Impact of the Type of Dialysate Acid Concentrate Container on the Environmental Footprint of Hemodialysis Centers

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Rationale & Objective: Hemodialysis is the most common form of kidney replacement therapy and has a significant environmental footprint, raising sustainability concerns as demand increases. This study aimed to assess the environmental impact of one aspect of the hemodialysis procedure, the type of container used to hold the acid concentrate that is used to prepare dialysate.

Study Design: A retrospective cross-sectional life cycle assessment (LCA) of acid concentrate containers used in hemodialysis was conducted.

Setting & Participants: 15 hemodialysis centers in 3 Spanish regions participated, representing approximately 5% of the national hemodialysis population.

Exposure: 4 acid concentrate container types from 2 manufacturers were assessed: canisters (3.9 L), flexible bags (4.2 L), and centralized storage tanks (300 L and 600 L).

Outcomes: The primary outcome was the environmental impact of each container measured by carbon footprint (measured in kilograms of CO_2 equivalent [CO_2eq]) and 16 additional environmental impact categories.

Analytical Approach: LCA was performed using openLCA software and the ecoinvent v3.10 database, considering the full life cycle of the containers, including production, transport, and waste disposal.

Results: The 3.9-L canister had a CO_2eq 1.63 times higher than the 4.2-L flexible bag and 2.63 times higher than the storage tanks (P < 0.001). The main contributors to the carbon footprint were container production and waste disposal, particularly plastic use and canister production and disposal. Storage tanks had the lowest CO_2eq (P < 0.001), with no difference between the 300-L and 600-L storage tanks. There were also significant differences in the environmental impact of different containers across 16 impact categories, with the greatest differences observed for freshwater ecotoxicity, nonrenewable energy use, and freshwater eutrophication.

Limitations: Assumptions regarding transport and disposal processes may introduce some variability. Additionally, financial costs were not assessed, which could influence container selection.

Conclusions: The choice of dialysate acid concentrate container is associated with a differential environmental impact. Thus, this study has identified a key potential approach to decrease the environmental impact of kidney replacement therapy.

Visual Abstract online

Complete author and article information provided before references.

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The global health care industry is crucial for human well-being, yet it carries a significant environmental burden.[1] Health care systems contribute to greenhouse gas emissions through different activities.[2-6]

There are 850 million people with kidney disease.[7] In Spain, the number of people receiving kidney replacement

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therapy has increased by 20% in recent years and is projected to reach as many as 1 million by the end of the 21st century.[8] Hemodialysis relies on disposable medical supplies, water purification systems, and energy-intensive equipment,[9] with production and distribution processes that have substantial environmental implications.

A key component of hemodialysis is the dialysate used to maintain body homeostasis.[10,11] Liquid acid concentrates used to adjust dialysate composition on site are available in various containers, including smaller formats such as flexible bags and canisters, as well as larger formats such as centralized storage tanks.[12]

Previous research by our group has explored strategies to optimize resource consumption in hemodialysis, highlighting factors such as water and energy use, waste reduction, and operational efficiency as key areas for sustainability improvement.[13] This study aimed to assess the sustainability performance of different dialysate acid concentrate containers from various manufacturing sites across Spain using life cycle assessment (LCA), a standardized methodology that evaluates the environmental impact of a product or process across its entire life cycle, from raw material extraction to disposal, under real-world conditions.

Methods

This is a retrospective cross-sectional study that used information from 2022-2023. Ethical approval from a

PLAIN-LANGUAGE SUMMARY

Hemodialysis is a lifesaving treatment for people with kidney failure, but it also has a significant environmental impact. One overlooked factor is the variety of formats in which the acidic solution used in dialysis is delivered: small plastic canisters, flexible bags, and large storage tanks. This study examined the environmental impact of these container options across multiple dialysis centers in Spain. We found that storage tanks had the lowest environmental footprint, whereas plastic canisters had the highest. These findings highlight a practical way for dialysis providers and consumers to reduce waste and carbon emissions by selecting more sustainable container options, improving the environmental impact of kidney care.

research ethics committee was not required because the study did not involve human participants, animals, or sensitive data. The research was conducted in compliance with institutional and ethical guidelines.

Fifteen of 19 hemodialysis centers run by the Spanish Renal Foundation had enough data to participate in this study. The locations of the centers are shown in Figure S1. Collectively, these centers provide hemodialysis to approximately 1,300 patients, which represents approximately the 5% of the Spanish hemodialysis population (N = 26,650 at the end of 2022).[14] Participating centers had different patterns of use of dialysate acid concentrate containers and used different providers that supplied acid concentrates with different compositions in different types of containers (Fig 1, Table 1, and Table S1).

The study analyzed the carbon footprint by using life cycle assessment (LCA), whereby each element, "from cradle to grave," was considered, including manufacturing and transportation of products, energy use, and transport and disposal of used products. Furthermore, 16 separate environmental impact categories were examined in this study (Table S2).[15]

Primary data include details about the dialysate acid concentrate (center, date, container consumption, container format, and distance between facilities), number of hemodialysis sessions (center, number of hemodialysis sessions, type of hemodialysis, date), and container packaging specifications (empty container weight, carton use per unit, container units per pallet; Supplementary File 2 and Table S3). Secondary data such as published evidence on water disposal were found online.

One-way travel from the factory to distribution centers and then to dialysis centers was calculated based on container weight, enclosed liquid, packaging, and wooden pallet material using Google Maps distances. Transport from the dialysis center to the incinerator considered only the container and packaging weight (Supplementary File 3). The system's scope is shown in Fig S2.

Table 1. Distribution of Centers by Manufacturer and Container Type

Manufacturer	3.9-L Canister	4.2-L Flexible Bag	Storage Tank 600 L	Storage Tank 300 L
A	9	0	4	0
B	0	7	0	3

The functional unit for this comparative LCA was the use of the different dialysate acid concentrate containers during one hemodialysis session for one patient.

The percentage of the storage tank volume consumed in one hemodialysis session was calculated monthly. First, the number of canisters or flexible bags (ie, small formats) used was subtracted from the total number of hemodialysis sessions performed, with the remaining sessions corresponding to the use of centralized acid storage (300-L or 600-L tanks). Then, the number of storage tanks consumed was divided by the remaining number of hemodialysis sessions in which individual canisters or bags had not been used. The percentages of the volumes of the storage tanks consumed in one hemodialysis session were approximately 0.6% and 1.2% for the 600-L and 300-L storage tanks, respectively. In other words, a single storage tank supplies approximately 85 and 174 hemodialysis sessions in the case of 300-L and 600-L storage tanks, respectively (Table S4).

LCA Assumptions and Exclusions

It was assumed that water used to dispose of the acid undergoes standard municipal treatment and is eventually discharged into waterways, reflecting common industry practices.[16] The consumption of canisters or bags was assumed to be 1 unit per hemodialysis session, as calculated for centers that used only small formats (average of 0.9 units per treatment for 2022 and 2023). The manufacturing method for canisters and bags involved stretch blow molding, a common packaging industry technique.[17] The 300-L storage tank was assumed to be 100% linear low-density polyethylene, although its actual composition was an unknown mix of polypropylene and polyethylene. The production phase of pallets was excluded from the assessment.

Recycling of plastic materials was not considered; disposal was assumed to occur through incineration at facilities.[18] Because of the absence of specific processes in the ecoinvent database v3.10, which provides high-quality life cycle inventory data for industries, materials, and energy sources, certain substitutions were made: glucose instead of glucose monohydrate, magnesium chloride instead of magnesium chloride hexahydrate, and calcium chloride instead of calcium chloride dihydrate (Supplementary File 3). Transportation of materials and products was assumed to be via diesel-powered 16- to 32-ton trucks.[19]

Although this study focuses on environmental impact, financial costs also influence container choice and should be explored in future research.

Figure 1. Visualization of the dialysate acid concentrate container formats: (A) A 3.9-L canister (manufacturer A), (B) 4.2-L flexible bag (manufacturer B), (C) 600-L storage tank (manufacturer A), and 300-L storage tank (manufacturer B).

LCA Software

openLCA, an open-source software used to analyze the environmental impact of products and processes (https://www.openlca.org/download-form/), was used alongside the ecoinvent database v3.10 (https://ecoquery.ecoinvent.org/3.10/cutoff/search) to calculate the environmental footprint of each acid form in kilograms of CO_2 equivalent (CO_2eq). CO_2eq is a standard unit referring to carbon dioxide and other greenhouse gases (eg, methane, nitrous oxide, and others).

Life Cycle Impact Assessment

Life cycle impact assessment is a phase of LCA that evaluates the environmental impacts of different dialysate acid concentrate containers. It was used to quantify 16 environmental impacts, including freshwater ecotoxicity, nonrenewable energy resource consumption, freshwater eutrophication, climate change, photochemical oxidant formation (which negatively affects human health), particulate matter formation, noncarcinogenic human toxicity, acidification, marine eutrophication, terrestrial eutrophication, metals and minerals resource depletion, water use, carcinogenic human toxicity, land use, ionizing radiation (which impacts human health), and ozone depletion (Table S2). Environmental impacts were normalized using global averages from the ecoinvent database and expressed in person-equivalents to measure their significance relative to an individual's typical daily environmental footprint.

A contribution analysis examined the impact of each process stage: transport from the factory to the logistic center, transport from the logistic center to the dialysis center, transport from the dialysis center to the incinerator, and acid container format production and waste disposal. Based on these results, a detailed analysis of the carbon footprint was conducted for the production and waste disposal of the canister and the flexible bag.

Statistics

RStudio (https://socialsciences.mcmaster.ca/jfox/Misc/Rcmdr/) was used for data management, calculations, and statistics to compare the environmental impact of different acid concentrate containers.

Table S4 summarizes the storage tank consumption for each treatment in each center. One outlier from center 1 was deleted as a result of suspected human error. The average tank consumption percentage for each hemodialysis session was used to obtain the carbon footprint per treatment in each center.

Based on the sample sizes of these groups—3.9-L canister (n = 9), 4.2-L flexible bag (n = 7), 600-L storage tank (n = 4), and 300-L storage tank (n = 3)—a nonparametric Mann-Whitney *U* test was performed to evaluate the difference in carbon footprints of a single hemodialysis session between the 3.9-L canister and the 4.2-L flexible bag and between the 600-L and 300-L storage tanks. Because the comparison between storage tanks did not yield significant results, storage tanks were treated as one group, and the same test was repeated for the 3.9-L canister versus the storage tanks and the 4.2-L flexible bag versus the storage tanks. GraphPad Prism 8 was used for data visualization.

Results

Carbon Footprint Analysis

The LCA analysis showed a CO_2eq footprint difference between the smaller formats and storage tanks ($P < 0.001$), as well as between the different-sized small-format containers from the 2 manufacturers ($P < 0.001$; Fig 2). Storage tanks displayed the lowest CO_2eq footprint, and there were no differences between the 300-L and 600-L storage tanks (1.54 [95% CI, 1.39-1.68] and 1.52 [95% CI, 0.1.05-1.99] kg of CO_2eq per hemodialysis session, respectively; $P = 0.4$). The largest CO_2eq

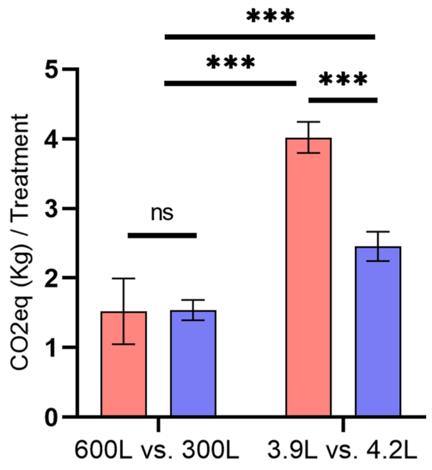

Figure 2. Bar plot of the average carbon footprint (with 95% CI) generated per single hemodialysis session in different centers according to the use of different acid concentrate containers: 600-L storage tank (n = 4) and 3.9-L canister (n = 9; manufacturer A) and 300-L storage tank (n = 3) and 4.2-L flexible bag (n = 7; manufacturer B). The Mann-Whitney *U* test was used to compare the following groups: 600-L vs 300-L storage tank, storage tank vs 3.9-L canister, storage tank vs 4.2-L flexible bag, and 3.9-L canister vs 4.2-L flexible bag. Asterisks indicate levels of statistical significance: *P < 0.05, **P < 0.01, and ***P < 0.001. ns, not significant ($P \geq 0.05$).

footprint was observed for the 3.9-L canister (4.02 [95% CI, 3.80-4.24] kg of CO_2eq per hemodialysis session), which was significantly higher than for the 4.2-L flexible bag (2.469 [95% CI, 2.25-2.67] kg of CO_2eq per hemodialysis session; Fig 2). Thus, the CO_2eq footprint for the 3.9-L canister was 1.63 times higher than for the 4.2-L flexible bag and 2.63 times higher than for the storage tanks.

Carbon Footprint Contribution Analysis

The largest contribution to the CO_2eq footprint of the different acid concentrate containers was the container production and waste disposal, which accounted for 77.22% of the overall CO_2eq footprint for 3.9-L canisters, 64.01% for 4.2-L flexible bags, and 59.58% for storage tanks, corresponding to absolute values of 3.10, 1.58, and 0.91 kg CO_2eq per hemodialysis session (Fig 3). Thus, container production and waste disposal also represent the main differences between the canisters and the flexible bags, as well as between them and the storage tanks. Storage tanks displayed the lowest values for all the processes involved.

Contribution Analysis of Production and Waste Disposal of Acid Concentrate Canisters and Flexible Bags

We next focused on the largest contributor to the CO_2eq footprint, the container production and waste disposal of acid concentrate canisters (Fig 4). The acid concentrate compounds were the largest individual contributor to the CO_2eq footprint. The different CO_2eq footprints between 3.9-L canisters and 4.2-L flexible bags was explained mainly by the plastic use, container stretch blow molding, and incineration. In this regard, plastic use was 5-fold higher in 3.9-L canisters than in 4.2-L flexible bags (0.3 g vs 0.059 g).

Life Cycle Impact Assessment

The normalized quantification of 16 environmental impact categories (Table S2) was also consistent with a gradient from highest to lowest environmental impact from 3.9-L canisters to 4.2-L flexible bags to storage tanks (Fig 5 and Table S5). The largest impacts corresponded to freshwater ecotoxicity, nonrenewable energy resources, and freshwater eutrophication.

Discussion

The main finding of the present study is that a holistic LCA approach indicates that the nephrologist choice of dialysate acid concentrate container has a large environmental impact, and this information should be incorporated into the overall decision-making process.

Storage tanks displayed the lowest carbon footprint, and there were no differences between the 300-L and 600-L storage tanks. The largest difference was observed between the use of canisters and storage tanks, with canisters exhibiting a carbon footprint 2.63 times larger than that of storage tanks. Furthermore, 3.9-L canisters appeared to be less sustainable than 4.2-L flexible bags, with a carbon footprint 1.63 times higher in the case of canisters.

This study supports that centralized delivery of acid concentrate into dialysate will decrease its environmental impact. Moreover, individualized dialysate would still be possible at centralized hemodialysis centers by using smaller containers for patients who need customization. Furthermore, the incorporation of centralized acid concentrate would reduce workers' health risks associated with handling multiple heavy containers.[20] In addition, the centralized liquid offers convenience in its use, avoids storage of individual containers, and simplifies waste disposal. However, centralized delivery of acid concentrate requires an initial investment in infrastructure and space to host the system. The decision regarding which type of container to use is made by consensus between medical management and the maintenance service. Management aims to protect the environment, but these decisions also depend on the available space within the center.

There are also differences in the environmental impact between smaller container formats mainly related to the 5-fold greater use of plastic in 3.9-L canisters versus 4.2-L flexible bags, which is associated with a lager carbon footprint for plastic use. Canister production and waste disposal were less sustainable than the use of flexible bags. Thus, the design of flexible bags by manufacturer B allows for better segregation of waste, reducing its weight and volume.

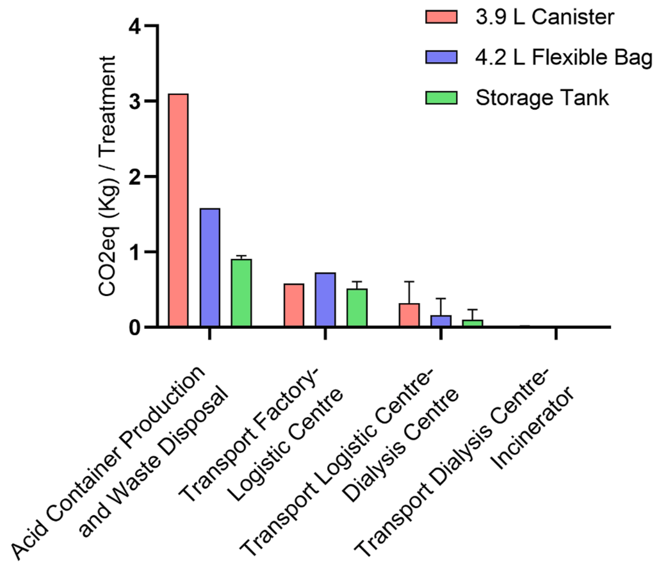

Figure 3. Carbon footprint contribution (with 95% CI) per single hemodialysis session (treatment) across each stage, from production to waste disposal, including transportation from the factory to the logistic center, from the logistic center to the dialysis center, and from the dialysis center to the incinerator for waste disposal. The analysis covers the following groups: 4.2-L flexible bag (n = 7), 3.9-L canister (n = 9), and storage tanks (600-L and 300-L combined; n = 7). CO_2eq, CO_2 equivalent.

LCA represents the current gold standard for assessing environmental impact because it accounts for the full life cycle of the assessed process. The results nicely complement those of Di Chiaro et al (2024),[21] providing valuable insights into "green nephrology." The dialysis centers in the present study perform 163,515 hemodialysis sessions every year. Thus, the 1.63-fold difference in the CO_2eq footprint between canisters and flexible bags represents an excess of 255,830 kg of CO_2eq per year if all patients in these centers used one versus the other type of container. This is equivalent to flying from London to New York 429 times; in other words, each hemodialysis session difference would correspond to driving a car for approximately 3.32 miles. When comparing storage tanks versus canisters, the difference would be 407,392 kg CO_2eq per year if all patients in these centers used one versus the other type of container. This is equivalent to flying from London to New York 682 times; each hemodialysis session difference would correspond to driving a car for approximately 5.29 miles.

Beyond carbon footprint, the 3 highest-impact categories were freshwater ecotoxicity, nonrenewable energy resource use, and freshwater eutrophication. Freshwater ecotoxicity is driven by acid-laden wastewater discharge, which lowers pH levels, disrupting the biological functions of organisms and decreasing biodiversity.[22] The 3.9-L canister is associated with considerably greater freshwater ecotoxicity impact, contributing approximately 33.3% of

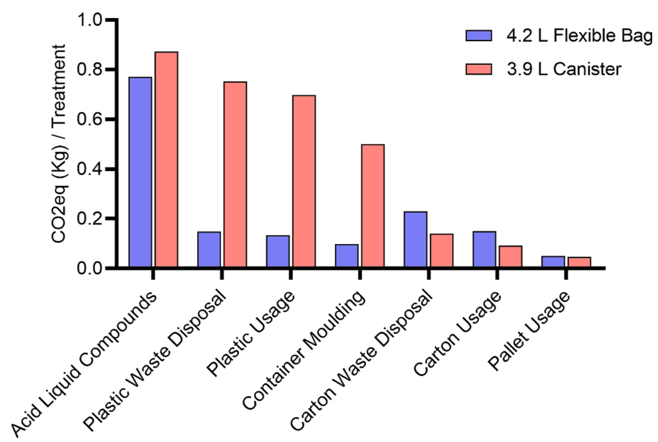

Figure 4. Carbon footprint contribution analysis per treatment of the production and waste disposal of 3.9-L canisters and 4.2-L flexible bags. CO_2eq, CO_2 equivalent.

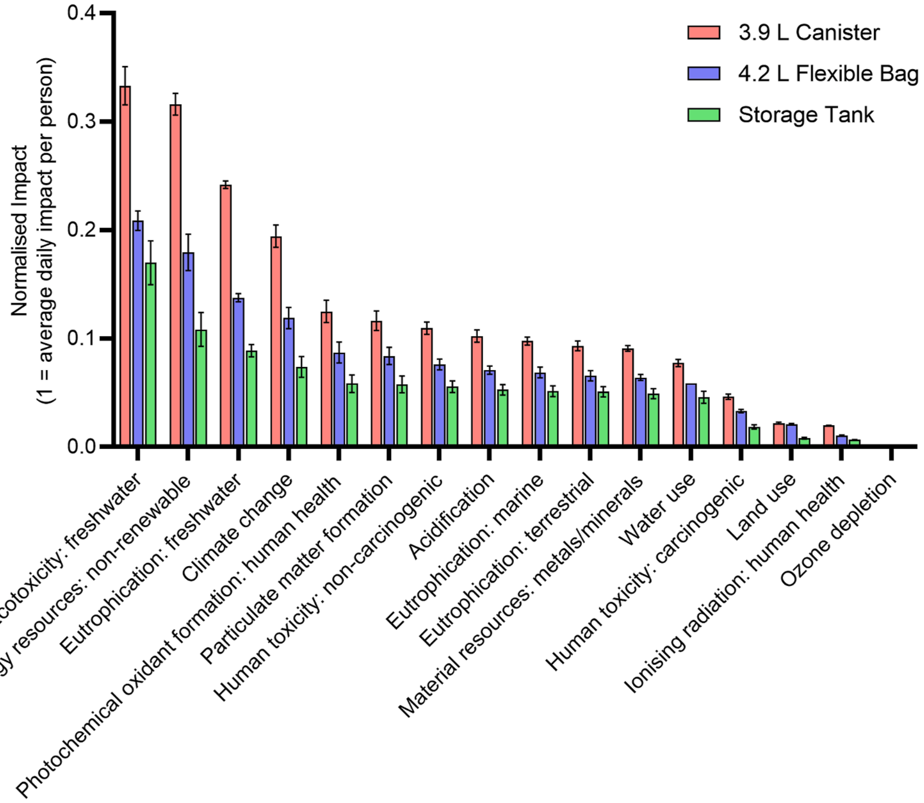

Figure 5. Bar plot of the normalized impact category results for the different dialysate acid concentrate containers when used in one hemodialysis session. Data are expressed as the average daily impact per person (95% CI). CO_2eq, CO_2 equivalent.

the average daily freshwater ecotoxicity impact of an individual, compared with 20.9% and 17.0% for the 4.2-L flexible bag and storage tanks, respectively. This trend is echoed in nonrenewable energy use, which is driven by transportation processes. Using the 3.9-L canister increases the average nonrenewable energy use by the patient by 31.6%, compared with 17.9% and 10.8% for the 4.2-L flexible bag and storage tanks, respectively. Finally, freshwater eutrophication is driven by nutrient runoff,[23] whereby the use of 3.9-L canisters increases the patient's contribution by 24.2%, compared with 13.8% and 8.9% for the 4.2-L flexible bag and storage tanks (Table S5).

To mitigate the environmental impact of dialysis, reducing reliance on distribution centers, implementing localized distribution networks, and adopting direct delivery models could minimize transportation emissions. Transitioning to electric or green-energy vehicles would further reduce carbon emissions. Furthermore, the adoption of in situ production of powder-based dialysate, which is currently not used in the studied centers, offers financial and environmental savings by reducing transportation and storage needs at the same time it reduces the carbon footprint and medical waste from liquid concentrates. However, it requires significant initial investment and trained personnel.[24]

Some limitations should be acknowledged. Assumptions were carefully considered to ensure a comprehensive yet manageable analysis of the products' life-cycle environmental impacts. Nevertheless, they might slightly influence the carbon footprint, such as the type of plastic used in the 300-L storage tank or the use of nonhydrated forms of dialysate components. However, these assumptions would only marginally influence the results and not affect the conclusions. Moreover, if plastic is recycled instead of incinerated, the carbon footprint would be significantly reduced, despite the challenges with plastic recycling and microplastic generation.[25] Furthermore, no comprehensive assessment of the environmental impact of other aspects of hemodialysis, such as water or power use, is provided. Ongoing studies are addressing this point that is not adequately covered in the existing literature.[26]

In conclusion, the choice of dialysate acid concentrate container has a large environmental impact. Transitioning to centralized acid, research on implementing localized distribution networks, and exploring the environmental impact of replacing liquid acid concentrate with acid powder can increase the sustainability of hemodialysis treatment. To achieve these goals, tools like openLCA are essential for measuring environmental indicators in nephrology. Finally, the environmental impact of hemodialysis is inevitable and inherent to its implementation, but it can be minimized if sustainability is included in decision-making.

Supplementary Material

Supplementary File 1 (PDF)

Figure S1: Map of Spain showing the locations of the production facilities, logistic centers, dialysis centers, and waste disposal centers.

Figure S2: System boundaries for the life cycle of the different types of dialysate acid concentrate containers.

Table S1: Composition of 1 L of dialysate acid concentrate according to the manufacturer

Table S2: Description of the 16 impact categories

Table S3: Packaging specifications

Table S4: Percentage of the volume of the storage tanks consumed in one hemodialysis session

Table S5: Impact category results for each acid concentrate container type

Supplementary File 2 (XLSX). Dialysate acid concentrate info and number of hemodialysis sessions.

Supplementary File 3 (XLSX). Liquid production, liquid packaging, transport logistics, and acid bag format consumption per center.

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Impact of the Type of Dialysate Acid Concentrate Container on the Environmental Footprint of Hemodialysis Centers

Setting & Participants	Exposure & Outcomes	Results

Retrospective cross-sectional life-cycle assessment

15 hemodialysis centers in Spain

2022-2023

Exposure

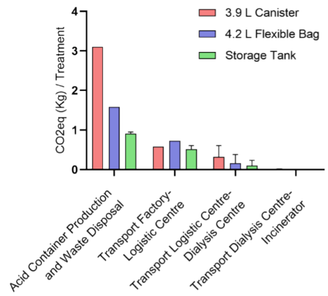
4 acid concentrate container types:
- Canisters (3.9 L)
- Flexible bags (4.2 L)
- Centralised storage tanks (300 L and 600 L)

Outcomes

Environmental impact of containers, measured by carbon footprint (CO_2eq in kg), and 16 additional impact categories

Carbon Footprint per Treatment:
- 3.9 L canister vs 4.2 L flexible bag: 1.63-fold higher
- 3.9 L canister vs storage tanks: 2.63-fold higher
- Storage tanks had lowest carbon footprint (*P*<0.001), with no difference between sizes

Largest Sources of Emissions:
- Plastic use
- Canister production
- Waste disposal



CONCLUSION: The choice of dialysate acid concentrate container is associated with a differential environmental impact.

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