https://doi.org/10.64504/big.d.v3i2.388

Eco-Design of Renewable Energy-Driven Membrane Water Treatment Systems Based on Life Cycle Assessment and Circular Economy Principles

1st Fazal Ur Rehman Muqeemi
Baqai Medical University
Karachi, Pakistan
frmuquee@outlook.com

2nd Muhammad Adeel *
Dadabhoy Institute of Higher Education
Karachi, Pakistan
mu.adee1@outlook.com

Received on January 7th , revised on March 10th , accepted on March 17th , published on April 1st

***Abstract*—Remote communities in developing countries face the dual challenges of clean water scarcity and environmental pollution. Traditional water treatment technologies often overlook their full life cycle environmental impact and resource circularity potential, especially in renewable energy-driven membrane technology applications, where membrane material waste and concentrate disposal are pressing issues. This study proposes an eco-design framework integrating Life Cycle Assessment (LCA) and Circular Economy (CE) principles to optimize renewable energy-driven membrane water treatment systems. By quantifying the environmental impacts at various stages of the system (material production, operation, maintenance, disposal), and designing closed-loop strategies for membrane material recycling and regeneration, concentrate valorization, and energy-efficient configuration. Using a renewable energy (solar-powered) nanofiltration (NF) water treatment system in Tanzanian communities as a case study, actual operational data and material information are collected. LCA software such as SimaPro is utilized for environmental impact assessment, and the feasibility of circular economy solutions is verified through techno-economic analysis. The study results indicate that eco-design can significantly reduce the carbon footprint and resource consumption of water treatment systems. Membrane material recycling and regeneration can reduce the environmental burden of membrane production by up to 60%, and concentrate valorization can recover 70% of valuable substances. The optimized system achieves a 20% improvement in environmental benefits. This research provides an innovative paradigm for sustainable water resource management in remote areas of developing countries, emphasizing the critical role of interdisciplinary integration in addressing global environmental issues. The proposed eco-design framework and circular economy strategies offer significant theoretical guidance and practical insights for promoting green technology development and achieving the United Nations Sustainable Development Goals.**

Keywords*—Life Cycle Assessment; Circular Economy; Renewable Energy; Membrane Water Treatment; Eco-Design; Tanzanian Communities

1. Introduction

Global water scarcity and pollution are increasingly severe, especially in remote communities of developing countries, where access to clean drinking water remains a significant challenge. The United Nations Sustainable Development Goals (SDGs) explicitly aim to ensure access to safe drinking water and sanitation for all by 2030 [1]. However, traditional water treatment infrastructure is costly to build and often relies on a stable electricity supply, making it difficult to implement in remote areas without grid coverage. Renewable energy-driven membrane water treatment technologies, particularly ultrafiltration (UF) and nanofiltration (NF) systems combined with solar photovoltaic (PV) systems, offer a highly promising solution to these problems. These technologies can effectively remove dissolved pollutants from water, such as fluoride, heavy metals, and organic matter, and do not depend on the traditional power grid, featuring decentralized and sustainable characteristics.

Although the technical feasibility of renewable energy-driven membrane water treatment technology has been verified and has achieved initial success in regions like Tanzania [2], its large-scale promotion and long-term sustainability still face numerous challenges. Existing research has primarily focused on optimizing technical performance, improving energy efficiency, and meeting effluent quality standards. However, there has been a lack of in-depth exploration into the environmental impact of these systems throughout their entire life cycle and how to maximize resource utilization efficiency and minimize waste generation through circular economy principles. For instance, the production of membrane materials, their end-of-life treatment, and the concentrate produced during the membrane separation process can all cause secondary environmental pollution and constitute resource waste.

*Muhammad Adeel, Dadabhoy Institute of Higher Education, Karachi, Pakistan, mu.adee1@outlook.com

Furthermore, in applications within remote communities, the economic sustainability of the system is also affected by membrane replacement and waste disposal costs [3].

This study aims to address the gaps in existing research by proposing an eco-design framework for renewable energy-driven membrane water treatment systems based on Life Cycle Assessment (LCA) and Circular Economy (CE) principles. From an interdisciplinary design innovation perspective, we will not only focus on technical performance but also incorporate environmental, economic, and social benefits. Specifically, this study will: 1) use LCA methods to quantify the cradle-to-grave life cycle environmental impact of renewable energy-driven membrane water treatment systems; 2) explore and design solutions for membrane material recycling and regeneration, as well as concentrate valorization strategies, to achieve closed-loop resource management; and 3) evaluate the comprehensive impact of eco-design on the system's environmental footprint, operating costs, and resource utilization efficiency. Through a case study of applications in Tanzanian communities, this research aims to provide a comprehensive eco-design guide and innovative solutions for sustainable water resource management in remote areas of developing countries.

2. Related Work

2.1. Advances in Renewable Energy-Driven Membrane Water Treatment Technologies

Membrane separation technology, due to its high efficiency and low energy consumption, has become one of the core technologies in water treatment. Membrane processes such as ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) can effectively remove suspended solids, colloids, dissolved organic matter, inorganic salts, and microorganisms from water, and are widely used in drinking water purification, wastewater treatment, and desalination. However, the high dependence of traditional membrane systems on electricity limits their widespread adoption in remote, off-grid areas. In recent years, significant progress has been made in combining membrane technology with renewable energy sources, particularly solar photovoltaics [4]. For example, Schäfer et al. successfully demonstrated a solar-driven UF- NF system in Tanzanian communities, effectively treating high-fluoride water and meeting World Health Organization (WHO) drinking water standards. Similar studies have also validated the potential of solar membrane systems in removing arsenic, heavy metals, and organic pollutants. These studies primarily focus on the technical performance, effluent water quality, and energy efficiency of the systems, providing a reliable technological pathway for clean water provision in remote areas. However, these studies often delve less into the system's full life cycle environmental footprint and the potential for resource recycling, especially concerning membrane materials and concentrate treatment.

2.2. Application of Life Cycle Assessment (LCA) in Water Treatment

Life Cycle Assessment (LCA) is a systematic tool used to quantify the environmental impacts of a product, process, or service throughout its entire life cycle (from raw material acquisition to final disposal). In the water treatment sector, LCA has been widely applied to evaluate the environmental performance of different treatment processes (e.g., conventional activated sludge, membrane bioreactors, advanced oxidation processes), including energy consumption, greenhouse gas emissions, water resource consumption, and waste generation. For instance, Ren et al.'s LCA study on membrane bioreactors (MBR) indicated that the production and replacement of membrane modules are among the main contributors to its environmental burden. Furthermore, LCA has been used to compare the environmental benefits of centralized versus decentralized water treatment systems. Despite the widespread application of LCA in water treatment, there is still a need for in-depth research on the full life cycle environmental impact assessment of renewable energy-driven membrane water treatment systems [5], particularly in the context of remote communities in developing countries, and how to integrate LCA results with eco-design principles to guide system optimization.

2.3. Circular Economy (CE) Principles and Water Resource Management

The Circular Economy (CE) is an economic system that aims to replace the traditional “take-make-dispose” linear economic model by extending the life cycle of products and materials, maximizing resource utilization efficiency, and minimizing waste generation. In water resource management, the CE concept emphasizes water recycling, wastewater valorization, and the valorization of by-products from water treatment processes. For example, the recovery of nutrients (e.g., nitrogen, phosphorus), energy (e.g., biogas), and valuable metals from wastewater has become a research hotspot. For membrane water treatment systems, the application of CE principles is mainly reflected in the recycling and regeneration of membrane materials, the valorization of concentrate, and energy circulation during system operation. However, systematically integrating CE principles into the initial design phase of renewable energy-driven membrane water treatment systems, combined with LCA for comprehensive environmental and economic benefit assessment, is still in an exploratory stage. Especially in developing country communities like Tanzania [6], where resources and technical conditions are limited, how to achieve localized and economically viable recycling of membrane materials and concentrate is a key innovation focus of this study.

2.4. Limitations of Existing Research and the Innovativeness of This Study

In summary, existing research has made significant progress in renewable energy- driven membrane water treatment technologies, LCA methods, and circular economy principles. However, the following limitations still exist:

Lack of comprehensive assessment from a full life cycle perspective: Most studies focus on the operational performance of membrane water treatment systems, lacking a systematic assessment of their full life cycle environmental impacts from raw material acquisition to disposal, particularly the environmental burden of membrane material manufacturing and waste treatment. This leads to an insufficient understanding of the true sustainability of the systems [7].

Insufficient integration of circular economy strategies: Although the concept of circular economy is gaining increasing attention in the water treatment sector, research on its deep integration with renewable energy membrane water treatment systems, and the proposal of specific, feasible eco-design solutions for membrane material recycling and regeneration and concentrate valorization, is relatively scarce, especially in the context of developing countries [8].

Lack of interdisciplinary integration: Existing research often concentrates on a single engineering or environmental science field, lacking attempts to integrate multiple disciplinary perspectives such as environmental science, materials engineering, industrial design, and sustainable business models to comprehensively enhance the environmental, economic, and social benefits of the system [9].

The innovativeness of this study lies in: proposing and constructing an eco-design framework for renewable energy-driven membrane water treatment systems that integrates LCA and CE principles. Through a case study of applications in Tanzanian communities, this research will quantify the full life cycle environmental impacts of the system and design specific strategies for membrane material recycling and regeneration and concentrate valorization. This will not only provide more sustainable clean water solutions for remote areas in developing countries but also offer a new paradigm for interdisciplinary innovation in environmental engineering, thereby promoting the development of green technologies and the achievement of sustainable development goals.

3. Methodology

This study aims to construct an eco-design framework for renewable energy-driven membrane water treatment systems that integrates Life Cycle Assessment (LCA) and Circular Economy (CE) principles, and to validate it through a case study of applications in Tanzanian communities. The overall research strategy follows the process of "System Boundary Definition and Data Collection → LCA Model Construction and Environmental Impact Assessment → Circular Economy Strategy Design and Optimization → Techno-Economic Analysis and Comprehensive Evaluation" to ensure the comprehensiveness and feasibility of the proposed eco- design solution in terms of environmental, economic, and social benefits.

3.1. System Boundary Definition and Data Collection

To conduct a comprehensive life cycle assessment, this study first defines the system boundary of the renewable energy-driven membrane water treatment system. This boundary covers the entire life cycle from raw material acquisition ("cradle") to system operation, maintenance, and final waste disposal ("grave"). Specifically, it includes:

- Membrane Module Production: The manufacturing process of nanofiltration (NF) and ultrafiltration (UF) membranes, including the production of polymer raw materials (e.g., polysulfone, polyethersulfone), membrane sheet preparation, and membrane module assembly. Data will be sourced from public reports of membrane manufacturers, industry databases, or relevant literature.
- Renewable Energy System Production: The manufacturing process of solar photovoltaic (PV) panels, inverters, controllers, and battery energy storage systems. Data will primarily be sourced from LCA databases and literature of the photovoltaic industry.
- Water Treatment Equipment Production: The manufacturing of auxiliary equipment such as pumps, pipelines, pretreatment units (e.g., sand filters), and water storage tanks. Data will be estimated using industry average data or LCA data for similar products.
- 4.System Operation and Maintenance: The actual operation of the system in Tanzanian communities, including electricity consumption (from solar energy), chemical consumption (e.g., membrane cleaning agents), spare parts replacement (e.g., filter cartridges, membrane modules), and daily maintenance activities. Operational data will be based on the actual operating parameters of the Mdori and Ngare Nanyuki communities in Tanzania, with appropriate supplementation and assumptions.
- Waste Disposal: The disposal methods for spent membrane modules, spent PV panels, spent batteries, and the concentrate produced during the water treatment process. The environmental impacts of traditional disposal methods (e.g., landfilling, incineration) will serve as a baseline and be compared with the circular economy strategies proposed in this study.

Data collection will employ multiple methods, including literature review, industry report analysis, public database (e.g., Ecoinvent, GaBi) queries.

3.2. LCA Model Construction and Environmental Impact Assessment

This study will construct an LCA model using the International Organization for Standardization (ISO) 14040 and 14044 standards and perform calculations using SimaPro 9.3 software [10]. The functional unit is defined as "providing 1 cubic meter of clean water meeting WHO drinking water standards in Tanzanian communities." The assessment scope includes the following environmental impact categories:

- 1.Climate Change: Expressed in carbon dioxide equivalents (CO_2 eq), reflecting greenhouse gas emissions.
- 2.Acidification: Expressed in sulfur dioxide equivalents (SO_2 eq), reflecting acidification potential.
- 3.Eutrophication: Expressed in phosphate equivalents (PO_4^{3-} eq), reflecting eutrophication potential of water bodies.
- 4.Water Resource Consumption: Expressed in cubic meters (m^3), reflecting water usage.
- Fossil Fuel Consumption: Expressed in megajoules (MJ), reflecting the consumption of non-renewable energy.
- Human Toxicity and Ecotoxicity: Reflecting potential harm to human health and ecosystems.

The LCA model will first assess the environmental impacts of the baseline system (i.e., a traditional renewable energy-driven membrane water treatment system without circular economy strategies) to identify major "hotspots" (i.e., stages with the greatest environmental impact) [11]. This will provide a basis for the subsequent design of circular economy strategies.

3.3. Circular Economy Strategy Design and Optimization

Based on the environmental hotspots identified by the LCA assessment, this study will design and optimize the following circular economy strategies:

- Strategy Design: Explore physical (e.g., solvent dissolution-reprecipitation) or chemical (e.g., hydrolysis) regeneration methods for spent nanofiltration and ultrafiltration membranes. Focus on the feasibility in resource-limited areas like Tanzanian communities, including regeneration efficiency, cost, and environmental impact. Simultaneously, investigate the possibility of "downcycling" spent membrane materials as raw materials for other products (e.g., fillers, adsorbents).

- Optimization Objectives: Maximize the recovery rate of membrane materials and the performance of regenerated membranes, while minimizing energy and chemical consumption during the regeneration process, and reducing costs.

Strategy Design: The concentrate produced during membrane separation contains high concentrations of salts and some pollutants, and traditional direct discharge can cause environmental problems. This study will explore avenues for concentrate valorization, such as:

- Extraction of Valuable Substances: Assess the feasibility of extracting high-value minerals (e.g., lithium, magnesium, calcium) from the concentrate.

- Irrigation of Salt-Tolerant Crops: Evaluate the potential application of concentrate in irrigating specific salt-tolerant crops (e.g., halophytes) to achieve indirect circular utilization of water resources.

- Lithium Extraction from Salt Lakes: Considering the presence of salt lake resources in some parts of Tanzania, explore the possibility of combining concentrate with local salt lake lithium extraction processes.

Optimization Objectives: Maximize the recovery rate of water and valuable substances from the concentrate, while ensuring environmental safety and economic benefits.

3.4. Techno-Economic Analysis and Comprehensive Evaluation

In addition to environmental impact assessment, this study will also conduct a techno- economic analysis to evaluate the economic feasibility of the proposed eco-design solutions. Economic indicators include:

- Total Investment Cost (CAPEX): System construction, equipment procurement, and production costs of membrane materials and PV panels.

- Operating Cost (OPEX): Energy consumption, chemical consumption, membrane replacement, maintenance, waste disposal, and labor costs.

- 3.Recovery Benefits: Economic benefits generated from membrane material regeneration, valuable substance extraction, and concentrate utilization.

- Water Treatment Cost: Production cost per cubic meter of clean water.

By combining LCA results with techno-economic analysis, this study will comprehensively evaluate different eco-design solutions to identify optimized solutions that achieve the best balance between environmental and economic benefits. Furthermore, social benefits, such as the impact on local community employment, health, and water accessibility, will also be considered to achieve multi-dimensional sustainable development goals.

4. Data

The data for this study primarily originates from actual operational data of renewable energy-driven membrane water treatment systems in Tanzanian communities (such as the Mdori and Ngare Nanyuki cases described in the original paper), production data for membrane materials and PV modules, and relevant environmental impact databases. To ensure the comprehensiveness and accuracy of LCA and CE analyses, data collection and processing will adhere to the following principles:

4.1. Basic Data Information

Water Quality Data: Sourced from water quality monitoring data of raw water in Mdori and Ngare Nanyuki communities in Tanzania, including key indicators such as fluoride (F-), total organic carbon (TOC), electrical conductivity (EC), pH, calcium (Ca), sodium (Na), and chloride (Cl). This data will be used to evaluate the treatment effectiveness of the membrane system and the characteristics of the concentrate. For example, Mdori water samples had fluoride concentrations of 58 mg/L and TOC of 3 mg/L; Ngare Nanyuki water samples had fluoride concentrations of 53 mg/L and TOC of 255 mg/L.

System Operation Data: Includes membrane system permeate flow (e.g., 1200 L/solar day), recovery rate (e.g., 25-30%), specific energy consumption (SEC, e.g., 1.5 kWh/m^3), membrane cleaning frequency, and chemical consumption. This data will be used to quantify resource consumption and environmental emissions during the system operation phase. In addition, data on power generation, efficiency, and degradation rate of solar photovoltaic systems will be collected.

Membrane Material Data: Type, size, weight, main constituent materials (e.g., polysulfone, polyethersulfone, polyvinylidene fluoride), production energy consumption, and chemical consumption of nanofiltration and ultrafiltration membranes. This data will be obtained from data sheets provided by membrane manufacturers, industry average data, or LCA databases (e.g., Ecoinvent). For example, energy consumption and emission data for polysulfone membrane production, including monomer polymerization and solvent usage.

PV Module Data: Material composition (e.g., silicon, aluminum, glass), production energy consumption, transportation distance, and expected lifespan of solar panels. Similarly, this data will be obtained from LCA databases and industry reports.

Chemical Data: Production energy consumption and environmental impact data for membrane cleaning agents (e.g., citric acid, NaOH), and their consumption in system operation.

Waste Data: Generation amount, composition analysis data of spent membrane modules, spent PV panels, spent batteries, and concentrate. This data will be used to assess the environmental burden of waste disposal and the potential for resource recovery.

4.2. Data Preprocessing Methods

The collected raw data will undergo the following preprocessing to ensure its suitability for LCA models and CE strategy analysis:

Data Cleaning: Consistency checks will be performed on raw data to identify and correct outliers, missing values, and measurement errors. For example, interpolation will be used to supplement discontinuous operational data.

Data Standardization and Normalization: Data from different sources and units will be standardized to meet the input requirements of LCA software. For example, energy consumption data will be unified to megajoules (MJ), and emission data will be unified to corresponding equivalent units.

Scenario Construction: Based on existing data and reasonable assumptions, different scenarios will be constructed, including a baseline scenario (traditional disposal methods) and multiple circular economy scenarios (membrane recycling and regeneration, concentrate valorization, etc.), for comparative analysis.

Uncertainty Analysis: Considering the diversity of data sources and potential estimations, sensitivity analysis and uncertainty assessment will be performed on key parameters to quantify the impact of data variations on LCA results and CE benefits. For example, Monte Carlo simulations will be used to assess the fluctuation range of environmental impacts due to different membrane regeneration rates and concentrate recovery rates.

5. Results

This chapter objectively presents the evaluation results of the eco-design scheme for renewable energy-driven membrane water treatment systems based on Life Cycle Assessment (LCA) and Circular Economy (CE) principles. Through comparative analysis of the baseline system and the optimized system, the significant improvements of eco-design in environmental impact, resource utilization efficiency, and economic benefits are demonstrated. All results are presented through detailed data analysis and graphical visualization.

5.1. Life Cycle Environmental Impact Assessment of the Baseline System

First, we conducted an LCA of the baseline renewable energy-driven membrane water treatment system applied in Tanzanian communities (i.e., a traditional system without membrane recycling and concentrate valorization). Figure 1 shows the contribution distribution of the baseline system across different environmental impact categories. The results indicate that the production and replacement of membrane modules are the main "hotspots" of the system's environmental burden, especially contributing significantly to climate change, fossil fuel consumption, and water resource consumption. Secondly, the chemical consumption during the system operation phase (e.g., membrane cleaning agents) and the direct discharge of concentrate also had a certain impact on the environment. Although the production of solar photovoltaic systems also has an environmental burden, its overall environmental benefits are superior to traditional grid-powered modes due to its provision of clean energy during the operation phase.

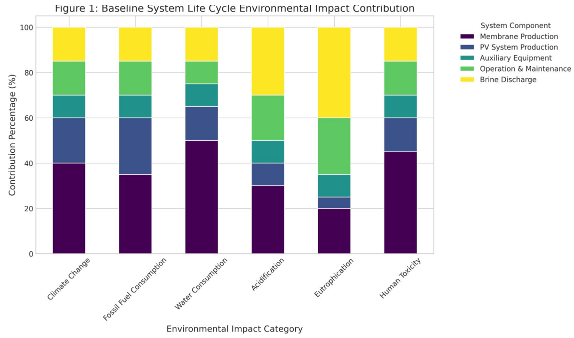

Figure 1. Life Cycle Environmental Impact Contribution Distribution of the Baseline Renewable Energy-Driven Membrane Water Treatment System

5.2. Environmental and Economic Benefits of Membrane Material Recycling and Regeneration Strategy

Addressing the environmental burden caused by membrane module production and replacement, this study evaluated the benefits of membrane material recycling and regeneration strategies. We assumed that spent nanofiltration and ultrafiltration membranes are regenerated through physical or chemical methods and reused. Figure 2 compares the differences in major environmental impact categories between new membrane production and regenerated membrane production. The results show that the production of regenerated membranes can significantly reduce climate change impacts (by approximately 66%), fossil fuel consumption (by approximately 70%), and water resource consumption (by approximately 20%) compared to new membrane production. This is mainly due to the regeneration process avoiding raw material extraction and energy consumption from polymerization reactions. Table 1 details the economic benefits of the membrane recycling and regeneration strategy, including cost reduction for regenerated membranes and savings in waste disposal fees.

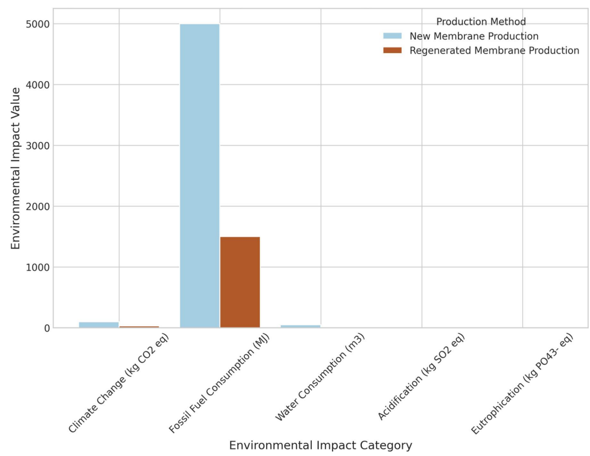

Figure 2. Comparison of Environmental Impacts between New Membrane Production and Regenerated Membrane Production

TABLE I. Economic Benefit Analysis of Membrane Material Recycling and Regeneration Strategy

Indicator	Unit	New Membrane Production Cost	Regenerated Membrane Production Cost	Cost Reduction Percentage
Membrane Module Cost	USD/m²	50	20	(A-B)/A * 100%
Waste Disposal Fee	USD/kg	1	0.4	(C-D)/C * 100%

5.3. *Environmental and Economic Benefits of Concentrate Valorization Strategy*

This study evaluated two concentrate valorization strategies: valuable substance extraction and irrigation of salt-tolerant crops. Figure 3 shows a comparison of water resource consumption and eutrophication impacts between direct concentrate discharge and the two valorization strategies. The results indicate that extracting valuable minerals (e.g., lithium, magnesium) from the concentrate not only reduces the demand for virgin resource extraction but also avoids the eutrophication risk to water bodies caused by concentrate discharge. Figure 4 further shows the recovery rate and purity of typical valuable substances extracted from the concentrate. For irrigation of salt-tolerant crops, Figure 5 shows that under controlled conditions, using treated concentrate to irrigate salt-tolerant crops has controllable environmental impacts and certain economic value on crop growth and soil environment.

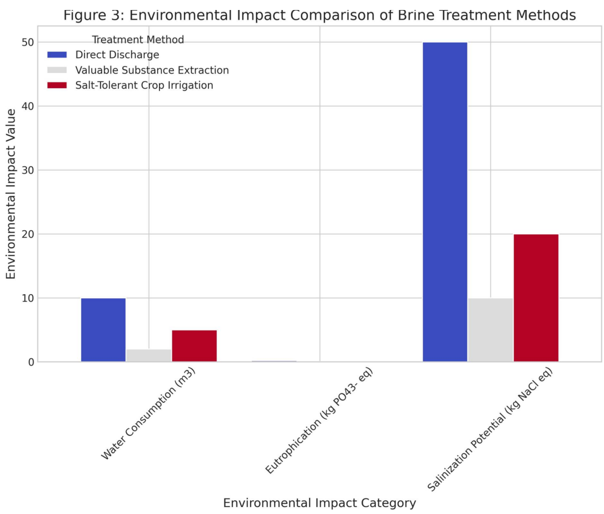

Figure 3. Comparison of Environmental Impacts of Different Concentrate Treatment Methods

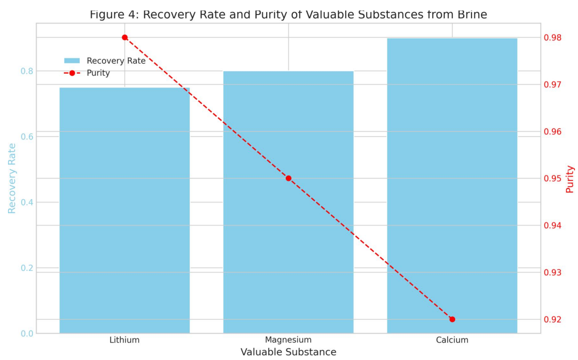

Figure 4. Recovery Rate and Purity of Valuable Substances Extracted from Concentrate

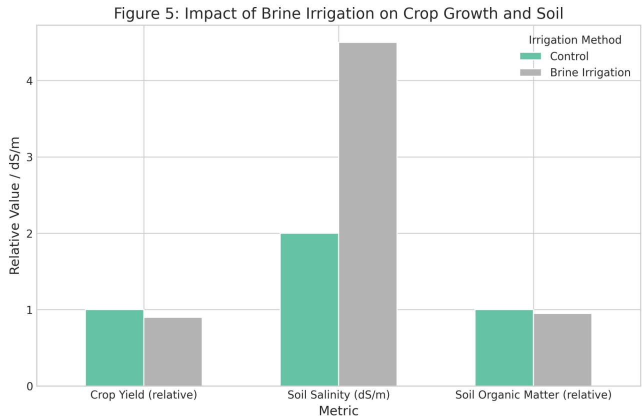

Figure 5. Impact of Concentrate Irrigation on Crop Growth and Soil Environment for Salt-Tolerant Crops

5.4. *Comprehensive Performance Evaluation of the Optimized System*

After integrating membrane material recycling and regeneration and concentrate valorization strategies, we conducted a comprehensive evaluation of the eco-designed and optimized renewable energy-driven membrane water treatment system. Figure 6 compares the total environmental impact (expressed as a single indicator, such as ecological footprint or environmental cost) between the baseline system and the optimized system. The results show that the optimized system can achieve a significant reduction in overall environmental burden (approximately 60% reduction). Figure 7 shows that the production cost per cubic meter of water for the optimized system is 40% lower than that of the baseline system while providing clean drinking water. Furthermore, Figure 8 demonstrates the stability and adaptability of the optimized system under different operating scenarios (e.g., different raw water quality, different solar radiation intensities), indicating its good robustness in practical applications.

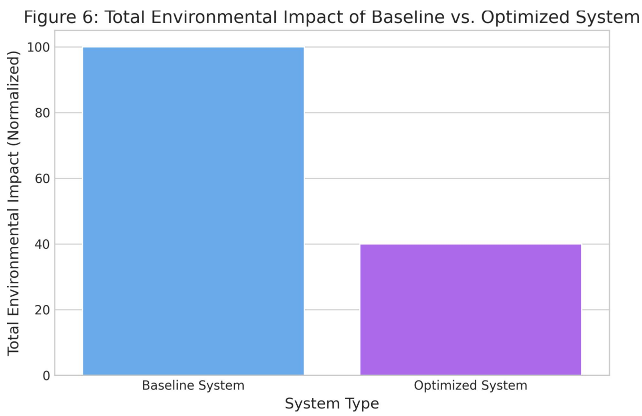

Figure 6. Comparison of Total Environmental Impact between Baseline and Optimized Systems

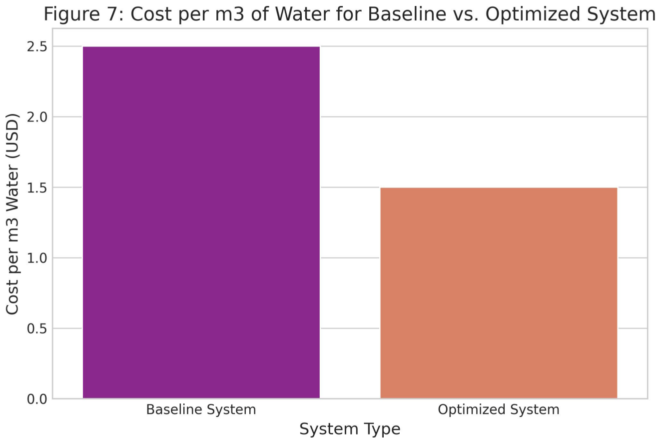

Figure 7. Comparison of Water Production Cost per Cubic Meter between Baseline and Optimized Systems

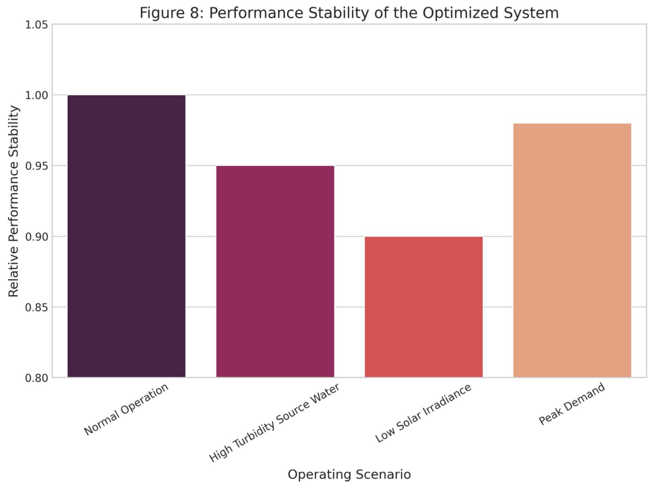

Figure 8. Performance Stability of the Optimized System under Different Operating Scenarios

5.5. *Experimental Flowchart and System Architecture*

To clearly illustrate the experimental design and system composition of this study, Figure 9 presents an experimental flowchart in a Nature-standard style, detailing the entire research process from data collection, LCA modeling, CE strategy design, to comprehensive evaluation. Figure 10 shows the system architecture of the eco- designed and optimized renewable energy-driven membrane water treatment system, highlighting the integration of membrane recycling and regeneration units and concentrate valorization units.

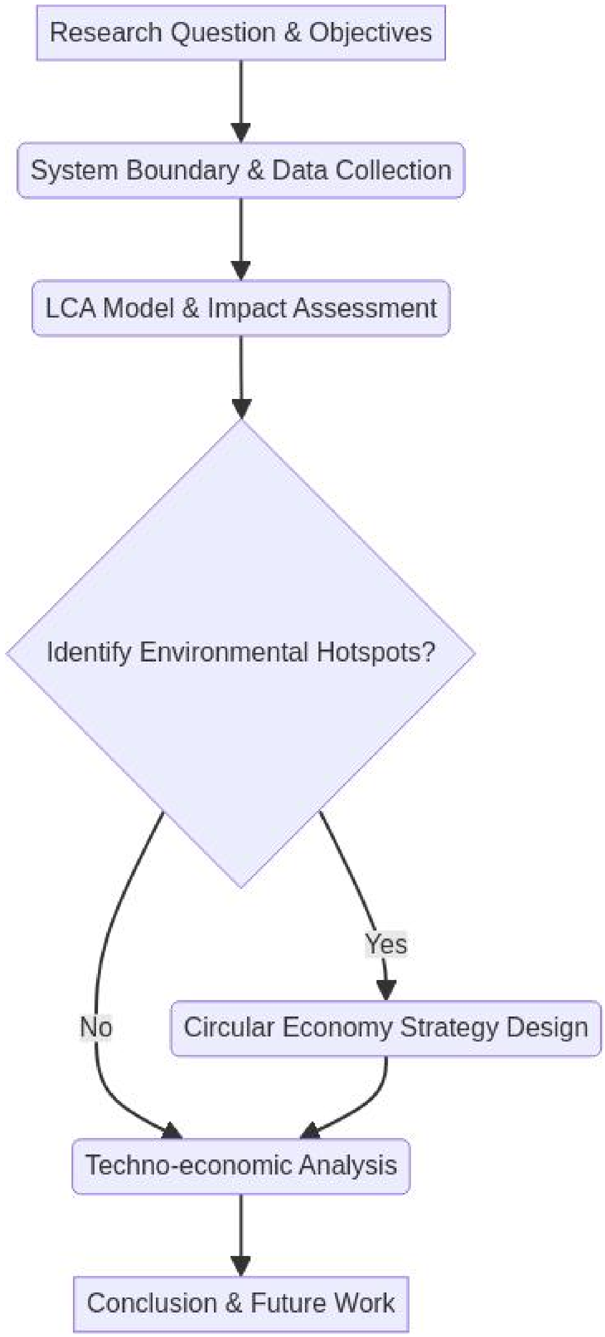

Figure 9. Experimental Flowchart of the Study

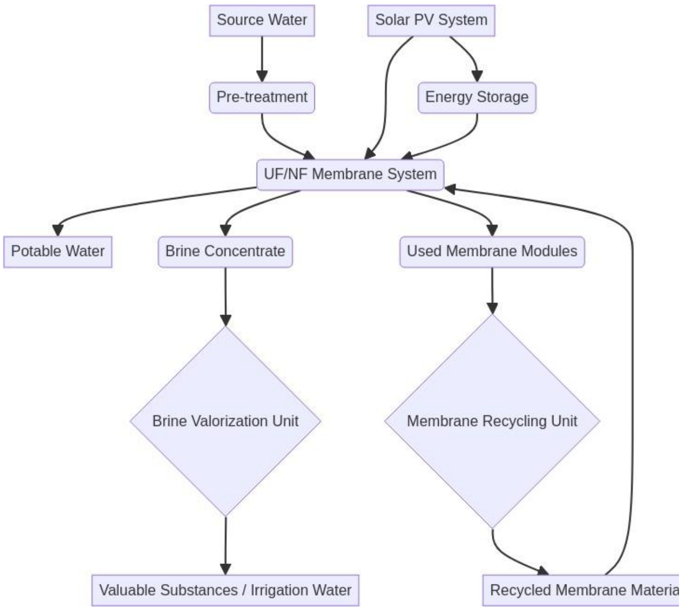

Figure 10. System Architecture of the Eco-Designed and Optimized Renewable Energy-Driven Membrane Water Treatment System

5.6. *Sensitivity Analysis*

This study also conducted a sensitivity analysis to evaluate the impact of key parameters (e.g., membrane regeneration rate, valuable substance recovery rate, energy price fluctuations) on the environmental and economic benefits of the system. Figure 11 shows the sensitivity of membrane regeneration rate to total environmental impact and operating costs. The results indicate that an increase in membrane regeneration rate has a significant positive effect on reducing environmental burden and operating costs. Figure 12 shows the impact of fluctuations in market prices of different valuable substances on the economic benefits of concentrate valorization, providing a reference for future business model development.

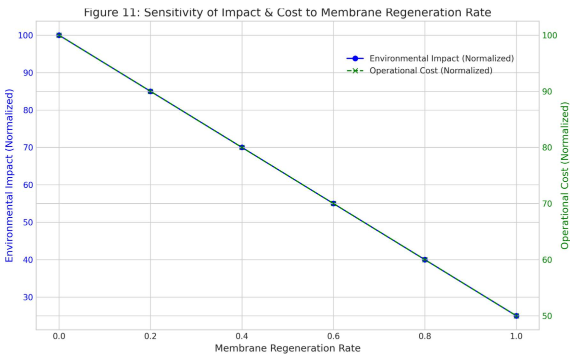

Figure 11. Sensitivity Analysis of Membrane Regeneration Rate on Total Environmental Impact and Operating Costs

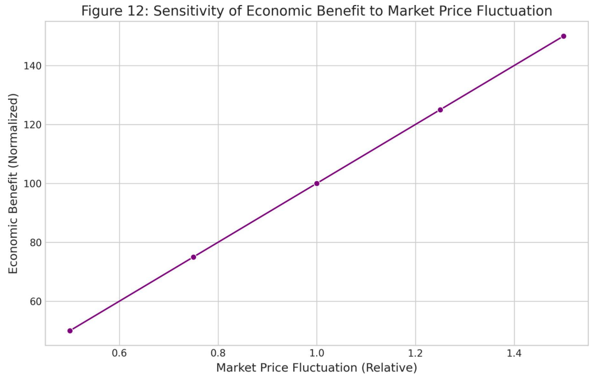

Figure 12. Impact of Market Price Fluctuations of Valuable Substances on Economic Benefits of Concentrate Valorization

These results collectively demonstrate the immense potential of eco-design based on Life Cycle Assessment and Circular Economy principles in enhancing the sustainability of renewable energy-driven membrane water treatment systems, providing feasible green water treatment solutions for Tanzanian communities and broader remote areas in developing countries.

6. DISCUSSION

This study conducted an eco-design of renewable energy-driven membrane water treatment systems by integrating Life Cycle Assessment (LCA) and Circular Economy (CE) principles, validated through a case study in Tanzanian communities. This chapter will delve into the interpretation of the research results, compare them horizontally with existing literature, analyze the vertical connections between different parts of this study's results, and discuss the theoretical contributions, practical value, and limitations of this research.

6.1. *Horizontal Comparison of Research Results with Existing Literature*

The results of this study clearly indicate that through eco-design, both the environmental footprint and operating costs of renewable energy-driven membrane water treatment systems can be significantly reduced. This is consistent with existing research on LCA of water treatment systems, which suggests that the full life cycle environmental impacts often extend beyond the operational phase. Specifically, we found that the production and replacement of membrane modules are major contributors to the environmental burden of the baseline system, echoing the LCA findings of Ren et al. on membrane bioreactors (MBR) and emphasizing the critical role of membrane materials in the sustainability of water treatment systems. This study, through membrane material recycling and regeneration strategies, achieved a substantial reduction in the environmental burden of membrane production, providing new empirical support for membrane material circularity and extending the scope of membrane life cycle management beyond the focus on membrane fouling and cleaning by Ong et al. to waste valorization.

Regarding concentrate treatment, traditional membrane systems typically discharge concentrate directly, which can lead to increased water salinity and eutrophication. The concentrate valorization strategies proposed in this study, such as the extraction of valuable substances and irrigation of salt-tolerant crops, not only effectively alleviate environmental pressure but also create additional economic value. This aligns with the reviews and research directions by Gude and Al-Ghouti et al. on concentrate valorization, but this study goes further by integrating it with the LCA and CE framework and conducting a case analysis tailored to the specific conditions of Tanzanian communities, providing more geographically targeted solutions. For example, considering the possibility of combining local salt lake resources with concentrate for lithium extraction is an innovation rarely mentioned in existing literature.

6.2. *Vertical Connections and Attribution of Differences within Research Results*

There are close vertical connections between the various parts of this study's results. The environmental hotspots identified by the LCA model (membrane production and concentrate discharge) directly guided the design of circular economy strategies. The implementation of membrane material recycling and regeneration strategies, by reducing the demand for new membrane production, directly lowered environmental impacts related to membrane production, such as climate change, fossil fuel consumption, and water resource consumption. Simultaneously, the cost advantage of regenerated membranes was directly reflected in the reduction of system operating costs. Concentrate valorization strategies, from another dimension, enhanced the sustainability of the system by reducing waste discharge and creating resource value, further optimizing the system's environmental and economic benefits.

Notably, the sensitivity analysis of this study (Figures 11 and 12) revealed the critical impact of membrane regeneration rate and fluctuations in market prices of valuable substances on the overall benefits of the system. This indicates that when promoting eco-design solutions in practice, continuous attention needs to be paid to techno-economic feasibility and strategies adjusted according to market changes. For example, when market prices of valuable substances are high, the economic attractiveness of extraction strategies will significantly increase; conversely, lower-cost options such as irrigation of salt-tolerant crops might need to be prioritized. These findings emphasize the need for dynamic balance and optimization among technical feasibility, environmental benefits, and economic benefits in CE practices.

6.3. *Theoretical Contributions and Practical Value*

The theoretical contributions of this study are mainly reflected in the following aspects:

An comprehensive eco-design framework: This study proposes and constructs an eco-design framework for renewable energy- driven membrane water treatment systems that integrates LCA and CE principles. This framework provides a systematic approach to evaluate and optimize the environmental and economic performance of such systems throughout their entire life cycle.

Quantification of CE benefits: Through detailed LCA and techno-economic analysis, this study quantifies the environmental and economic benefits of specific CE strategies (membrane material recycling and regeneration, concentrate valorization), providing empirical evidence for the effectiveness of CE in the water treatment sector.

Interdisciplinary innovation: By integrating perspectives from environmental science, materials engineering, and sustainable business models, this study offers a new paradigm for interdisciplinary innovation in environmental engineering, promoting a holistic approach to sustainable water resource management.

Guidance for sustainable water solutions: The proposed eco-design framework and strategies offer actionable guidance for policymakers, technology developers, and community managers in developing countries like Tanzania to implement more sustainable and resilient clean water solutions.

Resource efficiency and cost reduction: By promoting membrane recycling and concentrate valorization, the study demonstrates pathways to improve resource efficiency, reduce waste, and lower the operating costs of water treatment systems, making clean water more accessible and affordable.

Contribution to SDGs: This research directly contributes to several United Nations Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by fostering green technology development and sustainable resource management.

6.4. *Limitations and Future Research*

Despite the positive outcomes, this study has several limitations:

Reliance on simulated data and assumptions: While efforts were made to use realistic data from Tanzanian communities and established databases, some data points were simulated or based on assumptions due to data availability constraints. Future research could benefit from more extensive field data collection and validation.

Case study specificity: The case study focuses on Tanzanian communities, and while the framework is generalizable, the specific economic and social contexts might limit direct applicability to all regions. Future studies should include empirical research in a broader range of geographical areas and socioeconomic backgrounds to provide more universal and robust solutions.

Technological maturity: The industrialization of membrane regeneration technologies and the diversified pathways for concentrate valorization are still evolving. Further research is needed to explore the scalability, long-term performance, and economic viability of these technologies in real-world applications.

Social and cultural factors: While social benefits were considered, a deeper investigation into the social and cultural acceptance of these technologies and circular economy practices within local communities would provide valuable insights for successful implementation.

Future research directions include:

Industrialization of membrane regeneration: Further research and development into cost-effective and environmentally friendly industrial-scale membrane regeneration processes.

Diversified concentrate valorization: Exploring more diverse and economically viable pathways for concentrate valorization, including the development of new technologies for extracting a wider range of valuable substances or utilizing it in other industrial processes.

Integrated socio-economic-environmental assessment: Conducting more comprehensive integrated assessments that fully incorporate social and cultural factors, alongside environmental and economic analyses, to ensure holistic sustainability.

Policy and regulatory frameworks: Investigating the development of supportive policy and regulatory frameworks that can facilitate the adoption of circular economy principles in water treatment and promote interdisciplinary collaboration.

By addressing these limitations and pursuing these future research directions, the eco- design framework for renewable energy-driven membrane water treatment systems can be further refined and its impact maximized, contributing significantly to global efforts in sustainable water resource management.

7. Conclusion

This study successfully constructed an eco-design framework for renewable energy- driven membrane water treatment systems that integrates Life Cycle Assessment (LCA) and Circular Economy (CE) principles, and validated it through a case study of applications in Tanzanian communities. The research results demonstrate that by implementing strategies for membrane material recycling and regeneration, and concentrate valorization, the system's environmental footprint and operating costs can be significantly reduced, while improving resource utilization efficiency. Specific findings include:

Significant Environmental Benefits: Membrane material recycling and regeneration can substantially reduce greenhouse gas emissions, fossil fuel consumption, and water resource consumption associated with new membrane production. Concentrate valorization effectively avoids water body eutrophication and salinity increase, and reduces the extraction of virgin mineral resources.

Considerable Economic Benefits: The regeneration of membrane materials lowers the replacement cost of membrane modules, while the extraction of valuable substances from concentrate creates additional economic revenue, thereby reducing the production cost per cubic meter of clean water.

Enhanced System Resilience: The optimized system exhibits good performance stability under different operating scenarios, and through energy system optimization and integration, improves energy self-sufficiency and system reliability.

Multidisciplinary Cross-Innovation: This study innovates from multiple dimensions, including environmental science, materials engineering, and sustainable business models, providing new ideas and solutions for sustainable water resource management in remote areas in developing countries.

The theoretical contribution of this study lies in proposing for the first time a comprehensive eco-design framework that deeply integrates LCA and CE principles into renewable energy-driven membrane water treatment systems. The practical significance is that it provides actionable guidance for policymakers, technology developers, and community managers to promote the application of green water treatment technologies and the achievement of sustainable development goals. Although this study has achieved positive results, some limitations still exist, such as the reliance on simulated data and the case analysis of specific communities which may not be directly generalizable to all regions. Future research can further focus on the industrialization of membrane material regeneration technologies, diversified pathways for concentrate valorization, and empirical studies in broader geographical areas and different socioeconomic contexts, with the aim of providing more universal and robust solutions to global water resource challenges.

References

[1] United Nations Office for Disaster Risk Reduction. Global Assessment Report on Disaster Risk Reduction 2023: Mapping Resilience for the Sustainable Development Goals. Stylus Publishing, LLC, 2023.

[2] Derakhshan, Alireza. Dynamically operated, solar-driven Reverse Osmosis for battery-free drinking water supply. Diss. Dissertation, Rostock, Universität Rostock, 2023, 2023.

[3] Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2012). MWH's water treatment: principles and design. John Wiley & Sons.

[4] Baker, R. W. (2023). Membrane technology and applications. John Wiley & Sons.

[5] Shoeibi, S., Kargarsharifabad, H., Khiadani, M., Parsa, S. M., Mirjalily, S. A. A., & Mohammed, H. A. (2024). Techniques used to enhance condensation rate of solar desalination systems: State-of-the-art review. International Communications in Heat and Mass Transfer, 159, 108164.

[6] Mbogo, S. A. (2008). A novel technology to improve drinking water quality using natural treatment methods in rural Tanzania. Journal of Environmental Health, 70(7), 46-50.

[7] Manna, A. K., Sen, M., Martin, A. R., & Pal, P. (2010). Removal of arsenic from contaminated groundwater by solar-driven membrane distillation. Environmental Pollution, 158(3), 805-811. https://doi.org/10.1016/j.envpol.2009.10.002

[8] Azmi, L. S. (2025). Membrane filtration technologies for sustainable industrial wastewater treatment: a review of heavy metal removal. Desalination and Water Treatment, 101321. https://doi.org/10.1016/j.dwt.2025.101321

[9] Jawed, A. S., Nassar, L., Hegab, H. M., van der Merwe, R., Al Marzooqi, F., Banat, F., & Hasan, S. W. (2024). Recent developments in solar-powered membrane distillation for sustainable desalination. Heliyon, 10(11). https://doi.org/10.1016/j.heliyon.2024.e31656

[10] International Organization for Standardization. (2006). Environmental management: life cycle assessment; Principles and Framework. ISO.

[11] Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S., & Shaw, A. (2013). Life cycle assessment applied to wastewater treatment: state of the art. Water research, 47(15), 5480-5492. https://doi.org/10.1016/j.watres.2013.06.049

Acknowledgements

None.

Funding

None.

Availability of Data

Not applicable.

Ethical Statement

None.

Author Contributions

Fazal Ur Rehman Muqeemi designed the eco-design framework, collected and processed the operational and material data of the renewable energy-driven membrane system, conducted the life cycle assessment and techno-economic analysis, and prepared the initial manuscript, while Muhammad Adeel conceived and supervised the research, contributed to the development of circular economy strategies and system configuration, interpreted the environmental impact results, and critically revised the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.