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Nadeem, Abdullah, Tariq, Muhammad Atiq Ur Rehman, Sarwar, Kaleem, Iqbal, Mudassar, Ahmad, Khalil and Ahmed, Khalil (2024) Assessing the environmental impacts of reclaimed and conventional water in hydroponics based on a life cycle assessment approach. Water Supply, 24 (8). pp. 2765-2780. ISSN 1606-9749

Water Supply

Water Supply Vol 24 No 8, 2765 doi: 10.2166/ws.2024.160

Assessing the environmental impacts of reclaimed and conventional water in hydroponics based on a life cycle assessment approach

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ABSTRACT

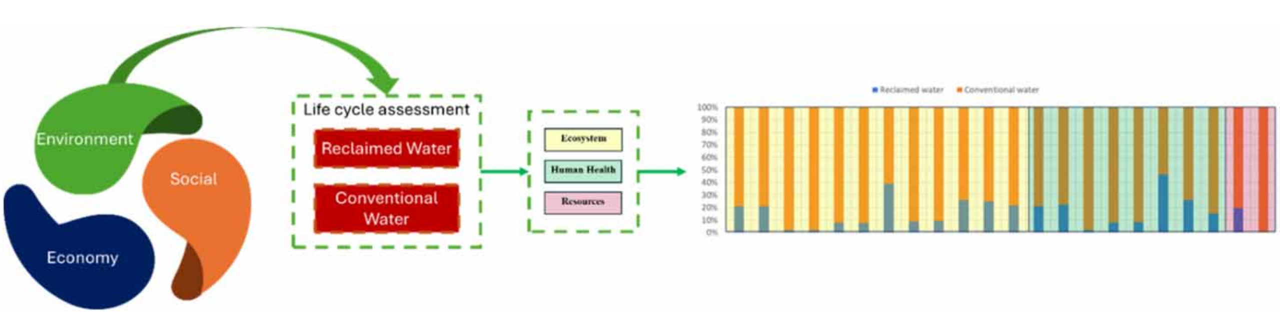
As the global population approaches 9 billion by 2050, challenges of food and water scarcity intensify. Hydroponics, an innovative and eco-friendly technology, has gained prominence in addressing these challenges. This study employs Life Cycle Assessment (LCA) to comprehensively evaluate the environmental and economic impacts of utilizing reclaimed water in a hydroponic system. Results from midpoint, endpoint, and normalized analyses reveal key contributors to the hydroponic system's environmental burden, including water, substrates, fertilizers, and energy sources. Significant impacts have been observed in marine and terrestrial ecotoxicity, as well as photochemical ozone formation. Reclaimed water consistently demonstrates lower environmental impacts compared to conventional water across various indicators, such as climate change (131 kg CO_2 eq.), fine particulate matter formation (0.108 kg PM2.5 eq.), and freshwater consumption (0.291 cubic meters). The study emphasizes the potential of hydroponics with reclaimed water to offer sustainable and environmentally friendly agricultural practices. The detailed LCA results provide valuable insights for policymakers and stakeholders, promoting the adoption of hydroponics to address food and water scarcity challenges. From the findings, reclaimed water in hydroponics lowers the environmental impacts as compared to conventional water and PVC (Polyvinyl chloride) along with electricity is the major contributor in environmental burden.

Key words: agricultural sustainability, emissions, hydroponics, LCA, reclaimed water

HIGHLIGHTS

- Water scarcity challenges can be addressed through hydroponics.
- Life cycle assessment evaluates reclaimed water usage.
- Contributors to Environmental burdens are water, substrates, fertilizers, and energy.
- Reclaimed water shows lower impacts, in climate change, particulate matter, and freshwater consumption.
- Advancing water reuse for sustainable agriculture is recommended in this study.

GRAPHICAL ABSTRACT



INTRODUCTION

As the global population is steadily approaching 9 billion inhabitants by 2050 (UN 2019), the challenges of food scarcity, water scarcity, and availability of land become increasingly pressing. With a projected 70% increase in food production required to feed the growing population in the coming years (FAO 2020), ensuring sustainable and efficient agricultural practices is paramount. However, freshwater scarcity poses a significant threat, with water crises listed as one of the top five global risks affecting the society (WEF 2019). Currently, an estimated 10% of the population lacks access to fresh drinking water, and the situation is projected to worsen, with at least 25% of the global population facing water shortages soon and a projected water deficit of 40% within a decade (Dos Santos *et al.* 2017). The assurance of a stable water supply is essential, considering its vital role in economic, social, and environmental activities (Blanco-Gutiérrez *et al.* 2013; D'Ambrosio *et al.* 2020). Meanwhile, the availability of land for agriculture is another critical concern due to encroaching urbanization responding to population growth, which competes with the demand for agricultural expansion. Only 12% of the global land mass is used for cultivating crops at present, with potential demand for agricultural land is expected to rise by 50% by 2050 (DeFries *et al.* 2010; FAO 2015). To address these issues, the reuse of water and the use of modern agricultural technologies will become increasingly important.

Utilizing an array of innovative and eco-friendly technologies, hydroponics has gained traction as a sustainable and reliable food production method that addresses the pressing concerns of food scarcity and water scarcity (Li *et al.* 2018). Notably, hydroponics surpasses traditional soil-based agricultural practices in optimizing resources, making it an efficient approach for large-scale crop production without exacerbating water scarcity challenges (Muller *et al.* 2017). Despite criticisms from proponents of agro-economic approaches, hydroponics presents a promising soil conservation technique due to its minimal soil usage, aligning well with the goals of sustainable agriculture while mitigating impacts on water resources (Giacomini 2010). The appeal of hydroponics lies in its ability to offer both environmental and production benefits, supporting the well-being of farmers and communities while contributing to water resource management (Li *et al.* 2018). To promote the adoption of hydroponics and to the challenges of food and water scarcity, it is crucial to tactically examine and maximize its social, economic, and environmental benefits, ensuring a sustainable and prosperous future for agriculture and food production (Seufert *et al.* 2012). However, when innovative modern technologies of agriculture have been introduced, sustainability has always been a major concern. To assess the sustainability of new innovative technologies, a life cycle assessment (LCA) can be used to soundly measure environmental impacts (Moretti *et al.* 2016).

Throughout human history dating back to prehistoric civilizations, the reuse of wastewater for agricultural irrigation has been an enduring practice (Salgot & Folch 2018). Globally, agricultural water consumption typically constitutes about 70% of total water withdrawals, rising to 90% in specific contexts (Fito & Van Hulle 2021). In the face of escalating global water stress, the adoption of reclaimed water for agricultural irrigation presents a pivotal opportunity for mitigation (Chen *et al.* 2013). Historical examples, including Paris, France, in 1872 and Melbourne, Australia, in 1897, showcase the utilization of sewage farms to manage significant wastewater volumes (Angelakis & Snyder 2015). While the practice of using reclaimed municipal wastewater for irrigation is established, the reuse of industrial effluent remains uncommon due to limited knowledge (Vergine *et al.* 2017). In Europe, water-scarce Mediterranean countries, such as Spain, Italy, Cyprus, and Greece, have been leaders in wastewater reuse for irrigation (Voulvoulis 2018). Moreover, in arid and semi-arid regions globally, including North Africa, Central America, Southern Europe, and Southern Asia, reclaimed water has been employed directly or indirectly for agricultural activities (Pedrero *et al.* 2010; Voulvoulis 2018). The use of reclaimed water offers multiple benefits by positively impacting global warming, acidification, ozone depletion, and respiratory effects (Tran *et al.* 2016; Markland *et al.* 2017; Romeiko 2019; Mirzaie *et al.* 2021).

LCA has emerged as a crucial tool in the realm of agricultural production, facilitating the identification of more sustainable options with implications for enhanced food security and reduced human health risks (Roy *et al.* 2009; Meier *et al.* 2015). This methodology is able to assess the energy consumption and environmental burdens associated with the production of protected crops in a Mediterranean agricultural district, as evidenced by its application in a study by Cellura *et al.* (2012). By providing a comprehensive evaluation of the environmental impacts throughout the life cycle of agricultural products, LCA can contribute significantly to evidence generation and the formulation of targeted environmental policy interventions in the agri-food sector. This, in turn, supports policymaking endeavors and facilitates the monitoring of achievements toward the UN 2030 Sustainable Development Goals, as emphasized in the study conducted by Gava *et al.* (2018).

Several studies have explored using different water sources to tackle water scarcity in agriculture while focusing on economic viability and sustainability. López-Serrano *et al.* (2020) showed that using tertiary treated water is financially feasible and better for the environment compared to desalinated water when used in greenhouse agriculture. Canaj *et al.* (2021) examined the application of reclaimed water for vineyard cropping systems and found that it reduced environmental impacts but may lead to lower economic returns due to reduced crop yield. However, an integrated system can be more environmentally friendly and economically profitable than conventional methods. Vinci & Rapa (2019) assessed various substrates for hydroponic systems and offered valuable guidance for choosing substrates based on environmental sustainability and cost. Cifuentes-Torres *et al.* (2021) highlighted hydroponics as a promising and economically viable method for crop production, especially when using reclaimed water as a nutrient solution thereby supporting sustainable agriculture and environmental efforts. Several studies have delved into the environmental implications and efficiencies of hydroponics across different regions. Blom *et al.* (2022) conducted research in the Netherlands, comparing the carbon footprint of closed-box vertical hydroponic farms to conventional farming practices, specifically focusing on the production journey of 1 kg fresh weight (FW) butterhead lettuce and concluded that hydroponics emits lower emissions. Martin & Molin (2019) examined a vertical hydroponic farm in Stockholm, Sweden, assessing its environmental impacts from retailer gate to operation and construction, considering the annual production available to consumers. Martin-Gorriz *et al.* (2021) studied a foil greenhouse in Almería, Spain, investigating the benefits of solar-powered drainage treatment for hydroponic tomato effluent recycling. They assessed the cultivation area (1 m^2) and 1 kg of marketable tomato from farm gate to operation, construction, and end-of-life. Romeo *et al.* (2018) explored a vertical hydroponic farm in Lyon, France, comparing its environmental performance with conventional farming, focusing on 1 kg of leafy greens delivered to the retailer from retailer gate to operation, construction, and end-of-life. Finally, Wimmerova *et al.* (2022) conducted research in the Czech Republic, comparing soil versus aeroponic/hydroponic cultivation for caffeine/rutin production using the 'Rainforest 2' system, considering 1 kg of total dried biomass, 100 g of caffeine, or 1 g of rutin, with a focus solely on operational aspects from gate to gate. These studies collectively contribute to understanding the environmental impacts and efficiencies of diverse farming methods across different geographic contexts.

The issue of environmental impact on hydroponics when reclaimed water has been added as a replacement of conventional water has not been reported to date.

Research questions

- What will be the sustainability of hydroponic system which reclaimed water introduced in it?
- Which components in the inventory has the highest contribution in environmental burden?

METHODS

LCA constitutes a structured procedure to the assessment of the environmental impacts of diverse stages throughout the entire lifecycle of a product or service. This comprehensive evaluation extends from the extraction of raw materials to manufacturing, distribution, utilization, maintenance, and eventual disposal or recycling. This method provides an analysis of energy and material inputs and the subsequent environmental outputs through the integration of quantitative variables, processed via mathematical equations and data. This, in turn, facilitates the identification of avenues to mitigate adverse environmental effects. The assessment was performed using the GaBi software by Sphera (Toboso-Chavero *et al.* 2021) and the education database 2020 was used (Walson 2020).

Goal and scope and functional unit

The LCA approach was systematically applied to a hydroponic system, focusing on the stages from initial setup to the operational phase. The goal and scope of this study was to apply the LCA approach to comprehensively assess the economic and environmental impacts of utilizing reclaimed water in a hydroponic system per square meter, focusing on the initial setup and operational stages (see Figure 1). The chosen functional unit was the utilization of 1 L of reclaimed water per square meter of cultivation area.

Activities beyond the cradle-to-gate system boundary, such as harvesting, packaging, retail, and waste management, were excluded from this LCA analysis. For this study, the first step is to specify the goal and the scope. Goal and scope definition in LCA establishes the purpose of the assessment of environmental (Curran 2016).

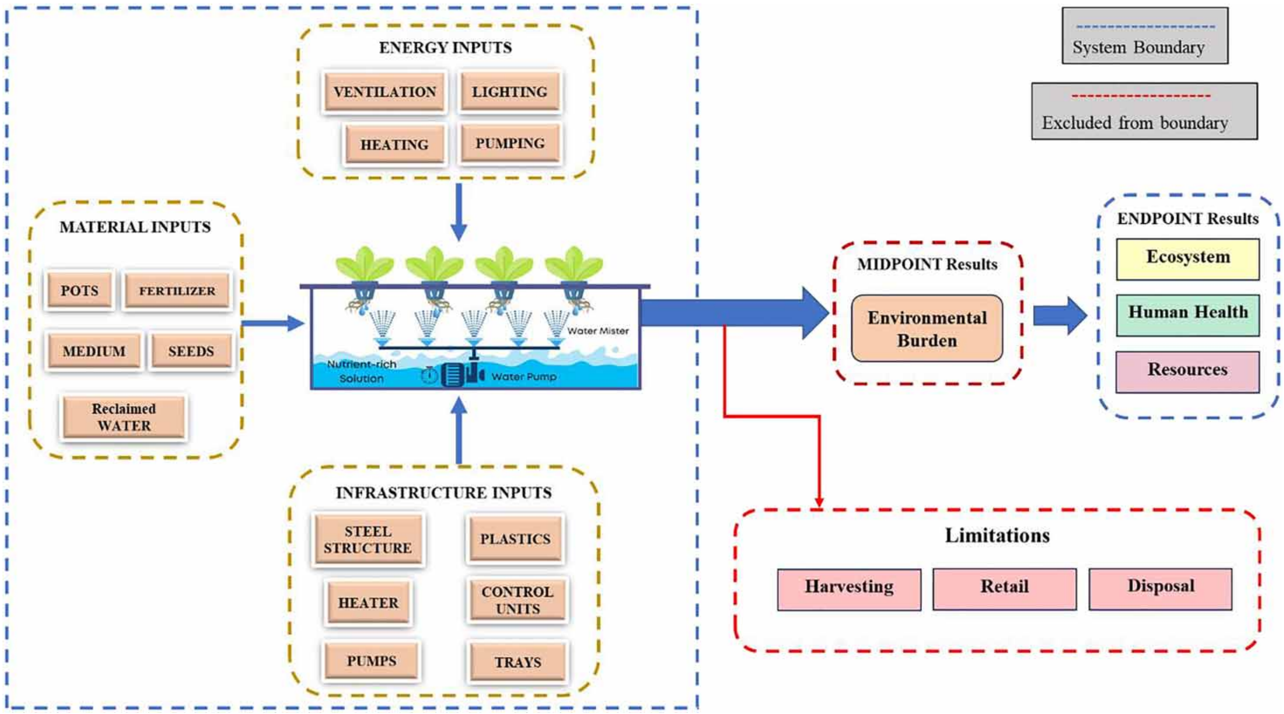


Figure 1 | Methodology diagram explaining the system boundaries, all three inputs, the hydroponic system, and emissions as the outputs of the analysis.

Study area

The hydroponic farm is located at the Mian Nawaz Sharif Agriculture University in Multan, Pakistan (see Figure 2), positioned at latitude 30.14° N and longitude 71.44° E. The farm spans an area of 10,890 m^2. The facility, with dimensions of 36.576 m in length, 22.86 m in width, and 3.9624 m in height, is a sizable and potentially productive unit capable of accommodating a variety of crops. The hydroponic farm employs a soil-less cultivation method, utilizing nutrient-rich water solutions to precisely control plant nutrition and growth factors, thereby maximizing yields and minimizing resource consumption. In this study, it was important to assess various aspects related to the hydroponic farm's sustainability and economic viability. Factors such as energy consumption, water usage, nutrient management, crop productivity, and economic considerations are crucial when evaluating the overall performance and potential of the hydroponic farm.

Figure 2 | Hydroponics greenhouse at the Mian Nawaz Sharif Agriculture University Multan in Pakistan.

Life cycle inventory

The LCA begins with detailed data collection. Inputs include energy sources, emissions, reclaimed water consumption, and growing medium as shown in Table 1. This phase aligns with the core principles of the life cycle inventory (LCI) (Guinee 2002).

Life cycle impact assessment

Following the LCI, a comprehensive life cycle impact assessment (LCIA) is conducted. This stage involves quantifying environmental impacts using established impact assessment methods, computing indicators such as carbon footprint, water footprint, and energy use per square foot of production. This step integrates the principles of the second methodology's LCIA stage (Pasqualino *et al.* 2011). In our study, the inventory including the main components, energy usage, and water usage as shown in Table 1. A water loss of 50 L has been observed in the system. Therefore, 50 L of water loss have been taken in account for this study.

Environmental interpretation

The environmental interpretation evaluates the system's environmental performance within the specified cradle-to-gate boundary. This assessment considers environmental impacts identified in the LCIA stage and compares the hydroponic system's sustainability and efficiency to conventional methods, highlighting potential trade-offs between economic gains and environmental benefits.

The LCA includes an economic interpretation phase that scrutinizes the cost-effectiveness and financial feasibility of integrating reclaimed water in the hydroponic system. This analysis, like the life cycle costing approach, identifies cost drivers and potential savings through materials, processes, or product innovations (Auer *et al.* 2017). In this study, the ReCiPe (H) 2016 impact assessment method is used for the quantification of environmental burden. The ReCiPe (H) 2016 impact assessment method is used to identify and assess various impact categories, such as global warming, acidification, eutrophication, and ozone layer depletion (Poopak & Agamuthu 2011).

RESULTS AND DISCUSSION

The complete illustration of environmental impacts has been provided using Gabi database software and the ReCiPe (H) 2016 impact assessment method (Wimmerova *et al.* 2022). The quantified results for each indicator have been provided for this study. Midpoint, endpoint, and normalized categories with the process contribution in each impact category are described below.

Midpoint results

Referring to Table 2, contributors to the environmental burden of nutrient film technique (NFT) hydroponics are water, substrates, fertilizers, and energy sources. The midpoint analysis of the hydroponic system's environmental impact revealed a comprehensive range of effects across various categories. In terms of climate change, the system contributes 131 kg of CO_2 equivalent emissions, considering both default and biogenic carbon factors. In this category, the value is near to the study of Wimmerova *et al.* (2022) (138 kg of CO_2 equivalent emissions) due to the same nature of inventory data, particularly energy source and substrate. In addition, it registers a minimal impact on fine particulate matter formation, fossil depletion, and freshwater consumption, with 0.108 kg of PM2.5 equivalent, 32.6 kg of oil equivalent, and 0.291 m^3 of freshwater

Table 1 | Inventory covering the inputs with major contribution in the hydroponic system

Process	Amount	Unit
Coconut coir grow bags	50	pieces
Fertilizers	Varies	kg
Plastic clips	1,000	pieces
Growing media (perlite)	30	cubes
Electricity	25	KWh
Reclaimed water	1,000	L

Table 2 | Midpoint results of the LCA (based on functional unit) using the ReCipe 2016 impact assessment method

Categories	Unit	Amount
Climate change, default, excluding biogenic carbon	kg CO_2 eq.	131
Climate change, including biogenic carbon	kg CO_2 eq.	131
Fine particulate matter formation	kg $PM_{2.5}$ eq.	0.108
Fossil depletion	kg oil eq.	32.6
Freshwater consumption	m^3	0.291
Freshwater ecotoxicity	kg 1,4-DB eq.	0.00951
Freshwater eutrophication	kg P eq.	0.000122
Human toxicity	kg 1,4-DB eq.	0.0388
Ionizing radiation	kBq Co-60 eq.	5.77
Land use	Annual crop eq.	0.464
Marine ecotoxicity	kg 1,4-DB eq.	1.77
Marine eutrophication	kg n eq.	0.0447
Metal depletion	kg Cu eq.	0.00102
Photochemical ozone formation, ecosystems	kg NOx eq.	0.0675
Photochemical ozone formation, human health	kg NOx eq.	0.177
Stratospheric ozone depletion	kg CFC-11 eq.	0.17
Terrestrial acidification	kg So_2 eq.	0.00138
Terrestrial ecotoxicity	kg 1,4-DB eq.	0.325

consumed, respectively. The system has low values in categories such as freshwater ecotoxicity, eutrophication, and human toxicity, with 0.00951 kg of 1,4-DB equivalent, 0.000122 kg of phosphorus equivalent, and 0.0388 kg of 1,4-DB equivalent, respectively. However, notable impacts are observed in categories including marine ecotoxicity, terrestrial ecotoxicity, and photochemical ozone formation affecting both ecosystems and human health. The hydroponic system records 1.77 kg of 1,4-DB equivalent for marine ecotoxicity, 0.325 kg of 1,4-DB equivalent for terrestrial ecotoxicity, and 0.0675 kg of NOx equivalent for photochemical ozone formation in ecosystems, along with 0.177 kg of NOx equivalent for human health concerns. The results also highlight minor contributions to categories like ionizing radiation, land use, metal depletion, stratospheric ozone depletion, and terrestrial acidification, showcasing a comprehensive overview of the system's environmental footprint across multiple impact categories. All the upper discussed results are nearly identical to the results of the study of Wimmerova *et al.* (2022). This is due to the similar nature of inventory (mainly energy source and substrate). Minor deviation in the results is observed which is due to change of system boundary and functional unit.

In Figure 3, a further breakdown of the environmental burden at the midpoint of the LCA is presented and identifies the contributions of PVC, reclaimed water, electricity, and fertilizer used in the hydroponic system to the various environmental impacts. In this figure, it is clearly seen that electricity is the major source of environmental burden as shown in the study by Chen *et al*. (2020).

Endpoint results

Referring to Table 3, the endpoint analysis of the hydroponic system identifies precise environmental impacts across multiple categories. In terms of climate change, emissions register at 3.47×10^{-12} species per year for freshwater ecosystems, 4.21×10^{-5} DALY for human health (excluding biogenic carbon), and 1.27×10^{-7} species per year for terrestrial ecosystems. Fine particulate matter formation is present at 9.15×10^{-6} DALY, while fossil depletion reaches 8.17 USD and 8.64×10^{-0} USD, respectively. Freshwater consumption shows impacts of 1.70×10^{-13} species per year for freshwater ecosystems, 1.58×10^{-7} DALY for human health, and 7.98×10^{-10} species per year for terrestrial ecosystems. Freshwater ecotoxicity tallies at 5.65×10^{-12} species per year and freshwater eutrophication at 6.63×10^{-11} species per year. Human toxicity results in 9.34×10^{-8} DALY for cancer-related impacts and 6.78×10^{-7} DALY for non-cancer-related impacts. Ionizing radiation impacts are noted at 3.47×10^{-9} DALY and land use at 1.06×10^{-8} species per year. Marine ecotoxicity and eutrophication reflect impacts of

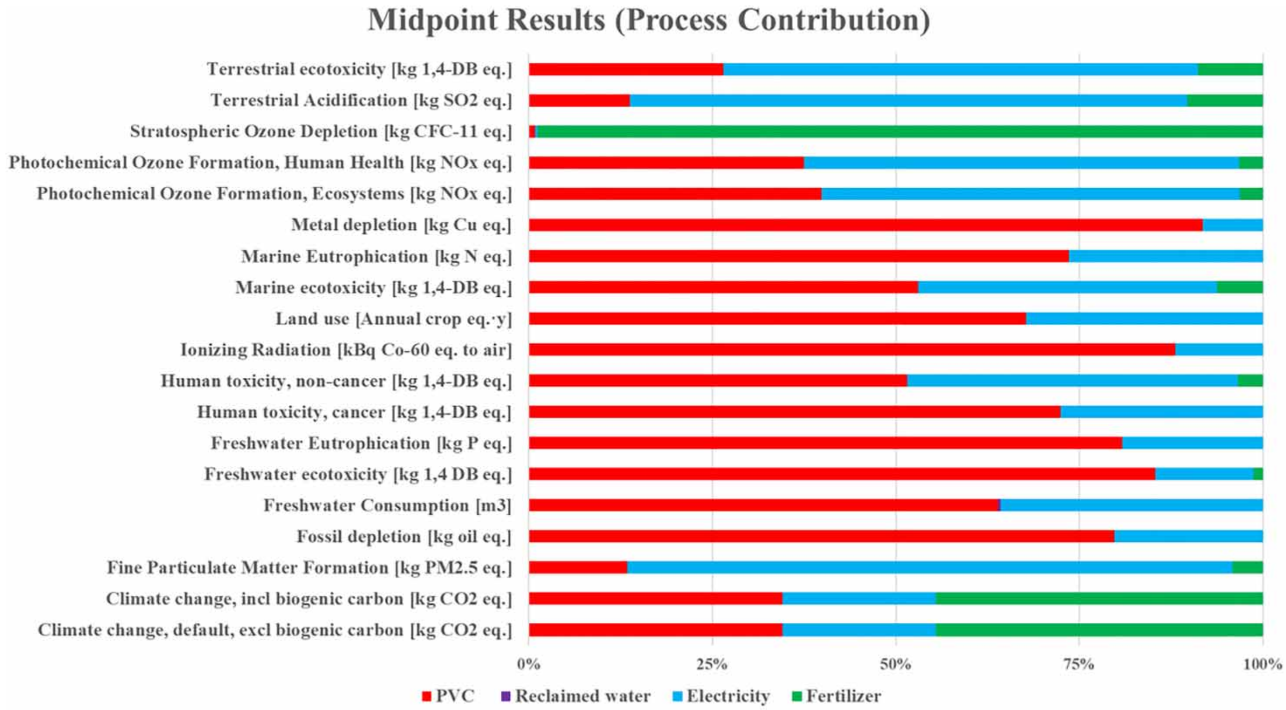


Figure 3 | Process contribution (percentage) to environmental burden at the midpoint of the LCA to assess the major contributor in environmental burden.

2.49×10^{-12} and 1.25×10^{-12} species per year, respectively. Metal depletion tallies at 0.0171 USD, and photochemical ozone formation at 9.11×10^{-09} species per year for ecosystems and 5.81×10^{-08} DALY for human health. Stratospheric ozone depletion stands at 6.33×10^{-09} DALY, terrestrial acidification at 9.51×10^{-09} species per year, and terrestrial ecotoxicity at 1.13×10^{-10} species per year. In the endpoint category, our results are similar to Cohen *et al.* (2018) in ecosystem, human health, and resources categories.

In Figure 4, a further breakdown of the environmental burden at the endpoint of the LCA is presented and identifies the contributions of PVC, reclaimed water, electricity, and fertilizer used in the hydroponic system to the various environmental impacts.

Normalized results

In Table 4, the ReCiPe 2016 v1.1 (H/H) analysis based on the functional unit and excluding biogenic carbon and weighted in person equivalents yields significant findings on the environmental impact of the hydroponic system. Climate change effects register at 2.60×10^{3} for overall impact, with minute impacts on freshwater ecosystems at 4.02×10^{-09} species per year and 0.000147 species per year on terrestrial ecosystems. Fine particulate matter formation stands at 0.0204 DALY, while fossil depletion shows an impact of $2.59 \times 10^{+03}$ USD. Freshwater consumption demonstrates slight impacts across different categories, such as 5.95×10^{-12} species per year for freshwater ecosystems, 4.47×10^{-05} DALY for human health, and 7.30×10^{-08} species per year for terrestrial ecosystems. Freshwater ecotoxicity and eutrophication tally at 2.64×10^{-09} and 3.28×10^{-08} species per year, respectively. Human toxicity indicates 3.86×10^{-05} DALY for cancer-related impacts and 0.000394 DALY for non-cancer-related impacts. Ionizing radiation shows an impact of 1.18E $\times 10^{-06}$ DALY, while land use registers at 6.29×10^{-06} species per year. Marine ecotoxicity and eutrophication present minimal impacts at 1.88E-09 and 6.78×10^{-10} species per year, respectively. In addition, metal depletion stands at 5.96 USD, and photochemical ozone formation registers at 9.13×10^{-06} species per year for ecosystems.

In Figure 5, a further breakdown of the environmental burden based on normalized results of the LCA is presented and identifies the normalized contributions of PVC, reclaimed water, electricity, and fertilizer used in the hydroponic system to the various environmental impacts.

In both (endpoint and normalized) results referring to Figures 4 and 5, electricity and PVC are the major contributors in environmental burden, which is also evident in the study of Chen *et al.* (2020).

Table 3 | Endpoint results of the LCA (based on functional unit) using the ReCipe 2016 impact assessment method

Categories	Amount
Climate change, freshwater ecosystems, default, excluding biogenic carbon (species/year)	1.00×10^{-11}
Climate change, freshwater ecosystems, including biogenic carbon (species/year)	1.00×10^{-11}
Climate change, human health, default, excluding biogenic carbon (DALY)	1.22×10^{-04}
Climate change, human health, including biogenic carbon (DALY)	1.22×10^{-04}
Climate change, terrestrial ecosystems, default, excluding biogenic carbon (species/year)	3.68×10^{-07}
Climate change, terrestrial ecosystems, including biogenic carbon (species/year)	3.68×10^{-07}
Fine particulate matter formation (DALY)	6.81×10^{-05}
Fossil depletion ($)	8.64×10^{00}
Freshwater consumption, freshwater ecosystems (species/year)	3.55×10^{-13}
Freshwater consumption, human health (DALY)	1.67×10^{-07}
Freshwater consumption, terrestrial ecosystems (species/year)	1.41×10^{-09}
Freshwater ecotoxicity (species/year)	6.62×10^{-12}
Freshwater eutrophication (species/year)	8.20×10^{-11}
Human toxicity, cancer (DALY)	1.29×10^{-07}
Human toxicity, non-cancer (DALY)	1.31×10^{-06}
Ionizing radiation (DALY)	3.94×10^{-09}
Land use (species/year)	1.57×10^{-08}
Marine ecotoxicity (species/year)	4.70×10^{-12}
Marine eutrophication (species/year)	1.69×10^{-12}
Metal depletion ($)	1.99×10^{-02}
Photochemical ozone formation, ecosystems (species/year)	2.28×10^{-08}
Photochemical ozone formation, human health (DALY)	1.55×10^{-07}
Stratospheric ozone depletion (DALY)	7.33×10^{-07}
Terrestrial acidification (species/year)	6.90×10^{-08}
Terrestrial ecotoxicity (species/year)	4.27×10^{-10}

Comparing environmental burden of reclaimed water and conventional water in hydroponics

To assess the sustainability of hydroponic system using reclaimed water or conventional water, the results for each category (midpoint, endpoint, and normalized) are compared, neglecting the other contributors in the environmental burden of hydroponic system.

Midpoint results

In Figure 6, the contributions of reclaimed water and conventional water at the midpoint of the LCA indicate that in relation to climate change impact, reclaimed water exhibits significantly lower emissions compared to conventional water, with 0.00117 kg CO_2 eq. for reclaimed water versus 0.00439 kg CO_2 eq. for conventional water (excluding biogenic carbon). This pattern persists across various categories such as fine particulate matter formation, where reclaimed water shows notably reduced impact at 5.76×10^{-07} kg PM2.5 eq. compared to 2.01×10^{-06} kg PM2.5 eq. for conventional water. Similarly, in fossil depletion and freshwater consumption, reclaimed water demonstrates substantially lower values (0.000443 kg oil eq. and 0.00101 m^3, respectively) compared to conventional water (0.00143 kg oil eq. and 0.0501 m^3, respectively).

Furthermore, in toxicity-related categories, reclaimed water consistently displays lower impact compared to conventional water. For instance, in freshwater ecotoxicity and eutrophication, reclaimed water showcases reduced impact at 8.56×10^{-07} kg 1,4-DB eq. and 4.85×10^{-08} kg P eq. respectively, in contrast to 9.78×10^{-06} kg 1,4-DB eq. and 5.75×10^{-07} kg P eq. for conventional water. Compared with the different water sources used in hydroponics, reclaimed water showed less

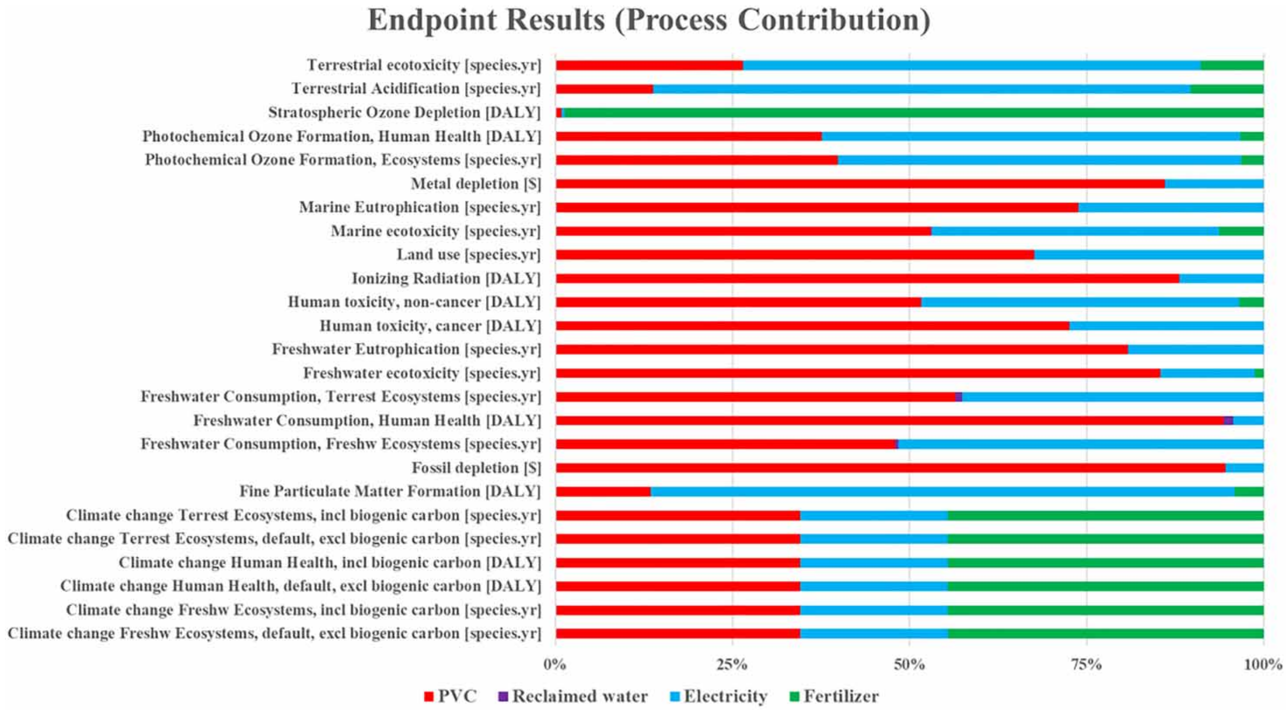


Figure 4 | Process contribution (percentage) to environmental burden at the endpoint of the LCA to assess the major contributor in environmental burden.

Table 4 | Normalized results of the LCA (based on functional unit) using the Recipe 2016 v1.1 (H/H) impact assessment method

Recipe 2016 v1.1 (H/H), excluding biogenic carbon (person equivalents weighted)	**2.60E + 03**
Climate change, freshwater ecosystems, default, excluding biogenic carbon (species/year)	4.02×10^{-09}
Climate change, human health, default, excluding biogenic carbon (DALY)	0.0365
Climate change, terrestrial ecosystems, default, excluding biogenic carbon (species/year))	0.000147
Fine particulate matter formation (DALY)	0.0204
Fossil depletion ($)	2.59×10^{03}
Freshwater consumption, freshwater ecosystems (species/year)	5.95×10^{-12}
Freshwater consumption, human health (DALY)	4.47×10^{-05}
Freshwater consumption, terrestrial ecosystems (species/year)	7.30×10^{-08}
Freshwater ecotoxicity (species/year)	2.64×10^{-09}
Freshwater eutrophication (species/year)	3.28×10^{-08}
Human toxicity, cancer (DALY)	3.86×10^{-05}
Human toxicity, non-cancer (DALY)	0.000394
Ionizing radiation (DALY)	1.18×10^{-06}
Land use (species/year)	6.29×10^{-06}
Marine ecotoxicity (species/year)	1.88×10^{-09}
Marine eutrophication (species/year)	6.78×10^{-10}
Metal depletion ($)	5.96
Photochemical ozone formation, Ecosystems (species/year)	9.13×10^{-06}

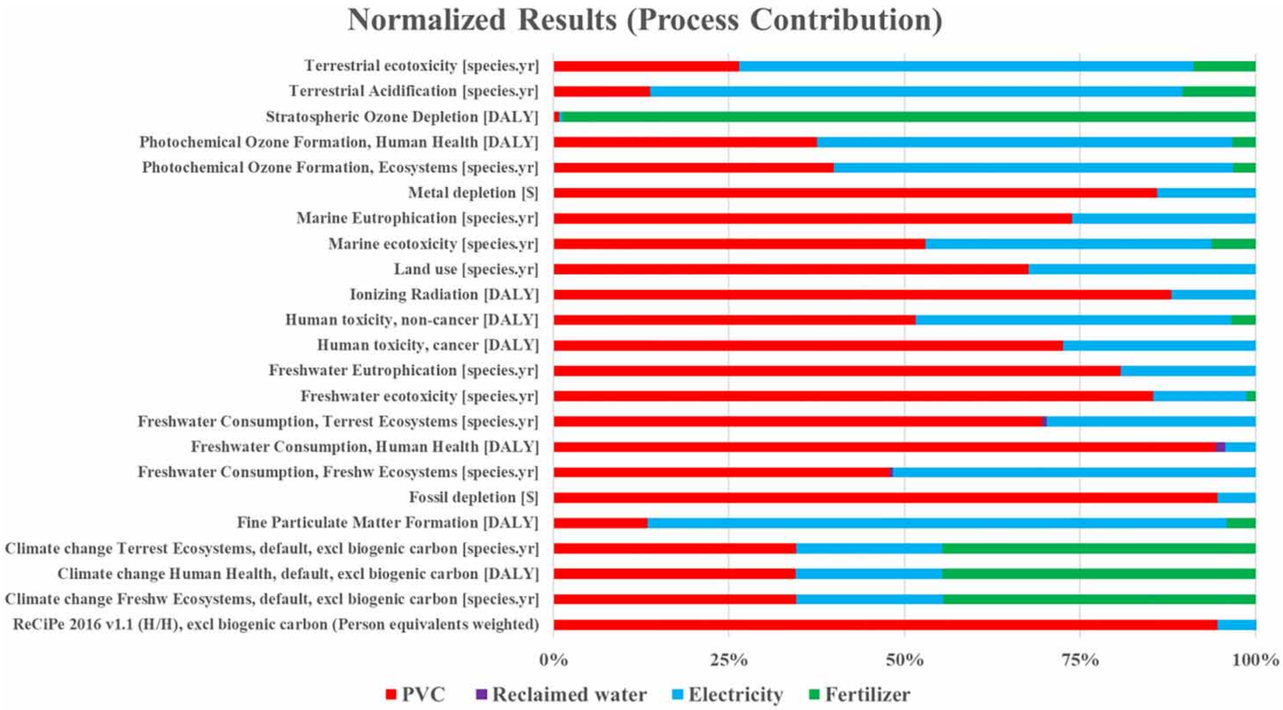


Figure 5 | Process contribution (percentage) to environmental burden in normalized category of the LCA to assess the major contributor in environmental burden.

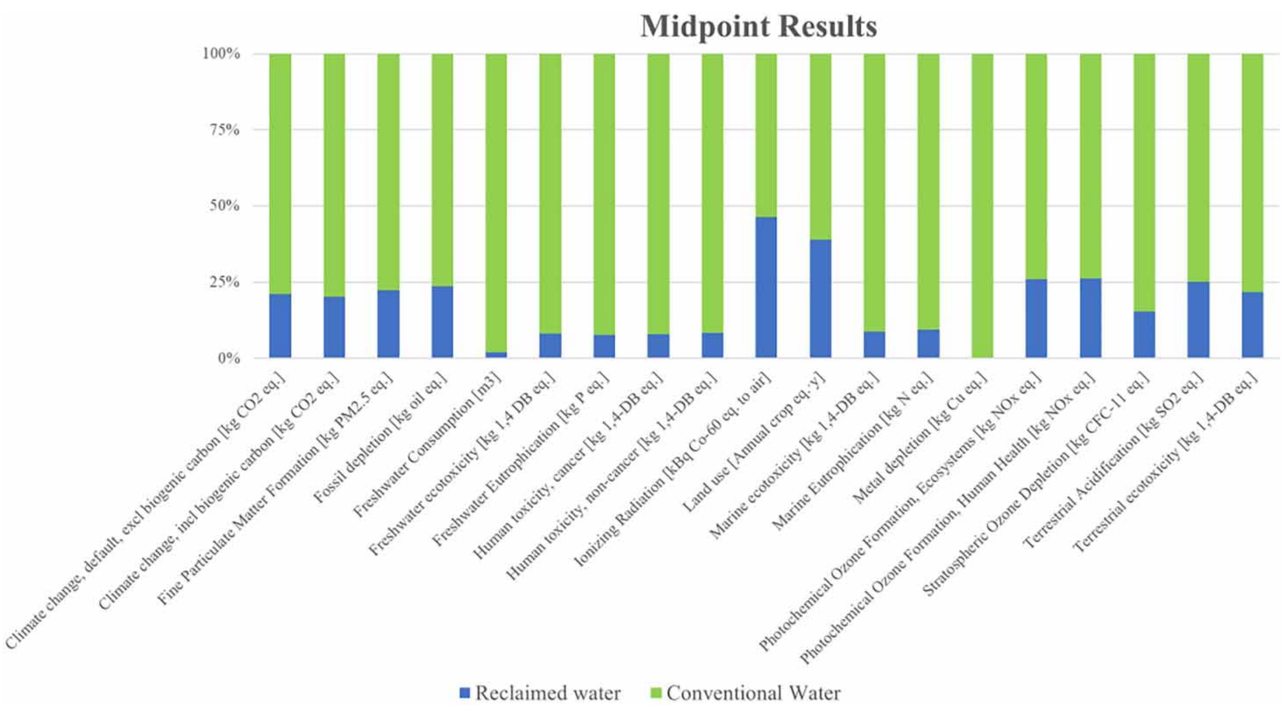


Figure 6 | Midpoint results of the LCA (based on functional unit) using the ReCipe 2016 impact assessment method.

environmental burden as compared to conventional water (López-Serrano *et al.* 2021) .This trend persists across categories such as human toxicity (both cancer and non-cancer), ionizing radiation, terrestrial and marine ecotoxicity, and photochemical ozone formation, where reclaimed water consistently demonstrates lower environmental burdens compared to conventional water.

Endpoint results

In Figure 7, the comparison of environmental burdens between reclaimed water and conventional water in hydroponics demonstrates substantial differences in impact categories. Reclaimed water, when evaluated against conventional water, consistently displays lower values across various environmental impact indicators (Canaj *et al.* 2021). In terms of climate change impacts on ecosystems, reclaimed water exhibits notably diminished impacts: for freshwater ecosystems, the impact is 8.97×10^{-17} (for reclaimed water) compared to 3.36×10^{-16} (for conventional water) species per year, and 3.28×10^{-12} (for reclaimed water) versus 1.23×10^{-11} (for conventional water) species per year for terrestrial ecosystems. This trend extends to freshwater and terrestrial ecotoxicity, eutrophication, and land use, where reclaimed water consistently demonstrates lower impacts.

In terms of health-related impacts, the use of reclaimed water shows marked advantages. Reclaimed water records lower impacts in climate change-related human health indicators, with values of 1.09×10^{-09} (for reclaimed water) versus 4.08×10^{-09} (for conventional water) DALY excluding biogenic carbon. It also exhibits lower impacts in freshwater consumption for human health, human toxicity (both cancer and non-cancer-related), ionizing radiation, and various depletion categories such as fossil and metal depletion, all of which display notably reduced values compared to conventional water.

Normalized results

In Figure 8, reclaimed water shows significantly reduced environmental burdens in climate change impact indicators. For freshwater ecosystems, the impact is notably lower with values of 3.59×10^{-14} (reclaimed) compared to 1.34×10^{-13} (conventional) species per year. Similarly, in terrestrial ecosystems, the impact of reclaimed water is diminished, measuring 1.31×10^{-09} (reclaimed) versus 4.92E-09 (conventional) species per year.

Freshwater consumption indicators show marked advantages for reclaimed water. Reclaimed water usage records significantly lower impacts in freshwater consumption (Chand *et al.* 2022), both for freshwater ecosystems (6.96×10^{-13} reclaimed versus 3.48×10^{-11} conventional species per year) and terrestrial ecosystems (5.40×10^{-09} reclaimed versus 2.70×10^{-07} conventional species per year).

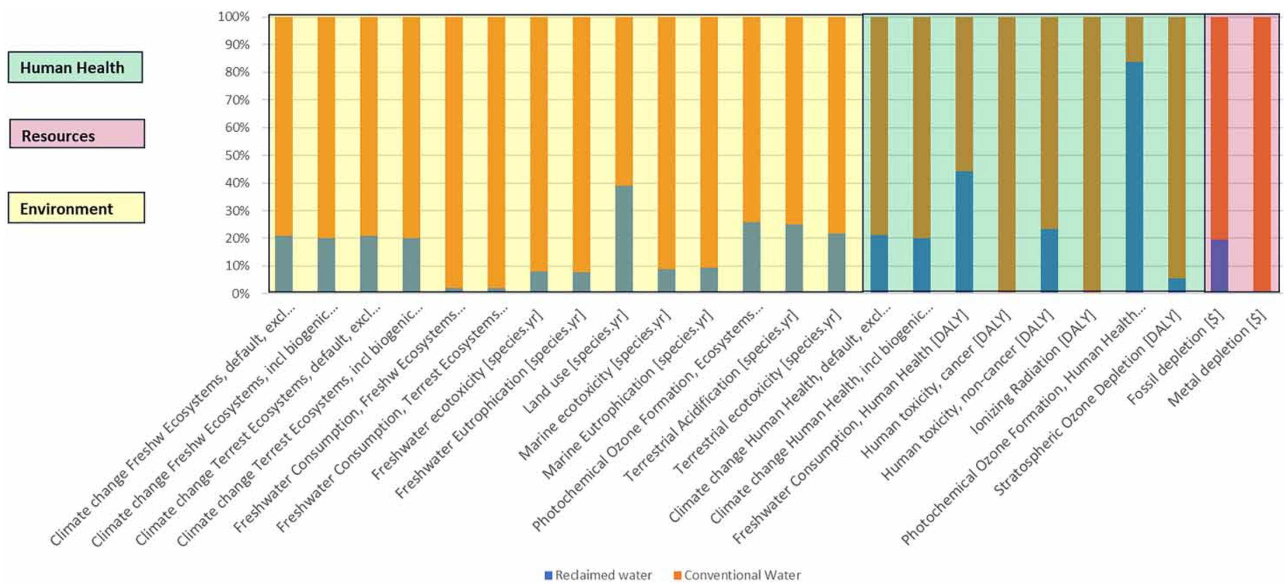


Figure 7 | Endpoint results (based on human health, resources, and environment categories) of the LCA based on the functional unit and using the ReCipe 2016 impact assessment method.

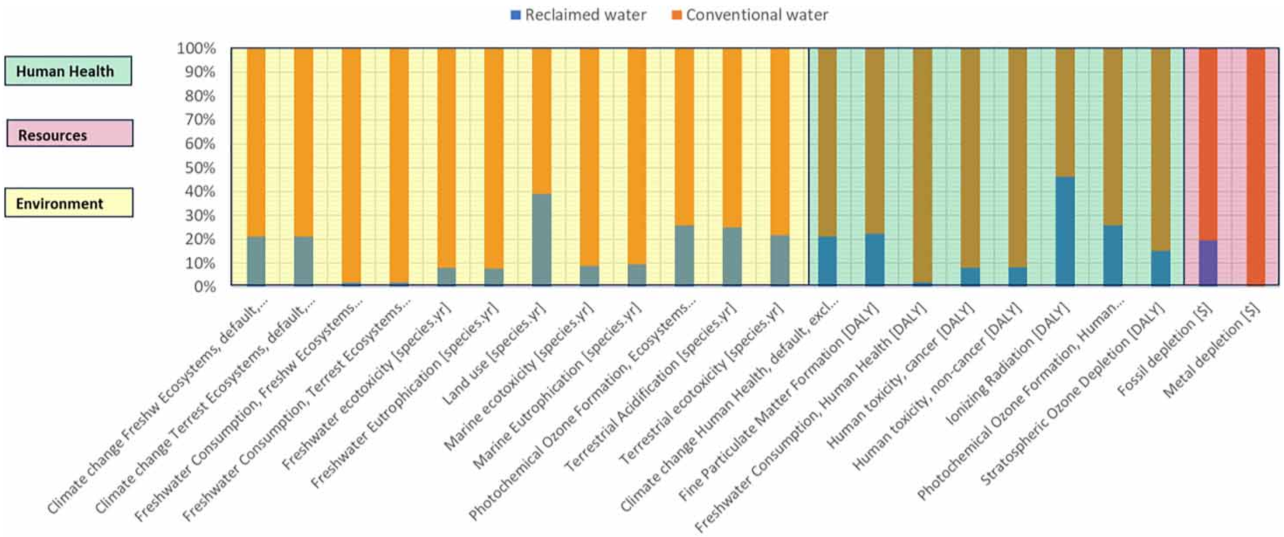


Figure 8 | Normalized results (based on human health, resources, and environment categories) of the LCA based on the functional unit and using the ReCipe 2016 impact assessment method.

Furthermore, reclaimed water demonstrates decreased impacts in various environmental categories (Chand *et al.* 2022) such as ecotoxicity (2.38E-13 reclaimed versus 2.72E-12 conventional species per year), eutrophication (1.30E-11 reclaimed versus 1.54E-10 conventional species per year), land use (2.08E-10 reclaimed versus 3.25E-10 conventional species per year), and photochemical ozone formation (1.06E-10 reclaimed versus 3.01E-10 conventional species per year).

In health-related indicators, reclaimed water exhibits reduced impacts across various dimensions (Gwynn-Jones *et al.* 2018). Notably, reclaimed water demonstrates lower impacts in freshwater consumption for human health (6.67E-07 reclaimed versus 3.33E-05 conventional DALY), human toxicity (cancer and non-cancer-related), ionizing radiation, photochemical ozone formation related to human health, stratospheric ozone depletion, and different depletion categories such as fossil and metal depletion.

The hydroponic system displays varying environmental footprints, presenting lower contributions to categories like fine particulate matter formation, fossil depletion, and freshwater consumption. Specifically, the system registers approximately 0.108 kg of PM2.5 equivalent, 32.6 kg of oil equivalent, and 0.291 m^3 of freshwater consumed. However, considerable impacts are observed in categories such as marine ecotoxicity (1.77 kg of 1,4-DB equivalent), terrestrial ecotoxicity (0.325 kg of 1,4-DB equivalent), and photochemical ozone formation in ecosystems (0.0675 kg of NOx equivalent), alongside 0.177 kg of NOx equivalent related to human health concerns.

The ReCiPe 2016 v1.1 (H/H) analysis, excluding biogenic carbon and weighted in person equivalents, quantifies substantial impacts associated with the hydroponic system. Notably, climate change effects reach 2.60E + 03 overall, while freshwater ecosystems display 4.02E-09 species per year and terrestrial ecosystems exhibit 0.000147 species per year impact. Fine particulate matter formation represents 0.0204 DALY, and fossil depletion records impacts of 2.59E + 03 USD. Freshwater consumption impacts range from 5.95E-12 to 7.30E-08 species per year across various categories, while freshwater ecotoxicity and eutrophication register at 2.64E-09 and 3.28E-08 species per year, respectively.

Comparatively, reclaimed water demonstrates significantly lower impacts across various indicators compared to conventional water. For instance, in climate change-related ecosystems, reclaimed water showcases reduced impacts: freshwater ecosystems show 3.59E-14 species per year compared to 1.34E-13 for conventional water. In terms of health-related impacts, reclaimed water exhibits lower values, such as 3.26E-07 DALY for climate change-related human health, 6.67E-07 DALY for freshwater consumption-related human health, and 3.86E-05 DALY for cancer-related human toxicity.

The use of LCA in hydroponics offers a comprehensive evaluation of environmental impacts (Heijungs & Dekker 2022). LCA allows for a detailed comparison of different components used in hydroponic systems, highlighting their environmental sustainability (Lenka *et al.* 2022). In contrast, other sustainability assessment methods like the response-inducing sustainability evaluation (RISE) model and multi-criteria decision analysis (MCDA) have their own strengths and weaknesses (Vinci &

Rapa 2019). While RISE excels in overall effectiveness, MCDA is a tool that gives subjective results (Nicolas *et al.* 2018). LCA in hydroponics provides a holistic view of the environmental burdens associated with different cultivation systems, aiding in decision-making for sustainable agricultural practices (Byomkesh *et al.* 2017). However, limitations such as the complexity of data management and uncertainties need to be considered when utilizing LCA for sustainability assessments.

LCA in hydroponics for sustainability assessment empowers communities in decision-making processes related to water management by providing a comprehensive evaluation of environmental impacts, uncertainties, and costs (Cai *et al.* 2016). LCA helps identify desired water allocation schemes to minimize life cycle environmental impacts, reflecting associated uncertainties and strengthening capabilities of decision-making processes (Cypra *et al.* 2020). By comparing different hydroponic substrates based on environmental and economic impacts, LCA highlights the most sustainable options like sand and bark, aiding in informed decision-making for community sustainability (Vinci & Rapa 2019). Integrating LCA results against sustainability boundaries enables consistent decision-making aligned with sustainability criteria, enhancing the role of LCA as a sustainability decision support tool (Hengen *et al.* 2016).

The findings have advanced the understanding in the context of sustainability of hydroponics when we replaced reclaimed water with conventional water. However, replacing reclaimed water with conventional water does not majorly impact overall sustainability. Therefore, to reduce the overall environmental burden of hydroponic systems, major contributors in environmental burden (PVC and electricity) should be replaced with some other sustainable option.

CONCLUSION

In conclusion, the LCA of the hydroponic system utilizing reclaimed water provides a detailed understanding of its environmental impacts. The midpoint results highlighted key contributors, with water, substrates, fertilizers, and energy sources playing significant roles. The endpoint and normalized results quantified specific values for various impact categories, such as climate change, fine particulate matter formation, fossil depletion, and freshwater consumption. Furthermore, the comparison between reclaimed water and conventional water in the hydroponic system revealed significant differences. Reclaimed water consistently demonstrated lower environmental impacts. The limitation of the study is the availability of inventory data as the scope of the study has been defined according to data availability.

Results of the study present vital guidance for policymakers shaping hydroponics policies, emphasizing environmental considerations across various indicators. It can also serve as a foundation for policymakers in developing hydroponics policies, specifically addressing water governance concerns. By thoroughly examining water usage and management within hydroponic systems, it provides essential guidance for crafting policies that ensure responsible water stewardship. Incorporating principles of water governance into policy frameworks is essential for promoting efficiency, conservation, and equitable access to water resources, ultimately fostering sustainable agricultural practices.

Future research should be conducted by expanding the system boundary from cradle to grave and by replacing PVC and electricity with some sustainable options to assess the environmental burden of hydroponic system.

Recommendations

Based on our findings, stakeholders should prioritize the use of reclaimed water and explore sustainable alternatives for key inputs like substrates and energy sources in hydroponic systems. Policies should research and eco-friendly practices, address data limitations through comprehensive research, and encourage the replacement of environmentally harmful materials. These actions will support the development of sustainable hydroponics policies and practices, minimizing environmental impacts and fostering a greener future for food production.

This study contributes significantly to the broader discussion on LCA in hydroponics and water governance. By providing detailed insights into environmental impacts, including water, substrates, fertilizers, and energy sources, it underscores the importance of considering multiple factors in LCA analyses for hydroponic systems. The comparison between reclaimed water and conventional water highlights the potential benefits of utilizing reclaimed water, demonstrating lower environmental impacts. These findings offer valuable guidance for policymakers in shaping hydroponics policies, emphasizing environmental considerations across various indicators. Lessons learned from this study can be applied to other contexts by encouraging the adoption of reclaimed water in hydroponic systems to reduce environmental burdens. In addition, future research should expand the system boundary and explore sustainable alternatives to materials and energy sources to further enhance the environmental sustainability of hydroponic systems.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 22 February 2024; accepted in revised form 3 June 2024. Available online 8 July 2024