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Evaluating The Environmental Burden of Alternative Water Sources Under Different Scenarios in Nutrient Film Technique Hydroponic System Using Life Cycle Assessment

Abdullah Nadeem[1], Muhammad Atiq Ur Rehman Tariq[2*], Muhammad Imran[1], Muhammad Minhaj Javed[1]

1. *Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore*
2. *College of Engineering, IT and Environment, Charles Darwin University, Darwin, NT 0810, Australia*

* **Corresponding Author:** Email: atiq.tariq@yahoo.com

Abstract

Sustainable agriculture practices are vital to mitigate environmental impacts and address food security. Nutrient film hydroponic system (NFHS) offer a promising alternative to soil based farming by enabling precise resource use and reduced water consumption. This study employees Life cycle Assessment (LCA) to evaluate the sustainability of hydroponic systems using three water sources, Reclaimed Water (RW), Deionised Water (DW) and Conventional Freshwater (CW). Across 15 mixing scenarios. Reclaimed Water consistently exhibited the lowest environmental impacts, including a biotic depletion. Global warming potential and eco toxicity. In contrast, CW-dominated scenarios showed the highest burdens due to energy intensive extraction and distribution. Results emphasize the need to maximize reclaimed water used, optimizing mixing ratios and implementing recycling systems. Policy incentives and stakeholder education are critical for scalable adoption. The findings highlight the potential of NFHS in promoting sustainable agriculture through efficient resource use and waste management. Enhance civility It is essential to maximise the use of reclaimed water while reducing reliance on demise and conventional fresh water. Additionally, optimising mixing ratios, implementing recycling system, monitoring use, educating stakeholder than advancing of supportive policies can further improve hydroponic sustainability.

Keywords: Environmental Impacts; Hydroponic system; LCA; Sustainability; Water Supply; Water Reuse

1. Introduction

Sustainable agricultural practices have gained importance due to the critical need to reduce environmental impacts [1] and ensure food security [2]. Among these practices, nutrient film hydroponic systems have emerged as a promising alternative to conventional soil-based cultivation [3]. These systems allow for precise nutrient delivery [4], reduced water usage [5], and efficient space utilization [6]. Sustainability has become a major key factor in agricultural practices due to climate change [7], water scarcity [8] and soil degradation [9] presenting nutrient film hydroponic system as a possible solution with higher yield [10], [11] and being favorable for areas with water scarcity [12] [13] as compared to conventional agriculture. However, for promoting sustainable agriculture we must not rely on a single sustainable water source to be secured against water scarcity.

Water scarcity presents a critical challenge for global agriculture [14] due to climate change, population growth [15], [16], [17], and unsustainable water management practices [18]. Traditional farming intensifies this issue, leading to overexploitation of aquifers [19] and degraded water quality [20]. In response, nutrient film hydroponic systems (NFHS) offer a promising alternative by significantly reducing water consumption [21] compared to conventional methods. NFHS can utilize alternative water sources like reclaimed water (RW) [22] and deionized water (DW) [23] and conventional Water (CW) , mitigating pressure on conventional supplies and encouraging sustainability. NFHS can utilise alternative water resources like reclaimed water (RW), deionized water (DW) and conventional water (CW). However, each source has specific constraint. reclaimed water typically requires filtration and disinfection to remove pathogen before use. Deionised water while free of contaminants, lacks essential minerals necessary for plant growth and required supplementation. Conventional fresh waterway though widely available, may still require treatment depending on its source quality. This approach not only addresses immediate water scarcity but also contributes to broader sustainability aims and conserving natural resources. However, successful integration requires understanding the environmental implications of using these alternatives in hydroponic system.

Hydroponic system offer sustainable alternatives to traditional agriculture, as evidenced by various studies. [24] focus on nutrient management to enhance crop quality, while [25] explore the use of organic waste for nutrient solutions. [3] compare hydroponic and conventional lettuce production, highlighting the economic and environmental benefits of soilless farming. [26] investigate zero-waste hydroponic systems utilizing agricultural waste, showing promise in reducing pollution. [27] discuss the shift towards soilless culture systems and alternative substrates for sustainability. Innovative solutions like urban acupuncture [28] address urban water scarcity through architectural interventions. Additionally, advancements in technology, such as plasma-treated water [14], contribute to improving crop productivity. Studies also tackle challenges like heavy metal remediation [29] and nutrient optimization [30], while methods for precise nutrient removal from soil aid in research [31]. Synthesizing water-soluble iron-rich compounds [32] offers solutions to nutrient deficiencies. These findings highlight hydroponics' role in sustainable agriculture through efficient resource use, waste management, and technological innovations.

Many studies have been done to assess the sustainability of the system. However, there is a gap in assessing the sustainability with mixing different percentages of various water sources in hydroponics. Aim of this study to assess the environmental burden of implying different compositions of alternate water sources in hydroponic systems.

1.1 Scenarios for Different Water Sources in LCA

Table 1: Different compositions of alternate water sources under different scenarios

Scenario	RW	DW	CW
1	100%	0%	0%
2	0%	100%	0%
3	0%	0%	100%
4	75%	25%	0%
5	0%	75%	25%
6	25%	0%	75%
7	50%	25%	25%
8	25%	50%	25%
9	25%	25%	50%
10	0%	50%	50%
11	50%	0%	50%
12	50%	50%	0%
13	0%	25%	75%
14	25%	75%	0%
15	75%	0%	25%

2. Methodology

The detailed methodology with data acquisition, study area and LCA is given below.

2.1 Data acquisition and Study Area

For assessing the sustainability of the hydroponic system was obtained from the hydroponic farm located at Mian Nawaz Sharif Agriculture University in Multan, Pakistan shown in Fig. ***1***. This hydroponic facility spans an area of 10,890 square meters, with specific geographical coordinates approximately at latitude 30.14° N and longitude 71.44° E. The dimensions of the facility measure 36.576 meters in length, 22.86 meters in width, and 3.9624 meters in height, indicating its substantial size and potential productivity. Data were collected from hydroponic facility at Mian Nawaz Sharif Agricultural University, Multan, Pakistan, over a 12-month period, weekly measurement including water consumption of energy use and material inputs were used. The functional unit of 2000 litre corresponds to weekly water demand of lettuce crop cycle and sharing consistency across scenarios. Operational data were cross validated with facility logs and prior studies.

To evaluate the environmental impact of the hydroponic system, a comprehensive life cycle assessment (LCA) methodology was employed. Following the guidelines outlined in ISO 14040 and ISO 14044, the assessment encompassed four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [33], [34]. Detailed methodology flowchart given in Fig. ***2***.

2.2 Goal and scope

The goal of this study was to quantify the environmental impacts associated with hydroponic cultivation using various water sources. The functional unit selected for analysis was the utilization of 2000 liters of different water types within the entire hydroponic system. Due to limitations in data availability, the system boundary was confined to the operational stage (gate to gate) [35], [36].

2.3 Life cycle inventory

The life cycle inventory (LCI) analysis involved compiling and quantifying inputs and outputs associated with the hydroponic system. Key components in Table 2, included perlite, fertilizers, PVC, electricity, and reclaimed water. The quantities of these components are detailed in [37].

Table 2: Inventory table covering the inputs with major contribution in the hydroponic system

Component	Amount	Unit
Perlite	41.7	Kg
Fertilizers	40	Kg
PVC	40	Kg
Electricity	25	KWh
Reclaimed water	2000	Liters

2.4 Life cycle impact assessment and interpretation

For the life cycle impact assessment (LCIA), the widely recognized CML 2001 impact assessment method was employed to evaluate various environmental burdens. This method enables the assessment of impact categories such as global warming potential, acidification, eutrophication, ozone layer depletion, and others, providing a comprehensive understanding of the environmental implications of hydroponic agriculture [23].

In the life cycle interpretation phase, the results of the LCI and LCIA phases were critically analyzed, taking into account uncertainties and assumptions inherent in the study. This phase involved conducting completeness checks, consistency checks, sensitivity analysis, and identifying significant issues. The interpretation aimed to ensure the relevance, soundness, and credibility of the LCA study, offering valuable insights for decision-making in both business and policy contexts [38], [39], [40].

The research presents a detailed analysis of different scenarios involving various water sources and their concentrations in hydroponic systems. Through this analysis, the study aims to contribute to the understanding of the environmental sustainability of hydroponic agriculture practices, thereby informing future agricultural decision-making processes.

3. Result and Discussion

Results obtained using LCIA CML 2001 have been given below.

3.1 Abiotic depletion potential (ADP)

Abiotic Depletion Potential (ADP) elements of various water sources, including reclaimed water (RW), deionized water (DW), and conventional freshwater (CW), across different mixing scenarios within hydroponic systems is provided. Each scenario, described by the percentage composition

Fig. 1: Study area showing hydroponic farm at Mian Nawaz Sharif Agriculture University Multan, Pakistan

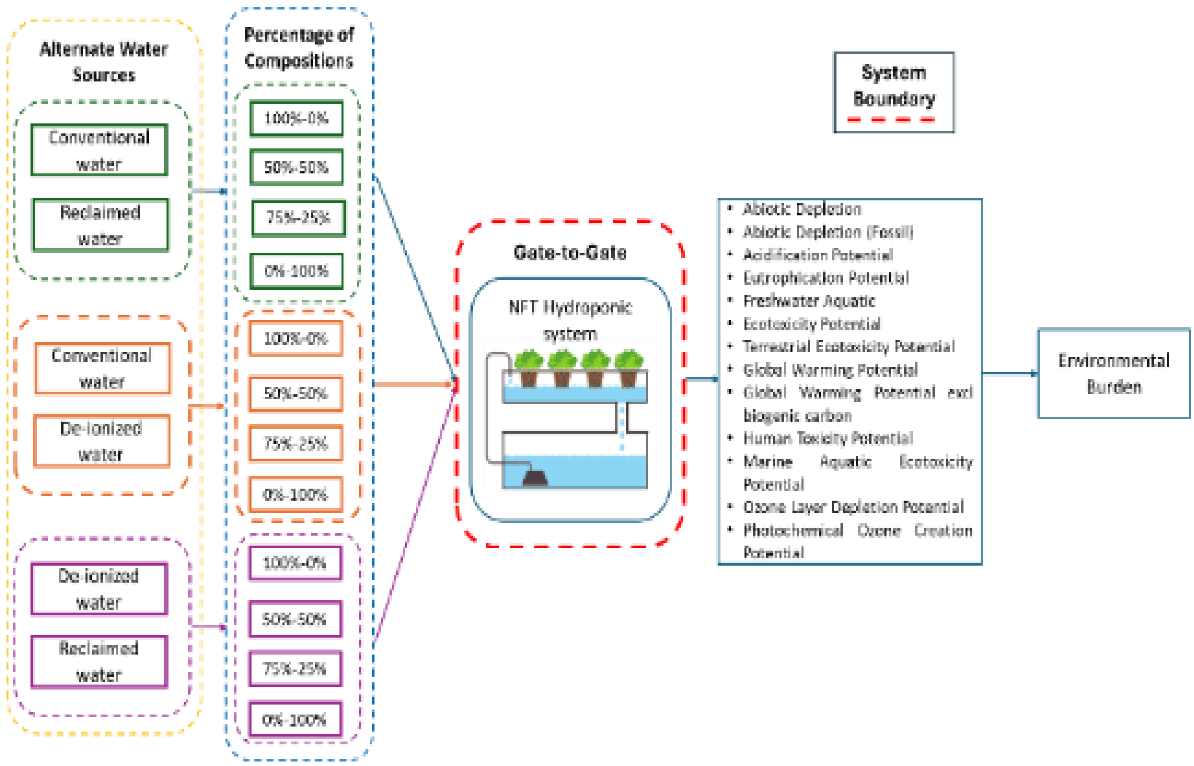

Fig. 2: The flowchart shows how different scenarios of alternate water sources in hydroponic system considering reclaimed, conventional and de-ionized water

of RW, DW, and CW, demonstrates distinct ADP elements values, indicative of their environmental burdens in terms of antimony (Sb) equivalents refer Fig. *3*. Reclaimed water consistently showcases the lowest ADP elements value across all scenarios, attributable to its recycled nature, with the minimum value recorded at 0.000022 kg Sb eq. This underscores its minimal resource consumption and reduces environmental impact compared to DW and CW. Conversely, scenarios where DW or CW dominate exhibit higher ADP elements values, reflecting increased resource depletion. For instance, when DW constitutes 100% of the mix, the ADP elements value rises to 0.0000259 kg Sb eq., while CW dominance yields the highest value at 0.0000311 kg Sb eq. Interestingly, as the proportion of RW decreases, such as in scenarios with 50% or 25% RW, the ADP elements values show intermediate levels, reflecting the influence of mixing ratios on overall resource consumption. Reclaimed water consistently exhibits the lowest Abiotic Depletion Potential (ADP). Primarily due to its low energy demand for treatment. Unlike Deionised Water (DW), which requires energy intensive ion removal and conventional fresh water, which involves energy used for extraction and distribution. Reclaimed Water (RW) utilises existing wastewater streams and mineral additional processing. This significantly reduces fossil fuel consumption and greenhouse gas emission, resulting in lower ADP values.

3.2 Abiotic Depletion (ADP fossil)

Various mixing scenarios of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW), alongside their corresponding Abiotic Depletion Potential (ADP) fossil values measured in megajoules (MJ) within hydroponic systems. Reclaimed water, constituting 100% in certain scenarios, exhibits the lowest ADP fossil value at 29.63 MJ, indicating minimal reliance on finite fossil resources due to its recycled nature Fig. *3*. Conversely, scenarios dominated by DW or CW result in higher ADP fossil values, reflective of increased fossil resource consumption. For instance, when DW constitutes 100% of the mix, the ADP fossil value rises to 37.6 MJ, while CW dominance yields the highest value at 40.08 MJ. As the proportion of RW decreases, such as in scenarios with 75%, 50%, and 25%, the corresponding ADP fossil values show incremental increases, indicating a proportional rise in fossil resource consumption. Notably, the scenario with 75% RW and 25% CW demonstrates an ADP fossil value of 18.9 MJ, while the scenario with 25% RW and 75% CW exhibits a value of 38.52 MJ, showcasing the influence of mixing ratios on environmental burdens.

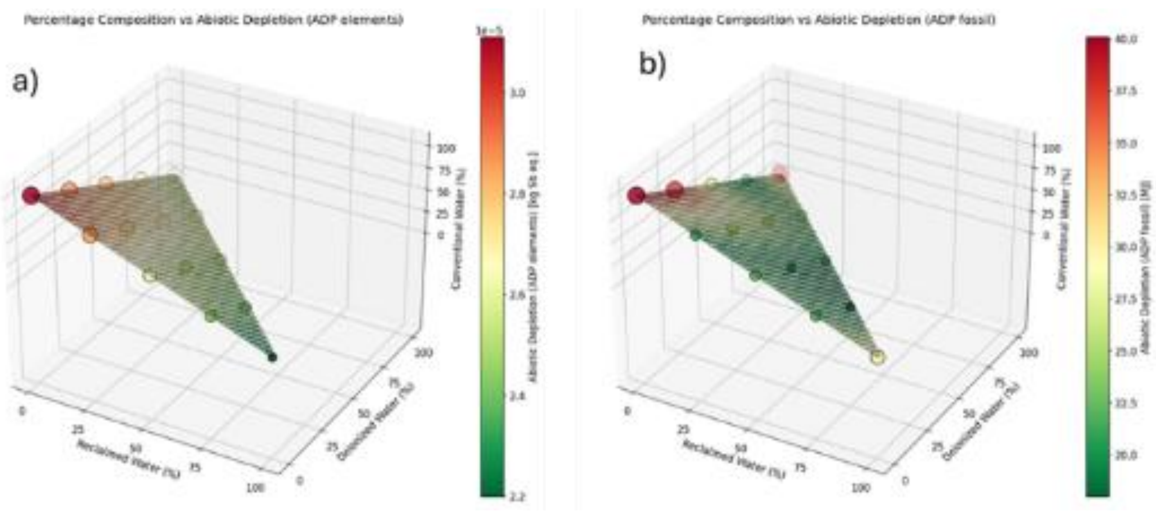

Fig. 3: Percentage composition of different water sources (conventional, reclaimed, and desalinated water). a) illustrates the relationship between the water sources and ADP elements, showing how varying compositions impact elemental depletion. Panel b) examines the same water sources in relation to ADP fossil, indicating the fossil resource depletion. Each data point represents a specific mixture of the three water types, with colors representing ADP values—red for higher depletion and green for lower depletion. The gradients in both panels help visualize how the proportion of each water type influences overall abiotic depletion

3.3 Acidification Potential (AP)

In Fig. *4*, various mixing scenarios of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW), accompanied by their respective Acidification Potential (AP) values measured in kilograms of sulfur dioxide (SO2) equivalents within hydroponic systems. Reclaimed water, composing 100% in certain scenarios, displays the lowest AP value at 0.00318 kg SO2 eq., indicative of its relatively lower contribution to acid rain formation owing to its recycled nature. Conversely, scenarios dominated by DW or CW result in higher AP values, reflecting increased potential harm to ecosystems. For instance, when DW constitutes 100% of the mix, the AP value rises to 0.00618 kg SO2 eq., while CW dominance yields the highest value at 0.00751 kg SO2 eq. As the proportion of RW decreases, such as in scenarios with 75%, 50%, and 25%, the corresponding AP values exhibit incremental increases, suggesting a proportional rise in potential harm to ecosystems due to acidification. Notably, the scenario with 75% RW and 25% CW demonstrates an AP value of 0.0036 kg SO2 eq., while the scenario with 25% RW and 75% CW exhibits a value of 0.0072 kg SO2 eq., highlighting the influence of mixing ratios on environmental impacts.

3.4 Eutrophication potential (EP)

In Fig. *4* different mixing scenarios of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW), along with their respective Eutrophication Potential (EP) values measured in kilograms of phosphate equivalents within hydroponic systems. Reclaimed water, present at 100% in certain scenarios, exhibits the lowest EP value at 0.00228 kg Phosphate eq., indicating a relatively low potential for nutrient enrichment due to its recycled nature. Conversely, scenarios dominated by DW or CW result in higher EP values, reflecting increased potential for nutrient enrichment in aquatic ecosystems. For instance, when DW constitutes 100% of the mix, the EP value rises to 0.00214 kg Phosphate eq., while CW dominance yields the highest value at 0.00312 kg Phosphate eq. As the proportion of RW decreases, such as in scenarios with 75%, 50%, and 25%, the corresponding EP values show incremental increases, suggesting a proportional rise in the potential for nutrient enrichment. Notably, the scenario with 75% RW and 25% CW demonstrates an EP value of 0.00239 kg Phosphate eq., while the scenario with 25% RW and 75% CW exhibits a value of 0.00308 kg Phosphate eq., highlighting the influence of mixing ratios on environmental impacts.

3.5 Freshwater Aquatic Ecotoxicity Potential (FAETP)

In Fig. ***5*** different mixing scenarios of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW), alongside their respective Freshwater Aquatic Ecotoxicity

Potential (FAETP) values measured in kilograms of 1,4-dichlorobenzene (DCB) equivalents within hydroponic systems. Reclaimed water, comprising 100% in certain scenarios, demonstrates the lowest FAETP value at 0.0165 kg DCB eq., suggesting a relatively lower risk to freshwater aquatic organisms due to its recycled nature. Conversely, scenarios dominated by DW or CW result in higher FAETP values, reflecting increased potential adverse effects on freshwater aquatic life. For example, when DW constitutes 100% of the mix, the FAETP value rises to 0.0223 kg DCB eq., while CW dominance yields the highest value at 0.025 kg DCB eq. As the proportion of RW decreases, such as in scenarios with 75%, 50%, and 25%, the corresponding FAETP values exhibit incremental increases, indicating a proportional rise in the potential adverse effects on freshwater aquatic organisms. Notably, the scenario with 75% RW and 25% CW demonstrates a FAETP value of 0.0171 kg DCB eq., while the scenario with 25% RW and 75% CW exhibits a value of 0.0302 kg DCB eq., highlighting the influence of mixing ratios on environmental impacts.

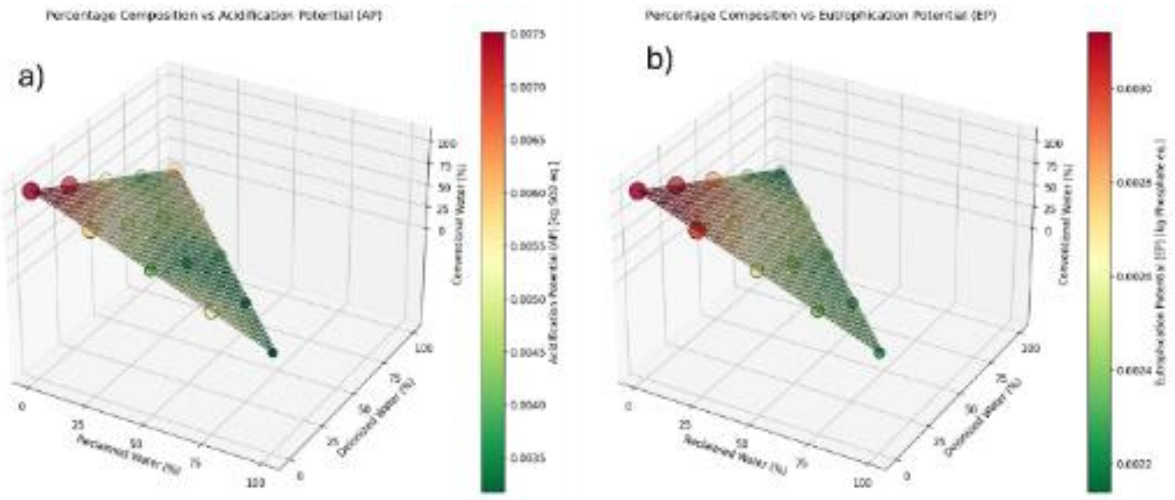

Fig. 4: Comparison the percentage composition of different water sources. Panel a) shows the relationship between conventional water, reclaimed water, and desalinated water with acidification potential, indicated by the color gradient from green to red. Panel b) illustrates the same relationship but for eutrophication potential, with the color gradient similarly representing the impact. Each point in the plot represents a specific mixture of the three water sources, highlighting how varying compositions influence the sustainability

3.6 Global Warming Potential (GWP 100 years)

In Fig. ***5*** various mixing scenarios of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW), along with their corresponding Global Warming Potential (GWP) values measured in kilograms of carbon dioxide equivalents (CO2 eq.) over a 100-year timeframe within hydroponic systems. Reclaimed water, comprising 100% in specific scenarios, exhibits the lowest GWP value at 2.14 kg CO2 eq., indicating relatively lower greenhouse gas emissions attributed to its recycled nature. Conversely, scenarios dominated by DW or CW result in higher GWP values, reflecting increased contributions to climate change. For example, when DW constitutes 100% of the mix, the GWP value rises to 2.95 kg CO2 eq., while CW dominance yields the highest value at 3.11 kg CO2 eq. As the proportion of RW decreases, such as in scenarios with 75%, 50%, and 25%, the corresponding GWP values exhibit incremental increases, indicating a proportional rise in greenhouse gas emissions. Notably, the scenario with 75% RW and 25% CW demonstrates a GWP value of 2.31 kg CO2 eq., while the scenario with 25% RW and 75% CW exhibits a value of 3.02 kg CO2 eq., highlighting the influence of mixing ratios on environmental impacts.

Reclaimed water consistently exhibits the lowest Global Warming Potential (GWP). Primarily due to its low energy demand for treatment. Unlike Deionised Water (DW), which requires energy intensive ion removal and conventional fresh water, which involves energy used for extraction and distribution. Reclaimed Water (RW) utilises existing wastewater streams and mineral additional processing. This significantly reduces fossil fuel consumption and greenhouse gas emission, resulting in lower GWP values.

3.7 Global Warming Potential (GWP 100 years) excl biogenic carbon

In Fig. ***6*** various mixing scenarios involving reclaimed water (RW), deionized water (DW), and conventional freshwater (CW), along with their associated Global Warming Potential (GWP) values measured in kilograms of carbon dioxide equivalent Reclaimed water consistently showcases ts (CO_2 eq.) over a 100-year timeframe, excluding biogenic carbon, within hydroponic systems. Reclaimed water, represented at 100% concentration in certain scenarios, demonstrates the lowest GWP value at 2.19 kg CO_2 eq., indicative of its relatively lower contribution to climate change mitigation owing to its recycled nature. Conversely, scenarios dominated by DW or CW result in higher GWP values, reflecting increased emissions. For instance, when DW constitutes 100% of the mix, the GWP value rises to 3.03 kg CO_2 eq., while CW dominance yields the highest value at 3.58 kg CO_2 eq. As the proportion of RW decreases, such as in scenarios with 75%, 50%, and 25%, the corresponding GWP values exhibit incremental increases, indicating a proportional rise in greenhouse gas emissions. Notably, the scenario with 75% RW and 25% CW demonstrates a GWP value of 2.5 kg CO_2 eq., while the scenario with 25% RW and 75% CW exhibits a value of 3.51 kg CO_2 eq., highlighting the influence of mixing ratios on environmental impacts.

3.8 Human Toxicity Potential (HTP)

Fig. ***6*** illustrates various combinations of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW) in hydroponic systems, alongside their corresponding Human Toxicity Potential (HTP) values measured in kilograms of 1,4-dichlorobenzene (DCB) equivalents. Reclaimed water, when present at 100% concentration, demonstrates the lowest HTP value at 0.145 kg DCB eq., indicating its relatively lower potential to pose human health risks compared to DW or CW. Conversely, scenarios dominated by DW or CW result in higher HTP values, reflecting increased toxicity potential. For instance, when DW constitutes 100% of the mix, the HTP value rises to 0.251 kg DCB eq., while CW dominance yields the highest value at 0.45 kg DCB eq. As the proportion of RW decreases, such as in scenarios with 75%, 50%, and 25%, the corresponding HTP values show incremental increases, suggesting a proportional rise in human health risks. Notably, the scenario with 75% RW and 25% CW demonstrates an HTP value of 0.216 kg DCB eq., while the scenario with 25% RW and 75% CW exhibits a value of 0.39 kg DCB eq., highlighting the influence of mixing ratios on potential toxicity.

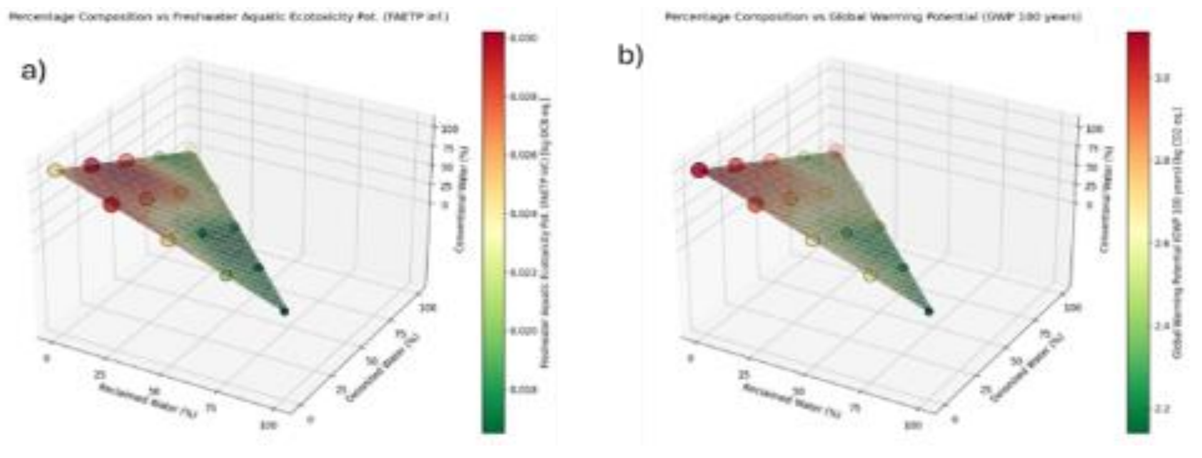

Fig. 5: a) illustrating the environmental impact of different water source compositions on Freshwater Aquatic Ecotoxicity Potential (FAETP inf.) and Global Warming Potential (GWP 100 years). The left plot maps the percentage composition of conventional water, reclaimed water, and deionized water against FAETP values, using a color gradient from green (low ecotoxicity) to red (high ecotoxicity). The right plot (b) similarly maps these water source compositions against GWP values over a 100-year period, with a color gradient from green (low GWP) to red (high GWP). Both plots highlight how varying mixtures of water sources influence these environmental impact metrics, revealing trends and potential areas for optimization

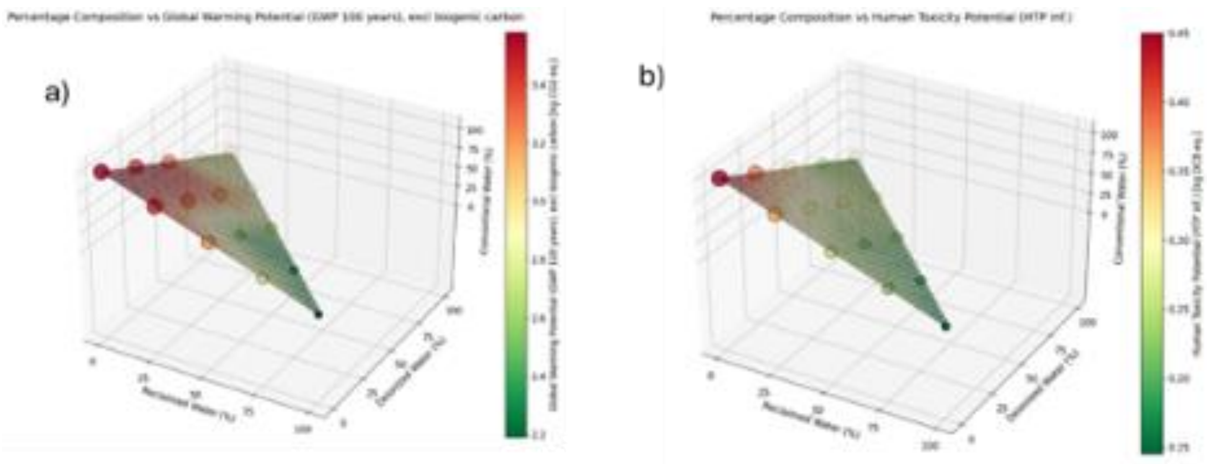

Fig. 6: a) illustrating the environmental impacts of different w ater source compositions on Global Warming Potential (GWP 100 years, excluding biogenic carbon) and Human Toxicity Potential (HTP inf.). The left plot shows the relationship between the percentage compositions of conventional water, reclaimed water, and deionized water with GWP values, represented by a color gradient from green (low GWP) to red (high GWP). The right plot (b) examines these same water compositions in relation to HTP values, using a color gradient from green (low toxicity) to red (high toxicity). These plots demonstrate how varying combinations of water sources influence these environmental impact metrics, highlighting trends and areas for potential improvement

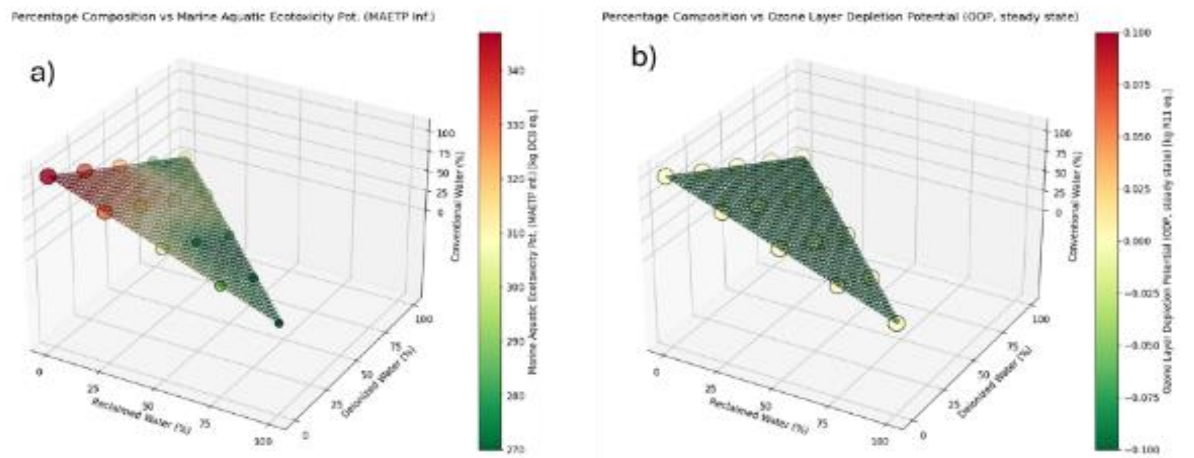

Fig. 7: Environmental impacts of different water source compositions on Marine Aquatic Ecotoxicity Potential (MAETP inf.) and Ozone Layer Depletion Potential (ODP, steady state). Plot (a) shows the relationship between the percentage compositions of conventional water, reclaimed water, and deionized water with MAETP values, represented by a color gradient from green (low ecotoxicity) to red (high ecotoxicity). Plot (b) examines these same water compositions in relation to ODP values, using a color gradient from green (low depletion potential) to red (high depletion potential). These plots demonstrate how varying combinations of water sources influence these environmental impact metrics, highlighting trends and areas for potential improvement

3.9 Marine Aquatic Ecotoxicity Potential (MAETP)

Fig. *7* outlines various compositions of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW) in hydroponic systems, along with their corresponding Marine Aquatic Ecotoxicity Potential (MAETP) values measured in kilograms of 1,4-dichlorobenzene (DCB) equivalents. When RW is present at 100% concentration, it demonstrates the lowest MAETP value of 270 kg DCB eq., indicating relatively lower potential toxicity to marine aquatic ecosystems compared to scenarios dominated by DW or CW. Conversely, scenarios where DW or CW are the sole components exhibit higher MAETP values, indicating increased ecotoxicity potential. For instance, when DW constitutes 100% of the mix, the MAETP value rises to 300 kg DCB eq., while CW dominance yields the highest value at 347 kg DCB eq. As the proportion of RW decreases and other components increase, such as in scenarios with 75%, 50%, and 25%, the corresponding MAETP values show incremental increases, suggesting a proportional rise in potential ecotoxicity to marine aquatic environments. Notably, the scenario with 75% RW and 25% DW demonstrates an MAETP value of 274 kg DCB eq., while the scenario with 25% RW and 75% CW exhibits a value of 338 kg DCB eq., highlighting the influence of mixing ratios on potential marine ecotoxicity.

3.10 Ozone Layer Depletion Potential (ODP)

Fig. *7* illustrates various compositions of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW) in hydroponic systems, alongside their corresponding Ozone Layer Depletion Potential (ODP) values measured in kilograms of R11 equivalents. When RW is present in a 100% concentration, it demonstrates the lowest ODP value of approximately 6.11E-14 kg R11 eq., indicating minimal potential for ozone layer depletion compared to scenarios dominated by DW or CW. Conversely, scenarios where DW or CW are the sole components exhibit higher ODP values, suggesting increased potential for ozone layer depletion. For instance, when DW constitutes 100% of the mix, the ODP value rises to approximately 7.28E-14 kg R11 eq., while CW dominance yields the highest value at approximately 9.54E-14 kg R11 eq. As the proportion of RW decreases and other components increase, such as in scenarios with 75%, 50%, and 25%, the corresponding ODP values show incremental increases, suggesting a proportional rise in potential ozone layer depletion. Notably, the scenario with 75% RW and 25% DW demonstrates an ODP value of approximately 6.23E-14 kg R11 eq., while the scenario with 25% RW and 75% CW exhibits a value of approximately 9.21E-14 kg R11 eq., highlighting the influence of mixing ratios on potential ozone layer depletion.

3.11 Photochemical Ozone Creation Potential (POCP)

In Fig. ***8*** various mixing scenarios of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW) in hydroponic systems, accompanied by their respective Photochemical Ozone Creation Potential (POCP) values measured in kilograms of ethene equivalents. Notably, scenarios with higher proportions of RW exhibit relatively lower POCP values, indicating reduced potential for photochemical ozone creation compared to scenarios dominated by DW or CW. For instance, when RW constitutes 100% of the mix, the POCP value is approximately 0.000471 kg Ethene eq., reflecting minimal photochemical ozone creation potential. Conversely, scenarios where DW or CW are predominant demonstrate higher POCP values, suggesting increased potential for photochemical ozone creation. When DW constitutes 100% of the mix, the POCP value rises to approximately 0.000502 kg Ethene eq., while CW dominance yields the highest value at approximately 0.000601 kg Ethene eq. Furthermore, as the proportion of RW decreases and other components increase, such as in scenarios with 75%, 50%, and 25% RW, the corresponding POCP values incrementally increase, indicating a proportional rise in potential photochemical ozone creation.

3.12 Terrestrial Ecotoxicity Potential (TETP)

Fig. ***8*** provides insights into different mixing scenarios of reclaimed water (RW), deionized water (DW), and conventional freshwater (CW) in hydroponic systems, accompanied by their corresponding Terrestrial Ecotoxicity Potential (TETP) values measured in kilograms of 1,4-dichlorobenzene (DCB) equivalents. Notably, scenarios with higher proportions of RW exhibit relatively lower TETP values, indicating reduced potential for terrestrial ecotoxicity compared to scenarios dominated by DW or CW. For instance, when RW constitutes 100% of the mix, the TETP value is approximately 0.012 kg DCB eq., reflecting minimal terrestrial ecotoxicity potential. Conversely, scenarios where DW or CW are predominant demonstrate higher TETP values, suggesting increased potential for terrestrial ecotoxicity. When DW constitutes 100% of the mix, the TETP value rises to approximately 0.0201 kg DCB eq., while CW dominance yields the highest value at approximately 0.0272 kg DCB eq. Furthermore, as the proportion of RW decreases and other components increase, such as in scenarios with 75%, 50%, and 25% RW, the corresponding TETP values incrementally increase, indicating a proportional rise in potential terrestrial ecotoxicity.

4. Discussion

The research reveals significant trends and insights into the environmental impacts associated with different mixing scenarios of water sources in hydroponic systems. Across various environmental indicators, including abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine

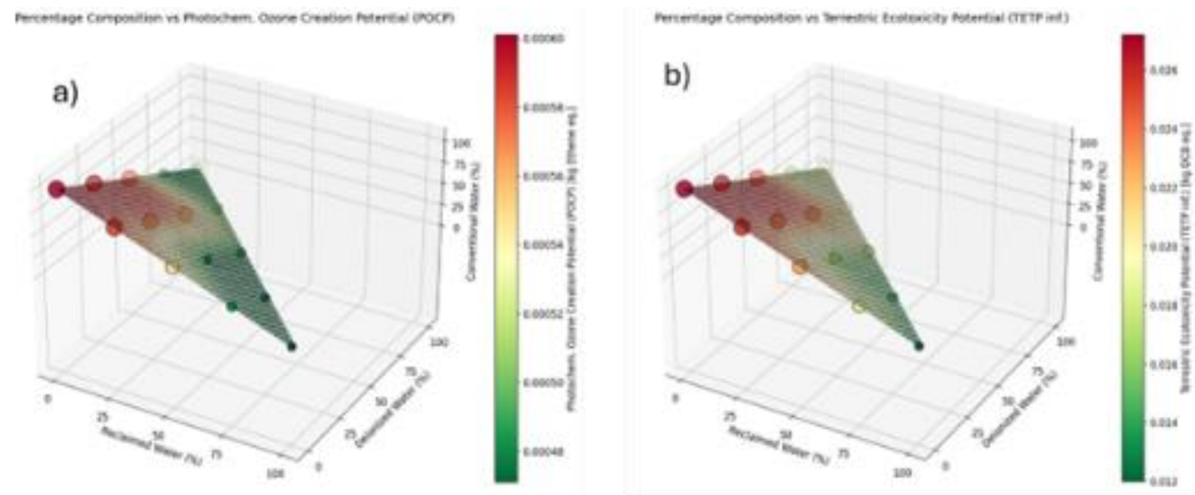

Fig. 8: Illustration of environmental impacts of different water source compositions on Photochemical Ozone Creation Potential (POCP) and Terrestrial Ecotoxicity Potential (TETP inf.). Plot (a) shows the relationship between the percentage compositions of conventional water, reclaimed water, and deionized water with POCP values, represented by a color gradient from green (low ozone creation potential) to red (high ozone creation potential). Plot (b) examines these same water compositions in relation to TETP values, using a color gradient from green (low terrestrial ecotoxicity) to red (high terrestrial ecotoxicity). These plots demonstrate how varying mixtures of water sources affect these environmental impact metrics, indicating trends and areas for potential optimization

aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP), and terrestrial ecotoxicity potential (TETP), distinct patterns emerge.

The composition of water sources, scenarios with a higher proportion of reclaimed water (RW) consistently demonstrate lower environmental burdens [41] across most indicators compared to scenarios dominated by deionized water (DW) or conventional freshwater (CW). For example, when RW constitutes 100% of the mix, it leads to the lowest values across various indicators, such as ADP elements (0.000022 kg Sb eq.), AP (0.00318 kg SO2 eq.), EP (0.00228 kg Phosphate eq.), FAETP (0.0165 kg DCB eq.), GWP (2.14 kg CO2 eq.), and others.

Scenarios where DW or CW dominate tend to exhibit higher environmental burdens [42]. For instance, in scenarios where DW constitutes 100% of the mix, the values for environmental indicators such as ADP elements (0.0000259 kg Sb eq.), AP (0.00618 kg SO2 eq.), EP (0.00214 kg Phosphate eq.), FAETP (0.0223 kg DCB eq.), GWP (2.95 kg CO2 eq.), and others are higher compared to scenarios with RW dominance. Our findings aligned with global research emphasising reclaimed waters sustainability, for instance, [3] reported a 40% reduction in water use for hydroponic lettuce compared to soil farming, consistent with reclaimed water efficiency metrics. Locally, studies in Pakistan with [7] highlighted groundwater exploitation. Underscoring the urgency of adopting reclaimed water to alleviate aquifer stress. The influence of mixing ratios on environmental impacts is evident. As the proportion of RW decreases and DW or CW increases, there is a proportional rise in environmental burdens. For example, in scenarios where RW constitutes only 25% of the mix and DW or CW dominate, values for environmental indicators such as ADP elements, AP, EP, FAETP, GWP, and others increase compared to scenarios with higher proportions of RW.

Specific environmental indicators show varying sensitivity to mixing ratios. For instance, while GWP tends to increase with decreasing RW proportion, the increase in values for AP, EP, FAETP, and others may vary depending on the specific mixing ratios.

While reclaimed water (RW) demonstrates superior environmental performance across indicators, its application in hydroponic system necessitates careful consideration of potential trade-off. For instance, reclaimed water may carry microbiological contaminants, e.g. pathogens, for elevated salinity levels, which could compromise crop health and food safety if inadequately managed. To mitigate these risks pre-treatment processes such as UV disinfection, ozonation or membrane filtration are critical for pathogen removal while periodic monitoring of electrical conductivity (EC) and nutrient solution composition can address salinity imbalance. These measures ensure that reclaimed water's sustainability benefits are realized without sacrificing operational reliability to crop yield.

The importance of considering the composition of water sources in hydroponic systems to minimize environmental impacts. Maximizing the use of reclaimed water and reducing reliance on DW and CW can significantly mitigate environmental burdens associated with agricultural practices, ensuring sustainability in hydroponic cultivation.

5. Conclusion

The life cycle impact assessment (LCIA) results reveal significant environmental implications of using different water sources—reclaimed water (RW), deionized water (DW), and conventional freshwater (CW)—in hydroponic systems. Across various environmental indicators, scenarios with a higher proportion of reclaimed water consistently demonstrate lower environmental burdens. For instance, RW shows the lowest Abiotic Depletion Potential (ADP) elements value at 0.000022 kg Sb eq., highlighting its minimal resource consumption. Conversely, DW and CW, when used in higher proportions, exhibit increased ADP elements values, with CW at 0.0000311 kg Sb eq., reflecting higher resource depletion. This pattern is consistent across other indicators such as ADP fossil, where RW at 100% yields 29.63 MJ, whereas CW dominance results in 40.08 MJ.

Similarly, for Acidification Potential (AP), RW at 100% results in the lowest AP value of 0.00318 kg SO_2 eq., while CW dominance increases the value to 0.00751 kg SO_2 eq. The trend continues with Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Potential (FAETP), and Global Warming Potential (GWP), where higher RW proportions consistently result in lower values compared to DW and CW. For instance, FAETP for RW at 100% is 0.0165 kg DCB eq., but increases to 0.025 kg DCB eq. with CW. The Global Warming Potential also follows this trend, with RW at 2.14 kg CO_2 eq., compared to 3.11 kg CO_2 eq. for CW.

The study demonstrates that reclaimed water minimises environmental impacts in hydroponic system across all assessed scenarios, outperforming diagnosed and conventional freshwater. Key findings include:

Reclaimed water reduces abiotic depletion by 30% compared to CW and 15% compared to DW. Scenarios offer intermediate sustainability benefits, balancing resources, efficiency, and practicality. Energy intensive processes for DW and CW (e.g. desalinated, groundwater, pumping) drive their higher global warming potential.

These results show the environmental benefits of maximizing RW use in hydroponic systems, minimizing reliance on DW and CW. As RW proportions decrease and DW or CW increase, environmental impacts, such as resource depletion, acidification, eutrophication, and ecotoxicity, proportionally rise. This data-driven conclusion highlights the necessity of prioritizing RW in hydroponic agriculture to enhance sustainability and reduce environmental burdens.

6. Recommendations

1. **Maximize Use of Reclaimed Water (RW):** Prioritize the use of RW in hydroponic systems to reduce environmental burdens. RW consistently shows the lowest values across multiple environmental indicators, including abiotic depletion, fossil resource depletion, acidification, eutrophication, ecotoxicity, global warming potential, and ozone layer depletion.
2. **Reduce Reliance on Deionized Water (DW) and Conventional Freshwater (CW):** Minimize the use of DW and CW, especially in high proportions. Scenarios where DW or CW dominate result in significantly higher environmental impacts across all measured indicators. By limiting their use, the overall sustainability of hydroponic operations can be improved.
3. **Optimize Mixing Ratios:** When it is necessary to use DW or CW, carefully optimize the mixing ratios to ensure that RW still makes up a substantial proportion of the water used. For example, a mix of 75% RW and 25% CW shows considerably lower environmental impacts compared to scenarios with higher proportions of DW or CW.
4. **Implement Recycling Systems:** Develop and implement advanced water recycling systems to increase the availability and use of RW. Recycling systems can help convert more water into RW, thus reducing the dependency on more environmentally burdensome water sources.
5. **Monitor and Adjust Water Use:** Regularly monitor the environmental impacts of water use in hydroponic systems. Use the data to adjust water sourcing strategies dynamically, ensuring that the most sustainable practices are always being followed.

6. **Educate Stakeholders:** Educate farmers, agronomists, and other stakeholders about the benefits of using RW and the environmental impacts associated with DW and CW. Training and awareness programs can encourage the adoption of more sustainable water use practices.
7. **Policy and Incentives:** Advocate for policies and incentives that support the use of reclaimed water in agricultural practices. Government and regulatory bodies can play a crucial role by providing subsidies, tax benefits, or other incentives for the adoption of sustainable water use strategies in hydroponics.

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