical suites had an annual carbon footprint of 5187936 kg CO_2e, USA's surgical suites had 4181 864 kg CO_2e, and in Canada, surgical suites had 3218907 kg CO_2e. In terms of carbon intensity per square meter, UK had the lowest level at 1702 kg $CO_2e/m2$, while Canada had 1951 kg $CO_2e/m2$ and USA had 2284 kg $CO_2e/m2$. A comparison of case volumes at all three sites showed that Canada has the lowest carbon intensity per case, averaging 146 kg CO_2e per case as compared to UK at 173 kg CO_2e per case and USA at 232 kg CO_2e per case. It was found that there was a three-to-six-fold increase in energy consumption in theatres than the hospital, primarily due to the need for heating, ventilation, and air conditioning. Again, Surgical headwear that can be reused provides environmental benefits (Gumera *et al* 2024).

4.6. Endoscopy

(Siau *et al* 2021) is a review article on Endoscopy and the purpose of this paper was to identify waste sources within endoscopy, create a framework for measuring the effect of endoscopy on the environment, and propose actionable steps that can be implemented to mitigate the impact of endoscopy on the planet. It was estimated that an annual carbon footprint of 85,768 metric tons for U.S. endoscopy procedures, based on operator energy consumption and plastic waste from endoscopic procedures alone.

4.7. Dermatologic surgery

Using a dermatology clinic as a diagnostic unit, the authors examined the literature on LCAs pertaining to dermatologic surgery in (Tan and Lim 2021). As a result of 263 291 dermatological surgeries performed annually (6751 tonnes from private clinical rooms and 1890 tonnes from hospitals), the authors concluded that 8641 tonnes of carbon dioxide are released. In addition to contributing to terrestrial ecotoxicity and acidification, the waste generated contributes to land and water acidification.

4.8. Renal service

In (Connor *et al* 2010), the authors evaluated the carbon footprinting of the Dorset Renal Service, for the purpose of providing an evidence base for future decision-making by highlighting the most carbon-intensive parts of a renal service. It is reported that, a carbon footprint of 3006 tonnes CO_2e is generated by Dorset Renal Service each year. This includes 381 tonnes CO_2e (13%) from building energy use, 462 tonnes CO_2e (15%) from travel and 2163 tonnes CO_2e (72%) from procurement. Within procurement, pharmaceuticals and medical equipment are the major contributors. As a result of the polypharmacy commonly experienced by patients with kidney disease, the pharmaceutical subsector's contribution to NHS England's carbon footprint has increased considerably and having a substantial contribution attributable to medical equipment as a result of the increasing availability of dialysis facilitated by single-use, pre-packaged products, and this is further evidenced by the high amount of waste to the overall emissions (Commission 2009). Developing strategies for improving patient compliance with pharmaceuticals and reducing waste; exploring opportunities for reusing medical equipment through re-evaluating how infection control policies are defined by risk management; and adopting sustainable policies of procurement can be considered as measures to reduce total emissions (Connor *et al* 2010).

Anaesthesia for knee replacement

Anaesthesia is a 'carbon hotspot,' and in (McGain *et al* 2021) carbon dioxide equivalent emissions during total knee replacement were estimated for general anaesthesia, spinal anaesthesia, and combined (general and spinal anaesthesia). After studying twenty-nine patients, it was found that the average CO_2e emission for general anaesthesia was 14.9 kg CO_2e, for spinal anaesthesia was 16.9 kg CO_2e and for combined anaesthesia it was 18.5 kg CO_2e. It was also noted that relatively large portion of pharmaceutical carbon dioxide equivalent emissions was attributed to drugs given in large quantities (cefazolin).

4.9. Cataract surgery

As one of the most common surgical procedures within the NHS in England, cataract surgery is an ideal target for reducing emissions, with over 300 000 operations performed each year (Craig *et al* 2008). DS Morris in (Morris *et al* 2013), assessed the amount of the greenhouse gas emissions resulting from cataract surgery for individual patient and also at service levels. The result found for carbon footprint of one cataract operation was 181.8 kg CO_2e. Total 2230 patients were treated in Cardiff for cataracts during year 2011, which in result had a CO_2e of total 405.4 tonnes CO_2e.

4.10. Regional hospital

Hospital Base, Puerto Montt (HBPM) was considered to estimate the total greenhouse gas emission by Marco Balkenhol in (Balkenhol *et al* 2018). The HBPM emitted 9,660.3 tons of CO_2e in 2016, of which 46% came from electricity consumption, 29% from residue generation, and 10% from the usage of clinical gas. Within the clinical gas consumption, Sevoflurane contributed the most.

4.11. Regular and intensive inpatient care

The authors in (Prasad *et al* 2022) considered an intensive care unit (ICU) with 12 beds and 2536 hospitalization days and an acute inpatient unit with 49 beds and 14,427 hospitalization days to estimate the carbon footprint of intensive and regular inpatient care service in USA. According to his study, in an acute care unit, solid waste was generated at a rate of 5.5 kg per person per day, and CO_2 emissions were 45 kg CO_2e. Each day, the ICU generated 7.1 kilograms of solid waste and 138 kilograms of CO_2-e emissions. Consumption of consumable goods, consumption of building energy, capital equipment purchases, transportation of staff, and food services contributed to most emissions.

4.12. Ambulance operation

To determine the predominant energy sources that contribute to greenhouse gas emissions associated with Australian ambulance operations, Lawrence H Brown analysed the energy consumption of these operations in (Brown *et al* 2012). According to this study, a ground ambulance response emitted an average of 22 kilograms of carbon dioxide equivalents, a patient transport emitted 30 kilograms of carbon dioxide equivalents and emitted 3 kilograms of carbon dioxide equivalents per capita. It is important to note that fuel consumption accounted for 58% of the ground ambulance emissions, while electricity consumption accounted for the remainder and compared with ground ambulance transport, air ambulance transport emitted nearly 200 times more emissions because of aviation fuel.

4.13. Peritoneal dialysis

In (Chen *et al* 2017), the researchers considered total of 68 patients who performed peritoneal dialysis (PD) treatment and with different modalities and treatment regimens PD was investigated to determine its carbon footprint. It was found from the study that patients receiving PD therapy in centres had higher fixed emissions than patients at home, primarily because of electricity consumption and PD's carbon footprint is mostly attributed to packaging consumption. The average emissions for PD at home was around 408 kg CO_2e and around 364 kg CO_2e at PD centre.

4.14. Haemodialysis (HD)

Two articles on hemodialysis are discussed in this review. By determining the carbon footprint of haemodialysis (HD) throughout Australia, Allan in (Lim *et al* 2013) sought to better understand its impact on greenhouse gas emissions, the contribution of different sectors to this footprint, and the impact of local factors on electricity and water consumption. From this study, it has been estimated that satellite HD in Victoria contributes 10.2 t CO_2-e per patient per year, with pharmaceuticals (35.7%) and medical equipment (23.4%) contributing most. To inform carbon reduction strategies at the level of both individual treatments and HD programs, another study on hemodialysis (Connor *et al* 2011), evaluated the carbon footprints of the different modalities and treatment regimens used for maintenance hemodialysis (HD). It was concluded that, an average three times weekly in-center HD treatment produces anually 3.8 tons of carbon dioxide equivalents per patient, with frequency being more important than duration in determining HD's carbon footprint.

4.15. Minimally invasive surgery

To identify the potential global warming impact of minimally invasive surgery (MIS), CO_2 emissions were determined in (Power *et al* 2012) through an estimation of scope 1 to 3. In total, 355,924 tonnes of CO_2 were emitted per year for minimally invasive surgery (MIS).

4.16. Robotically assisted laparoscopy, laparoscopy, and laparotomy

In order to quantify and compare the total greenhouse gas emissions resulting from three surgical modalities, laparotomy (LAP), conventional laparoscopic surgery (LSC) and robotic-assisted laparoscopic surgery (RA-LSC), 150 staging procedures were reviewed in (Woods *et al* 2015). RA-LSC procedures result in a carbon footprint of 40.3 kg CO_2e/patient, which is 38% higher than LSC procedure (29.2 kg CO_2e/patient) and 77% higher than LAP procedure (22.7 kg CO_2e/patient).

4.17. Long-acting injections

An analysis of the economic costs and carbon footprint of prescribing long-term flupentixol decanoate long acting injections is presented in (Maughan *et al* 2016). The total carbon emissions were 11519 kg CO_2e in Oxford Health NHS Foundation Trust. Following the projected reduction, it is likely that the majority of the carbon emissions can be reduced from the appointment − 88000 kg CO_2e (including materials and energy consumption) and from overprescribing medication − 66000 kg CO_2e in England.

5. Challenges and roadmap to overcome challenges

This review has outlined the current prospect of healthcare services from the perspective of carbon footprint in previous sections. Taking into account various emission sources, the carbon footprints were estimated for different healthcare services. While estimating the carbon footprint of different sectors, many difficulties and limitations were mentioned in the considered articles. In most of the articles, the activity data for regarded analysis such as - Anesthesia for total knee replacements (McGain *et al* 2021), cataract surgery (Morris *et al* 2013), Australian ambulance (Brown *et al* 2012), regular and intensive inpatient care (Prasad *et al* 2022), home and in-center peritoneal dialysis (Chen *et al* 2017), home and in-center maintenance of hemodialysis (Connor *et al* 2011), were collected considering only single circumstances and for any particular region. These results may vary depending on different areas, settings, and usage patterns. Another challenge mentioned extensively was the lack of availability of data, because of which different types of activity data were assumed to complete the process of estimations of carbon emissions. Depending on the accuracy of those assumption, the results might vary in wide range. Another thing is known that energy consumption is the first greenhouse emission gas emission source according to the greenhouse gas protocol. But uncertainty of the estimation of electricity consumption was also a well stated limitation for determining the carbon footprint in various areas. The environmental impact of manufacturing equipment was excluded, such as considering that the amortised impact per scan of radiological equipment is very small and it is impossible to estimate the impact with precision without detailed manufacturer information on the weight and composition of each scanner's components, so the environmental impact of manufacturing radiological equipment was excluded by the authors in (McAlister *et al* 2022). For obtaining the accurate result of carbon emissions, it requires to include all the aspects with detailed available data considering different regions of the world for determining the carbon footprint of any healthcare service as shown in figure 4 but is technically difficult. Based on the boundaries of each study, emissions were classified into a few categories and among them energy consumption was the largest of all. The shift from fossil fuels to renewable energy will result in a larger reduction in healthcare's carbon footprint by changing clinical care, rather than concentrating on buildings, which will see mitigation occurring naturally from market-based mechanisms (Sherman *et al* 2021). In case of medical instruments and consumables, single-use instruments and consumables should be avoided as they have a cycle of manufacturing, delivery and waste disposal which are largely responsible for carbon emissions. Instead of using single-use instruments and consumables, recycling should be encouraged for consumables and sterilising should be practiced for surgical instruments (Tan and Lim 2021). Medical services such as - pathology tests, image scanning, inhaler intakes etc are areas where reducing unnecessary ordering can decrease the total emission entirely. It is possible to reduce the carbon costs of tests by reducing the factors that drive excessive testing other than clinicians (Rao *et al* 2003, Spelman 2015, Pathirana *et al* 2017). In a recent opinion piece, it was noted that '… eliminating unnecessary care reduces unnecessary resource use and emissions. Such partnerships could be encouraged to bring environmental stewardship into the health care quality discourse' (Sherman *et al* 2019).

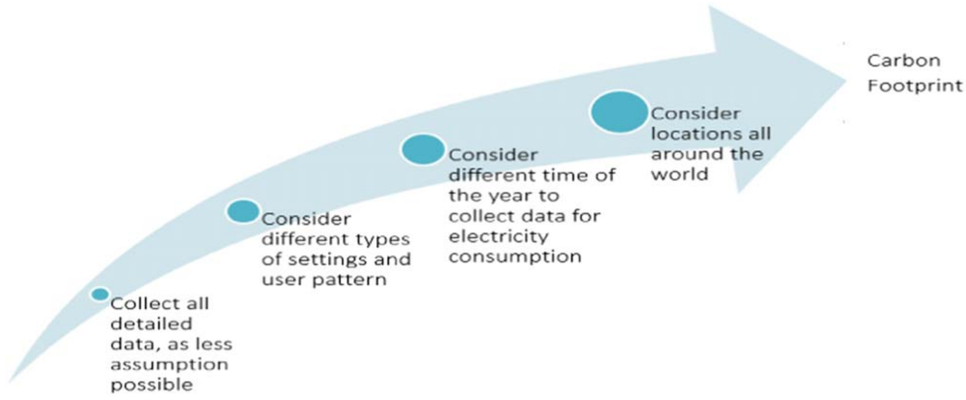

Figure 4. Future roadmap to overcome challenges.

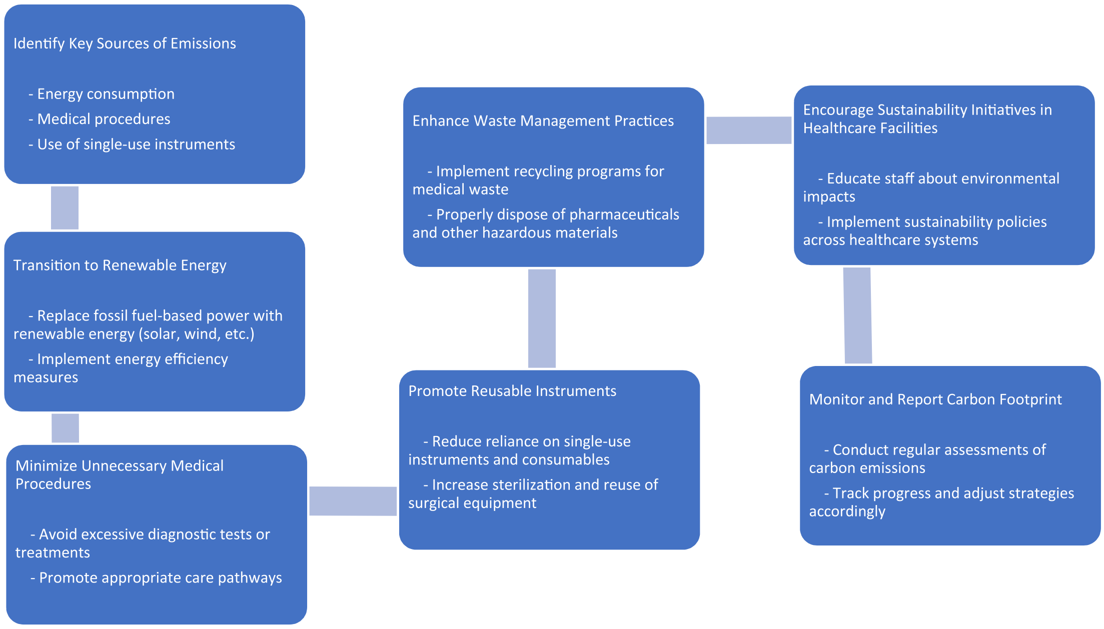

Figure 5. Strategies to reduce healthcare's carbon footprint.

6. Conclusion

The health care system itself contributes to climate change as it is a carbon-intensive industry. As the part of the process of decarbonizing the economy, healthcare services must be included. In order to effectively reduce emissions, it is important to identify the sources of emissions in a specific care pathway. This article presents a comprehensive review of the carbon footprint of different healthcare services and the methods they use to estimate them. It can be stated that among the used approaches, life cycle assessment is mostly used by the authors in recent research works, as in LCA it is possible to consider the background data which makes it more precise. Energy consumption contributes the most in carbon emission, so minimizing the conventional power consumption can reduce the total carbon footprint. Study related to carbon footprint of medical services are very limited up to date. Before now the research works done are based on specific settings, location, and conditions. There are certain areas where carbon footprint or environmental impact are not estimated yet. Lack of data on environmental impacts of patient care teams substantially limits their ability to provide environmental-friendly services. By knowing the amount of carbon emissions and the environmental impact of each medical services, the patient care team can be encouraged to develop their innovative solutions to improve the environment and at the same time maintain the quality of patient care. Further research works should be considered to explore the amount of greenhouse gas emission of many more healthcare services which are not reported previously.

To effectively reduce healthcare's carbon footprint, the transition from fossil fuels to renewable energy is crucial, alongside minimizing unnecessary medical procedures and promoting the use of reusable instruments. A flowchart is presented in figure 5 including the strategies to reduce the carbon emission in healthcare. However, the current research on the carbon footprint of healthcare services is limited, and there is a need for more comprehensive studies that consider diverse regions and broader aspects of healthcare operations. Addressing these gaps will be essential for developing strategies that not only reduce emissions but also maintain the quality of patient care, ultimately contributing to the decarbonization of the healthcare sector. This research holds significant value for the healthcare industry and the community at large. By offering precise data on the carbon footprint of various medical procedures, the study highlights areas where emissions can be significantly reduced, thus enabling healthcare providers to develop more sustainable practices. These insights can guide hospitals and clinics in adopting greener procurement strategies, reducing reliance on energy-intensive procedures, and promoting the use of renewable energy sources. On a broader scale, reducing healthcare's carbon footprint will directly contribute to global climate change mitigation efforts, promoting public health and environmental well-being.

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Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

Credit authorship contribution statement

Afsana Jerin: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Visualization, Writing—original draft, Writing—review & editing, Funding acquisition. **M. A. Parvez Mahmud:** Conceptualization, Resources, Supervision, Funding acquisition, Writing - review & editing. **M. Leigh Ackland:** Conceptualization, Supervision, Writing—review & editing. **Abbas Z. Kouzani:** Conceptualization, Supervision, Writing—review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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