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Original Article

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What drives the environmental footprint of in-centre haemodialysis? A multicentre European life cycle assessment

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Abstract

Background **Haemodialysis (HD) is among the most resource-intensive long-term therapies in medicine. Comparative life cycle assessment evidence across European in-centre HD settings remains limited.**

Methods **Cradle-to-grave life cycle assessment was conducted at four European HD centres in Spain (FJD), Netherlands (UMCU), Italy (UNIMORE), and Poland (WUM); functional unit: one patient-year (156 sessions, 4 hours). Primary data covered consumables, electricity, water, travel, and waste; Environmental Footprint 3.1 in OpenLCA v2.5 with EcoInvent v3.11. Sensitivity analyses modelled patient transport modal shift to 75% (S1b) or 100% public transport (S1c), and battery electric vehicle adoption for car-using patients (S2), at fixed distances.**

Results **Annual climate change impacts ranged from 1829 to 4894 kg CO_2e per patient-year (2.7-fold difference). Consumables ranged from 953 (UNIMORE) to 1975 (WUM) kg CO_2e per patient-year, electricity from 149 (FJD) to 659 (UMCU) kg CO_2e, patient travel from 265 (FJD) to 2548 (UNIMORE) kg CO_2e, staff travel from 80 (FJD) to 615 (UNIMORE) kg CO_2e, and waste from 97 (FJD) to 146 (WUM) kg CO_2e. Modal shift to public transport (S1c) reduced patient travel emissions by 57.9 to 64.7%, while electrification (S2) achieved smaller reductions of 3.9 to 30.6%. Public transport delivered two- to fivefold larger absolute carbon savings than electrification at every centre.**

Conclusions **The HD carbon footprint varies nearly threefold across European settings. Centre-specific emission hotspots identified through absolute life cycle stage comparisons define the most actionable intervention priorities. Where public transport is structurally feasible, modal shift is the single largest modifiable lever.**

Keywords life cycle assessment, haemodialysis, sustainability, transport modal shift

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Graphical abstract

What Drives the Environmental Footprint of In-Centre Haemodialysis? A Multicentre European Life Cycle Assessment

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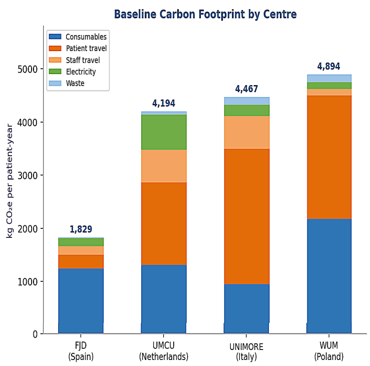
Background

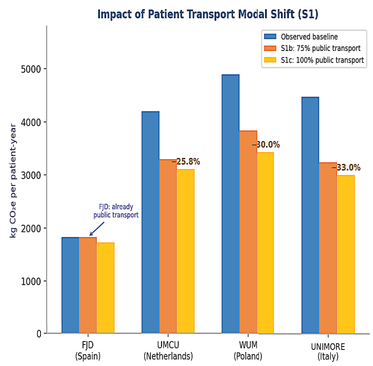
Haemodialysis (HD) is among the most resource-intensive long-term therapies in medicine. Comparative LCA evidence across European in-centre HD settings remains scarce.

Aim: To quantify and compare the environmental footprint of in-centre HD across four European centres and identify centre-specific emission hotspots and mitigation levers.

Methods

Design: Cradle-to-grave LCA (ISO 14040/44) • Functional unit: 1 patient-year (156 sessions)
Centres: FJD/Spain • UMCU/Netherlands • UNIMORE/Italy • WUM/Poland
Inventory: Consumables weighed per session; electricity from facility metering; travel by patient/staff survey; waste from audit records
Tool: EF 3.1 • OpenLCA v2.5 • ecoinvent v3.11 • 16 impact categories; climate change (kg CO_2e) primary indicator
Sensitivity analysis: Patient transport modal shift modelled at 75% (S1b) and 100% (S1c) public transport at observed distances; FJD as real-world reference





Annual climate change impact ranged from 1,829 to 4,894 kg CO_2e per patient-year, a 2.7-fold difference. Dominant emission drivers varied markedly by centre: consumables at FJD (68%) and WUM (44%), patient travel at UNIMORE (57%) and combined travel at UMCU and WUM (50%). Full modal shift to public transport (S1c) reduced total footprints by 26–33% at travel-dominated centres; the remaining gap with FJD reflects both shorter catchment distances (8 km vs 17–29 km) and its already high public transport uptake.

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Conclusions: HD carbon footprint varies nearly 3-fold across Europe. Patient transport modal shift is the largest modifiable lever at travel-dominated centres, though catchment geography sets an irreducible floor. Sustainability strategies must target centre-specific emission hotspots.

Introduction

Chronic kidney disease (CKD) is a rapidly growing global health challenge. Recent estimates place the number of people living with CKD at nearly 700 million worldwide, with broader kidney-disease estimates exceeding 850 million people when considering the full spectrum of kidney conditions and treated kidney failure.[1,2] The burden has grown markedly, with Global Burden of Disease analyses reporting a substantial rise in CKD prevalence since 1990.[1] This trajectory is projected to continue due to ageing populations and rising rates of diabetes and hypertension. Consequently, the number of patients requiring kidney replacement therapy (KRT) is expected to increase substantially, with global use projected to exceed 5 million by 2030.[3]

Given the expanding dialysis population, the environmental consequences of renal care have become an increasingly important sustainability concern. Health care is estimated to contribute a material share of global greenhouse gas emissions, with supply chains accounting for a large proportion of this footprint.[4] Dialysis is among the most resource-intensive long-term therapies because it relies on recurrent treatments, energy and water-intensive infrastructure, and large volumes of single-use consumables.[5–7]

In-centre haemodialysis (HD) is particularly resource intensive. Each session consumes large quantities of water and energy and generates substantial clinical waste. Haemodialysis treatments (including priming and rinse phases) can require up to 490 litres of water per session, and global dialysis-related water use has been estimated at approximately 265 billion litres per year.[5] Direct measurements of modern haemodialysis systems show that per-treatment electricity consumption can vary considerably depending on dialysis machines and water treatment operations, while centre-level monitoring indicates that water treatment plant type and operating schedules can meaningfully shift per-session energy and water requirements.[6,8] Solid and plastic waste generation is also substantial: published estimates suggest plastic waste per session can range from 1.5 to 8 kg depending on protocols and classification, accumulating to hundreds of kilograms per patient-year.[7,8]

Life cycle assessment (LCA) offers a standardised and rigorous approach to quantifying these impacts. Governed by ISO 14040 and ISO 14044 standards,[9,10] life cycle assessment enables evaluation of environmental burdens across the life cycle of a treatment, from material extraction and manufacturing of supplies, through transport and facility operations, to end-of-life disposal. Such assessments quantify impacts across multiple categories (eg, carbon footprint, energy use, water use, and waste generation), supporting the identification of "hotspots" where targeted interventions may deliver meaningful reductions.

Evidence increasingly suggests that haemodialysis footprints are driven not only by on-site electricity and water use but also by travel and procurement. A recent web-based carbon footprint calculator developed by Beige et al. across five German haemodialysis centres found that manufacturing, energy consumption, and patient transportation were the dominant emission contributors.[11] Large-scale facility analyses have identified patient and staff transportation as a major contributor to haemodialysis emissions, alongside electricity and heating fuels.[12] Recent process-based life cycle assessments reinforce this pattern: an Italian comparison of HD and online haemodiafiltration (OL-HDF) found broadly similar annual footprints between modalities but reported travel as the dominant source of greenhouse gas emissions, highlighting the importance of care models and travel patterns in addition to technology choice.[13]

Procurement choices within dialysis centres can also change environmental performance substantially. Two recent studies demonstrated that dialysate acid concentrate logistics are a material lever: a life cycle assessment comparing acid concentrate container types showed that smaller canister-based systems can have markedly higher footprints than flexible bags or storage tanks, while a separate life cycle assessment found that implementing a central acid concentrate delivery system using dry powder with reusable packaging reduced carbon emissions by more than half in a large European centre and remained favourable across long-distance delivery scenarios when reuse assumptions were met.[14,15]

Importantly, kidney-care sustainability evidence is expanding beyond in-centre HD to include other modalities and pathway-based analyses. Recent life cycle assessments of peritoneal dialysis (PD) in Italy showed that automated PD (APD) can generate higher annual emissions than continuous ambulatory PD (CAPD) primarily due to electricity demand and material choices, while incremental PD approaches can substantially reduce emissions.[16] Procurement-focused life cycle assessment shows that a small number of high-use PD consumables (notably dialysate bags) dominate procurement-related footprint, driven by plastics and long-distance transport.[17] Together, these findings support a pathway-based view of sustainable kidney care in which travel, energy, procurement, and waste are treated as interconnected design targets rather than isolated operational issues.

Given the heterogeneity in infrastructure, electricity mixes, and resource constraints across Europe including pronounced water stress in parts of southern Europe,[18] comparative environmental analyses across clinical sites can provide actionable insights into how specific practices shape haemodialysis sustainability. This study conducts a cradle-to-grave life cycle assessment of in-centre HD across four European clinical centres: the University Medical Centre Utrecht (UMCU) in the Netherlands, Fundación Jiménez Díaz (FJD) in Spain, Warszawski Uniwersytet Medyczny (WUM) in Poland, and the IOU/Policlinico (UNIMORE) in Modena, Italy. By applying ISO-aligned life cycle assessment methods,[9,10] the study quantifies impacts across key dimensions (carbon footprint, energy use, water use, and waste), compares cross-centre performance, and explores which clinical and technological factors most influence sustainability outcomes.

Methods

Study design and life cycle assessment framework

We conducted a cradle-to-grave life cycle assessment of in-centre HD at four European clinical centres: Fundación Jiménez Díaz (FJD, Spain), University Medical Centre Utrecht (UMCU, the Netherlands), IOU/Policlinico di Modena (UNIMORE, Italy), and Warszawski Uniwersytet Medyczny (WUM, Poland). The study followed ISO 14040 and ISO 14044 standards.[9,10] The functional unit was one patient-year of in-centre HD, defined as 156 sessions on a standard thrice-weekly schedule, with an average duration of 4 hours per session.

System boundary

A cradle-to-grave system boundary was applied, encompassing manufacture and inbound transport of all consumables (dialyzers, bloodlines, needles, saline, dialysate concentrates), facility electricity consumption (HD machines and reverse osmosis [RO] water treatment system), patient and staff travel, and clinical waste treatment. Pharmaceuticals administered during dialysis and capital equipment (dialysis machines, reverse osmosis water treatment systems, building infrastructure) were excluded from the system boundary. A schematic depiction of the system boundary is shown in Figure 1.

Site description

All four participating centres provide outpatient in-centre HD on a thrice-weekly schedule with conventional bicarbonate-based dialysate. FJD (Madrid, Spain) is an urban hospital-based unit with a short patient catchment area (mean one-way travel distance 8 km); patient transport is predominantly by public transport. UMCU (Utrecht, Netherlands) is an academic medical centre with patients drawn from a regional catchment (mean 17 km); patient transport is predominantly by private car/taxi. The IOU/Policlinico unit in Modena (UNIMORE) Italy serves a dispersed regional catchment (mean 29 km), with patient transport predominantly by private car. WUM (Warsaw, Poland) is an academic centre serving a large catchment (mean 23 km); patient transport is predominantly by organised transport dispatched through an external provider. All centres use clinically equivalent consumables (dialysers, bloodlines, dialysate concentrates) although specific brands differ. Reverse osmosis water treatment systems are used at all four centres, with system size and operating schedules differing across sites.

Data collection and modelling

Primary inventory data were collected directly from each centre across five domains: consumables, electricity, water, travel, and waste. Consumables were inventoried by physically dismantling and weighing all items used in a standard dialysis session at each centre, including dialysers, bloodlines, needles, saline bags, and dialysate concentrate containers. Material weights were confirmed against manufacturer specifications and scaled to 156 sessions per patient-year. Electricity consumption was measured using direct meter readings at UMCU under operational conditions, capturing the combined consumption of haemodialysis machines and the reverse osmosis water treatment system. At FJD, UNIMORE, and WUM, electricity consumption was estimated from manufacturer specifications and equipment ratings. This methodological asymmetry is acknowledged in the Limitations. Waste volumes were collected from clinical waste audit data.

Patient travel data were collected through structured self-report surveys administered to patients at each centre, capturing one-way travel distance and mode of transport. Staff travel data were collected by equivalent survey. Patient and staff transport were modelled on a per-passenger basis without explicit occupancy factors for organised fleet or shared transport modes. Staff travel emissions were normalised to the functional unit using a time-based allocation approach, attributing the proportion of each staff member's commute corresponding to time spent delivering

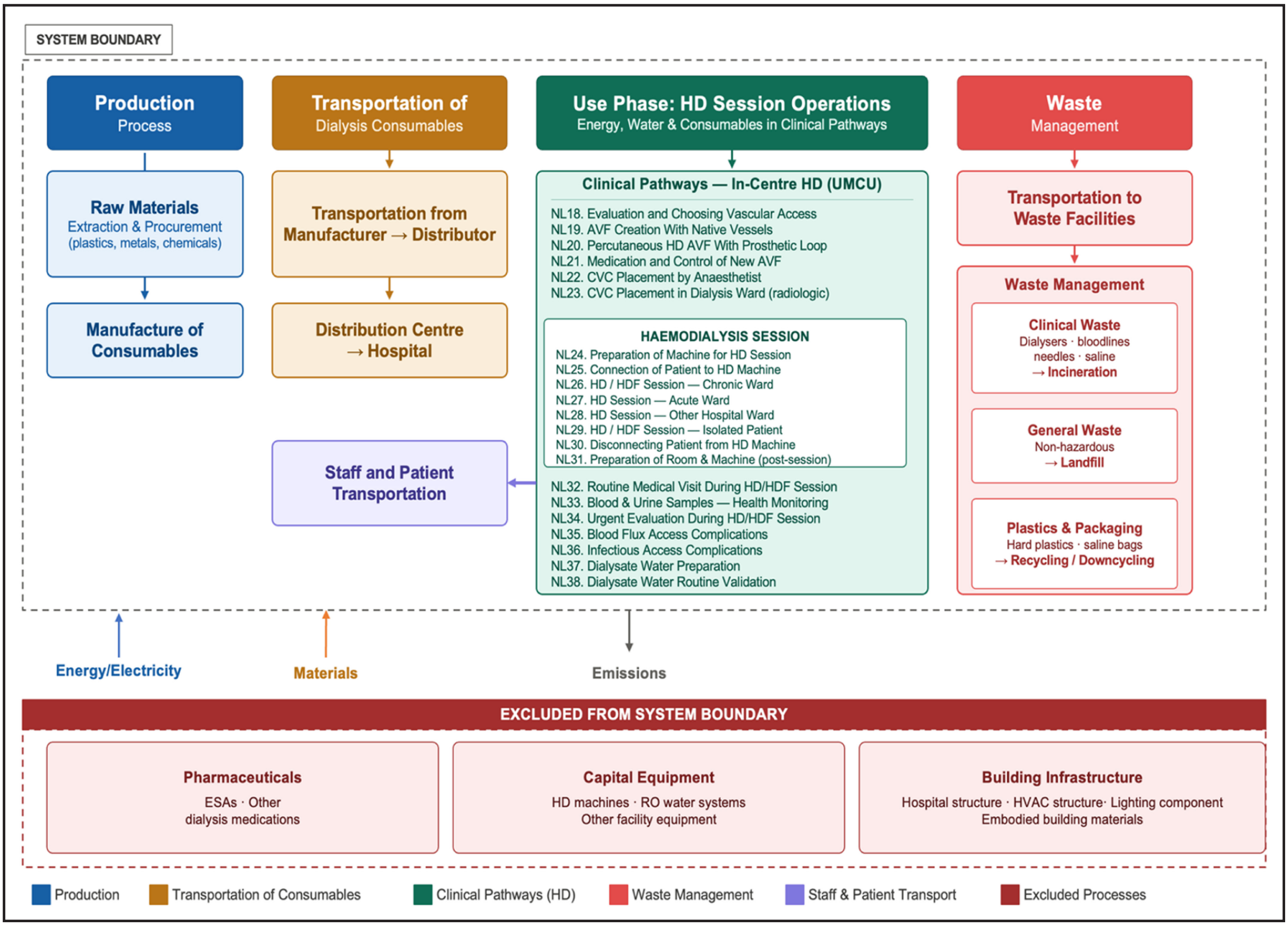

Figure 1 System boundary.

haemodialysis care during the session. At WUM specifically, organised patient transport involves shared vehicles dispatched by an external provider but was modelled using equivalent emission factors to private car travel. Real-world emissions from shared transport with high occupancy would be lower per patient than the per-vehicle modelling presented here; conversely, low-occupancy or empty return trips for ambulances and dedicated transport would increase per-patient emissions. The relative comparisons between scenarios within each centre remain valid because the same modelling assumption applies across S1a, S1b, S1c, and S2.

Inventory domains were aggregated for contribution analysis as follows: electricity into a single combined category encompassing facility-level and device-level electricity (haemodialysis machines and reverse osmosis water treatment system) plus upstream electricity embodied in consumables and supply chain processes; water through the EF 3.1 water use midpoint indicator (Table 1) rather than as a duplicate contribution category. Detailed inventory protocols are provided in the Supplementary Methods (SM5, SM6, SM8).

All data are available in a public repository on Zenodo.org listed in the data availability statement (1,2,3,4). Background life cycle inventory data were sourced from the EcoInvent v3.11 database (cut-off system model). Life cycle impact assessment was performed using the Environmental Footprint 3.1 (EF 3.1) method, implemented in OpenLCA v2.5. All sixteen impact categories are reported. Contribution analysis and sensitivity analyses focus on climate change (kg CO_2e) as the primary indicator, with non-renewable cumulative energy demand (MJ) and water scarcity (m^3 world-equivalent) reported as secondary indicators. A glossary box SG1, explaining the terminology is a supplementary file. Full inventory data, background dataset references, and modelling assumptions are provided in the Supplementary Methods.

Sensitivity analysis

Two sensitivity analyses were conducted to explore the effect of patient transport choices on overall HD carbon footprint.

Scenario S1 modelled a patient transport modal shift to isolate the effect of transport mode on travel-related emissions. S1a reflects observed primary data from each centre. At UMCU, UNIMORE, and WUM, S1a represents a car-dominant modal composition; in this analysis, "car" is used as a proxy for all non-public road-based transport including private cars, taxis, ambulances, and organised fleet transport, since detailed modal disaggregation within the road-based category was not consistently available across centres. Car emission factors approximate the per-passenger emissions of these alternative road-based modes within the order of magnitude relevant to this analysis. S1b (75% public transport/25% car) and S1c (100% public transport) are modelled sensitivity scenarios applied at the observed travel distances of each centre (UMCU: 17 km, UNIMORE: 29 km, WUM: 23 km

Table 1 Life cycle assessment results across all 16 Environmental Footprint 3.1 impact categories per patient-year (156 sessions). Values represent absolute characterised results.

Impact category	Unit	FJD (Spain)	UMCU (Netherlands)	UNIMORE (Italy)	WUM (Poland)
Acidification	mol H^+ eq	8.58	11.32	16.35	18.35
Climate change	kg CO_2e	1829.7	4194.23	4469.6	4893.6
Ecotoxicity: freshwater	CTUe	24 958	15 334	46 523	42 222
Energy resources: non-renewable	MJ	28 200	52 797	60 136	64 786
Eutrophication: freshwater	kg P eq	0.419	0.689	0.906	1.267
Eutrophication: marine	kg N eq	2.24	2.90	4.12	4.46
Eutrophication: terrestrial	mol N eq	20.41	30.32	42.69	47.14
Human toxicity: carcinogenic	CTUh	1.73×10^{-6}	1.47×10^{-6}	2.09×10^{-6}	2.97×10^{-6}
Human toxicity: non-carcinogenic	CTUh	1.94×10^{-5}	2.99×10^{-5}	6.16×10^{-5}	4.55×10^{-5}
Ionising radiation: human health	kBq U_{355} eq	426.8	144.9	148.1	124.6
Land use	Pt	14 353	16 431	24 976	46 415
Material resources: metals/minerals	kg Sb eq	0.0090	0.0286	0.0584	0.0399
Ozone depletion	kg CFC-11 eq	9.15×10^{-5}	2.10×10^{-4}	3.45×10^{-4}	2.77×10^{-4}
Particulate matter formation	disease incidence	8.32×10^{-5}	1.53×10^{-4}	2.34×10^{-4}	2.48×10^{-4}
Photochemical oxidant formation: human health	kg NMVOC eq	5.76	12.78	15.90	18.60
Water use	m^3 world eq	1285.5	619.4	1361.6	1326.2

All values are per patient-year (156 haemodialysis sessions). Environmental Footprint 3.1 impact assessment method in OpenLCA v2.5 with EcoInvent v3.11. Climate change reported as kg CO_2-equivalent using 100-year global warming potentials.
Abbreviations: CFC-11, trichlorofluoromethane; CO2e, carbon dioxide equivalent; CTUe, comparative toxic units for ecosystems; CTUh, comparative toxic units for humans; NMVOC, non-methane volatile organic compounds; Pt, ecopoints; Sb, antimony.

one-way). FJD, where primary data confirm predominantly public transport use, serves as the real-world empirical reference for the S1c endpoint. We present S1b and S1c as illustrative scenarios reflecting potential modal shift; real-world feasibility depends on the availability of accessible public transport along patient travel routes, which we did not formally assess in this study.

Scenario S2 modelled an electrification scenario in which the car-using fraction of patients at each centre was assumed to switch from internal combustion vehicles to battery electric vehicles, holding all other modal shares and travel distances constant. Electric vehicle electricity consumption was modelled using the country-specific grid mix at each centre. At UMCU, UNIMORE, and WUM, where car use predominates in the baseline, S2 represents 100% of car users switching to electric vehicles. At FJD, where 25% of patients use cars in the baseline, S2 represents the same 25% switching to electric vehicles, with the public transport (68%) and other low-emission (7%) shares unchanged.

Results

Climate change impact across centres

The annual climate change impact of in-centre haemodialysis varied substantially across the four participating European centres. Total greenhouse gas emissions ranged from 1829 kg CO_2-equivalent (CO_2e) per patient-year at FJD to 4894 kg CO_2e per patient-year at WUM. UMCU and UNIMORE demonstrated comparable total impacts of 4194 kg CO_2e and 4467 kg CO_2e per patient-year, respectively.

A standard thrice-weekly schedule corresponds to 156 sessions per year. This equates to approximately 11.7 kg CO_2e per session at FJD, 26.9 kg CO_2e at UMCU, 28.6 kg CO_2e at UNIMORE, and 31.4 kg CO_2e at WUM. The overall spread between lowest and highest emitting centres was therefore approximately 2.7-fold.

Contribution analysis

Absolute kg CO_2e emissions for each life cycle stage are presented for all centres in Figure 2A, with proportional contributions in Figure 2B. The five contributors showed substantially different ranges across centres.

Consumables ranged from 953 kg CO_2e per patient-year at UNIMORE to 1975 kg CO_2e at WUM (2.1-fold spread). UMCU (1257 kg CO_2e) and FJD (1239 kg CO_2e) showed comparable values. WUM's higher value was associated with longer inbound supply chain distances.

Electricity showed the largest relative variation, ranging from 149 kg CO_2e at FJD to 659 kg CO_2e at UMCU (4.4-fold spread). UNIMORE (208 kg CO_2e) and WUM (324 kg CO_2e) fell in between. Notably, electricity consumption was quantified by direct meter readings at UMCU but estimated from manufacturer specifications at FJD, UNIMORE, and WUM; the implications of this measurement asymmetry are addressed in the Discussion.

Patient travel showed the largest absolute variation, ranging from 265 kg CO_2e at FJD to 2548 kg CO_2e at UNIMORE (9.6-fold spread). UMCU (1676 kg CO_2e) and WUM (2325 kg CO_2e) fell at intermediate values.

Staff travel ranged from 80 kg CO_2e at FJD to 615 kg CO_2e at UNIMORE (7.7-fold spread). WUM (124 kg CO_2e) was closer to FJD, while UMCU (497 kg CO_2e) was closer to UNIMORE.

Waste was the smallest contributor at all centres, ranging from 97 kg CO_2e at FJD to 146 kg CO_2e at WUM (1.5-fold spread).

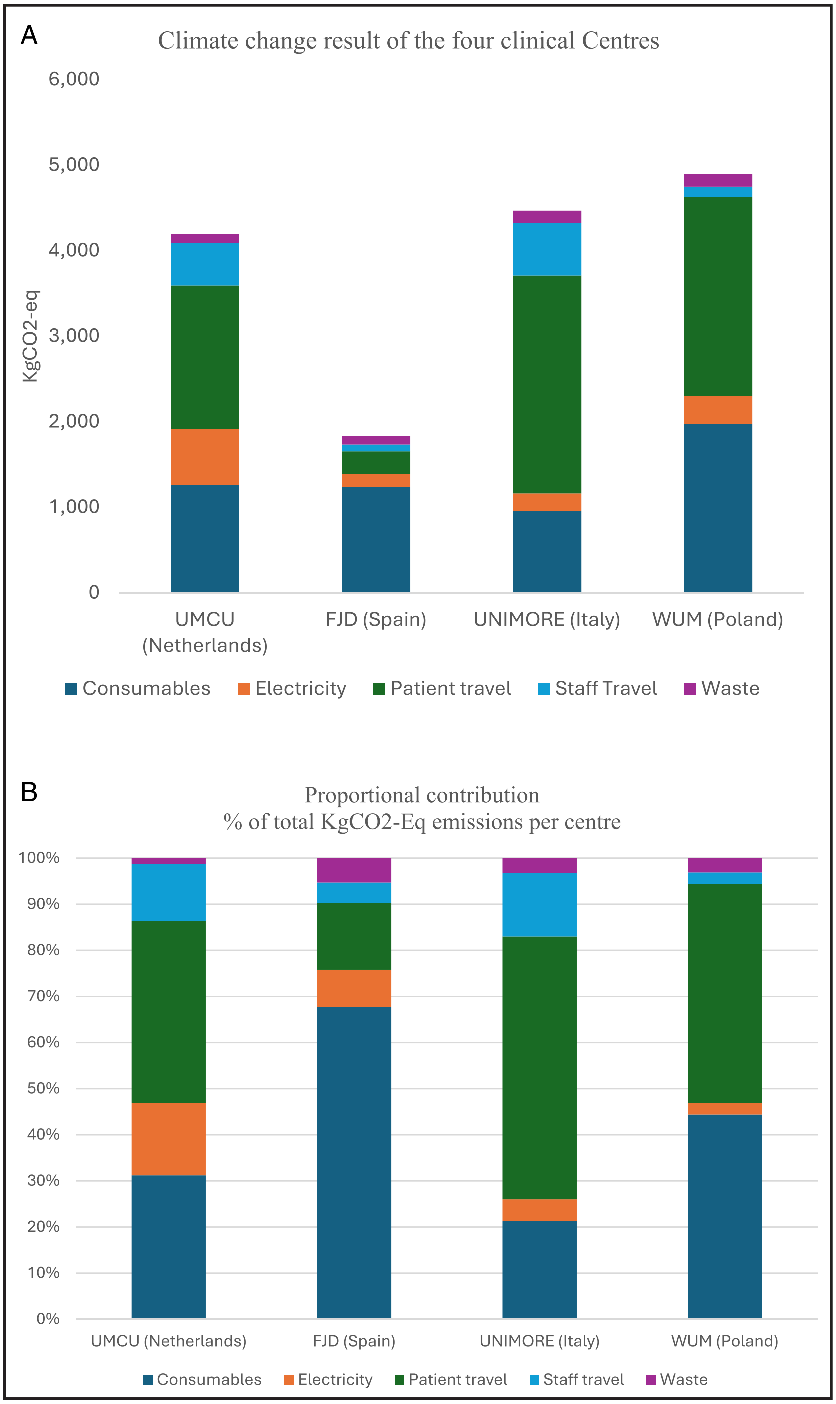

Figure 2 (A) Climate change contribution graph across the four centres. (B) Proportional contribution % of total KgCO2-Eq emissions per centre.

Energy and water-related midpoint indicators

The life cycle midpoint indicator for non-renewable energy resources ranged from 28 200 MJ per patient-year at FJD to 64 786 MJ at WUM. UNIMORE (60 136 MJ) and UMCU (52 797 MJ) demonstrated intermediate values.

The water use indicator showed a different pattern. UMCU had the lowest reported water-related impact (619 m^3 world equivalent per patient-year), while FJD (1285), WUM (1326), and UNIMORE (1362) were comparatively higher. These results reflect life cycle water use as modelled within the chosen impact assessment method, rather than direct metered water consumption at facility level. All the impact results are shown in Table 1.

Sensitivity analysis results

Patient transport modal shift (scenario S1)

Patient travel emissions under the observed baseline (S1a) were 2548 kg CO_2e per patient-year at UNIMORE, 2325 kg CO_2e at WUM, and 1676 kg CO_2e at UMCU. Shifting to 75% public transport (S1b) reduced patient travel emissions by 39.1% at UNIMORE, 45.7% at

WUM, and 41.4% at UMCU. Full modal shift (S1c) achieved reductions of 57.9% at UNIMORE (1073.7 kg CO_2e), 63.1% at WUM (858.6 kg CO_2e), and 64.7% at UMCU (592.4 kg CO_2e) relative to S1a. Applied to total centre footprints, the transition from S1a to S1c corresponds to reductions of 33.0% at UNIMORE, 30.0% at WUM, and 25.8% at UMCU (Table 2). At FJD, the observed patient travel footprint (265.2 kg CO_2e per patient-year) serves as the real-world S1b reference, reflecting a modal composition of 68% public transport and 7% other non-motorised or low-emission modes that already approximates the 75% target; the modelled S1c scenario yields 166.1 kg CO_2e per patient-year.

Even under full modal shift (S1c), patient travel emissions at UMCU, UNIMORE, and WUM remained 2.2-, 4.1-, and 3.2-fold higher than the FJD observed reference (265.2 kg CO_2e per patient-year). These ratios closely mirror the distance ratios between centres (UMCU 2.1×, WUM 2.9×, UNIMORE 3.6× FJD at 8 km).

Patient transport electrification (scenario S2)

Replacing car-based patient travel with battery electric vehicles delivered modest reductions in patient travel emissions across all centres. Patient travel emissions under S2 were 254.9 kg CO_2e per patient-year at FJD (a 3.9% reduction from the observed baseline), 1193.2 kg CO_2e at UMCU (28.8% reduction), 2035.5 kg CO_2e at UNIMORE (20.1% reduction), and 1614.4 kg CO_2e at WUM (30.6% reduction). At centres where car use dominates the baseline modal mix, S2 reductions were therefore substantially smaller than the equivalent S1c modal shift to public transport (a 2.1- to 4.9-fold difference in absolute kg CO_2e saved). At FJD, where 75% of patients already use public transport or other low-emission modes, the additional reduction from electrifying the residual 25% car users was small in absolute terms (10.3 kg CO_2e per patient-year), reflecting both the limited share of car-using patients and the short catchment distance (8 km one-way) (Table 2).

Discussion

This four-centre life cycle assessment demonstrates substantial variability in the environmental footprint of in-centre haemodialysis across European settings, with nearly a threefold difference in annual carbon emissions between centres. Importantly, this variability is not driven by dialysis as a clinical modality *per se*, but by structural and contextual factors embedded within each centre's service configuration, procurement systems, and patient logistics. These findings are consistent with prior reports of substantial inter-facility variation in dialysis carbon footprints.[11,19]

Patient travel emissions showed the largest cross-centre variation, with a 9.6-fold spread ranging from 265 kg CO_2e per patient-year at FJD to 2548 kg CO_2e at UNIMORE. The pronounced differences between centres reflect both modal mix and catchment geography. FJD's emissions advantage arises from a combination of short catchment distance (8 km one-way) and high public transport uptake (68% of patients), while emissions at UMCU, UNIMORE, and WUM are dominated by car use across longer catchment distances (17 to 29 km one-way). The transport modal shift sensitivity analysis (Scenario S1) demonstrates that achieving FJD-like modal composition at the other centres would reduce patient travel emissions by 57.9 to 64.7%, but residual emissions would remain proportionally higher in absolute terms because of the longer distances. Specifically, even under full modal shift (S1c), patient travel emissions at UMCU, UNIMORE, and WUM remained 2.2-, 4.1-, and 3.2-fold higher than the FJD observed reference, ratios that align almost exactly with the underlying distance ratios.

Staff travel emissions showed substantial variation across centres (80 to 615 kg CO_2e per patient-year, a 7.7-fold spread) driven by similar modal and distance factors as patient travel. Lower staff travel emissions at FJD and WUM reflect higher rates of public transport use and shorter average commuting distances, while higher emissions at UNIMORE and UMCU reflect longer car-based commutes. At WUM specifically, although staff distances are intermediate, the relatively low absolute emissions partly reflect public transport use; at UNIMORE, by contrast, longer distances combine with predominantly car-based commuting to produce the highest absolute staff travel emissions of any centre.

Consumables emissions were comparable at three of four centres (953 to 1257 kg CO_2e per patient-year at UNIMORE, FJD, and UMCU) and substantially higher at WUM (1975 kg CO_2e). The WUM excess reflects longer inbound supply chain distances rather than fundamentally different products: all four centres procure clinically equivalent dialysers, bloodlines, and dialysate concentrates from broadly similar product categories, and minor brand-level weight differences contributed only a small secondary effect. This

Table 2 Patient transport sensitivity analyses (scenarios S1 and S2); patient travel emissions (kg CO_2e per patient-year).

Centre	One-way distance (km)	S1a: 100% car (kg CO_2e)	S1b: 75% public transport (kg CO_2e)	Reduction S1a→S1b (%)	S1c: 100% public transport (kg CO_2e)	Reduction S1a→S1c (%)	S2: battery electric vehicle (kg CO_2e)
FJD	8	—	265.2[a]	—	166.1	—	254.9
UMCU	17	1676	982.6	41.4%	592.4	64.7%	1193.2
UNIMORE	29	2548	1550.6	39.1%	1073.7	57.9%	2035.5
WUM	23	2325	1263.1	45.7%	858.6	63.1%	1614.4

Patient travel emissions only (staff travel not included). S1a = observed primary data (100% car modal composition at UMCU, UNIMORE, WUM); S1b = modelled sensitivity scenario (75% public transport/25% car); S1c = modelled sensitivity scenario (100% public transport applied at observed distances). Travel distances held constant.

[a]FJD S1b: observed primary data (n = 56, ambulance excluded); actual modal composition (68% public transport, 7% other non-motorised and low-emission modes, 25% car) approximates the 75% public transport scenario applied at other centres. FJD S1a not modelled as car use has never predominated in this patient population. S2 = modelled electrification scenario in which the car-using fraction of patients at each centre switches to battery electric vehicles, holding all other modal shares and travel distances constant. Electric vehicle electricity consumption modelled using country-specific grid mix.

pattern indicates that consumables-related mitigation potential is concentrated in supply chain optimisation, supplier consolidation, and packaging reduction, rather than in product substitution.[8,20] The clustering of three centres within an approximately 300 kg CO_2e range suggests this represents a baseline level achievable through standard Western European procurement, against which WUM's higher value is best understood as a function of geographic supply chain distance. The higher emissions observed at WUM are driven primarily by systemic factors rather than differences in dialysis technology. Patient transport is predominantly organised through an external provider using relatively old fleet vehicles, serving a large catchment area in which patients do not routinely travel to dialysis by public transport. This means that achieving the modal shift reductions modelled in S1b, S1c and S2 would require renegotiating or restructuring the organised transport contract rather than individual behavioural change, a distinction relevant for policy translation. Together, these factors illustrate how the carbon footprint of a dialysis centre is strongly shaped by national and urban structural conditions, including energy systems, transport infrastructure, and housing markets, rather than solely by clinical practice choices.

Electricity emissions showed a 4.4-fold variation across centres, ranging from 149 kg CO_2e per patient-year at FJD to 659 kg CO_2e at UMCU. Three factors contribute to this variation. First, country-specific grid carbon intensity, modelled using national EcoInvent v3.11 datasets. Second, centre-specific energy consumption, particularly the reverse osmosis water treatment system and HD machines which differs in size and models across sites. Third, methodological differences in how electricity consumption was measured: at UMCU, electricity use from haemodialysis machines and the reverse osmosis water treatment system was quantified using direct meter readings under operational conditions; at the other three centres, energy consumption was estimated from manufacturer specifications and equipment ratings, which represent rated rather than operational consumption and may underestimate real-world energy use. The higher absolute electricity emissions at UMCU should therefore be interpreted partly as a consequence of more rigorous measurement methodology rather than indicating substantively higher energy use. Updated benchmarking data on the resource consumption of modern HD systems confirm that electricity use per session varies substantially across machine types and operational configurations.[6,21]Waste treatment processes consistently represented the smallest share of emissions across all sites and range around 1.5-fold. The narrow range reflects broadly relatively similar waste management practices across the four sites. This finding aligns with the broader literature[11,18,22] indicating that upstream production and transport of materials generally outweigh downstream waste management in carbon contribution. While waste minimisation remains important from a circularity and resource perspective, its impact on total carbon footprint appears secondary relative to travel and consumables in this analysis.

While climate change has been the focus of this analysis, centre rankings differ across the 16 EF 3.1 impact categories presented in Table 1. Annual non-renewable cumulative energy demand patterns broadly tracked climate change emissions across centres, reflecting the shared dependence of both indicators on fossil fuel inputs across grid electricity, vehicle fuel, and consumable manufacturing. The water use indicator, however, showed a different pattern. UMCU recorded the lowest annual water use (619 m^3 world-eq per patient-year), reflecting the relatively water-abundant Dutch context where freshwater extraction carries lower scarcity weighting in the EF 3.1 impact model and the automated draining of dialysers and bloodlines at UMCU, which enables their classification as plastics for downcycling rather than wet clinical waste, thereby reducing the need to manufacture new plastic, which carries a high water footprint of its own. FJD's water use value (1285 m^3 world-eq), although associated with the lowest absolute climate change footprint, was higher than UMCU's, reflecting the higher water scarcity weighting applied to Spanish freshwater inputs combined with disposal of consumables via incineration, which does not capture the same upstream water savings available through material recovery. These results reflect modelled life cycle water use rather than direct metered freshwater consumption at the dialysis facility and incorporate water inputs across the upstream supply chain (consumable manufacturing, energy production) as well as direct facility use. The ionising radiation indicator at FJD is approximately threefold higher than the other three centres, an observation consistent with the known nuclear share of the Spanish electricity grid (approximately 19 to 20% in 2024),[23,24] although direct attribution would require facility-level energy provenance data not collected as part of this study. These cross-category differences indicate that mitigation strategies optimised for climate change reduction may have differential effects on other impact categories. A focus on supply chain consolidation would be expected to reduce both climate change and ionising radiation indicators in parallel, while a shift toward electric patient transport may reduce climate change emissions while having more limited or even neutral effects on water use depending on the country grid mix.

The transport modal shift sensitivity analysis (Scenario S1) provides arguably the most policy-relevant finding of this study. By holding travel distances constant and comparing observed car-dominated footprints (S1a, primary data) against modelled public transport scenarios (S1b, S1c), the analysis isolates the contribution of transport mode to inter-centre variation in travel-related emissions. The empirical grounding of S1a in primary centre data, and the availability of FJD as a real-world public-transport reference centre, lend the sensitivity analysis a degree of evidential credibility that is rarely achievable in this type of comparative life cycle assessment.

The results demonstrate that modal shift from private car to public transport has substantial mitigation potential at all three car-dependent centres. Applying a full public transport modal composition (S1c, modelled sensitivity scenario) reduced patient travel emissions by 57.9–64.7% across UMCU, UNIMORE,and WUM relative to their observed car-dominated baselines (S1a, primary data), with the largest absolute reduction at UNIMORE (1474 kg CO_2e per patient-year), where travel dominates the total footprint. The modelled intermediate scenario (S1b: 75% public transport) achieved reductions of 39.1–45.7%, while we present these as illustrative scenarios reflecting potential modal shift, real-world feasibility depends on the availability of accessible public transport along patient travel routes, which we did not formally assess in this study; centres considering modal shift interventions should first audit local transport infrastructure and public transport accessibility for their specific patient populations.

Critically, even under full modal shift (S1c), patient travel emissions at UMCU, UNIMORE, and WUM remained 2.2-, 4.1-, and 3.2-fold higher than the FJD observed reference (265.2 kg CO_2e per patient-year the real-world S1b equivalent), respectively. Travel distances at these centres are 2.1 to 3.6 fold greater than at FJD (8 km one-way), UMCU 17 km (2.1×), WUM 23 km (2.9×), and UNIMORE 29 km (3.6×). Strikingly, the emission ratios under S1c (2.2×, 3.2×, and 4.1× FJD, respectively) align almost precisely with these distance ratios, confirming that after full modal shift the remaining gap is almost entirely attributable to catchment geography rather than any residual mode-related factor. This finding cleanly decomposes FJD's emissions advantage into two components: a replicable component (public transport use, as captured by the S1b scenario) and a structural component (shorter patient-to-centre distances), confirming that distance accounts for much of the residual gap.

This distinction carries direct implications for sustainability planning. Centres seeking to reduce their travel footprint should first assess the modal composition of their patient population. Where private car use predominates due to perceived necessity rather than fixed geography, for example in centres with good public transport access but limited patient awareness or support, targeted behavioural interventions, subsidised travel passes or coordinated patient transport services may achieve substantial emissions reductions without requiring changes to centre location or service structure. Conversely, at centres serving genuinely dispersed rural populations, travel emissions may be structurally irreducible through mode shift, and investment in home haemodialysis or satellite centre models may offer greater environmental returns. Notably, smaller satellite haemodialysis centres are typically associated with a higher per-patient carbon footprint due to fixed infrastructure requirements, including minimum power and water consumption that does not scale linearly with patient numbers;[25] this trade-off should be considered in service planning alongside any travel-related benefits.

The data from FJD serve as an important proof of concept. The centre's combination of short catchment distances and high public transport uptake produces patient travel emissions that are 6.6- to 11.2-fold lower than those modelled at other centres under full car use. While geography contributes to this advantage, the modal data confirm that the behavioural and infrastructural dimension is independently significant and should not be overlooked in comparative sustainability assessments.

The electrification scenario (S2) provides additional context for the modal shift findings. Replacing car-based patient travel with battery electric vehicles reduced patient travel emissions by 3.9 to 30.6% across centres, but at every centre the corresponding modal shift to public transport (Scenario S1c) delivered approximately two- to fivefold larger absolute carbon savings. This pattern reflects the carbon intensity of European electricity grids: even when EVs are charged using national grid mixes, per passenger-kilometre emissions remain higher than for shared public transport in countries with non-trivial fossil-fuel electricity dependence. Electrification is therefore a meaningful adjunct strategy where modal shift is structurally infeasible, particularly for centres serving dispersed rural catchments, but should not be considered a substitute for modal shift where public transport is accessible. For centres using organised patient transport fleets, including WUM, the equivalent intervention is electrification of the dispatched fleet rather than individual EV purchases by patients.

Several limitations should be acknowledged. First, each participating centre represents a single institution within its respective country, and findings should be interpreted as centre-specific environmental profiles rather than national estimates, given the substantial within-country variation in procurement, infrastructure, and local transport networks. Second, patient and staff travel data were collected through self-reported surveys, which are subject to recall bias and do not capture seasonal variation in transport mode or the full heterogeneity of travel patterns across the dialysis population. Third, patient and staff transport were modelled on a per-passenger basis without explicit occupancy factors. At WUM specifically, organised patient transport involves shared vehicles, and the S1a baseline therefore reflects an upper-bound emissions estimate for that centre's transport. The relative comparisons between scenarios within each centre remain valid because the same modelling assumption applies across S1a, S1b, S1c, and S2. Fourth, electricity consumption was quantified through direct meter readings at UMCU but estimated from manufacturer specifications at FJD, UNIMORE, and WUM, which may contribute to the observed cross-centre variation in electricity-related emissions. Future multicentre life cycle assessments would benefit from harmonised on-site metering protocols.

Conclusions

This four-centre European life cycle assessment demonstrates that the carbon footprint of in-centre haemodialysis varies nearly threefold across equivalent settings, driven primarily by patient travel patterns and consumables supply chain geography rather than by dialysis technology. Examining absolute emissions for each life cycle stage reveals where mitigation potential exists at each centre: supply chain optimisation for consumables, modal shift or fleet electrification for patient transport, and harmonised energy measurement for benchmarking. The findings support a context-sensitive approach to sustainable dialysis planning, using centre-level life cycle assessment hotspot mapping to direct interventions where they will have the greatest impact. The framework presented here is replicable and applicable to dialysis programmes, including settings where the anticipated rapid growth in dialysis provision makes early sustainability planning particularly consequential.

Author contributions

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Validation [supporting]), Marta Arias-Guillén (Supervision, Writing—review & editing [supporting]), Karin G.F. Gerritsen (Supervision, Writing—review & editing [supporting]), and Brett Duane (Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Writing—review & editing [supporting], Data curation [equal], Funding acquisition, Supervision [lead])

Conflict of interest

The authors declare that they have no competing interests.

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Data availability

All environmental inventory and modelling data generated or analysed during this study are publicly available in the following Zenodo repository:

1. Fehintola, A., Larkin, J., Martinez, R., & Duane, B. (2025). Life Cycle Assessment Dataset For Haemodialysis in Utrecht, Netherlands [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17140768
2. Fehintola, A., James Larkin, Cadenas, R., & Duane, B. (2025). Life Cycle Assessment Dataset For Haemodialysis in Warsaw [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16760349
3. Larkin, J., Fehintola, A., Martinez, R., & Duane, B. (2024). Life Cycle Assessment Dataset For Haemodialysis in Modena [Data set]. Brett Duane. https://doi.org/10.5281/zenodo.14272816
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Ethical disclosure

Ethical approval was obtained for the collection of travel-related data from clinical staff and patients at University Medical Centre Utrecht (UMCU, Netherlands), Medical University of Warsaw (WUM, Poland), and Hospital Universitario Fundación Jiménez Díaz Madrid (FJD, Spain). For AOU Policlinico di Modena (UNIMORE, Italy), ethical approval was not required, as only publicly available information was used. All data were pseudonymized before analysis to ensure participant confidentiality and data protection compliance.

Informed consent

Informed consent was obtained from all participants involved in the staff and patient travel data collection at Centres where ethical approval was granted.

Supplementary data

Supplementary material is available at *Journal of Nephrology* online.

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