Sustainable water filtration: Life Cycle Assessment of recycled Polysulfone membranes within a Circular Economy framework

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Introduction

The manufacturing of disposable medical devices in the MedTech industry leads to the generation of plastic waste, particularly from polymeric hollow fiber membranes (HFM). During the assembly process, HFM bundles require resizing, resulting in significant amounts of scrap material that must be managed as plastic waste. Manufacturers of hollow fiber membranes in polysulfone (PSU), polyethersulfone (PES), and polysulfone enriched with graphene oxide (PSU-GO), produce tons of HFM scraps annually as a by-product of its production and assembly processes. This study explores strategies for repurposing these polymeric scraps as granular sorbent material, aligning with circular economy principles to enhance sustainability in the MedTech sector, leveraging upon the case study of Medica S.p.A., the only Italian hollow fibers manufacturer.
The proposed materials can be integrated into commercialized products, such as cartridges for Point-of-Use (PoU) drinking water treatment systems, prototypes are shown in Figure.1. Alternatively, they can be utilized in municipal water purification plants as an enhancement to existing quaternary treatment technologies, such as Granular Activated Carbon (GAC) and Reverse Osmosis (RO), to improve water refinement efficiency.

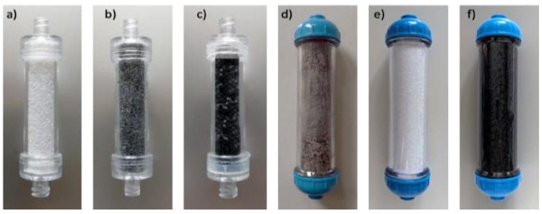

Figure 1. Cartridge filled with granules: a-c: prototypes, d-f standard sized cartridges. a) PSU (0.4 g), b) PSU-GO (0.73 g), c) GAC (2.3 g), d) PSU-GO granules (33 g), e) PSU granules (33 g), f) GAC (130 g).

In specific, the aim of the study is to explore the second life of HFM scraps of PSU by repurposing them as granular adsorbents for water filtration, thereby extending their lifecycle. Eco-design and Life Cycle Thinking should be the standard framework for developing remediation technologies to prevent environmental trade-offs, such as achieving higher performance at the cost of increased resource consumption or waste generation (Omer et al., 2025). A comprehensive Life Cycle Assessment (LCA) was conducted to evaluate the environmental impact of reusing HFM scraps generated by Medica S.p.A. during medical device manufacturing. The preliminary findings assess the environmental sustainability of this approach and highlight the potential benefit of adopting PSU-based filtration systems. This initiative aligns with circular economy principles and aims to mitigate pollution by reducing industrial waste while enhancing water treatment technologies.

Materials and methods

A LCA was conducted to evaluate the environmental impact of PSU-derived granular adsorbents. In specific, the study assessed the environmental impact of PSU filter production at both laboratory and industrial scales, comparing it to conventional filtration methods, including RO and GAC filtration. The LCA methodology, in compliance with ISO 14040:2006, following a gate-to gate approach. The first part of LCA study considered the phases from the utilization of PSU scraps to the assembly and creation of the filtration device; the second part of the LCA considered 2 scenarios: the current state-of-the-art of water filtration and the project one. The choice of Functional Unit (FU) was different for the two parts; for the first part of LCA a single finished filter was selected, for the second part, 1000 liter of filtered water.
An *ad hoc* checklist for primary data collection was designed. Medica S.p.a. manufacturer was visited and interviewed the experts for collecting the necessary documents. The collected data and documents were transferred to Microsoft Excel files. For secondary data, that could not be collected on-site, default values were defined based on the processes available on Ecoinvent and Industrial Data databases, with geographical reference to Italy or the European context and literature reviews. The life cycle impact assessment (LCIA) was carried out using the SimaPro software v 9.2 alongside the Ecoinvent v.3.8 and Industrial Data 2.0 databases. The assessment was performed with Recipe2016 method and endpoint categories investigated, focusing on the eight (8) impact

categories: Global Warming Potential Human Health, Global Warming Potential Terrestrial Ecosystem, Global Warming Potential Freshwater Ecosystem, Marine ecotoxicity, Human carcinogenic toxicity, Water consumption Human health, Water consumption, Terrestrial ecosystem, Water consumption, Aquatic ecosystem. These impact categories were selected after an extensive literature review and based on their application in environmental impact assessments of water filtration system (Prézélus et al., 2021; Yadav et al., 2021). The results were analyzed to identify environmental hotspots and potential areas for improvement.

Results and discussion

Preliminary LCA of the second phase of LCA results indicate a favourable environmental impact of PSU-derived adsorbents, particularly in reducing greenhouse gas (GHG) emissions compared to conventional filtration methods (i.e. GAC and RO). The environmental assessment highlighted key impact categories, including global warming potential (GWP), water consumption, and human toxicity. The impact assessment highlighted that fiber grinding and energy consumption in PSU filter production are key contributors to global warming potential and other environmental burdens. Transport emissions were found to be negligible.

A comparative analysis with RO and GAC filters revealed that PSU filters have significantly lower environmental impacts in most categories, except for energy consumption during the production phase. The major findings, showed in Figure 2, include: -PSU filters reduce water consumption compared to RO filters, which produce high wastewater volumes; - PSU-based filtration system demonstrates competitive environmental performance in comparison to GAC filters in terms of global warming potential; - PSU filter production process can be optimized by integrating renewable energy sources.

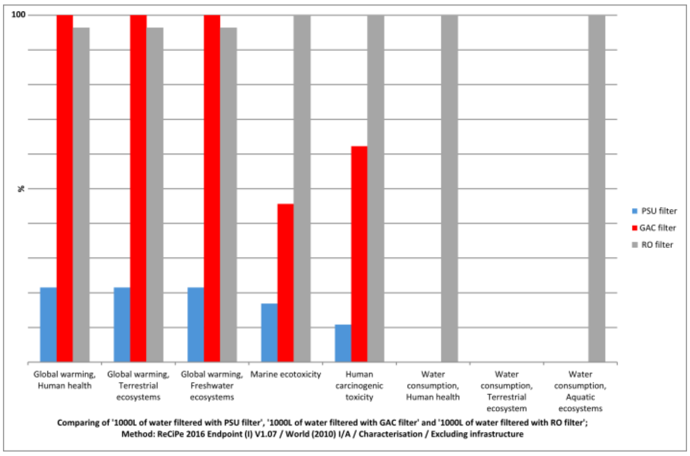

Figure 2. Comparison of impact results of PSU, GAC, and RO filters

Conclusions

The preliminary LCA results highlight the potential of reusing PSU scraps for water filtration as a sustainable and cost-effective solution. Future research will refine the LCA model with other primary data from demonstration sites and assess economic feasibility through Life Cycle Costing. PSU granules show promise for both PoU and municipal water treatment applications, complementing existing technologies such as GAC and RO. However, large-scale adoption requires further validation through pilot studies and stakeholder engagement. A structured monitoring framework ensures ongoing evaluation of environmental performance, supporting the integration of PSU-derived adsorbents into existing water treatment systems.

In future studies a socio-economic assessment will be undertaken to quantify the broader implications of the technology on market adoption and cost-effectiveness. A structured monitoring framework will be developed to systematically collect and analyze data related to environmental and socio-economic impacts.

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