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Sources of Variation in the Carbon Footprint of Hemodialysis Treatment

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Abstract: Background: Greenhouse gas emissions from hemodialysis treatment in the United States have not been quantified. In addition, no previous studies have examined how much emissions vary across facilities, treatments, and emission contributors.

Methods: To estimate the magnitude and sources of variation in the carbon footprint of hemodialysis treatment, we estimated life-cycle greenhouse gas emissions in carbon dioxide equivalents (CO2-eq) associated with 209,481 hemodialysis treatments in 2020 at 15 Ohio hemodialysis facilities belonging to the same organization. We considered emissions from electricity, natural gas, water, and supply use; patient and staff travel distance; biohazard waste and landfill waste.

Results: Annual emissions per facility averaged 769,374 kg CO2-eq (95% confidence limits, 709,388 to 848,180 kg CO2-eq). The three largest contributors to total emissions were patient and staff transportation (28.3%), electricity (27.4%), and natural gas (15.2%). Emissions per treatment were 58.9 kg CO2-eq, with a three-fold variation across facilities. The contributors with the largest variation in emissions per treatment were transportation, natural gas, and water (coefficients of variation, 62.5%, 42.4%, and 37.7%, respectively). The annual emissions per hemodialysis facility are equivalent to emissions from the annual energy use in 93 homes; emissions per treatment are equivalent to driving an average automobile for 238 km (149 miles).

Conclusions: Similar medical treatments provided in a single geographic region by facilities that are part of the same organization may be expected to have small variations in the determinants of greenhouse gas emissions. However, we found substantial variation in carbon footprints across facilities, treatments, and emission contributors. Understanding the magnitude and variation in greenhouse gas emissions may help identify measures to reduce the environmental impact of hemodialysis treatment.

Significance Statement

Studies have demonstrated that hemodialysis facilities have a high environmental impact because the treatment requires large amounts of energy, water, and supplies. However, data regarding how much greenhouse gas emissions from hemodialysis treatment vary across facilities, treatments, and emission contributors have been lacking. In this study, the authors estimated magnitude and sources of variation in the carbon footprint of hemodialysis treatment. They found that the annual emissions per hemodialysis facility are equivalent to emissions from the annual energy use of 93 homes, and emissions per treatment are equivalent to driving an average automobile for 238 km (149 miles). Carbon footprints across facilities, treatments, and emission contributors also varied substantially. Understanding the magnitude and variation in greenhouse gas emissions may help identify measures to reduce the environmental impact of hemodialysis treatment.

Sources of Variation in the Carbon Footprint of Hemodialysis Treatment

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INTRODUCTION

About 500,000 Americans receive chronic hemodialysis treatment for kidney failure.[1] Compared to other medical treatments, hemodialysis has a high environmental impact because it requires large amounts of energy, water, and supplies and is accompanied by substantial waste production.[2] In addition, hemodialysis treatment generally involves patients and staff travelling several times a week to a dialysis facility.

The accelerating impacts of climate change make it critical to understand and address the carbon footprint of healthcare, which is responsible for about one-tenth of all greenhouse gas emissions in the United States.[3] Three previous studies from the United Kingdom, Australia, and Morocco estimated greenhouse gas emissions related to hemodialysis treatment by analyzing specific contributors such as electricity, supplies, transportation, and waste production.[4-6] However, the healthcare sectors (and accompanying emissions) are a much smaller proportion of the economies in those countries.[7] Energy sources, transportation use, and practice patterns can also be quite different across countries.

Emissions related to hemodialysis treatment in the United States have not been quantified. Moreover, no previous studies have examined how much emissions vary across facilities, treatments, and emission contributors. Understanding the magnitude and variation of emissions may help identify measures to reduce the carbon footprint of hemodialysis treatment. Reducing environmental impact is also likely to decrease both facility costs and overall healthcare expenditures. We therefore sought to estimate the magnitude and sources of variation in the carbon footprint of hemodialysis treatment.

METHODS

Facilities

This study was conducted at 15 free-standing dialysis facilities in Northeast Ohio. All facilities are part of the same non-profit organization, have a centralized system for managing staff and supplies, and provide in-center hemodialysis treatment. The study was approved by the Institutional Review Board of MetroHealth Medical Center, Cleveland, Ohio.

Data Elements

We obtained data for each facility on resource use, patient and staff travel, and waste production for the year 2020 from administrators of the dialysis organization. Electricity, natural gas, and water use data were based on utility bills. Actual supply usage is tracked monthly for each facility. We obtained and disassembled each supply item into components of identical composition and weighed each component (Supplemental Table 1). For example, there are six different dialyzers used at the participating facilities. Each dialyzer includes five components: fibers, potting material, housing, caps, and an outer wrap. Note that there are variations in the weight and composition of these components (e.g. polycarbonate vs. polypropylene for the housing material). All supplies at the participating facilities are single use. We also observed several treatments and talked to dialysis technicians to ensure that no supplies were missed. Patient home addresses and modes of transportation were obtained from electronic medical records. Staff home addresses were obtained from employment records. There were no data available on staff mode of transportation. Based on discussions with facility head nurses, we assumed that all staff used a car for transportation. We also obtained total quantities of three types of waste produced: biohazard, landfill, and recycling.

Statistical Analyses

Carbon footprint calculations are based on greenhouse gas emission factors, or the amount of carbon dioxide produced on average per unit of fuel consumed or material used. The impact of other greenhouse gases, such as methane and nitrous oxide, is included in emission factors as carbon dioxide equivalents. We used a life-cycle approach that includes emissions associated with raw material extraction and processing; product manufacture, distribution, and use; and recycling or disposal. We followed the International Organization for Standardization 14040 family of standards for life-cycle assessment to capture the inputs and outputs of hemodialysis treatment. The functional unit is provision of one hemodialysis treatment, and the system boundary is shown in Supplemental Figure 1. The data elements above were first translated into manufacturing and disposal (for the waste quantities) unit processes in the ecoinvent 3 database included in SimaPro 9.2.0.1 (PRé Sustainability, Amersfoot, The Netherlands). Supplemental Table 1 lists specific unit processes for supplies, and Supplemental Table 2 lists unit processes used for other inputs. We then used the United States Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) version 2.1 to calculate mid-point environmental impacts (in this case, kg CO_2-eq) from unit process data.[8] Upper and lower confidence intervals were calculated as the 2.5 and 97.5 percentiles of 1000 Monte Carlo simulations that take into account the uncertainty and variability inherent in environmental emissions data within ecoinvent.[9] Note that these confidence intervals are not symmetric because environmental emissions are generally not normally distributed and have long tails. We used EPA data to compare emissions from dialysis treatment to emissions from the energy use of homes and automobiles.[10] Recycled waste was not included in these estimates as only one facility participates in recycling, and the proportion of all waste that was recycled was less than 3%. Medications used during hemodialysis were also excluded as life cycle inventory data on emissions from pharmaceutical production are not available from manufacturers.

We used descriptive statistics (mean, percent, range, standard deviation, coefficient of variation) to analyze total emissions per facility, emissions per treatment, and emissions per contributor (e.g. electricity) as well as variation across facilities, treatments, and contributors. These analyses were performed with JMP Pro 15, SAS, Cary, North Carolina.

RESULTS

The 15 participating facilities provided a total of 209,481 hemodialysis treatments in the year 2020, for an average of 13,965 treatments per facility and an average treatment time of 3.8 hours. Table 1 includes details about resource use, patient and staff travel, and waste production. For example, patients traveled a total of 310,009 km annually and staff traveled a total of 322,238 km annually per facility. Of all patient travel, 170,164 km (55%) was by van, 127,590 km (41%) was by car, and 12,255 km (4%) was by bus. Supplemental Table 1 lists the composition and weights of all supplies used during hemodialysis treatment.

As indicated in Table 2, the total annual emissions per facility averaged 769,374 kg CO_2-eq (confidence limits 709,388 – 848,180 kg CO_2-eq). The three largest contributors to total emissions were patient and staff transportation (28.3%), electricity (27.4%), and natural gas (15.2%). Emissions per treatment were 58.9 kg CO_2-eq with a three-fold variation across facilities. There was also a three-fold variation in electricity use per treatment, eight-fold variation in natural gas use, and five-fold variation in water use across the participating facilities. As indicated in the Figure 1, the contributors with the largest variation in emissions per treatment were transportation (coefficient of variation 62.5%), natural gas (42.4%), and water (37.7%).

The annual emissions per hemodialysis facility are equivalent to emissions from the annual energy use of 93 homes while emissions per treatment are equivalent to driving an average automobile for 238 km (149 miles). There was a moderate inverse correlation between number of treatments provided by a facility and emissions per treatment (Pearson correlation coefficient -0.38, p=0.16). There was no correlation between building age and energy-related (electricity plus natural gas) emissions per treatment (correlation coefficient 0.03, p=0.91). Transportation-related emissions per treatment averaged 12.8, 17.7, and 30.1 kg CO_2-eq at 3 urban facilities, 10 suburban facilities, and 2 rural facilities, respectively (p=0.26).

DISCUSSION

We found that hemodialysis treatment has a sizeable carbon footprint, with the largest contributions coming from transportation, electricity, and natural gas. More importantly, there was a great deal of variation in both total greenhouse gas emissions and the contributors to these emissions. This is a surprising finding because similar treatments provided in a single geographic region by facilities that only provide dialysis and are part of the same organization would be expected to have small variations in emission contributors such as electricity. Strengths of this study include the use of identical data sources for each facility, the ability to obtain and disassemble all supplies, and the analyses of variation at multiple levels, including facility, treatment, and emission contributor.

We also found that the relative importance of specific emission contributors is different between hemodialysis treatment and healthcare in general. For example, about 11% of all healthcare emissions in the United States are from purchased electricity use.[3] By contrast, 27.4% of emissions in this study are from electricity, probably due to the energy-intensive nature of hemodialysis treatment. It is likely that the wide geographic area served by the participating facilities, including urban, suburban, and rural regions, as well as the limited use of public transportation contributed to both the large emissions due to transportation and a high coefficient of variation.

Three previous studies from the United Kingdom, Australia, and Morocco estimated greenhouse gas emissions per hemodialysis treatment as 24.5, 65.1, and 32.8 kg CO_2-eq, respectively.[4-6] However, it is difficult to directly compare those results with each other or with our study because of some differences in the emission contributors included. For example, the British estimate includes emissions related to facility construction, vascular access surgery, and outpatient visits while the Moroccan estimate includes computers and furniture.[4,6] Comparisons limited to specific contributors such as energy use and transportation may be more informative. Emissions related to energy use ranged from 5.1 to 12.1 kg CO_2-eq across the three studies which is substantially less than the 23.9 kg CO_2-eq we found for electricity and natural gas combined. Emissions related to transportation accounted for 9-24% of all emissions across the three studies and for 28% of all emissions in our study. These differences likely reflect regional variations in amount of energy use, carbon intensity of local energy sources, distances traveled by patients and staff, and mode of transportation. Studies of carbon footprints of surgical procedures found differences of similar magnitudes across countries.[11]

It would be worthwhile to quantify how much electricity use is from hemodialysis machines and reverse osmosis equipment vs. from general building purposes such as lighting, computers, and other appliances. An Australian study of in-center hemodialysis estimated dialysis-related electricity use at 7.2 kWh per treatment for a mean treatment time of 4 hours.[5] A Canadian study of home hemodialysis estimated dialysis-related electricity use at 4.0 kWh per four hour treatment.[12] Another Australian study of a solar-assisted home hemodialysis training unit estimated dialysis-related power use as 5.2 kWh over four hours.[13] We did not directly measure hemodialysis and reverse osmosis electricity use at the facilities that participated in our study. However, manufacturer specifications for their dialysis equipment indicate that 5.7 kWh of electricity would be required for a 3.8 hour treatment. By comparison, total electricity use per treatment was 25.9 kWh (Table 1). Thus, it is likely that the bulk of electricity usage at the facilities that participated in our study is attributable not to dialysis equipment but to other building purposes. The magnitude of and variation in non-dialysis electricity use should be better quantified and addressed as a target of improvement.

Our findings point to four actions that renal providers can take to reduce greenhouse gas emissions. First, they should work with patients, primary care providers, and public health agencies to prevent kidney failure. Screening for and aggressively managing kidney disease and its causes (such as hypertension and diabetes), limiting exposure to potentially nephrotoxic drugs, using angiotensin inhibitors in proteinuric patients, and smoking cessation are all worth pursuing. Preventing, or even delaying, the onset of kidney failure will not only reduce hemodialysis-related greenhouse gas emissions but also decrease health care expenditures and enhance patient quality of life.

Second, renal providers should examine and reduce variation in both total emissions and specific emission contributors. The procedures and processes at more efficient facilities may be models for other facilities. This will require comparing data across a number of facilities. As a result, large dialysis organizations or End Stage Renal Disease Networks (regional Medicare renal quality improvement organizations) are well suited to take on this task.[14] Examining variation across countries in the carbon footprint of hemodialysis may also help to identify best practices. In addition, it would be worthwhile to treat greenhouse gas emissions as a marker of quality of care.

Third, renal providers should pay particular attention to the emission contributors with large magnitudes. For example, we found that landfill waste is the fourth largest contributor to total greenhouse gas emissions. Conducting a waste audit, which is a detailed analysis of a facility's waste stream, may help identify areas for improvement. Recycling all recyclable products and ordering supplies with minimal or recyclable packaging will also help. Emissions from recycled waste are substantially lower than emissions from landfill waste for most materials.[15] In addition, disposing of waste locally will reduce travel-related emissions.

Fourth, renal providers should purchase electricity from renewable sources such as solar and wind. Electricity is the largest emission contributor in this study so switching to renewable sources would greatly reduce greenhouse gas emissions. Using high-efficiency electric heat pumps instead of natural gas for heating would also be beneficial. In addition, renal providers can act as citizens and consumers to encourage a society-wide shift to use of renewable electricity and transportation with electric vehicles. A strategy of electrifying as much as possible accompanied by using electricity from renewable sources would virtually eliminate three of the largest sources of hemodialysis-related emissions, i.e. transportation, electricity, and natural gas (Figure 1). Manufacturers should also work to develop dialysis machines that use less electricity and water.

Several limitations must be considered in interpreting our findings. We focused on one dialysis organization in a single geographic region so our results may not apply to other facilities and regions. We did not include medications administered during dialysis since emission factors for specific medications are not available from manufacturers. Policy makers should require pharmaceutical companies (and other manufacturers) to make emission data readily available. Our emission estimates are based on generic industrial processes and may not accurately reflect specific manufacturing steps and inputs for medical equipment. We assumed that all staff traveled by car. We do not have information on other tasks, e.g. getting groceries, that patients and staff may combine with travel to dialysis facilities. Thus, allocating the entire distance traveled to hemodialysis may be an overestimate. The number of participating facilities was too small to make definitive conclusions about the association between emissions per treatment and 1) number of treatments provided, 2) geographic location of facilities, or 3) age of facilities. We did not analyze emissions related to other types of dialysis such as home hemodialysis or peritoneal dialysis.

Future work on this topic should determining whether similar variation exists across other dialysis facilities. It would also be important to better pinpoint reasons for variation such as the presence of windows or insulation in walls; water use for reverse osmosis vs. other building functions; and energy consumption by specific dialysis machines and by lighting, heating, and cooling systems. The latter will require careful metering of water and energy use for each task or equipment. Other areas to explore include specific hemodialysis parameters (e.g. high dialysate flow rates) and the carbon footprint of home hemodialysis.

In conclusion, hemodialysis treatment has a sizeable carbon footprint that varies substantially across facilities, treatments, and emission contributors. The large magnitude of this footprint presents a challenge in addressing climate change while the substantial variation presents potential opportunities to reduce emissions. Our approach may also be useful to understand and address the carbon footprint of other aspects of health care.

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AUTHOR CONTRIBUTIONS

Ashwini Sehgal: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Jonathan Slutzman: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – review & editing

Anne Huml: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Writing – review & editing

DISCLOSURES

A. Sehgal reports Advisory or Leadership Role: Associate Editor of Annals of Internal Medicine. A. Huml reports Advisory or Leadership Role: Cleveland MOTTEP Advisory Board, Chairperson for IPRO ESRD Network of the Ohio River Valley Medical Review Board, Member of the Medical Director Advisory Council for The National Forum of ESRD Networks; and Other Interests or Relationships: Cleveland Kidney Precision Medicine Project (KPMP) Community Advisory Board.

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None.

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Table 1. Resource use, patient and staff travel, and waste production in the year 2020 (n=15 facilities).*

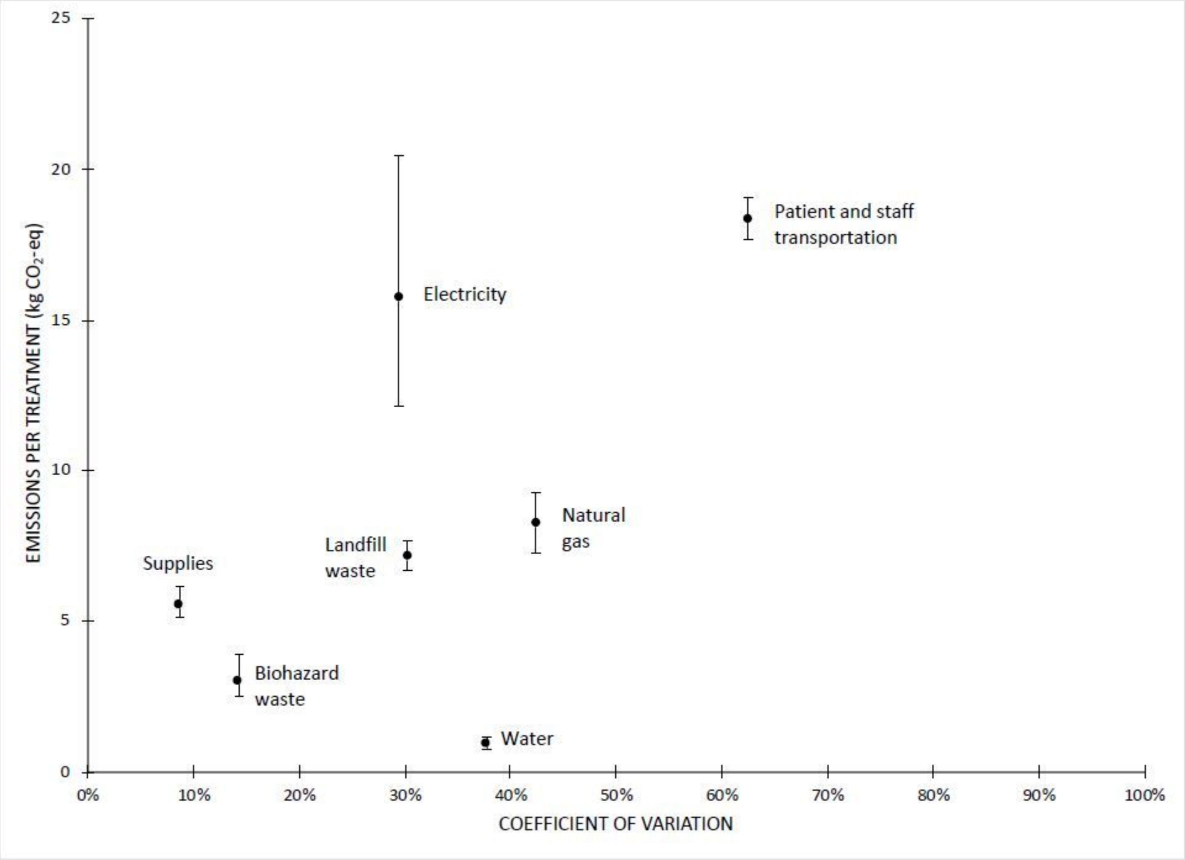
	Annual per facility	Per treatment
Electricity use, kWh	346,783 (239,771)	25.9 (7.6)
Natural gas use, m^3	41,358 (35,234)	2.9 (1.2)
Water use, m^3	7,858 (5,207)	0.6 (0.2)
Supply use, kg	63,014 (40,392)	4.5 (0.4)
Patient travel distance, km	310,009 (181,905)	28.8 (27.8)
Staff travel distance, km	322,238 (263,584)	23.6 (10.1)
Biohazard waste, kg	17,161 (10,984)	1.2 (0.2)
Landfill waste, kg	173,924 (97,925)	13.4 (4.1)

*Values represent mean (standard deviation)

Table 2. Greenhouse gas emissions by contributor in kg CO_2-eq.

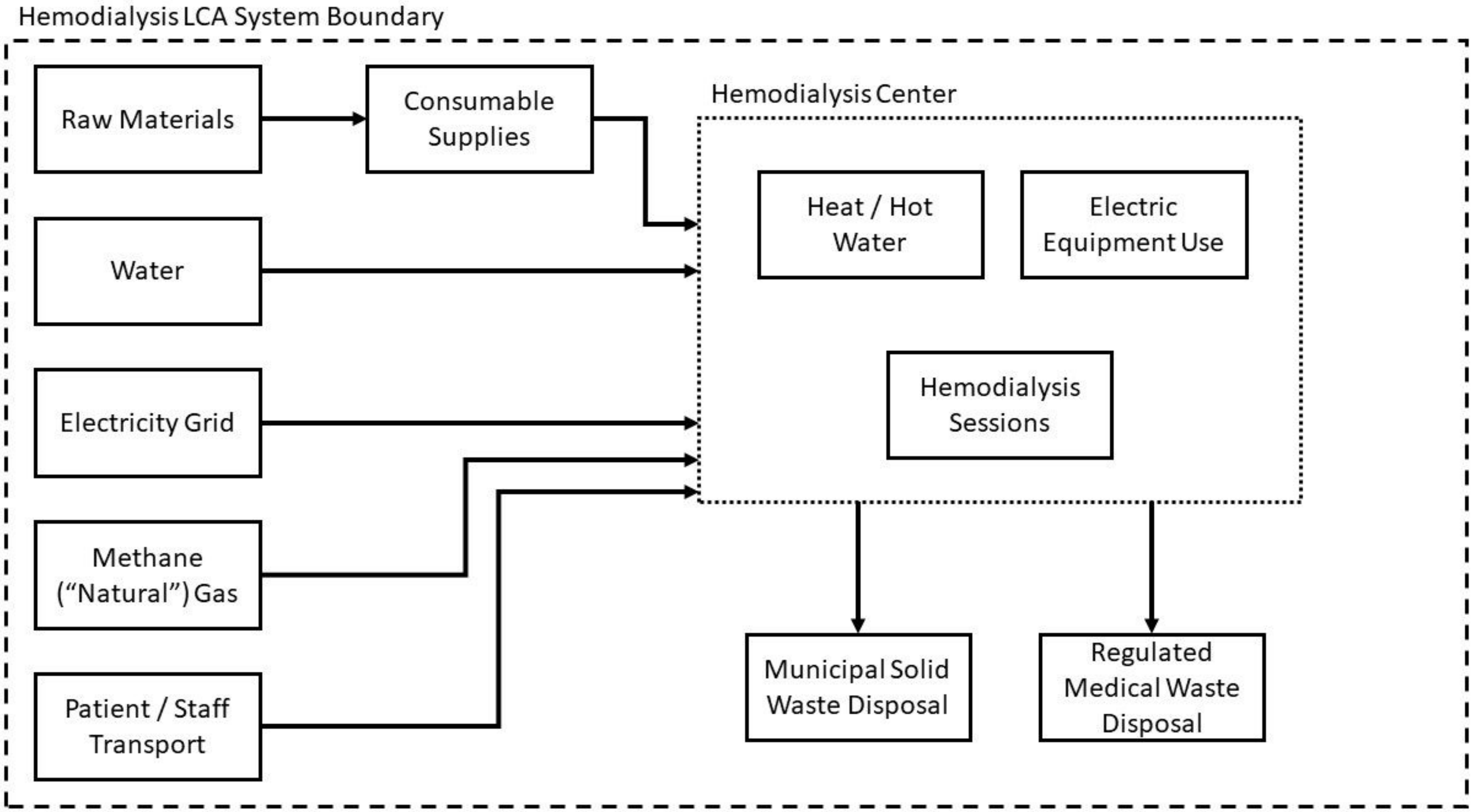
Contributor	Annual emissions per facility		Emissions per treatment	
	Mean (confidence interval)	Percent of total	Mean (confidence interval)	Range
Electricity	210,983 (160,472 – 276,405)	27.4%	15.7 (12.1 – 20.4)	8.6-25.5
Natural gas	116,999 (102,478 – 131,588)	15.2%	8.2 (7.2 – 9.2)	2.0-16.1
Water	12,245 (11,166 – 13,809)	1.6%	0.9 (0.8 – 1.0)	0.3-1.6
Supplies	77,662 (71,909 – 85,530)	10.1%	5.5 (5.1 – 6.1)	4.9-6.4
Patient and staff transportation	218,015 (208,287 – 227,960)	28.3%	18.4 (17.7 – 19.1)	9.0-52.5
Biohazard waste	42,100 (34,749 – 54,909)	5.5%	3.0 (2.5 – 3.9)	2.1-3.7
Landfill waste	93,165 (86,263 – 100,528)	12.1%	7.2 (6.7 – 7.7)	5.0-13.5
TOTAL	769,374 (709,388 – 848,180)	100.0%	58.9 (54.6 – 64.5)	33.3-97.7

Figure 1. Contributors to carbon footprint of hemodialysis (n=15 facilities). Y-axis indicates magnitude of emissions per treatment with error bars representing upper and lower confidence intervals. For example, electricity use is associated with 15.7 kg CO_2-eq emissions per treatment (confidence interval 12.1 – 20.4 kg CO_2-eq). X-axis indicates variation across facilities. For example, natural gas use is associated with a 42.4% coefficient of variation in emissions per treatment across the 15 facilities. Other contributors with either a high magnitude of emissions or extensive variation across facilities include landfill waste, water, and transportation. By contrast, supply use and biohazard waste have lower magnitudes and variation.



Supplemental Table of Contents:

Supplemental Figure 1. System boundary for life cycle assessment of hemodialysis.



Supplemental Table 1. Composition, weight, and ecoinvent manufacturing unit process inputs of supplies used in hemodialysis treatment.

Item and Components	Composition	Weight (g)	ecoinvent Unit Process[1]
Acid concentrate, 1 L			
Sodium chloride	Sodium chloride	263.00	Sodium chloride, brine solution {GLO}| market for | Cut-off, U
Potassium chloride	Potassium chloride	10.10	Potassium chloride {RoW}| market for potassium chloride | Cut-off, U
Calcium chloride	Calcium chloride	6.24	Calcium chloride {RoW}| market for calcium chloride | Cut-off, U
Magnesium chloride	Magnesium chloride	2.14	Magnesium sulfate {GLO}| market for | Cut-off, U[2]
Acetate	Acetate	1.11	Acetic acid, without water, in 98% solution state {GLO}| market for | Cut-off, U[3]
Citrate	Citrate	6.92	Citric acid {GLO}| market for | Cut-off, U
Dextrose	Dextrose	45.00	Glucose {GLO}| market for glucose | Cut-off, U
Acid concentrate bottle	High density polyethylene	30.58	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U Blow moulding {GLO}| market for | Cut-off, U
Adhesive bandage			
Adhesive strip	Polyvinyl chloride	0.37	Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Pad	Woven cotton	0.05	Textile, woven cotton {GLO}| market for | Cut-off, U
Peel-off backing	Coated paper	0.09	Paper, wood free, coated {RoW}| market for | Cut-off, U
Packaging	Coated paper	0.52	Paper, wood free, coated {RoW}| market for | Cut-off, U
Bicarbonate concentrate, 1 L			
Sodium bicarbonate	Sodium bicarbonate	81.25	Sodium bicarbonate {GLO}| market for sodium bicarbonate | Cut-off, U
Bicarbonate concentrate bottle	High density polyethylene	30.37	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U Blow moulding {GLO}| market for | Cut-off, U
Blood tubing set A			
Tubing	Polyvinyl chloride	184.50	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Drip chamber	Polyvinyl chloride	44.72	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Clamps, caps, and joints	Polypropylene	43.93	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion of plastic sheets and thermoforming, inline {GLO}| market for | Cut-off, U
Medication ports	Silicone	11.47	Silicone product {RoW}| market for silicone product | Cut-off, U
Outer plastic wrapper	Polyethylene film	5.82	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Blood tubing set B			
Tubing	Polyvinyl chloride	132.42	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Drip chamber	Polyvinyl chloride	12.53	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Clamps, caps, and joints	Polypropylene	45.75	Polypropylene, granulate {GLO}| market for | Cut-off, U

			Extrusion of plastic sheets and thermoforming, inline {GLO}| market for | Cut-off, U
Outer plastic wrapper	Polyethylene film	4.10	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Chair drape	Kraft paper	64.72	Kraft paper {RoW}| market for kraft paper | Cut-off, U
Cleansing towelette			
Towelette	Cellulose fiber	2.79	Cellulose fiber {RoW}| market for cellulose fiber | Cut-off, U
Wrapper	Aluminum foil, paper, and polyethylene terephthalate	0.70	Aluminum, primary, cast alloy slab from continuous casting {GLO}| market for | Cut-off, U Kraft paper {RoW}| market for kraft paper | Cut-off, U Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U
Dialyzer A			
Fibers	Polysulfone	20.65	Polysulfone {GLO}| market for | Cut-off, U
Potting material	Polyurethane	3.98	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U
Housing	Polycarbonate	136.91	Polycarbonate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Caps	Polyethylene	7.11	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Outer wrap	Polyethylene film	10.80	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Dialyzer B			
Fibers	Polysulfone	24.40	Polysulfone {GLO}| market for | Cut-off, U
Potting material	Polyurethane	4.70	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U
Housing	Polycarbonate	169.23	Polycarbonate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Caps	Polyethylene	7.29	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Outer wrap	Polyethylene film	11.22	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Dialyzer C			
Fibers	Polysulfone	28.83	Polysulfone {GLO}| market for | Cut-off, U
Potting material	Polyurethane	5.56	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U
Housing	Polycarbonate	163.77	Polycarbonate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Caps	Polyethylene	7.10	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Outer wrap	Polyethylene film	10.80	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Dialyzer D			
Fibers	Polysulfone	27.67	Polysulfone {GLO}| market for | Cut-off, U
Potting material	Polyurethane	5.33	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U
Housing	Polypropylene	107.78	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion of plastic sheets and thermoforming, inline {GLO}| market for | Cut-off, U
Caps	Polyethylene	8.39	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U

Outer wrap	Polyethylene film	25.54	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Dialyzer E			
Fibers	Polysulfone	31.15	Polysulfone {GLO}| market for | Cut-off, U
Potting material	Polyurethane	6.00	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U
Housing	Polypropylene	112.54	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion of plastic sheets and thermoforming, inline {GLO}| market for | Cut-off, U
Caps	Polyethylene	8.36	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Outer wrap	Polyethylene film	25.01	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Dialyzer F			
Fibers	Polysulfone	35.07	Polysulfone {GLO}| market for | Cut-off, U
Potting material	Polyurethane	6.76	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U
Housing	Polypropylene	119.95	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion of plastic sheets and thermoforming, inline {GLO}| market for | Cut-off, U
Caps	Polyethylene	8.38	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Outer wrap	Polyethylene film	25.28	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Disinfecting wipe			
Wipe	Woven cotton	0.19	Textile, woven cotton {GLO}| market for | Cut-off, U
Alcohol	Isopropyl alcohol	0.62	Isopropanol {RoW}| market for isopropanol | Cut-off, U
Wrapper	Aluminum foil, paper, and polyethylene terephthalate	0.58	Aluminum, primary, cast alloy slab from continuous casting {GLO}| market for | Cut-off, U Kraft paper {RoW}| market for kraft paper | Cut-off, U Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Cut-off, U
Disposable gloves	Latex	4.21	Latex {RoW}| market for latex | Cut-off, U
Fistula needle			
Metal needle	Steel	0.54	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U
Needle cap	Polycarbonate	0.39	Polycarbonate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Butterfly wings	Polyvinyl chloride	0.55	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Clamp	Polyoxymethylene[4]	1.18	Tetrafluoroethylene {GLO}| market for | Cut-off, U
Safety cover	Polyoxymethylene[4]	2.23	Tetrafluoroethylene {GLO}| market for | Cut-off, U
Tubing	Polyvinyl chloride	3.54	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Luer connector	Polycarbonate	1.13	Polycarbonate {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Outer plastic wrap	Polyethylene film	1.98	Packaging film, low density polyethylene {GLO}| market for | Cut-off, U
Outer paper wrap	Kraft paper	1.77	Kraft paper {RoW}| market for kraft paper | Cut-off, U
Gauze pad	Woven cotton	0.28	Textile, woven cotton {GLO}| market for | Cut-off, U

Normal saline, small bag			
Bag	Polyvinyl chloride	24.42	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Outer plastic wrapper	Polypropylene film	5.76	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion, plastic film {GLO}| market for | Cut-off, U
250 mL saline	Water, sodium chloride	260.87	Sodium chloride, powder {GLO}| market for | Cut-off, U Water, unspecified natural origin, GLO
Normal saline, large bag			
Bag	Polyvinyl chloride	40.00	Polyvinylchloride, bulk polymerized {GLO}| market for | Cut-off, U Injection moulding {GLO}| market for | Cut-off, U
Outer plastic wrapper	Polypropylene film	14.88	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion, plastic film {GLO}| market for | Cut-off, U
1000 mL saline	Water, sodium chloride	1050.00	Sodium chloride, powder {GLO}| market for | Cut-off, U Water, unspecified natural origin, GLO
Paper tape roll			
Paper tape	Kraft paper	1.53	Kraft paper {RoW}| market for kraft paper | Cut-off, U
Cardboard roll	Core board paper	1.67	Core board {GLO}| market for | Cut-off, U
Pillow case	Kraft paper	21.35	Kraft paper {RoW}| market for kraft paper | Cut-off, U
Skin cleanser			
Skin cleanser bottle	High density polyethylene	60.00	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U Blow moulding {GLO}| market for | Cut-off, U
Liquid skin cleanser	Sodium hypochlorite	580.00	Sodium hypochlorite, without water, in 15% solution state {RoW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, U
Surgical mask			
Fabric	Polypropylene textile	2.79	Textile, non-woven polypropylene {GLO}| market for textile, non woven polypropylene | Cut-off, U
Ear loops	Polyester yarn	0.30	Fiber, polyester {GLO}| market for fiber, polyester | Cut-off, U
Syringe, 3cc			
Syringe body and plunger	Polypropylene	3.37	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion of plastic sheets and thermoforming, inline {GLO}| market for | Cut-off, U
Plunger seal	Polyisoprene	0.45	Synthetic rubber {GLO}| market for | Cut-off, U
Outer plastic wrap	Polyethylene	0.44	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U
Outer paper wrap	Kraft paper	0.34	Kraft paper {RoW}| market for kraft paper | Cut-off, U

Syringe, 10cc			
Syringe body and plunger	Polypropylene	7.10	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion of plastic sheets and thermoforming, inline {GLO}| market for | Cut-off, U
Plunger seal	Polyisoprene	0.83	Synthetic rubber {GLO}| market for | Cut-off, U
Outer plastic wrap	Polyethylene	0.93	Polyethylene, low density, granulate {GLO}| market for | Cut-off, U
Outer paper wrap	Kraft paper	0.48	Kraft paper {RoW}| market for kraft paper | Cut-off, U
Technician gown	Polypropylene textile	73.09	Textile, non-woven polypropylene {GLO}| market for textile, non woven polypropylene | Cut-off, U
Tourniquet	Polyisoprene	5.92	Synthetic rubber {GLO}| market for | Cut-off, U
Waterproof absorbent pad			
Absorbent top layer	Super absorbent polymer	7.35	Polyacrylamide {GLO}| market for | Cut-off, U
Waterproof backing	Polypropylene	7.95	Polypropylene, granulate {GLO}| market for | Cut-off, U Extrusion, plastic film {GLO}| market for | Cut-off, U

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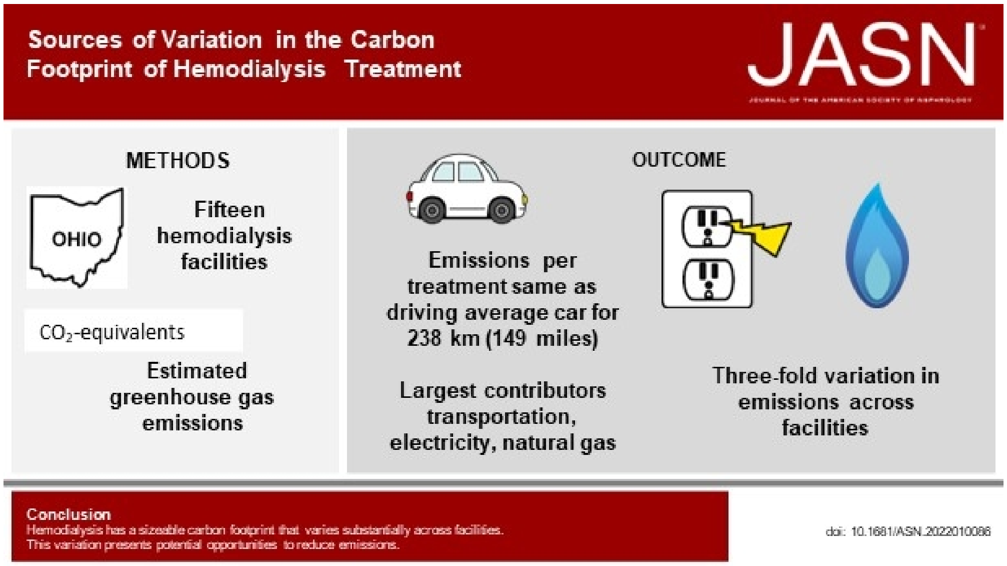
1. Cut-off refers to omission of de minimis life cycle stages; GLO refers to global manufacturing processes; market refers to all steps necessary to get a product to market, including infrastructure and transportation; RoW refers to non-global processes ("rest of the world"); and U refers to unit processes.
2. Additional unit processes included to convert magnesium sulfate to magnesium chloride.
3. Acetate unit processes from Jungbluth N. Life Cycle Inventory of Sodium Acetate and Expanded Graphite: Short Report. 15 January 2008. Available at https://www.osti.gov/etdeweb/servlets/purl/22119615 Accessed March 8, 2022.
4. Emission factor for polyoxymethylene not available. Substituted emission factor for another thermoplastic (polytetrafluoroethylene).

Supplemental Table 2. Other input ecoinvent unit processes.*

Electricity	Electricity, low voltage {RFC}| market for | Cut-off, U
Natural gas	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | Cut-off, U
Water	Tap water {RoW}| market for | Cut-off, U
Transportation	Transport, passenger car {RoW}| market for | Cut-off, U Transport, regular bus {GLO}| market for | Cut-off, U Transport, van {RoW}| market for | Cut-off, U
Biohazard waste	Hazardous waste, for incineration {RoW}| market for hazardous waste, for incineration | Cut-off, U
Landfill waste	Disposal, municipal solid waste, to US sanitary landfill/US US-EI, U

*Cut-off refers to omission of de minimis life cycle stages; GLO refers to global manufacturing processes; market refers to all steps necessary to get a product to market, including infrastructure and transportation; RoW refers to non-global processes ("rest of the world"); and U refers to unit processes.



Sources of Variation in the Carbon Footprint of Hemodialysis Treatment

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METHODS

Fifteen hemodialysis facilities

CO_2-equivalents

Estimated greenhouse gas emissions

OUTCOME

Emissions per treatment same as driving average car for 238 km (149 miles)

Largest contributors transportation, electricity, natural gas

Three-fold variation in emissions across facilities

Conclusion

Hemodialysis has a sizeable carbon footprint that varies substantially across facilities.
This variation presents potential opportunities to reduce emissions.

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