www.kidney-international.org

Green dialysis: environmentally sustainable care, growth, and innovation: conclusions from a Kidney Disease: Improving Global Outcomes (KDIGO) Controversies Conference

Katherine A. Barraclough[1], Nathan Berman-Parks[2], Vivekanand Jha[3,4,5], Giorgina B. Piccoli[6], Caroline Stigant[7], Benjamin Talbot[8,9], Faissal Tarrass[10], Michael Cheung[11], Jennifer M. King[11], Morgan E. Grams[12], Michel Jadoul[13] and Jennifer E. Flythe[14]; for Conference Participants[15]

[1]Department of Nephrology, Royal Melbourne Hospital, Melbourne Health, Parkville, Victoria, Australia; [2]Department of Nephrology and Mineral Metabolism, Instituto Nacional de Ciencias Médicas y Nutrición Salvador Zubirán, Mexico City, Mexico; [3]The George Institute for Global Health, University of New South Wales, New Delhi, India; [4]School of Public Health, Imperial College, London, UK; [5]Prasanna School of Public Health, Manipal Academy of Higher Education, Manipal, Karnataka, India; [6]Nephrology Unit, Centre Hospitalier Le Mans, Le Mans, France; [7]Division of Nephrology, Island Health Authority, Department of Medicine, University of British Columbia, Vancouver, British Columbia, Canada; [8]The George Institute for Global Health, University of New South Wafles, Sydney, New South Wafles, Australia; [9]School of Population Health, University of New South Wales, Sydney, New South Wales, Australia; [10]Center of Hemodialysis 2 Mars, Casablanca, Morocco; [11]KDIGO, Brussels, Belgium; [12]Department of Medicine, Division of Precision Medicine, New York University Langone School of Medicine, New York, New York, USA; [13]Division of Nephrology, Cliniques Universitaires Saint Luc, Université Catholique de Louvain, Brussels, Belgium; and [14]Division of Nephrology and Hypertension, University of North Carolina School of Medicine, Chapel Hill, North Carolina, USA

Hemodialysis, hemodiafiltration, and peritoneal dialysis are among the most resource-intensive medical therapies, owing to their high energy and water consumption, heavy reliance on disposable materials, and frequent, recurring delivery. Although "green dialysis" initiatives have been adopted in some regions, broader implementation is needed, together with the development of new technologies and care models to further mitigate the environmental impact of dialysis. In April 2025, Kidney Disease: Improving Global Outcomes (KDIGO) held the Controversies Conference on Green Dialysis: Environmentally Sustainable Care, Growth, and Innovation. Participants included physicians, nurses, patients, and engineers who examined how existing hemodialysis (in-center and home) and peritoneal dialysis practices might be optimized to promote environmental sustainability. Additionally, opportunities for green innovations in dialysis procedures and technologies were identified. Recognizing the need for urgent and coordinated action among patients, clinicians, and organizations, participants also discussed how industry, policy, and regulations could support embedding environmental sustainability within dialysis care.

Kidney International (2026) ■, ■–■; https://doi.org/10.1016/j.kint.2026.01.015

KEYWORDS: environment; green dialysis; green nephrology; life cycle assessment; sustainability

The converging environmental crises of climate change, pollution, biodiversity loss, and freshwater depletion pose escalating threats to global and kidney health. The health care sector is a major contributor, responsible for 5.2% of global greenhouse gas emissions,[1] while also consuming vast amounts of water and generating immense waste.[2,3] Hemodialysis and peritoneal dialysis (PD) are among the most resource-intensive medical therapies, driven by their recurring nature, high energy and water consumption, and reliance on disposable materials.[4–6] Reducing the environmental footprint of dialysis is therefore both an ethical and an emerging regulatory imperative. In an increasingly resource-constrained world, and as the number of people requiring dialysis grows, improving sustainability is also a practical necessity to maintain or improve quality of care and to increase access, especially in underserved regions. Furthermore, as dialysis availability increases in low- and middle-income countries, it must be implemented in environmentally sustainable ways to avoid exacerbating environmental injustice—for example, by aggravating pollution or water scarcity.

Correspondence: *Katherine A. Barraclough, Department of Nephrology, Royal Melbourne Hospital, Melbourne Health, 55 Grattan Street, Parkville, Victoria 3050, Australia. E-mail: Katherine.barraclough@mh.org.au; or Jennifer E. Flythe, Division of Nephrology and Hypertension, Department of Medicine, Kidney Center, University of North Carolina at Chapel Hill, 7024 Burnett-Womack CB #7155, Chapel Hill, North Carolina 27599, USA. E-mail: jflythe@med.unc.edu*

[15] Other Conference Participants are listed in the Appendix.

Received 3 December 2025; revised 19 January 2026; accepted 30 January 2026

Although innovative "green dialysis" initiatives have been variably implemented in the United Kingdom, the European Union, Australia, and elsewhere,[4,7–11] widespread adoption is needed. In parallel, new technologies and care models must be developed to further mitigate the environmental impact of dialysis. To advance this agenda, in April 2025, Kidney Disease: Improving Global Outcomes (KDIGO) held the Controversies Conference on Green Dialysis: Environmentally Sustainable Care, Growth, and Innovation in Berlin, Germany (https://kdigo.org/conferences/green-dialysis/). Conference participants, including physicians, nurses, engineers, dietitians, and patients, considered how existing hemodialysis (in-center and home) and PD practices might be optimized and identified opportunities for green innovations in dialysis care.

Foundational concepts

From the outset, conference attendees agreed that efforts to reduce the environmental impact of kidney care must foremost focus on promoting health, identifying early kidney disease, and slowing disease progression. Furthermore, they underscored the importance of improving access to and optimizing nondialysis kidney failure therapies (transplantation and supportive care). However, given the disproportionately high environmental impact of dialysis and the growing number of individuals requiring it, the conference focused specifically on the environmental sustainability of maintenance dialysis. Many concepts may also apply to acute dialysis, but this was deemed out of scope, as were health system considerations not specific to dialysis, such as patient and staff travel and the environmental impact of medications.

A crosscutting conference theme was that *health care sustainability*—defined as the capacity of a health system to deliver care over time, with consideration for future generations—should be recognized as a core domain of quality health care and assessed using a "triple bottom line" approach, measuring health outcomes relative to environmental, social, and financial costs[12] (Figure 1). This approach positions patient outcomes as the numerator in the value equation while acknowledging the broader impacts of health care delivery. Reflecting this, patient perspectives were sought during conference discussions, with patient attendees emphasizing the importance of environmental sustainability to their well-being and their experience of dialysis care. Participants also relied on "life cycle thinking" to identify strategies to improve the environmental sustainability of dialysis. This framework considers impacts across the full life cycle of products or services (Figure 2).[13,14] In prioritizing strategies, they applied the waste hierarchy (ranked from most to least preferable): (i) prevention (waste reduction), (ii) reuse, (iii) recycling, (iv) other recovery (e.g., energy recovery), and (v) disposal (e.g., landfilling and incineration).[15] Box 1 displays additional key concepts and terms.

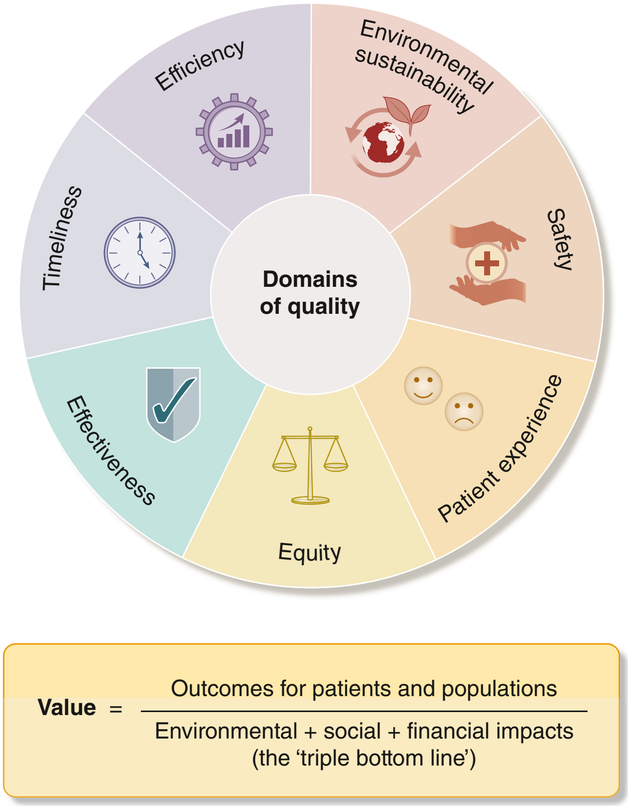


Figure 1 | The value of sustainability in health care. Adapted from *Future Healthcare Journal*, Volume 5, Issue 2, Frances Mortimer, Jennifer Isherwood, Alexander Wilkinson, Emma Vaux, Sustainability in quality improvement: redefining value, Pages 88–93,[12] Copyright © Royal College of Physicians 2018. All rights reserved, with permission from Elsevier under the terms of a CC BY-NC-ND 4.0 license, https://creativecommons.org/licenses/by-nc-nd/4.0/.

Optimization of existing clinical and operational processes

Dialysis prescriptions. Conference attendees acknowledged that reducing the frequency or length of dialysis offers environmental benefits. In parallel, and consistent with the principle of value-based health care (Figure 1),[12] they emphasized that any prescription adjustment must not only maintain but also ideally enhance patient outcomes.

Personalizing the timing of dialysis initiation and adopting incremental dialysis were identified as ways to reduce environmental burden without compromising care. Randomized trial data show no survival disadvantage with later dialysis initiation,[16] and most guidelines therefore recommend commencing dialysis only when clinical indications arise rather than at an estimated glomerular filtration rate threshold.[17–19] Incremental PD similarly achieves survival outcomes comparable to standard regimens, with potential benefits including preservation of residual kidney function and improved quality of life.[20–23] The International Society for Peritoneal Dialysis guidelines endorse incremental PD, provided small-solute clearance targets are met and residual kidney function is monitored,[24] and its uptake is increasing. By contrast, despite growing evidence that incremental

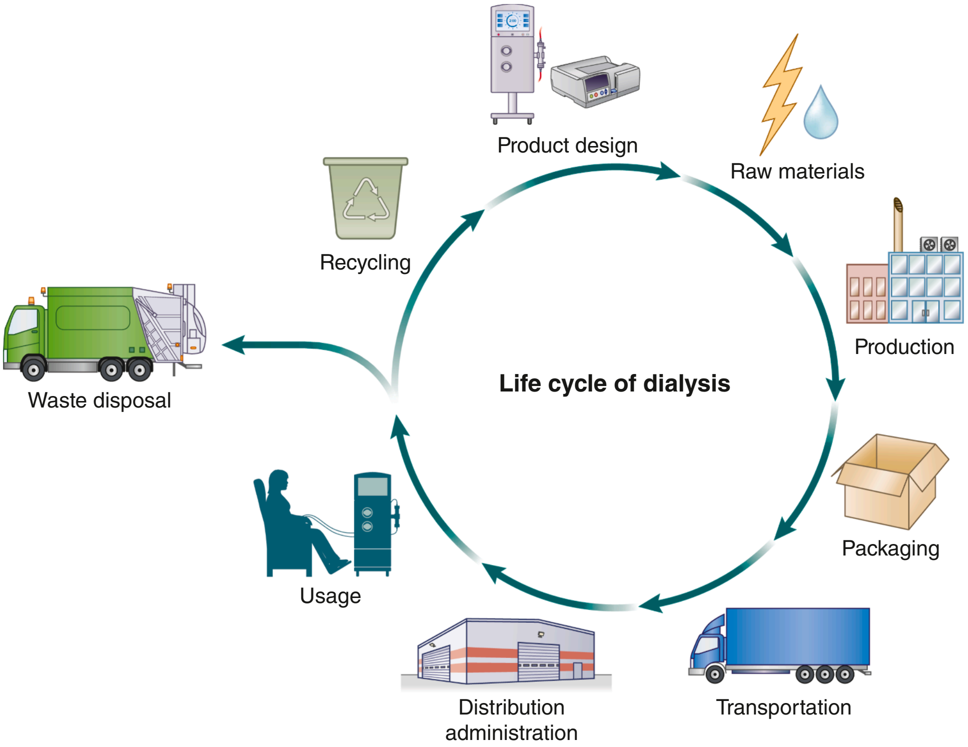


Figure 2 | Life cycle thinking applied to dialysis. The figure illustrates a conceptual framework for considering the environmental, social, and economic consequences of a product, service, or system throughout its entire life cycle, from product design and raw material extraction to disposal or recycling.

hemodialysis achieves outcomes equivalent to standard initiation and may provide benefits similar to incremental PD, its adoption remains limited.[25–27]

To increase appropriate use of personalized dialysis initiation and incremental dialysis, clinician education, decision-support tools, guideline development, and health system enablers, such as optimized reimbursement and adaptable dialysis scheduling, are needed. Conference attendees recognized that decremental dialysis—planned reductions in dose or frequency—may also provide clinical and environmental benefits in settings such as kidney function recovery or palliative care and should be considered when aligned with clinical situations and patient goals. It was emphasized that personalized alterations in dialysis frequency or duration must be distinguished from low-dose regimens driven by resource constraints, as the former represents a deliberate patient-centered choice, not a compromise in care.

Diet. Unprocessed, predominantly plant-based diets—characterized by high intake of fruits, vegetables, legumes, whole grains, seeds, and nuts, with animal-derived foods consumed sparingly or not at all—deliver substantial environmental benefits.[28–32] Cohort studies and small randomized controlled trials also demonstrate that such diets can reduce proteinuria, lessen metabolic acidosis, slow chronic kidney disease progression, delay kidney failure, and lower mortality risk.[33] Consistent with this evidence, the KDIGO 2024 Clinical Practice Guideline for the Evaluation and Management of Chronic Kidney Disease recommends healthy, varied dietary patterns that prioritize plant-based over animal-based foods and minimize ultra-processed products.[33]

Extending these principles to incremental dialysis, evidence suggests that combining a low-protein diet with once- or twice-weekly hemodialysis can maintain nutritional status and well-being as effectively as thrice-weekly dialysis while preserving residual kidney function, reducing hospitalizations, lowering medication use, and possibly improving survival.[34–43] However, the safe implementation of such diets requires multidisciplinary input and careful oversight to ensure cultural appropriateness, acceptability, and nutritional adequacy.

Dialysate flow rate. Dialysate flow rate (Qd) is the primary driver of water and concentrate use during hemodialysis and contributes modestly to energy consumption.[44] Practice varies regionally: although 500 ml/min is common, many centers routinely prescribe higher Qd values of 700–800 ml/min. At a Qd of 500 ml/min, approximately 120 l of dialysate is used over a 4-hour treatment; increasing Qd to 800 ml/min results in an additional 72 l of dialysate per session, with a corresponding increase in source water demand, the magnitude of which depends on reverse osmosis plant efficiency.

However, evidence suggests limited clinical benefit from higher flow rates with modern dialyzers. Short-term studies comparing Qd 700, 500, and 400 ml/min show minimal

Box 1 | Key terms

Term[a]	Definition
Health care sustainability	Capacity of a health system to deliver care over time, with consideration for future generations.
Life cycle thinking	A conceptual (qualitative) framework for considering the environmental, social, and economic consequences of a product, service, or system throughout its entire life cycle, from raw material extraction to disposal or recycling.
Waste hierarchy	A framework that prioritizes different waste management options based on their environmental impact. It typically includes 5 stages (ranked from most to least preferable): prevention, reuse, recycling, recovery, and disposal.
Reverse osmosis water recovery ratio	The proportion of the influent water in the system that is converted into product water or permeate; calculated as follows: [(input flow rate − wastewater flow rate)/input flow rate] × 100.
A_o value	A measure of the effectiveness or lethality of a thermal disinfection process, expressing the combined impact of time and temperature to quantify microbial kill rate.
Passive house standards	Standard for energy efficiency in buildings that leads to reduced heating and cooling needs. The standard has 5 core principles: continuous insulation, minimized thermal bridging, airtight construction, high-performance windows and doors, and a heat recovery ventilation system.
Climate resilience	The ability of a health system or service to anticipate, prepare for, respond to, and recover from climate-related stressors and shocks while maintaining essential functions.
Technology readiness level (TRL)	A scale for assessing the maturity of technologies in research, development, and innovation. It ranges from TRL 1, where basic principles are first observed and reported, to TRL 9, where the system is proven and operational in a real-world environment.
Life cycle assessment	A systematic methodology to quantify the environmental, social, or economic impacts of a product or service throughout its entire life cycle. Environmental life cycle assessments commonly evaluate impact categories such as global warming potential (carbon footprint), acidification, and eutrophication.
Bioplastics	Plastics that are made from renewable resources (bio-based), are biodegradable, are made through biological processes, or a combination of these.
Bio-based	Made wholly or in part from renewable biological resources, such as cornstarch or sugarcane. Bio-based materials may not necessarily be biodegradable.
Biodegradable	Capable of being broken down naturally by the actions of living things, such as microorganisms, and reabsorbed by the natural environment within a defined time frame (e.g., the European Union requires that 90% of the original material can be degraded within 6 months); typically requires specific environmental conditions.
Produced via biological processes	Manufactured using living organisms or their enzymes, such as microbial fermentation, plant or animal cell culture, or enzymatic conversion, rather than through chemical synthesis.
International Organization for Standardization	International body that writes widely used technical standards for conducting life cycle assessments.
Product category rules	Rules and guidelines for calculating and reporting environmental data related to a product's life cycle. These rules ensure consistency and comparability when assessing the environmental impact of products within the same category and can be used to increase the rigor and consistency of life cycle assessments.
Servitization	A shift from product sales to service-based models in which suppliers retain responsibility for maintenance and end-of-life management, encouraging efficiency, durability, and reuse.
Reverse logistics	Planned process of moving products, components, and materials from the point of use back upstream in the supply chain to recover value (reuse, repair, refurbish, remanufacture, or recycle) or ensure compliant disposal.

[a] Listed in order of appearance in the article.

differences in dialysis dose (Kt/V), blood pressure, interdialytic weight gain, or biochemical parameters,[45–49] although some studies of Qd 400 ml/min enrolled only lower-weight patients. Similarly, increasing the dialysate-to-blood flow ratio above 1.5:1 yields no additional benefit in small solute clearance.[45,48] Long-term data are limited, but a 2-year study of patients weighing less than 70 kg reported equivalent adequacy and survival with Qd 400 and 500 ml/min.[50]

Accordingly, attendees suggested Qd 500 ml/min as a pragmatic upper limit for routine care, with lower Qd considered on an individual basis according to factors such as blood flow rate (Qb), body size, and metabolic needs, provided dialysis adequacy and patient outcomes are closely monitored. They also emphasized the need for long-term studies of lower or proportional flow rates to define the optimal lower limit, with assessment across clinical end points and biochemical parameters, including middle molecule clearance.

Hemodiafiltration. Postdilution hemodiafiltration (HDF) is the most widely used HDF modality, except in Asia, where predilution HDF, usually with lower Qb and Qd, is standard.[51] Postdilution HDF typically uses a Qd of 500–800 ml/min and infuses sterile substitution fluid to drive convection, typically targeted at approximately 25 l per session. This increases total water use by 30–75 l per session (depending on reverse osmosis plant efficiency), along with acid, bicarbonate, and energy demand. However, some HDF machines have the option of dynamically adjusting dialysate and substitution flow rates to Qb and real-time blood indices (e.g., hematocrit). In a short-term crossover trial ($N = 54$),[52] HDF targeting a Qd/Qb ratio of 1.2 increased Kt/V by 3.5% while reducing dialysate use by 8% compared with hemodialysis at a fixed Qd of 500 ml/min. A recent simulation study[53] showed that HDF achieved superior urea and β_2-microglobulin clearance than did HD at the same dialysis fluid consumption. When Qd/Qb was optimized to deliver an equivalent Kt/V to hemodialysis—reduced to 1.2 for HDF while keeping a high blood flow, versus 1.4 for HD, both targeting Kt/V 1.65—total fluid consumption fell by 21%. Real-world data from 26,031 treatments support this: patients treated with high-volume postdilution HDF at a Qd/Qb ratio of 1.2 (mean delivered Qd 430 ml/min) achieved an average Kt/V of 1.7.[53]

Although these findings suggest that optimized postdilution HDF may be more resource-efficient than conventional hemodialysis, not all HDF machines allow automated flow coupling. Where unavailable, Qd must be manually set, an approach that has not been formally evaluated. HDF additionally requires a substitution line and, in some cases, a dialysate-sterilizing filter, but avoids the need for rinsing solutions packaged in plastic. The environmental impact of these differing consumables remains unquantified.

Dialysis equipment and operational settings. Reverse osmosis plant performance is the main determinant of water and energy consumption in hemodialysis.[44] Modern systems are markedly more efficient than older models[44] because of features such as demand-driven permeate production, variable-speed pumps, automated switch-on and standby modes, recirculation of unused permeate, adjustable reject water recovery ratios, and heat disinfection that targets a microbicidal A_0 value (see Box 1) rather than heating for a fixed time at a set temperature. There was consensus that procurement decisions should prioritize systems offering maximal water and energy savings, with selection criteria reflecting both environmental benefits and associated cost savings. Differences in water, energy, and consumable use among dialysis machines should likewise inform procurement choices.

Reverse osmosis plant operating hours should be adjusted to ensure that the system runs only when permeate is required, and disinfection schedules for the reverse osmosis membrane, loop, and dialysis machines should align with manufacturer guidance to avoid unnecessary cycles. At the same time, participants noted that the evidence underpinning current disinfection practices is limited and likely overly conservative, potentially leading to avoidable water, energy, and disinfectant use.

In reverse osmosis systems with adjustable water recovery settings, the recovery ratio may be incrementally increased when the conductivity of the blended feed (mains water plus any recirculated reject at the existing recovery ratio) provides sufficient margin. Each adjustment should be accompanied by close monitoring of key indicators, including feed conductivity as a proxy for scaling risk, permeate conductivity to ensure that ionic quality remains within specifications, and fouling metrics such as differential pressure and normalized permeate flow.

Reverse osmosis reject water recycling. Between 20% and 80% of feed water may be rejected by reverse osmosis systems, depending on the specific reverse osmosis unit and quality of feed water.[54,55] Conference attendees agreed that reuse of reverse osmosis reject water should be universally considered. Feasibility assessments should evaluate the volume and chemical composition of reject water, and therefore its suitability for various reuse applications, along with local reuse opportunities, policies, and costs.[55,56] Economic evaluations suggest short payback periods,[55] although these are expected to vary with factors such as center size, ease of installing new infrastructure into existing buildings, proximity to the reuse site, and water costs.

Central delivery of acid concentrate. Acid concentrate for hemodialysis is most commonly supplied in single-use plastic bags or canisters, generating substantial plastic and residual fluid waste and carbon emissions from container manufacture, transport, and disposal. An alternative is centralized delivery via a bulk storage tank and distribution loop, with concentrate supplied as premixed liquid (delivered by a tanker or in transportable containers) or as semidry/dry powder for on-site reconstitution. Compared with point-of-use delivery systems, centralized systems reduce waste, carbon emissions, storage requirements, manual labor, and operational costs.[57–61] Dry powder formats offer the greatest carbon savings and can be integrated with automated mixing units.[62] Conference attendees agreed that all dialysis facilities should consider the possibility of transitioning to centralized delivery, particularly larger units, where payback periods are shorter, and new builds, where infrastructure can be integrated from the outset. As bulk acid for central delivery is not yet available in all regions, engaging industry to address access gaps was considered a priority.

Consumables. Across dialysis modalities, consumables such as hemodialyzers, blood tubing, arteriovenous access needles, PD fluids, effluent drainage bags, infusion lines, gloves, and cleaning and disinfection products, are the main sources of carbon emissions and waste.[63] Although clinical appropriateness must guide use, reducing consumption is a priority and can be achieved through optimized procurement, clinical practices, and education. During procurement, preference should be given to equipment and consumables that minimize materials, including packaging, without compromising effectiveness. Concurrently, dialysis teams should audit consumable use to identify safe opportunities for reduction (Table 1).[5,8–10,44–46,49,52–54,57,58,61,63–75] Although individual changes may yield small benefits, their implementation cost is negligible and their cumulative effect is substantial.

Table 1 | Opportunities to enhance the sustainability of dialysis

Theme	Intervention	Environmental benefit(s)
Prescriptions	Individualized initiation of dialysis	Reduces consumable use, water, waste, and CO_2e: • Prolonging time to HD initiation by 1 mo can conserve up to 6000 l of water.[54]
	Incremental dialysis	Reduces consumable use, water, CO_2e, and waste: • Omitting an icodextrin exchange may lower CO_2e by up to 26% for CAPD and 15% for APD.[5] • Reducing HD frequency has a greater impact on CO_2e than shortening treatment duration owing to reduced consumable use[63] and associated transportation.
	Lower Qd or AutoFlow	Reduces water, concentrate use, and energy: • Treatment with Qd 500 ml/min used 24 l more dialysate per 4-hr treatment than that with Qd 400 ml/min, whereas Qd 700 ml/min used an additional 48 l.[45,64] • AutoFlow (Fresenius Medical Care) implementations report 9%–23% reductions in dialysate, acid concentrate, and bicarbonate use[46,49,65] in the setting of a well-functioning vascular access.
	Use of HDF	May save water and dialysate compared with HD: • Targeting a Qd/Qb ratio of 1.2 may reduce dialysate use by 8% compared with HD at Qd 500 ml/min while increasing Kt/V by 3.5%.[52] • Optimizing Qd/Qb to deliver an equivalent Kt/V to HD may reduce total fluid consumption by 21%.[53] HDF also requires a substitution line and an additional dialysate-sterilizing filter, but avoids the need for plastic-packaged rinsing solutions; environmental impact unknown.
Procurement	Prioritization of RO systems that use the lowest amounts of water and energy	Reduces water, energy, and CO_2e: • Installation of a new water treatment system reduced water use by 50%.[8] • Per-treatment RO water and power consumption were 357 l and 3.1 kWh, respectively, with a modern RO system compared with 548 l and 7.2 kWh with an older RO system.[44]
	Prioritization of HD machines with online fluid production to replace saline bags	Reduces fluid and packaging waste and CO_2e: • Use of online fluid for priming, blood return, and fluid boluses in a 15-chair unit, combined with correct bicarbonate bag disposal, saved 21.5 tons of waste and approximately 26.8 tonnes CO_2e/yr.[64]
	Prioritization of HD machines that use longer-life endotoxin filters and that require lower volumes of citric acid per disinfection and/or accept bulk citric acid (vs. single-use cartridges)	Reduces filter use, packaging waste, citric acid, and/or CO_2e.
	Selection of acid and bicarbonate concentrate package sizes that match the amount required for patient treatments	Reduces product and packaging waste and CO_2e: • A switch from 4.5- to 3.5-l acid concentrate bags, which was suitable for 92% of patient treatments, avoided waste of 14,350 l of acid concentrate annually.[66]
	Prioritization of PD suppliers that provide lean packaging, recyclable fluid bags and packaging, and/or take-back recycling	Reduces waste and CO_2e: • PVC recycling may reduce CO_2e by up to 14% for APD and 30% for CAPD.[5]
	Prioritization of PD suppliers whose fluid bags have a lower environmental footprint during both production and disposal	Reduces environmental impact: • Some PD fluid bags are made from polyolefins, which are PVC- and phthalate-free.[67,68] Limited recycling options; net environmental benefit unclear.
	Prioritization of PD suppliers whose fluid bag sizes match typical local prescribed volumes	Reduces waste and CO_2e: • Matching icodextrin bag size to prescription may reduce PVC waste by 35%.[69]
Operations	Optimized RO settings	Reduces water, energy, and CO_2e.
	Optimized segregation (i.e., hazardous vs. landfill) and recycling of waste	Reduces waste and CO_2e related to disposal and new material manufacture: • Emptying residual fluids from receptacles and directing all HD waste to the right stream reduced hazardous waste by up to 7 kg per HD treatment.[70]

Table 1 | (Continued)

Theme	Intervention	Environmental benefit(s)
	Avoidance of redundant disinfection of HD machines	Reduces water, energy, CO$_2$e, citric acid, and related packaging waste: • For ICHD, rescheduling automated citric acid heat disinfection to the morning dialysis shift ensured only machines unused in the previous 24 hours underwent scheduled disinfection, preventing duplicate cycles for machines already disinfected after treatment while maintaining required disinfection intervals. This reduced disinfections by 25%, saving approximately 160,000 l of water, 6.4 MWh of energy, and 720 l of citric acid annually.[71] • For home HD, switching to pretreatment disinfection only after $\geq$1 day of nonuse while retaining posttreatment disinfection reduced annual cycles by 33%, saving approximately 2100 l of water, 70 kWh of energy, and 20 l of citric acid.[71]
Consumables	Use of a microcritical aseptic field and nontouch technique with nonsterile gloves for AV and catheter access[a]	Reduces waste and CO$_2$e: • In a dialysis service center caring for approximately 40 patients dependent on catheters, switching from large aseptic fields and sterile gloves to microcritical aseptic fields and standard gloves prevented 96,000 single-use plastic items going to landfill annually.[72]
	Disposal of APD peritoneal effluent directly to a nearby plumbing fixture (e.g., bathtub/sink/shower) or via a fixed drainage system[b]	Reduces waste and CO$_2$e: • Use of a U-Drain system saved 0.8 kg of nonrecyclable clinical waste per patient per treatment day[73] and 791 kg of CO$_2$e per patient annually.[73]
	Avoidance of glove use for PD connections/disconnections[c]	Reduces waste and CO$_2$e.
	Use of a reusable effluent reservoir in PD instead of a single-use drainage bag	Reduces waste and CO$_2$e: • Saved 148.6 kg of plastic waste and 151 kg of CO$_2$e emissions per patient annually.[5]
	Cotton-gauze use limited to the minimum clinically required[d]	Reduces waste and CO$_2$e: • Cotton gauze identified as a major contributor to variation in the carbon footprint of PD between centers in the European Union.
	Prioritization of long-acting ESAs	Reduces syringe and packaging waste and CO$_2$e.
	Use of multidose anticoagulant vials rather than single-dose syringes (regulations permitting)	Reduces syringe and packaging waste and CO$_2$e.
Infrastructure	RO reject water recycling	Reduces water: • One UK service described saving approximately 4,492,000 l annually.[10] • RO reject water successfully used for hydroponics and aquaponics, producing approximately 150–350 kg of fish every 6 months and approximately 4–8 kg of vegetables per month.[9]
	Central delivery of acid concentrate	Reduces acid concentrate, waste, and CO$_2$e: • In a 30-station unit, bulk acid supply by a tanker and central delivery could reduce concentrate use by 33%, plastic waste by 6773 kg/yr, and CO$_2$e by approximately 1 ton/station/yr.[57] • Compared with transport-related CO$_2$e from individual concentrate delivery, transport-related CO$_2$e from semidry concentrate delivery was 63% lower and dry powder 75% lower.[58] • Storage tanks and central acid delivery produced 62% and 38% less CO$_2$e than did 3.9-l canisters and 4.2-l bags, respectively ($P < 0.001$).[61]
	On-site waste treatment to convert hazardous waste into general waste	Reduces carbon and toxic pollutant emissions: • Modeling suggests that on-site autoclaving may reduce CO$_2$e from hazardous HD waste disposal by approximately 85% compared with incineration (K. A. Barraclough, written communication, February 2026).

APD, automated peritoneal dialysis; AV, arteriovenous; CAPD, continuous ambulatory peritoneal dialysis; CO$_2$e, carbon dioxide equivalent emissions; ESA, erythropoiesis-stimulating agent; HD, hemodialysis; HDF, hemodiafiltration; ICHD, in-center hemodialysis; Kt/V, dialysis dose; PD, peritoneal dialysis; PVC, polyvinyl chloride; Qb, blood flow rate; Qd, dialysate flow rate; RO, reverse osmosis.

[a] International guidelines recommend a clean aseptic technique rather than maximal sterile precautions.[74]

[b] When disposing of effluent directly to a plumbing fixture, careful fixation is essential to prevent contact of the drain tip.

[c] Aseptic technique and hand hygiene are the essential components for minimizing infection risk[75]; gloves may provide a false sense of security.

[d] Usually 1 pad for the exit-site dressing and 1 as a sterile surface rest.

Dialyzer reuse. Dialyzer reuse reduces solid hazardous waste. However, this environmental benefit must be weighed against the resource demands of reprocessing, including water, energy, and chemical disinfectants, which carry their own environmental and occupational risks.[76] Evidence on safety is mostly derived from older studies, and results are mixed: a 2012 systematic review found no mortality difference, but the studies were mostly retrospective, used outdated membranes, and were methodologically heterogeneous, limiting relevance to current practice.[77] Some data suggest increased infection and hospitalization rates and reduced dialyzer performance with repeated use.[76]

Conference attendees from low- and middle-income countries underlined the value of dialyzer reuse for cost containment and expanding access to treatment. In contrast, high-income country attendees questioned its reintroduction, given uncertain environmental gains, potential risks, and the operational complexity and cost of reprocessing. Nonetheless, there was broad agreement that new automated systems using environmentally safe cleaning technologies hold promise and may renew interest in reuse (e.g., ClearFlux[78]). Overall, attendees agreed that dialyzer reuse may be a pragmatic strategy for improving treatment access in resource-limited settings, but its wider adoption warrants further investigation. Notably, reuse is currently prohibited in several jurisdictions, including Japan, Australia,[79] and many European Union member states,[80] meaning that reintroduction would require regulatory reform.

Waste management. Recycling nonhazardous waste reduces environmental impacts relative to landfilling, whereas the disposal of hazardous waste incurs markedly higher environmental and economic costs than both recycling and landfilling.[5,81] Misclassification of waste therefore has significant consequences.[70] Effective waste segregation at the point of use, rather than defaulting to hazardous waste disposal, represents an immediately available, no-cost intervention.[70] Similarly, compactors or shredders can reduce waste volume requiring transport and facilitate recycling of plastics and cardboard, contributing to carbon and cost savings.[82,83]

There was consensus that on-site hazardous waste sterilization systems, using technologies such as steam autoclaving, microwaves, or chemical disinfection, have potential to reduce the environmental burden of dialysis waste. By enabling reclassification of treated material as general waste, on-site waste sterilization eliminates the need for high-emission off-site incineration, reduces disposal costs, and creates potential for recycling. However, hazardous waste management is currently tightly regulated in many countries. This may restrict or preclude the realization of these benefits.

Patient conference participants underscored the personal burden of waste management in the home, highlighting not only the logistical issues associated with large amounts of waste but also the stigma. Well-designed recycling programs, such as those for polyvinyl chloride (PVC) PD bags in Mexico,[84] Australia,[85] Colombia, and Guatemala, can reduce this burden. These programs may be particularly effective when manufacturers assume responsibility for the end-of-life management of products. In Australia, for example, an industry-supported recycling service collects PVC fluid bags, high-density polyethylene outer packaging, and cardboard cartons from patients undergoing PD in metropolitan areas.[85]

Obsolete dialysis machines represent another form of dialysis-related waste. With approximately 1 million hemodialysis machines in use worldwide and an average lifespan of 10 years, an estimated 100,000 machines are discarded annually. Waste from electric and electronic equipment is particularly toxic,[86] and reuse is largely limited to metal components. Reducing the environmental impact of hemodialysis machines and other large medical devices will require redesign to incorporate more reusable and recyclable materials and to extend device longevity, alongside evidence-based updates to obsolescence policies.[87]

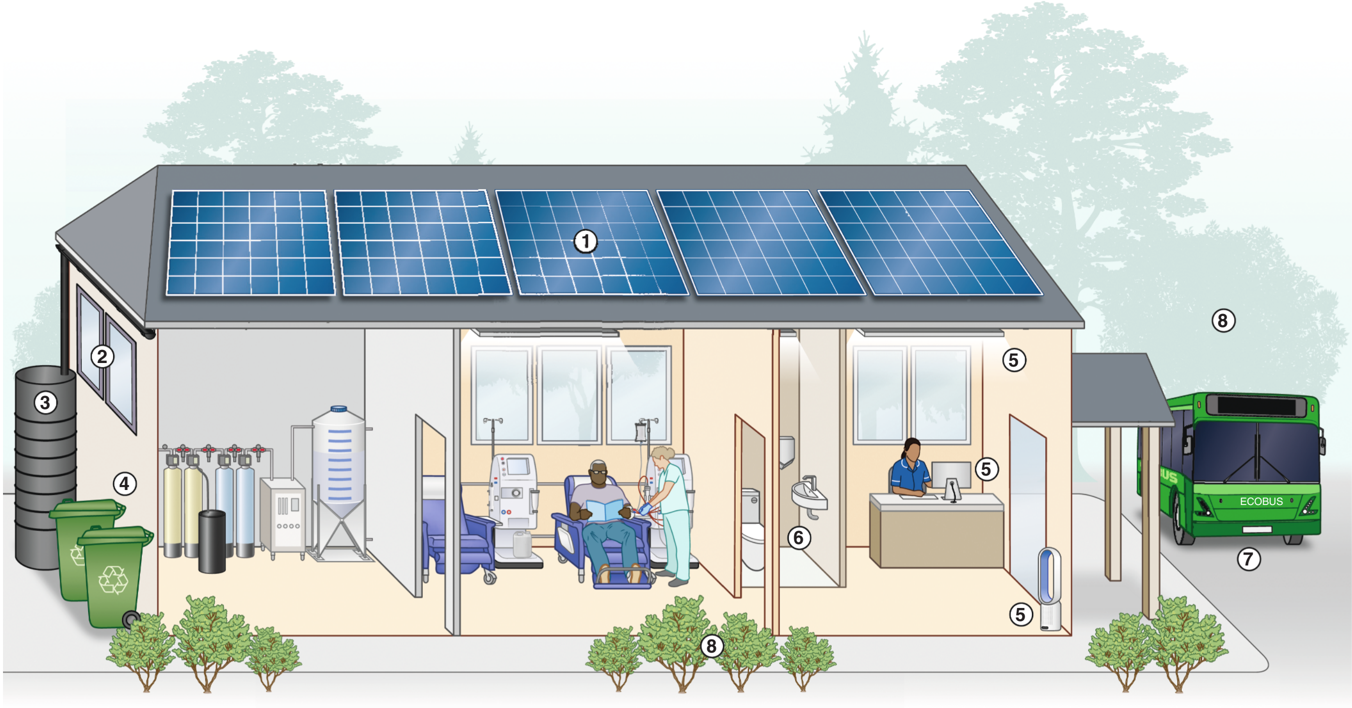
Building design. Building design is central to environmental performance and climate resilience. Structures constructed to Passive House standards can reduce heating and cooling demand—and thus overall energy use and operational carbon emissions—by up to 80% compared with buildings meeting conventional codes.[88–90] In dialysis settings, good design also enables integration of dialysis-specific sustainability features, such as centralized acid delivery and reverse osmosis reject water reuse. Success depends on early collaboration among architects, engineers, sustainability consultants, builders, and clinical teams.

Retrofitting existing units can also deliver substantial environmental benefits and is often preferable to demolishing or abandoning functional infrastructure; however, it is typically more costly than embedding sustainability features upfront.[91] Figure 3 outlines elements of an environmentally sustainable dialysis unit.

Optimizing and developing green dialysis innovations

To conceptualize the maturity of technologies related to green dialysis, Figure 4[92] outlines technology readiness levels[93] and the approximate levels of select green dialysis innovations.

Reducing redundancy in consumables. Shortening hemodialysis bloodlines would reduce plastic waste, lower carbon and toxic emissions from plastic manufacturing and disposal, decrease priming saline use, reduce heparin requirements,[94] and lessen heat loss. However, bloodlines must retain a minimum length (approximately 1.7 m) to prevent embolization after air detection and electroclamp activation, accommodate various vascular access sites, and maintain needle stability. Clinical trials are needed to evaluate the feasibility and safety of shorter designs. Future developments may include optimizing flow dynamics via computational modeling and incorporating hemocompatible coatings to reduce thrombogenicity and inflammation, improve



Building exterior

- ① Solar panels (onsite renewable energy)
- ② Windows with glazing optimized to climate
- ③ Rainwater capture and reuse
- ④ Insulation and ecofriendly building materials

Dialysis-specific (not shown)

- Central acid delivery
- Water and power usage monitoring
- Reverse osmosis reject water recycling
- Heat exchangers and heat recovery
- On-site waste processing machine

Building interior

- ⑤ Energy-efficient lighting, heating, cooling, and appliances
- ⑥ Water-saving taps and toilets

Surroundings

- ⑦ Environmentally friendly transportation
- ⑧ Green space to create positive patient experience and for cooling

Figure 3 | Features of good building design for hemodialysis clinics. The figure shows aspects of green building design that should be considered when designing and building a hemodialysis clinic.

hemodynamics, and limit phthalate leaching from PVC into the bloodstream.[95]

Conference attendees identified redesign priorities for PD consumables, including automated PD cassettes and tubing kits, owing to material redundancy and their contributions to the higher carbon footprint of automated PD relative to continuous ambulatory PD.[5] Suggestions for reducing plastics included shortening cassette lines, offering cassette variants with fewer lines, and aligning bag sizes with common clinical prescriptions. Although drain line reuse in automated PD is discouraged owing to concerns about peritonitis,[96–98] attendees proposed design modifications—such as incorporating 1-way valves to prevent backflow and reprocessing drain lines—to mitigate risk. These suggestions warrant formal evaluation. In continuous ambulatory PD, attendees proposed evaluating whether the emptied inflow solution bag could be repurposed as a drainage bag for the subsequent exchange by retaining the Y connector and connecting a new modular inflow bag.

Waste management innovations. Conference attendees highlighted the need to reduce waste from packaging and equipment. Identified opportunities included adopting reusable packaging systems (e.g., washable totes), redesigning cardboard packaging for easier folding and recyclability, and reconceptualizing PD bag sets by limiting individual tube wrapping and/or by integrating the outer plastic wrap as an inner lining of the solution box or tote to enclose multiple sets in a single polyethylene barrier. Attendees also recommended considering how PD components that do not contact body fluids and therefore pose minimal risk of infectious contamination (e.g., packaging, infill bags, and associated tubing) could be safely reprocessed and reused.

Where reuse is not feasible, recycling components not in touch with body fluids should be the default. Furthermore, the panel suggested that with appropriate baseline infection screening and standardized disinfection procedures, there may be potential for the safe recycling of components of PD drainage systems—particularly PVC tubing and bags—pending further investigation. To enhance recyclability, PD and hemodialysis consumables could be redesigned as modular components to allow easy separation and minimize material mixing, and labeling should use degradable adhesives and recycling-compatible inks.

Forward osmosis. Although newer reverse osmosis units and optimized operational settings reduce water use in

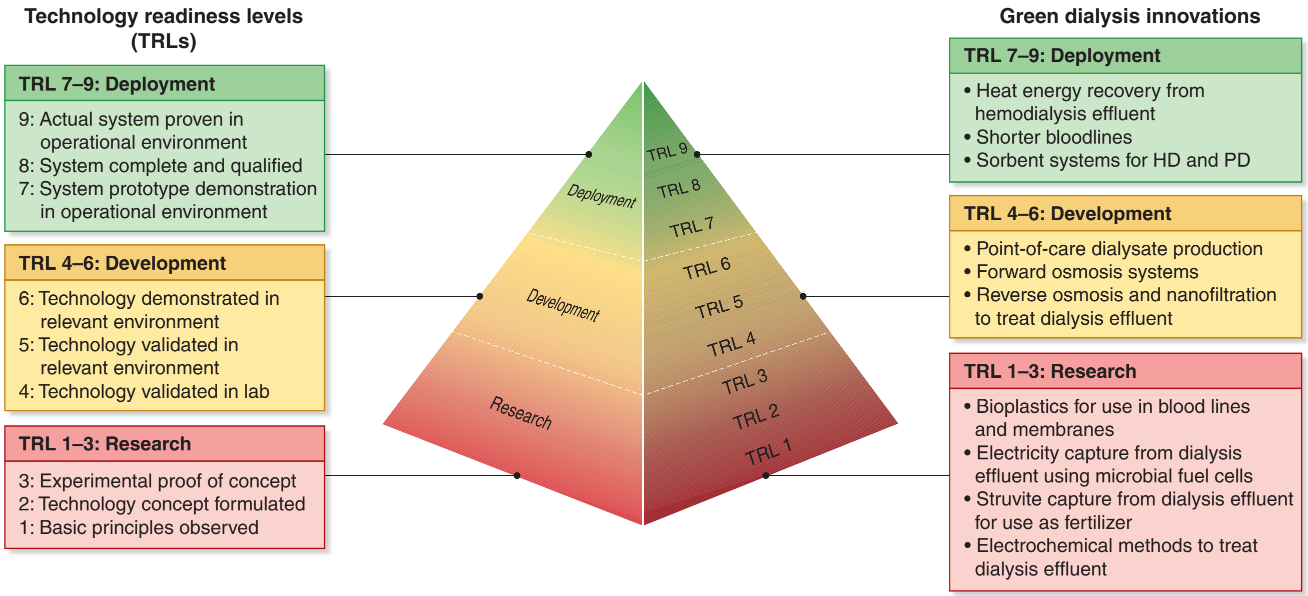


Figure 4 | Technology readiness level (TRL) of select green dialysis innovations. The TRL scale is used to assess the maturity of technologies in research, development, and innovation. This figure is a graphical summary; a more detailed description can be found in Table 1 of Wieringa *et al.*, 2024.[92] HD, hemodialysis; PD, peritoneal dialysis.

hemodialysis, achieving more substantial savings will require alternative water purification technologies. Forward osmosis uses an osmotic gradient to draw water across a semipermeable membrane, leaving behind salts, microbes, and endotoxins.[99] Unlike high-pressure reverse osmosis, forward osmosis operates at low pressure and energy, reducing electricity consumption and reject water production. It is also less prone to membrane fouling, potentially lowering maintenance requirements and extending membrane lifespan.[99,100]

Potential forward osmosis applications in hemodialysis include (i) recovering water from spent dialysate to partially dilute bicarbonate concentrate before blending with a smaller volume of reverse osmosis permeate to produce fresh dialysate[101,102] and (ii) drawing water directly from municipal supply for dialysate preparation. Although work is needed to optimize urea rejection, confirm microbiological safety, and ensure compatibility with routine disinfection, current evidence supports forward osmosis as a practical adjunct to reverse osmosis today (application i) and a promising candidate for future replacement (application ii). As forward osmosis has not yet been deployed in clinical hemodialysis, the cost implications remain uncertain. Forward osmosis membranes are likely to be more expensive than conventional reverse osmosis membranes because of lower manufacturing scale and greater membrane complexity. However, these higher upfront costs may be at least partially offset by reduced energy requirements and water consumption, and potentially by simpler pumping requirements and longer membrane lifespans, although these advantages remain to be demonstrated in clinical practice.

Advances in biomimetic membranes, such as the incorporation of aquaporin proteins into synthetic and ceramic substrates, which enables high water flux, low salt leakage, and robust performance after drying and rehydration,[103] may further support forward osmosis uptake.

Reusing dialysis effluent. Spent hemodialysis effluent is a saline, highly conductive fluid, rich in uremic solutes and containing diverse micropollutants, including pharmaceuticals, per- and polyfluoroalkyl substances, and antibiotic resistance genes.[104–107] Typically discharged as wastewater, it represents a source of potentially recoverable resources. Membrane treatment technologies, such as reverse osmosis and nanofiltration, can yield high-quality water by removing salts and a broad range of contaminants; however, they are energy-intensive, and the microbiological safety of the final product must still be verified. Electrochemical methods offer a lower-energy alternative for removing organic matter and pollutants including pharmaceuticals,[108–110] but these are less effective for desalination and nitrogen removal and produce only irrigation-grade water. They may also serve as a pretreatment step to reduce membrane fouling and enhance system efficiency.[108,111] Beyond water, high concentrations of phosphorus and ammonium nitrogen in spent dialysate can be recovered as struvite, a valuable slow-release fertilizer.[112] A cost model for a 20-station dialysis unit estimated struvite production at approximately 2.4 kg/d, enough to fertilize approximately 5 ha annually, while avoiding synthetic fertilizer use.[112]

Thermal energy is another resource. Globally, the discharge of dialysate at body temperature from dialysis units into sewerage systems wastes an estimated 1700 GWh/yr of recoverable heat.[112,113] In Europe, this energy potential is equivalent to the annual heating demand of roughly 140,000 households, based on an average consumption of 12,000 kWh per household. Some of this energy can be reclaimed using heat exchangers and repurposed for applications such as on-site space or water heating.[55,112,113] The electrical conductivity of spent dialysate has also been explored in microbial fuel cells, which use bacteria to break down organic matter and generate small amounts of electricity.[114] However, innovation will be needed to achieve significant energy gains.

Sorbent systems. Sorbent dialysis regenerates and recirculates spent effluent in a closed-loop system, reducing water use by 95%–99% in hemodialysis and approximately 75%–85% in PD prototypes.[115,116] In hemodialysis, sorbent systems also lower power consumption and eliminate the need for water treatment infrastructure, whereas in PD, they reduce reliance on emissions-intensive fluid and consumable transport and likely markedly reduce solid waste generation.[115] Dialysis sorbent technologies have attracted attention because of their potential to enable portable and wearable treatments, with systems under development for both hemodialysis and PD.[117–121] However, key challenges remain, including limited urea-binding capacity, suboptimal selectivity for protein-bound and middle-molecule toxins, sorbent regeneration capability, concerns around material stability and biocompatibility, and the need for effective gas and pressure management in compact cartridge designs.[122–128] Environmentally, the impacts of raw material extraction, large-scale sorbent production, and spent cartridge disposal remain poorly understood. Accordingly, although participants agreed that sorbent technologies offer environmental promise, rigorous life cycle assessments during research and development are essential to avoid unintentional introduction of new environmental burdens.

Point-of-care PD fluid production. As transport and storage of prepackaged fluids contributes substantially to the carbon footprint and logistical burden of PD,[5] point-of-care dialysate production offers an attractive alternative. Early prototypes have demonstrated acceptable chemical and microbiological performance in short-term studies.[129,130] Conference attendees agreed on the potential of such technologies to reduce environmental, economic, and practical impacts but highlighted the need for longer-term validation of dialysate quality, including testing across settings with variable source water quality. Priorities for development include design improvements to reduce equipment size and medicalization of the home, patient usability and acceptability assessments, life cycle environmental comparisons with current systems, and policies to protect patients from higher utility costs.

Bioplastics. Plastic production is almost entirely dependent on fossil feedstocks, primarily petroleum products and natural gas.[131] In dialysis, PVC is widely used in tubing and fluid bags, but it raises environmental and health concerns due to the use of plasticizers such as di(2-ethylhexyl) phthalate and release of toxic emissions during incineration.[4] Some PD products now use polyolefins, which are PVC- and phthalate-free and certified by Nordic Swan Ecolabel.[67,68] However, most polyolefins are still fossil-derived, and recycling pathways remain limited.

Bioplastics—plastics that are bio-based, biodegradable, or produced through biological processes—have been proposed as a more sustainable alternative.[132] Emerging applications, such as bioplastic hemodialysis bloodlines and membranes,[133,134] show promise; however, bioplastics may not be inherently environmentally preferable to fossil-based alternatives. Although the use of renewable feedstocks can lower carbon emissions, large-scale substitution would increase land and water use, with implications for biodiversity and competition with food production.[131,132] Bio-based polymers derived from nonedible crops such as castor seed oil[135]—which can be cultivated on marginal or degraded land—may reduce land-use pressures; however, any environmental advantages are likely to be context-dependent and require full life cycle evaluation. Recycling infrastructure for all plastics, including bioplastics, remains underdeveloped, and biodegradability typically requires controlled industrial composting.[131] Regulatory changes would be necessary to allow hazardous bioplastics to be treated via composting or similar pathways. Additional challenges include heat sensitivity during sterilization,[136] mechanical brittleness,[137] and high production costs.[138]

Given these factors, attendees agreed that although bioplastics may hold potential, caution is warranted. Life cycle assessments are needed to clarify environmental trade-offs, alongside regulatory reform and investment in waste management infrastructure. In the interim, creating replacement materials with equivalent performance specifications and lower environmental impact may be most rapidly achieved by incorporating certified recycled polymer resins into medical-grade manufacturing, thereby reducing reliance on virgin fossil-based feedstocks. Recycling pathways for current plastics should also be optimized.

Transport considerations. Conference attendees suggested that remote patient monitoring[139] may reduce emissions by limiting the need for in-person visits and enabling earlier interventions to prevent hospitalizations. However, further research is needed to clarify its clinical value and to quantify the energy demands of data analytics and cloud storage to determine its net environmental impact.

Given regional variability in infrastructure and logistics, there was consensus that context-specific life cycle assessments are needed to optimize product transport and distribution. These must balance resilience, feasibility, patient acceptance, cost, and environmental impact. For example, larger but less frequent shipments to local hubs using low-emission freight may reduce transport emissions and boost resilience but increase storage-related energy use and costs. Less frequent home deliveries may also lower emissions but may be impractical owing to limited household storage.

Concerns were raised about increasing centralization of dialysis fluid and consumable production, with agreement on

Table 2 | Potential unit- and system-level metrics for monitoring the environmental impact of dialysis

Level	Metric	Measurement/method
Unit (dialysis center/home)		
	Water use per treatment (l per treatment)	Metered incoming (feed) water/number of treatments
	RO plant efficiency (recovery rate)	[(Input flow rate − wastewater flow rate)/input flow rate] × 100; also report reject volume per treatment
	Electricity use per treatment (kWh per treatment)	Submeter dialysis equipment (RO plant and HD machines); allocate by treatment count
	Waste per treatment (kg by type)	Weigh segregated streams (plastic, sharps, and dialysate)
	Recycling rate (%)	(Weight of recyclables collected/total recyclable material generated) × 100
	Sustainable consumables (%)	(Sustainable items/total items) × 100; criteria: reusable, recyclable, items with recognized ecolabels, etc
	Carbon emissions per treatment (kg of CO_2e)[a]	Sum emissions from consumables, energy, waste, and transport using standard factors divided by number of treatments
System (health service/region)		
	Annual water use per patient-year	Aggregate meters divided by total number of patient-years
	Annual electricity use per patient-year	Aggregate submeters; normalize by patient-years
	Total dialysis waste by type (ton/yr)	Sum of unit data
	Recycling rate (%)	Aggregate of unit data
	Modality mix (% by modality)	Registry/audit
	Tonnes CO_2e/per patient-year	Sum of unit data
	Cost savings from sustainability (local currency per year)	Baseline cost − current cost (energy, water, waste, and transport)

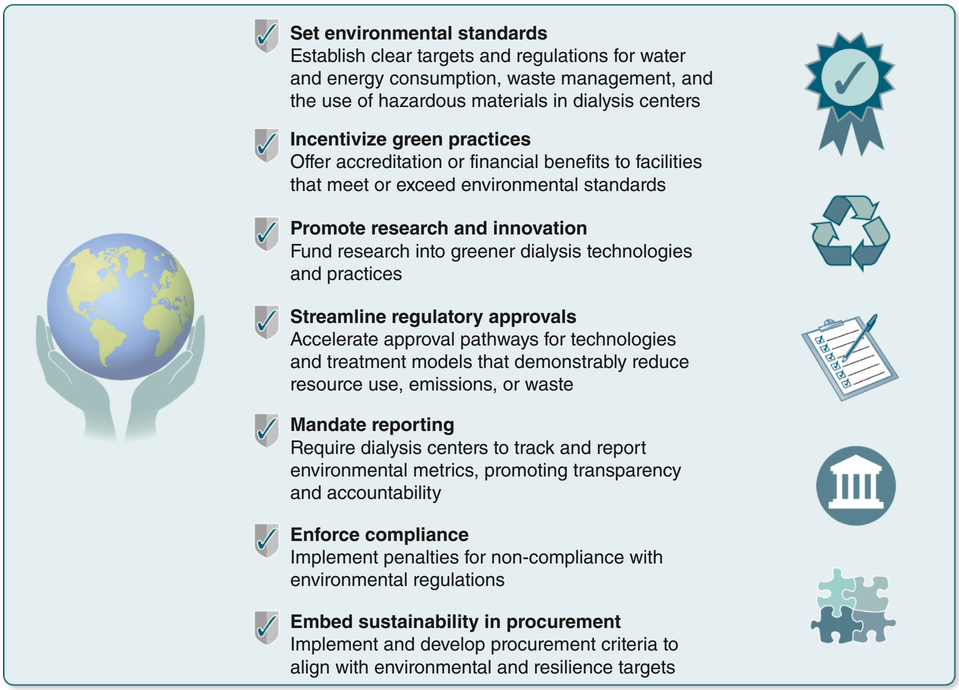
CO_2e, carbon dioxide equivalent emissions; HD, hemodialysis; RO, reverse osmosis.

[a] Input from a life cycle assessment expert is recommended for carbon footprint analyses until validated, simplified carbon calculator tools or transparent industry-level reporting enable reliable independent assessment.

the importance of regional or local manufacturing for enhancing resilience. However, this may come at higher cost, or reduced environmental efficiency in some contexts, because of lost economies of scale. In rural or remote areas, regional cross-supply agreements could bolster resilience in the face of extreme weather or other supply chain disruptions. Public-private partnerships, such as Project Last Mile (www.projectlastmile.com), may offer more efficient and flexible delivery models by leveraging existing logistics networks.

Health system, policy, and regulatory perspectives

Choice of dialysis modality. There is some evidence suggesting that home-based therapies (PD and home hemodialysis) have lower carbon footprints than does in-center



Set environmental standards
Establish clear targets and regulations for water and energy consumption, waste management, and the use of hazardous materials in dialysis centers

Incentivize green practices
Offer accreditation or financial benefits to facilities that meet or exceed environmental standards

Promote research and innovation
Fund research into greener dialysis technologies and practices

Streamline regulatory approvals
Accelerate approval pathways for technologies and treatment models that demonstrably reduce resource use, emissions, or waste

Mandate reporting
Require dialysis centers to track and report environmental metrics, promoting transparency and accountability

Enforce compliance
Implement penalties for non-compliance with environmental regulations

Embed sustainability in procurement
Implement and develop procurement criteria to align with environmental and resilience targets

Figure 5 | Policy and regulatory approaches for promoting environmentally sustainable dialysis.

Table 3 | Barriers and potential solutions to adopting green nephrology practices

Category	Barriers	Potential solutions/enablers
Evidence, awareness, and culture	• Lack of robust evidence for some green practices	• Prioritize research funding to generate environmental and clinical data
	• Absence of supportive clinical guidelines in some cases (e.g., for incremental HD)	• Develop evidence-based guidelines where appropriate
	• Limited familiarity with or support for sustainable treatments and technologies	• Embed sustainability in curricula, orientation programs, and continuing medical education
	• Variable staff engagement in sustainability practices • Not knowing “where to start” • Perception that environmentally sustainable care will be more costly or diminish quality of care for patients	• Identify and support local “green champions” to model and mentor • Develop, share, and maintain a repository of case studies, including documented cost savings and benefits to patients and staff
Operations and service models	• Logistical challenges of individualized prescriptions (e.g., variable HD frequency)	• Enable flexible scheduling models (e.g., hybrid once a week + twice a week)
	• Reimbursement models incentivize higher treatment volumes • Diverse procurement strategies (hospital vs. regional vs. national level) with variable awareness of potential for environmental improvement	• Align reimbursement models with value-based health care principles
	• Manufacturer-imposed defaults can limit ability to adjust equipment settings for improved sustainability	• Collaborate with industry to optimize settings without compromising safety
Measurement and data	• Most facilities lack submetering for water and energy	• Mandate submetering in new builds and incentivize retrofits
	• No agreed-upon environmental key performance indicators	• Develop standard metrics for dialysis resource use and emissions
	• Inconsistent and complex LCA methods limit comparability across studies and hinder practical implementation	• Develop and disseminate LCA guidelines and carbon calculators tailored to dialysis
Infrastructure, equipment, and product design	• Environmental data on machines and products are not readily available	• Require disclosure of energy/water/resource data per treatment
	• High capital cost of new technologies	• Ensure cost-benefit analyses account for operational cost savings from reduced resource use and environmental value; explore subsidies or incentives • Use green procurement frameworks and servitization contracts
	• Older facilities are often difficult or costly to retrofit for sustainability upgrades	• Incentivize retrofits and include sustainability specifications in new facility planning
	• Packaging and product design hinder recyclability	• Promote eco-design (modular, recyclable, and minimal adhesives/labels) via procurement standards and coordinated international advocacy to industry
Supply-chain and industry engagement	• Proprietary data restrict LCAs and product comparisons	• Require public disclosure of cradle-to-grave impacts
	• Limited availability of recyclable consumables and bulk concentrates and commercial disincentives to redesign or reduce material use	• Use green procurement frameworks and servitization contracts
	• Limited reverse logistics for collection/recycling	• Implement take-back systems
Regulatory and policy	• No requirement to report or reduce environmental impact	• Mandate environmental disclosures for providers and suppliers
	• Waste classifications are often outdated, inconsistently applied across countries, and not based on current evidence	• Update waste codes on the basis of evidence of actual risk
	• Health technology assessments for new products can be challenging and regulatory approvals slow	• Collaborate with industry and regulators to establish confidence in marketability of products and in swift but safe approval pathways
	• Regulations restrict dialyzer reuse and on-site waste treatment in some places	• Align regulatory requirements with scientific evidence and sustainability objectives

HD, hemodialysis; LCA, life cycle assessment.

Table 4 | Key questions, knowledge gaps, and research recommendations

Realm	Questions and knowledge gaps	Strategies for research
Prescriptions	• What is the minimum Qd that can be applied in HD and HDF while maintaining long-term outcomes? • What is the environmental impact of the differing consumables used in HDF compared with HD?	• Conduct prospective dose-ranging studies with long-term follow-up. • Compare the full environmental impacts of HD and HDF using life cycle assessment.
Operations	• What are the optimal disinfection frequencies and intensities for reverse osmosis membranes, loops, and dialysis machines to ensure safety while minimizing resource use? • How do new dialyzer reprocessing technologies compare with single-use models?	• Collaborate with manufacturers to trial reduced disinfection frequencies, supported by strict microbial monitoring. • Conduct comparative life cycle assessments across environmental, clinical, and regionally stratified economic domains.
Innovations	• What are the environmental impacts of emerging dialysis innovations, and how do they compare with those of existing treatments and technologies? • Can shorter bloodline configurations be implemented safely and feasibly? • What design modifications to APD cassettes and tubing kits would most effectively reduce plastic use? • What safeguards would enable safe reuse of PD drain lines? • Can emptied CAPD fluid bags be repurposed as drainage bags for subsequent exchanges, and what safety issues must be addressed? • How does PD solution packaging affect dialysate integrity under suboptimal conditions, such as elevated temperatures during transport or prolonged storage? • What refinements to forward osmosis systems are needed to optimize urea rejection, validate microbiological safety, and ensure that they are compatible with routine disinfection protocols? • Can microbiological safety be ensured across different dialysis effluent treatment strategies, and are these strategies economically viable and suitable for large-scale implementation? • Can point-of-care PD dialysate production reliably meet quality standards across variable water sources while remaining acceptable and practical for patients? • Can appropriate use of remote monitoring reduce environmental impact while matching or improving upon the clinical outcomes and patient experience compared with in-person care? • What are the safety and efficacy profiles of bioplastics? • Do bioplastics pose any risks to humans and the environment, and, if so, how can these risks be mitigated? • What are the risks (to patients and to the environment) of the release of microplastics from dialysis components, and how can these be mitigated?	• For all listed innovations, conduct full life cycle assessments in parallel with feasibility, safety, cost, and user-centered design evaluations. • Clinician-investigators and patients partner with industry in the development of green dialysis innovations. • Regulators expeditiously approach approval processes for environmentally progressive products without compromising safety.
Health system/ policy/ regulation	• What delivery and recycling pathways for dialysis consumables are optimal, and how do these differ across regions and health care settings? • Are home therapies environmentally preferable to facility-based care across different settings? • What waste management approaches are optimal for home dialysis therapies to minimize patient burden? • How can dialysis access in LMICs be expanded without worsening environmental injustice?	• Consult waste management experts and/or environmental engineers. • Conduct local/regional life cycle assessments and stakeholder-engaged scenario modeling.

APD, automated peritoneal dialysis; CAPD, continuous ambulatory peritoneal dialysis; HD, hemodialysis; HDF, hemodiafiltration; LMICs, low- and middle-income countries; PD, peritoneal dialysis; Qd, dialysate flow rate.

hemodialysis because of reduced patient travel and treatment-related energy use,[63,140] though they shift the burden of waste management, and, for many, water and energy costs, to patients. Although modality choice should be driven by patient preferences and clinical suitability, conference attendees agreed that environmental considerations should be incorporated into shared decision making. At the system level, there was consensus that environmental impact should be viewed as a key factor in dialysis planning and service delivery, with broad support for policies that expand access to home dialysis and foster incremental and personalized dialysis treatments.

Metrics. There was consensus that the systematic collection and application of environmental metrics is essential for identifying opportunities, tracking progress, and evaluating policy impact. However, widely accepted, standardized metrics are lacking. Table 2 displays potential unit- and system-level indicators.

Participants also noted that inconsistencies in life cycle assessment methodology hinder robust metric collection and cross-center and regional comparisons. They emphasized the need for a consistent and transparent approach to life cycle assessments. Although standards developed by the International Organization for Standardization provide a framework, sector-specific guidance, such as that developed by the Sustainable Healthcare Coalition[141] or reporting guidelines under development via the Equator Network,[142] can support practical application in health care. The development of dialysis-specific product category rules, building on similar efforts underway for pharmaceuticals,[143] would further strengthen consistency by defining standardized parameters for carbon assessment across products and services.

It was also noted that life cycle assessments are methodologically complex. To support their broader application, participants highlighted the need for simplified user-friendly tools. For example, an online carbon calculator for in-center hemodialysis (https://ichdcarbon.org/) has been developed in the United Kingdom; this should be validated for broader applicability or adapted to local contexts.

Industry. Conference attendees agreed that industry has a critical role in advancing environmentally sustainable dialysis, as most dialysis-related carbon emissions arise from the supply chain, and industry drives technological innovation.

One barrier to accurate environmental impact assessments is limited access to proprietary data. Policies mandating greater transparency and data sharing could help overcome this. In parallel, the use of standardized life cycle assessment guidance and the development of product category rules might support industry in conducting more consistent environmental footprint assessments of dialysis products.

To counter incentives that favor short-term cost savings over long-term sustainability, participants highlighted the potential of servitization: a shift from product sales to service-based models in which suppliers retain responsibility for maintenance and end-of-life management of products. Reverse logistics—the process of returning products from end users back through the supply chain for reuse, recycling, or safe disposal—was also identified as a key opportunity. This could include retrieving PD-related waste for recycling or returning dialysis machines for refurbishment or reuse of parts rather than disposal. These changes will require enabling policy and regulatory frameworks to drive uptake and accountability.

Participants recognized the potential of a global sustainable procurement strategy, as is being developed by the International Society of Nephrology,[144] to aggregate demand across countries and institutions and provide industry with the commercial certainty needed to innovate.

Policy and regulation. A supportive policy and regulatory environment was considered essential for embedding environmental sustainability within dialysis care (Figure 5). Although stand-alone initiatives were welcomed, participants emphasized that sustainability should be integrated into broader health system objectives. A value-based health care framework that considers environmental impacts alongside clinical outcomes and economic costs (Figure 1) was viewed as important to aligning environmental and health priorities. However, participants also noted that the substantial environmental burden of health care, including dialysis, remains insufficiently recognized by policymakers, highlighting the need for proactive advocacy and continued engagement to ensure that both impacts and solutions are incorporated into future policy and regulatory frameworks.

Participants further emphasized the importance of embedding climate resilience and supply chain risk management into dialysis policy and system design. For example, aligning procurement criteria, providing targeted incentives, and/or streamlining regulatory approvals for regional manufacturing could support decentralized production, acknowledging potentially higher upfront costs. Barriers and strategies for scaling green nephrology practices are provided in Table 3.

Future directions and conclusions

Grounded in the shared recognition that human and planetary health are inextricably linked and that environmental sustainability is a core dimension of health care quality, conference participants identified opportunities to reduce environmental harm across clinical, operational, technical, and policy domains while improving patient outcomes. This remains an underexplored research area, with key questions and directions outlined in Table 4. Advancing this green dialysis agenda will require a shared sense of urgency and coordinated action from clinicians, patients, industry, and policymakers.

APPENDIX

Other Conference Participants

Fiona Adshead, UK; Carla Maria Avesani, Sweden; Sunita Bavanandan, Malaysia; Joachim Beige, Germany; Mohamed Ben Hmida, Tunisia; Peter J. Blankestijn, The Netherlands; Carole Bonnet, France; Edwina A. Brown, UK; Christopher T. Chan, Canada; Eason Chang, Malaysia; Charles Chazot, France; Rolando Claure-Del Granado, Bolivia; Rhea Danner, Australia; Andrew Davenport, UK; Gabriele Donati, Italy; Hafedh Fessi, France; Marjorie Wai Yin Foo, Singapore; Winston W.S. Fung, Hong Kong; Karin G.F. Gerritsen, The Netherlands; Rafael Alberto Gomez Acevedo, Colombia; Samuel O. Haddad, USA; Mark Harber, UK; Anne M. Huml, USA; Michelle A. Josephson, USA; Rümeyza Kazancioğlu, Turkey; Seiji Kishi, Japan; Susi Knöller, Germany; Gang Jee Ko, South Korea; Martin K. Kuhlmann, Germany; Haroon R. Mian, Canada; Borislava Mihaylova, UK; Angela Monecke, Germany; Frances Mortimer, UK; Gloria Patricia Munoz-Figueroa, UK; Reem A. Mustafa, USA; Abdou Niang, Senegal; Jeffrey Perl, Canada; Rossella Picillo, Italy; Fanny Poia, France; Megha Salani, USA; Alina Seman, Italy; Junelle Speller, USA; Peter Stenvinkel, Sweden; Paul E. Stevens, UK; Rita S. Suri, Canada; Massimo Torreggiani, France; Ifeoma I. Ulasi, Nigeria; Raymond Vanholder, Belgium; Chetan Kumar Velumurugan, France; Suzanne Watnick, USA; Jane Waugh, Australia; Fokko P. Wieringa, The Netherlands; Jihyun Yang, South Korea.

DISCLOSURE

Kidney Disease: Improving Global Outcomes (KDIGO) provided travel and medical writing support to all conference participants. GBP discloses receipt of consulting fees and speaker honoraria from Fresenius Kabi; travel support from Baxter, the European Renal Association, and Fresenius Kabi; serving in leadership roles for the European Renal Association and Italian Society of Nephrology; and serving as Editor-in-Chief of the *Journal of Nephrology*. CS discloses serving in volunteer roles as chair for the Sustainable Nephrology Action Planning Committee of the Canadian Society of Nephrology and a steering committee member for the International Society of Nephrology's GREEN-K (Global Environmental Evolution in Nephrology and Kidney Care) initiative as well as in a paid role as a medical lead for planetary health for BC Renal, British Columbia, Canada. BT discloses receipt of scholarship grants from the University of New South Wales, Sydney, Australia; consulting fees from Emerald Clinical (previously George Clinical); and travel support from the Australia and New Zealand Society of Nephrology (ANZSN). BT also discloses stock ownership in Ellen Medical Devices and volunteer service for the ANZSN Pacific Working Group. MEG discloses receipt of grants from the National Institutes of Health (NIH)/National Institute of Diabetes and Digestive and Kidney Diseases, NIH/National Heart, Lung, and Blood Institute, and National Kidney Foundation; speaker honoraria from Columbia University Medical Center, the Nephrology Self-Assessment Program of the American Society of Nephrology, and the University of Pennsylvania; and travel support from the European Renal Association, the Hong Kong Society of Nephrology, KDIGO, the Kidney Research Institute, the Korean Society of Nephrology, and the University of Pennsylvania. MEG also serves as cochair of KDIGO and on boards or committees for the *American Journal of Kidney Diseases*, the American Society of Nephrology, the *Clinical Journal of the American Society of Nephrology*, the *Journal of the American Society of Nephrology*, the Kidney Institute, the National Kidney Foundation, and the United States Renal Data System. MJ discloses receipt of consulting fees from Astellas, AstraZeneca, Boehringer Ingelheim, Menarini, and STADA EG; speaker honoraria from Astellas, AstraZeneca, Boehringer Ingelheim, CSL Vifor, GSK, Novo Nordisk, STADA EG, and Vertex Pharmaceuticals; and travel support from AstraZeneca, Boehringer Ingelheim, and GSK. MJ also discloses serving as volunteer cochair of KDIGO and volunteer copresident of the European Kidney Health Alliance. JEF discloses receipt of advisory fees from Fresenius Medical Care and consulting fees from Aquapass. All the other authors declared no competing interests.

FUNDING STATEMENT

The conference was sponsored by Kidney Disease: Improving Global Outcomes (KDIGO) and was in part supported by unrestricted educational grants from B. Braun, Fresenius Medical Care, and Vantive.

ACKNOWLEDGMENTS

Tanya Green and Coral Cyzewski of Kidney Disease: Improving Global Outcomes (KDIGO) assisted with conference planning and implementation. The German Society of Nephrology and ECENT (Munich, Germany) provided guidance related to the meeting location. Debbie Maizels of Zoobotanica Scientific Illustration assisted with figure illustrations.

Conference participants acknowledge Henning Søndergaard (Denmark), a passionate patient advocate, who passed away on April 8, 2025. Søndergaard was committed to improving the lives of people living with kidney disease, and he had planned to attend this conference and share his experiences in a panel discussion. Søndergaard was a long-time contributor to the global kidney community, and his absence is deeply felt.

REFERENCES

1. Romanello M, Di Napoli C, Drummond P, et al. The 2022 report of the Lancet Countdown on health and climate change: health at the mercy of fossil fuels. *Lancet*. 2022;400:1619–1654.
2. Lenzen M, Malik A, Li M, et al. The environmental footprint of health care: a global assessment. *Lancet Planet Health*. 2020;4:e271–e279.
3. World Health Organization. Health-care waste: key facts. Accessed October 2, 2025. https://www.who.int/news-room/fact-sheets/detail/health-care-waste?utm_source=chatgpt.com
4. Barraclough KA, Agar JWM. Green nephrology. *Nat Rev Nephrol*. 2020;16:257–268.
5. McAlister S, Talbot B, Knight J, et al. The carbon footprint of peritoneal dialysis in Australia. *J Am Soc Nephrol*. 2024;35:1095–1103.
6. Sehgal AR, Slutzman JE, Huml AM. Sources of variation in the carbon footprint of hemodialysis treatment. *J Am Soc Nephrol*. 2022;33:1790–1795.
7. Agar JWM, Simmonds RE, Knight R, et al. Using water wisely: new, affordable, and essential water conservation practices for facility and home hemodialysis. *Hemodial Int*. 2009;13:32–37.
8. Bendine G, Autin F, Fabre B, et al. Haemodialysis therapy and sustainable growth: a corporate experience in France. *Nephrol Dial Transplant*. 2020;35:2154–2160.
9. Chang E, Lim JA, Low CL, et al. Reuse of dialysis reverse osmosis reject water for aquaponics and horticulture. *J Nephrol*. 2021;34:97–104.
10. Connor A, Milne S, Owen A, et al. Toward greener dialysis: a case study to illustrate and encourage the salvage of reject water. *J Ren Care*. 2010;36:68–72.
11. Choo SMY, Murcutt G, Steinbach I, et al. Sustainable health care in a renal centre—carbon saving is coupled with cost-efficiency. *J Nephrol*. 2025;38:2321–2331.
12. Mortimer F, Isherwood J, Wilkinson A, et al. Sustainability in quality improvement: redefining value. *Future Healthc J*. 2018;5:88–93.
13. Gheewala SH, Silalertruksa T. Life cycle thinking in a circular economy. In: Liu L, Ramakrishna S, eds. *An Introduction to Circular Economy*. Singapore: Springer; 2021:35–53.
14. Gutiérrez-Ibarluzea I, Chiumente M, Dauben H-P. The life cycle of health technologies: challenges and ways forward. *Front Pharmacol*. 2017;8:14.
15. European Union. EUR-Lex: Access to European Union law. Waste hierarchy. Accessed August 25, 2025. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=legissum:waste_hierarchy
16. Cooper BA, Branley P, Bulfone L, et al. A randomized, controlled trial of early versus late initiation of dialysis. *N Engl J Med*. 2010;363:609–619.
17. Nesrallah GE, Mustafa RA, Clark WF, et al. Canadian Society of Nephrology 2014 clinical practice guideline for timing the initiation of chronic dialysis. *CMAJ*. 2014;186:112–117.
18. Watanabe Y, Yamagata K, Nishi S, et al. Japanese Society for Dialysis Therapy Clinical Guideline for "Hemodialysis Initiation for Maintenance Hemodialysis.". *Ther Apher Dial*. 2015;19:93–107.
19. Daugirdas JT, Depner TA, Inrig J, et al. KDOQI Clinical Practice Guideline for Hemodialysis Adequacy: 2015 update. *Am J Kidney Dis*. 2015;66:884–930.
20. Garofalo C, Borrelli S, De Stefano T, et al. Incremental dialysis in ESRD: systematic review and meta-analysis. *J Nephrol*. 2019;32:823–836.
21. Xu S, Wu W, Cheng J. Comparison of outcomes of incremental vs. standard peritoneal dialysis: a systematic review and meta-analysis. *BMC Nephrol*. 2024;25:308.
22. Fernandes A, Matias P, Branco P. Incremental peritoneal dialysis—definition, prescription, and clinical outcomes. *Kidney360*. 2023;4:272–277.
23. Blake PG, Dong J, Davies SJ. Incremental peritoneal dialysis. *Perit Dial Int*. 2020;40:320–326.
24. Brown EA, Blake PG, Boudville N, et al. International Society for Peritoneal Dialysis practice recommendations: prescribing high-quality goal-directed peritoneal dialysis. *Perit Dial Int*. 2020;40:244–253.
25. Takkavatakarn K, Jintanapramote K, Phannajit J, et al. Incremental versus conventional haemodialysis in end-stage kidney disease: a systematic review and meta-analysis. *Clin Kidney J*. 2024;17:sfad280.
26. Caton E, Sharma S, Vilar E, et al. Impact of incremental initiation of haemodialysis on mortality: a systematic review and meta-analysis. *Nephrol Dial Transplant*. 2023;38:435–446.

27. Wolley MJ, Hawley CM, Johnson DW, et al. Incremental and twice weekly haemodialysis in Australia and New Zealand. *Nephrology*. 2019;24:1172–1178.
28. Springmann M, Clark M, Mason-D'Croz D, et al. Options for keeping the food system within environmental limits. *Nature*. 2018;562:519–525.
29. Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. *Science*. 2018;360:987–992.
30. Scarborough P, Appleby PN, Mizdrak A, et al. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. *Clim Change*. 2014;125:179–192.
31. Ritchie H, Rosado P, Roser M. Environmental impacts of food production. Accessed August 19, 2025. https://ourworldindata.org/environmental-impacts-of-food
32. Scarborough P, Clark M, Cobiac L, et al. Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts. *Nat Food*. 2023;4:565–574.
33. Kidney Disease: Improving Global Outcomes (KDIGO) CKD Work Group. KDIGO 2024 Clinical Practice Guideline for the Evaluation and Management of Chronic Kidney Disease. *Kidney Int*. 2024;105(4S):S117–S314.
34. Bolasco P, Cupisti A, Locatelli F, et al. Dietary management of incremental transition to dialysis therapy: once-weekly hemodialysis combined with low-protein diet. *J Ren Nutr*. 2016;26:352–359.
35. Locatelli F, Del Vecchio L, Aicardi V. Nutritional issues with incremental dialysis: the role of low-protein diets. *Semin Dial*. 2017;30:246–250.
36. Kittiskulnam P, Tiranathanagul K, Susantitaphong P, et al. Stepwise incremental hemodialysis and low-protein diet supplemented with keto-analogues preserve residual kidney function: a randomized controlled trial. *Nutrients*. 2025;17:2422.
37. Hanafusa N, Lodebo BT, Kopple JD. Current uses of dietary therapy for patients with far-advanced CKD. *Clin J Am Soc Nephrol*. 2017;12:1190–1195.
38. Caria S, Cupisti A, Sau G, et al. The incremental treatment of ESRD: a low-protein diet combined with weekly hemodialysis may be beneficial for selected patients. *BMC Nephrol*. 2014;15:172.
39. Takkavatakarn K, Kittiskulnam P, Tiranathanagul K, et al. The role of once-weekly online hemodiafiltration with low protein diet for initiation of renal replacement therapy: a case series. *Int J Artif Organs*. 2021;44:900–905.
40. Piccoli GB, Guzzo G, Vigotti FN, et al. Tailoring dialysis and resuming low-protein diets may favor chronic dialysis discontinuation: report on three cases. *Hemodial Int*. 2014;18:590–595.
41. Xie J, Liu X, Ling Y, et al. The impact of low-protein diet on residual renal function in dialysis patients: a systematic review and meta-analysis. *BMC Nephrol*. 2025;26:122.
42. Otero Alonso P, Pérez Fontán M, López Iglesias A, et al. High rates of protein intake are associated with an accelerated rate of decline of residual kidney function in incident peritoneal dialysis patients. *Nephrol Dial Transplant*. 2019;34:1394–1400.
43. Jiang N, Qian J, Sun W, et al. Better preservation of residual renal function in peritoneal dialysis patients treated with a low-protein diet supplemented with keto acids: a prospective, randomized trial. *Nephrol Dial Transplant*. 2009;24:2551–2558.
44. Barraclough KA, Moller S, Blair S, et al. Updating the data: the resource consumption of modern-day hemodialysis systems. *Kidney Int Rep*. 2024;9:1521–1524.
45. Albalate M, Pérez-García R, de Sequera P, et al. Is it useful to increase dialysate flow rate to improve the delivered Kt? *BMC Nephrol*. 2015;16:20.
46. Molano Triviño A, Wancjer Meid B, Guzman G, et al. SP491: effects of decreasing dialysis fluid flow rate on dialysis efficacy and interdialytic weight gain in chronic patient with hemodialysis—FLUGAIN Study. *Nephrol Dial Transplant*. 2018;33:i514–i515.
47. Ducuara D, Martínez A. Effect of flow adjustment dialysate (Qd) hemodialysis on effectiveness of underweight patients. *Rev Cienc Salud*. 2013;11:173–183.
48. Alayoud A, Benyahia M, Montassir D, et al. A model to predict optimal dialysate flow. *Ther Apher Dial*. 2012;16:152–158.
49. Iman Y, Bamforth R, Ewhrudjakpor R, et al. The impact of dialysate flow rate on haemodialysis adequacy: a systematic review and meta-analysis. *Clin Kidney J*. 2024;17:sfae163.
50. Molano Trivino A, Galván Á, Wancjer Meid B, et al. SAT-342 Long term outcomes of lowering dialysate flow (QD) in a population of chronic hemodialysis in RTS Colombia [abstract]. *Kidney Int Rep*. 2019;4:S151–S152.
51. Watanabe Y, Kawanishi H, Suzuki K, et al. Japanese Society for Dialysis Therapy Clinical Guideline for "Maintenance Hemodialysis: Hemodialysis Prescriptions.". *Ther Apher Dial*. 2015;19(suppl 1):67–92.
52. Mesic E, Bock A, Major L, et al. Dialysate saving by automated control of flow rates: comparison between individualized online hemodiafiltration and standard hemodialysis. *Hemodial Int*. 2011;15:522–529.
53. Canaud B, Gagel A, Peters A, et al. Does online high-volume hemodiafiltration offer greater efficiency and sustainability compared with high-flux hemodialysis? A detailed simulation analysis anchored in real-world data. *Clin Kidney J*. 2024;17:sfae147.
54. Ben Hmida M, Mechichi T, Piccoli GB, et al. Water implications in dialysis therapy, threats and opportunities to reduce water consumption: a call for the planet. *Kidney Int*. 2023;104:46–52.
55. Tarrass F, Benjelloun M, Piccoli GB. Hemodialysis water reuse within a circular economy approach. What can we add to current knowledge? A point of view. *J Nephrol*. 2024;37:1801–1805.
56. Tarrass F, Benjelloun O, Benjelloun M. Towards zero liquid discharge in hemodialysis: possible issues. *Nefrología*. 2021;41:620–624.
57. Murcutt G, Hillson R, Goodlad C, et al. Reducing the carbon footprint for a 30-bed haemodialysis unit by changing the delivery of acid concentrate supplied by individual 5 L containers to a central delivery system. *J Nephrol*. 2024;37:1949–1955.
58. Zawierucha J, Marcinkowski W, Prystacki T, et al. Green dialysis: let us talk about dialysis fluid. *Kidney Blood Press Res*. 2023;48:385–391.
59. Di Chiaro G, Alfano G, Cancelli Y, et al. ["Green" hemodialysis: the centralized acidic concentrate from the Dialysis Center of Policlinico of Modena]. *G Ital Nefrol*. 2024;41:2024-vol3 [in Italian].
60. Centre for Sustainable Healthcare. Central delivery of acid for haemodialysis. Accessed August 11, 2025. https://map.sustainablehealthcare.org.uk/bradford-teaching-hospitals-nhs-foundation-trust/central-delivery-acid-haemodialysis
61. Cadenas RM, Audije-Gil J, Arenas MD, et al. Impact of the type of dialysate acid concentrate container on the environmental footprint of hemodialysis centers. *Am J Kidney Dis*. 2025;86:616–623.
62. Barraclough KA, Waugh J. Reducing the environmental footprint of hemodialysis: the case for centralized acid delivery. *Am J Kidney Dis*. 2025;86:585–587.
63. Barraclough KA, Talbot B, Knight J, et al. Carbon emissions from different dialysis modalities: a life cycle assessment. *Am J Kidney Dis*. 2025;86:465–474.e1.
64. Centre for Sustainable Healthcare. Reducing waste in the Dialysis Unit Queen Margaret Hospital, Dunfermline. Accessed August 26, 2025. https://networks.sustainablehealthcare.org.uk/sites/default/files/2024-04/Reducing%20Waste%20in%20the%20Dialysis%20Unit%20Queen%20Margaret%20Hospital%2C%20Dunfermline.pdf
65. Centre for Sustainable Healthcare. Systematic review of dialysis prescriptions (use of dialysate autoflow facility). Accessed August 26, 2025. https://map.sustainablehealthcare.org.uk/bradford-teaching-hospitals-nhs-foundation-trust/systematic-review-dialysis-prescriptions-use-dialys
66. Australian and New Zealand Society of Nephrology. Optimizing dialysis acid concentrate consumption. Accessed October 2, 2025. https://nephrology.edu.au/int/anzsn/uploads/Green%20Neph/Optimising%20dialysis%20acid%20concentrate%20consumption.pdf
67. Fresenius Medical Care. Fresenius Medical Care's peritoneal dialysis products certified by Nordic Ecolabel—first health care company with ecolabelled products. Accessed March 11, 2026. https://www.fresenius.com/sites/default/files/2021-11/Nordic_Ecolabel_FMC_111208-e.pdf
68. FDA Reporter. Fresenius Medical Care: FDA approves new container system for peritoneal dialysis. Accessed August 25, 2025. https://fdareporter.com/stories/fresenius-medical-care-fda-approves-new-container-system-for-peritoneal-dialysis-solutions/
69. Ghimire A, Shah M, Qirjazi E, et al. Estimating the costs and amount of recyclable polyvinyl chloride plastic waste associated with discarded icodextrin. *Perit Dial Int*. Published online May 27, 2025. https://doi.org/10.1177/08968608251344074
70. Piccoli GB, Nazha M, Ferraresi M, et al. Eco-dialysis: the financial and ecological costs of dialysis waste products: is a 'cradle-to-cradle' model feasible for planet-friendly haemodialysis waste management? *Nephrol Dial Transplant*. 2015;30:1018–1027.
71. Australian and New Zealand Society of Nephrology. Practical ways to optimize dialysis machine disinfection schedules. Accessed August 26,

2025. https://nephrology.edu.au/int/anzsn/uploads/Green%20Neph/ESC%20Optimising%20Disinfection%20of%20Dialysis%20machines.pdf
72. Sunshine Coast Hospital and Health Service. Waste reduction during haemodialysis access procedures. Accessed August 26, 2025. https://nephrology.edu.au/int/anzsn/uploads/Green%20Neph/case%20study%20-%20central%20line%20access%20schhs.pdf
73. Poulikakos D, Martin J, Collier J, et al. A pilot project evaluating a fixed drainage system (U-Drain) for automated peritoneal dialysis. *Perit Dial Int*. 2022;42:530–534.
74. National Kidney Foundation. NFK KDOQI Guidelines. Clinical Practice Guidelines and Clinical Practice Recommendations: 2006 Updates. Hemodialysis Adequacy. Peritoneal Dialysis Adequacy. Vascular Access. Accessed August 26, 2025. https://kidneyfoundation.cachefly.net/professionals/KDOQI/guideline_upHD_PD_VA/va_guide3.htm
75. Vantive. Treatment: connecting and disconnecting. Accessed August 26, 2025. https://www.pdempowers.com/patientpreparing-and-doing-your-pd-treatment/treatment-connecting-and-disconnecting
76. Upadhyay A, Sosa MA, Jaber BL. Single-use versus reusable dialyzers: the known unknowns. *Clin J Am Soc Nephrol*. 2007;2:1079–1086.
77. Galvao TF, Silva MT, Araujo MEDA, et al. Dialyzer reuse and mortality risk in patients with end-stage renal disease: a systematic review. *Am J Nephrol*. 2012;35:249–258.
78. NovaFlux. ClearFlux. Accessed November 18, 2025. https://www.novaflux.com/clearflux-1
79. Association of Medical Device Reprocessors. Australia. Therapeutic Goods Administration: Regulatory Guidelines for Medical Devices (2011), Section 19 Single-Use Devices (SUDs) and the Reuse of SUDs. Accessed August 25, 2025. https://amdr.org/australia-therapeutic-goods-administration/
80. European Union. Commission Implementing Regulation (EU) 2020/1207 of 19 August 2020. Rules for the application of Regulation (EU) 2017/745 of the European Parliament and of the Council as regards common specifications for the reprocessing of single-use devices. Accessed August 25, 2025. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R1207
81. Rizan C, Bhutta MF, Reed M, et al. The carbon footprint of waste streams in a UK hospital. *J Clean Prod*. 2021;286:125446.
82. Centre for Sustainable Healthcare. Diversion of waste to the recycling stream through the use of bailing machines. Accessed August 25, 2025. https://networks.sustainablehealthcare.org.uk/sites/default/files/2024-04/Diversion%20of%20Waste%20to%20the%20Recycling%20Stream%20through%20the%20Use%20of%20Baling%20Machines.pdf
83. The Campaign for Greener Healthcare. Green nephrology: reduce, reuse, recycle in the dialysis unit case studies and how-to guides. Version 1.0 – 9th April 2010. Accessed August 25, 2025. https://networks.sustainablehealthcare.org.uk/sites/default/files/resources/case_study_reduce_reuse_recycle_in_the_dialysis_unit_v1.0_0.pdf
84. Berman-Parks N, Berman-Parks I, Gómez-Ruíz IA, et al. Combining patient care and environmental protection: a pilot program recycling polyvinyl chloride from automated peritoneal dialysis waste. *Kidney Int Rep*. 2024;9:1908–1911.
85. Baxter. PD recycling at home. Accessed August 25, 2025. https://athome.baxter.com/system/files/2022-05/baxter_pd_recycling_at_home.pdf
86. Parvez SM, Jahan F, Brune M-N, et al. Health consequences of exposure to e-waste: an updated systematic review. *Lancet Planet Health*. 2021;5:e905–e920.
87. Bonnet C, Torreggiani M, Bianco L, et al. Autopsy of a hemodialysis machine: potential for recycling at the end of the life cycle. *J Am Soc Nephrol*. 2025;36:1126–1137.
88. Piccardo C, Dodoo A, Gustavsson L. Retrofitting a building to passive house level: a life cycle carbon balance. *Energy Build*. 2020;223:110135.
89. Arbulu M, Oregi X, Etxepare L. Optimisation of passive energy renovation strategies in residential buildings for life cycle global warming potential reduction and cost-effectiveness. *Circ Econ Sustain*. 2025;5:6803–6823.
90. Elaouzy Y, El Fadar A. Energy, economic and environmental benefits of integrating passive design strategies into buildings: a review. *Renew Sustain Energy Rev*. 2022;167:112828.
91. Barraclough KA, Ashley G, Krishnan A, et al. Environmentally sustainable design guide for haemodialysis facilities: an Australian and New Zealand Society of Nephrology initiative. *Nephrology (Carlton)*. 2024;29:446–451.
92. Wieringa FP, Bolhuis D, Søndergaard H, et al. Transportable, portable, wearable and (partially) implantable haemodialysis systems: Comparison of technologies and readiness levels. *Clin Kidney J*. 2024;17:sfae259.
93. Australian Renewable Energy Agency. Technology Readiness Level. Accessed November 18, 2025. https://arena.gov.au/assets/2019/01/trl-guide.pdf
94. Hass SL, Ahuja M. Improving hemodialysis adequacy, anticoagulation and dialyzer efficiency with streamline bloodlines. *J Am Soc Nephrol*. 2010;21:435A.
95. Ljunggren L. Plasticizer migration from blood lines in hemodialysis. *Artif Organs*. 1984;8:99–102.
96. Ponferrada LP, Prowant BF, Rackers JA, et al. A cluster of gram-negative peritonitis episodes associated with reuse of HomeChoice cycler cassettes and drain lines. *Perit Dial Int*. 1996;16:636–638.
97. Chow J, Munro C, Wong M, et al. HomeChoice automated peritoneal dialysis machines: the impact of reuse of tubing and cassettes. *Perit Dial Int*. 2000;20:336–338.
98. Agarwal G, Foster D, Schlageter K, et al. Increase in peritonitis rates with the reuse of drain tubing of the Fresenius Liberty cycler. *Perit Dial Int*. 2013;33:583–585.
99. Zhao S, Dou P, Song J, et al. Direct preparation of dialysate from tap water via osmotic dilution. *J Membr Sci*. 2020;598:117659.
100. NetSol Water. Difference between forward osmosis vs. reverse osmosis. Accessed October 2, 2025. https://www.netsolwater.com/forward-osmosis-vs-reverse-osmosis.php?blog=271
101. Dou P, Zhao S, Xu S, et al. Feasibility of osmotic dilution for recycling spent dialysate: process performance, scaling, and economic evaluation. *Water Res*. 2020;168:115157.
102. Kim C, Lee C, Kim SW, et al. Performance evaluation and fouling propensity of forward osmosis (FO) membrane for reuse of spent dialysate. *Membranes*. 2020;10:438.
103. Fuwad A, Ryu H, Han ED, et al. Highly permeable and shelf-stable aquaporin biomimetic membrane based on an anodic aluminum oxide substrate. *npj Clean Water*. 2024;7:11.
104. Machado CK, Pinto LH, Del Ciampo LF, et al. Potential environmental toxicity from hemodialysis effluent. *Ecotoxicol Environ Saf*. 2014;102:42–47.
105. Huang J-K, Chuang Y-S, Wu P-H, et al. Decreased levels of perfluoroalkyl substances in patients receiving hemodialysis treatment. *Sci Total Environ*. 2023;896:165184.
106. Tarrass F, Benjelloun M, Benjelloun O. Recycling wastewater after hemodialysis: an environmental analysis for alternative water sources in arid regions. *Am J Kidney Dis*. 2008;52:154–158.
107. Zhu X, Ye C, Wang Y, et al. Assessment of antibiotic resistance genes in dialysis water treatment processes. *Front Environ Sci Eng*. 2019;13:45.
108. Hakizimana JN, Gourich B, Vial C, et al. Assessment of hardness, microorganism and organic matter removal from seawater by electrocoagulation as a pretreatment of desalination by reverse osmosis. *Desalination*. 2016;393:90–101.
109. Al-Othman AA, Kaur P, Imteaz MA, et al. Modified bio-electrocoagulation system to treat the municipal wastewater for irrigation purposes. *Chemosphere*. 2022;307:135746.
110. Zhang L, Zhu X, Wang H, et al. Research progress in the treatment of high-salinity wastewater. *J Phys Conf Ser*. 2024;2706:012042.
111. Espinoza Márquez E, Soto Zarazúa GM, Pérez Bueno JDJ. Prospects for the use of electrooxidation and electrocoagulation techniques for membrane filtration of irrigation water. *Environ Process*. 2020;7:391–420.
112. Tarrass F, Benjelloun H, Benjelloun M. Nitrogen and phosphorus recovery from hemodialysis wastewater to use as an agricultural fertilizer. *Nefrología*. 2023;43:32–37.
113. nextGen Circular Water Solutions. Factsheet—low grade heat recovery from water. Version v6. Accessed August 25, 2025. https://mp.watereurope.eu/media/factsheets/Factsheet_Heat_recovery_sewer_V6.pdf
114. Das B, Pasawan M, Wang CT, et al. Low-cost crosslinked PVA membranes as alternative proton exchange membrane in hemodialysis wastewater fed bioelectrochemical fuel cells. *Process Saf Environ Prot*. 2025;196:106915.
115. Salani M, Roy S, Fissell WH. Innovations in wearable and implantable artificial kidneys. *Am J Kidney Dis*. 2018;72:745–751.
116. Wieringa FP, Suran S, Søndergaard H, et al. The future of technology-based kidney replacement therapies: an update on portable, wearable, and implantable artificial kidneys. *Am J Kidney Dis*. 2025;85:787–796.

117. Gura V, Rivara MB, Bieber S, et al. A wearable artificial kidney for patients with end-stage renal disease. *JCI Insight*. 2016;1:e86397.
118. Htay H, Gow SK, Jayaballa M, et al. Preliminary safety study of the automated wearable artificial kidney (AWAK) in peritoneal dialysis patients. *Perit Dial Int*. 2022;42:394–402.
119. Lau TW, Bluechel C, Khaopaibul P, et al. First-in human trial of the NeoKidney Portable Hemodialysis Device Sorbent System: FR-OR23. *J Am Soc Nephrol*. 2024;35:10S.
120. Foo MWY, Brown EA, Jain A, et al. Prepivotal study exploring safety, efficacy, and usability of the automated wearable artificial kidney (AWAK) PD device: TH-OR69. *J Am Soc Nephrol*. 2024;35(10S):22.
121. Samuelsson O, Heijdenberg L, de Leon C, et al. SuO014: peritoneal dialysis with the new portable Carry Life® System. *Nephrol Dial Transplant*. 2018;33:i621.
122. McGill RL, Bakos JR, Ko T, et al. Sorbent hemodialysis: clinical experience with new sorbent cartridges and hemodialyzers. *ASAIO J*. 2008;54:618–621.
123. Kooman JP. The revival of sorbents in chronic dialysis treatment. *Semin Dial*. 2025;38:54–61.
124. Agar JW. Review: understanding sorbent dialysis systems. *Nephrology*. 2010;15:406–411.
125. Fabiani T, Zarghamidehaghani M, Boi C, et al. Sorbent-based dialysate regeneration for the wearable artificial kidney: advancing material innovation via experimental and computational studies. *Sep Purif Technol*. 2025;360:130776.
126. Ramada DL, de Vries J, Vollenbroek J, et al. Portable, wearable and implantable artificial kidney systems: needs, opportunities and challenges. *Nat Rev Nephrol*. 2023;19:481–490.
127. Ash SR. The quest for a urea sorbent: from frustration, to failure, to the KidneyX Prize. *J Am Soc Nephrol*. 2026;37:180–182.
128. McGrath SB, Kosalka P, Foo MW, et al. Advances in sorbent peritoneal dialysis technologies: a narrative review. *Perit Dial Int*. Published online September 18, 2025. https://doi.org/10.1177/08968608251371951
129. Talbot B, Davies S, Burman J, et al. The Point-of-Care Peritoneal Dialysis System Early Evaluation Study (POC-PDEE): a pilot proof-of-principal study of the Ellen Medical Devices Point-of-Care affordable peritoneal dialysis system. *Perit Dial Int*. 2025;45:52–56.
130. Sharma S, Shamy OE, Wilmington A, et al. Performance evaluation of an automated peritoneal dialysis solution generation system in patients using automated peritoneal dialysis. *Kidney Int Rep*. 2024;9:1752–1757.
131. Bauer F, Nielsen TD, Nilsson LJ, et al. Plastics and climate change—breaking carbon lock-ins through three mitigation pathways. *One Earth*. 2022;5:361–376.
132. Rosenboom J-G, Langer R, Traverso G. Bioplastics for a circular economy. *Nat Rev Mater*. 2022;7:117–137.
133. Zhu L, Liu F, Yu X, et al. Poly(lactic acid) hemodialysis membranes with poly(lactic acid)-*block*-poly(2-hydroxyethyl methacrylate) copolymer as additive: preparation, characterization, and performance. *ACS Appl Mater Interfaces*. 2015;7:17748–17755.
134. MacKenzie J, Siren E, Daneshi M, et al. Fibre-reinforced biocompatible hydrogel to replace single-use plastic tubing in the clinical setting. *Chem Eng J*. 2022;428:131786.
135. Nuñez-Perez FA. Obtaining bioplastic films from castor oil plant. *Rev Mex Cienc Agríc*. 2024;15:1.
136. Krug N, Zarges JC, Heim HP. Influence of ethylene oxide and gamma irradiation sterilization processes on the properties of poly-l-lactic-acid (PLLA) materials. *Polymers*. 2023;15:3461.
137. Kelaniyagama SH, Gannoruwa A, Nilmini AHLR. Synthesize and applications of biodegradable plastics as a solution for environmental pollution due to non-biodegradable plastics, a review. *Sustain Polym Energy*. 2024;2:10011.
138. Planet Pristine. Cost comparison of biodegradable materials: what you should know. Accessed August 26, 2025. https://planetpristine.com/sustainable/products/cost-comparison-of-biodegradable-materials/
139. Yeter HH, Manani SM, Ronco C. The utility of remote patient management in peritoneal dialysis. *Clin Kidney J*. 2021;14:2483–2489.
140. Saleem S, Stigant C, Rajan T, et al. Environmental impacts of kidney replacement therapies: a comparative lifecycle assessment. *Am J Kidney Dis*. 2025;87:65–74.
141. Sustainable Healthcare Coalition. Greenhouse gas accounting sector guidance for pharmaceutical products and medical devices. Accessed August 26, 2025. https://shcoalition.org/wp-content/uploads/2019/10/Guidance-2Document-Pharmaceutical-Product-and-Medical-Device-GHG-Accounting-November-2012.pdf
142. Equator Network. ECoHealth – reporting guideline for assessments of the environmental consequences of healthcare. Accessed August 26, 2025. https://www.equator-network.org/library/reporting-guidelines-under-development/reporting-guidelines-under-development-for-other-study-designs/#ECO
143. bsi Communities. Pharmaceuticals Standards Hub. Accessed October 2, 2025. https://pharmaenvironment.bsigroup.com/
144. International Society of Nephrology. GREEN-K – Global Environmental Evolution in Nephrology and Kidney Care. Accessed October 16, 2025. https://www.theisn.org/initiatives/green-k-global-environmental-evolution-in-nephrology-and-kidney-care/#procurement