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Evaluating sustainable water and wastewater management strategies for Kerman city: A life cycle assessment approach

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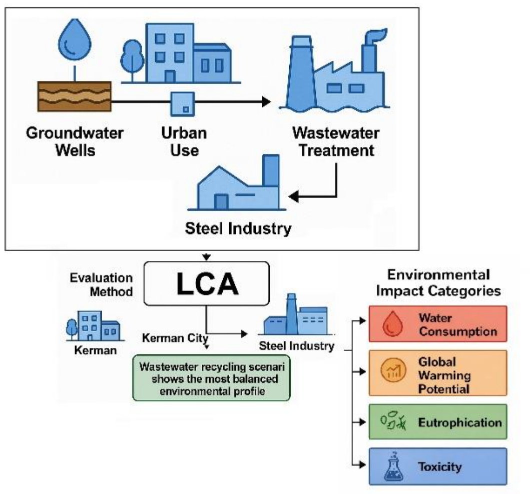
GRAPHICAL ABSTRACT



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ABSTRACT

This study evaluates four alternative water and wastewater management scenarios for Kerman City using Life cycle assessment based on the ReCiPe 2016 Midpoint (H) method and the World (2010) H normalization and weighting set. The scenarios include: (1) pre-industrial baseline without centralized sewage collection, (2) current practice where treated effluent is predominantly allocated to the steel industry, (3) partial reallocation of wastewater to green urban use, and (4) reduced industrial allocation with seawater substitution. The functional unit is the management of 1 m³ of urban wastewater. Results show that Scenario 1 has the lowest Global Warming Potential (0.36 kg CO_2-eq), followed by Scenario 3 (0.49 kg CO_2-eq), while Scenario 4 shows the highest impact (1.25 kg CO_2-eq) due to desalination energy use. In the water consumption category, Scenario 4 performs best (0.05 m³ water consumed), compared to 0.22 m³ in Scenario 2. Regarding freshwater eutrophication, Scenario 4 also outperforms other options, with an impact score of 0.0018 kg P-eq. Monte Carlo simulation was conducted for uncertainty analysis, indicating a high degree of robustness in the comparative rankings. The findings highlight the trade-offs between energy use, water reuse, and environmental burden, providing insights for sustainable water planning in arid urban regions.

1. Introduction

Water is an essential resource that sustains life, industry, and ecosystems. However, the increasing global demand for water, driven by population growth, urbanization, and industrialization, poses significant challenges, particularly in arid and semi-arid regions. Water-intensive industries face acute challenges in securing sustainable water resources due to the compounded effects of climate change, water scarcity, and the

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unsustainable management of conventional water sources (Jain *et al*., 2024). These issues necessitate innovative approaches to water management, with wastewater reuse emerging as a viable and sustainable solution.

In regions like Kerman, a city located in the south-eastern part of Iran, these water challenges are even more pronounced. Kerman is a predominantly arid region where water scarcity is a critical concern (Soleimani Damaneh *et al*., 2024). The city has been grappling with the depletion of its groundwater resources, a consequence of over-extraction and mismanagement of local water sources (Azizi *et al*., 2024). The increasing water demand for urban consumption, coupled with prolonged droughts and reduced rainfall, has further exacerbated the crisis. To address these challenges, innovative solutions, such as wastewater reuse, have been explored to supplement conventional water sources and meet the growing demands of both the urban population and local industries.

Wastewater, generated by urban, industrial, agricultural, and commercial activities, contains a wide range of contaminants that require proper collection, treatment, and recycling to prevent environmental degradation and public health risks (Manasa and Mehta, 2020). The untreated disposal of wastewater has long been a pressing concern, leading to groundwater contamination, eutrophication, and the disruption of aquatic ecosystems. As a result, urban wastewater treatment systems are essential to safeguard public health, protect natural water bodies, and promote water reuse for agricultural and industrial purposes. In water-scarce regions, industrial water demand exacerbates the already critical water crisis, highlighting the need for more efficient water management practices (Crini and Lichtfouse, 2018).

One of the most water-intensive industries in Kerman is the steel industry, which requires significant amounts of water for cooling, cleaning, and processing operations (Gargari *et al*., 2024). Efficient water management and recycling within the steel industry are critical for minimizing environmental impact and ensuring sustainability. As such, the steel industry is increasingly turning to treated urban wastewater as an alternative water source. The proximity of the steel industry to urban centers enables the reuse of treated wastewater, reducing the dependency on non-renewable surface and groundwater resources while alleviating environmental pollution. This reuse strategy not only conserves valuable water resources but also exemplifies a circular economy approach, aligning with sustainable development goals by minimizing waste and promoting resource efficiency.

However, the use of treated wastewater in industry, while offering numerous benefits, also presents a range of challenges. In Kerman, the steel industry has invested in the completion of the urban sewage collection network and the development of the city's treatment plant. In return, the industry has secured the exclusive right to use treated wastewater for its operations under a 29-year agreement. Since the project's initiation, Kerman has witnessed significant environmental changes, including a sharp decline in groundwater levels, reduced water quality, and an alarming increase in soil salinity. The municipal water supply, primarily sourced from groundwater, has been negatively impacted, limiting its use for irrigation of urban green spaces and other essential services.

Moreover, the decrease in groundwater levels and water quality has forced the water and sewage company to dig new wells to meet urban water demands, further exacerbating the problem. The steel industry's exclusive access to treated wastewater has led to a situation where excess water, exceeding the industry's needs, has created new challenges and opportunities. The industry is now exploring ways to expand its capacity and even sell the surplus treated wastewater to other nearby industries, which could increase economic benefits but also raise concerns about the long-term sustainability of the practice.

The environmental and socio-economic impacts of such water management policies have sparked debate among stakeholders, with proponents arguing that the policy promotes efficient resource use and economic growth, while critics highlight the detrimental effects on the environment and the limited availability of water for municipal use. As the Kerman model progresses, it remains unclear whether this long-term investment in wastewater infrastructure and the exclusive use of treated water by industry can be considered a sustainable approach for Kerman and similar cities across Iran. Given the uncertainties surrounding the sustainability of the current water management scenario, this study aims to answer a crucial question: Can the policy of industry investment in the urban sewage collection and treatment network, and the long-term monopolization of treated wastewater for industrial purposes, be considered a sustainable approach for Kerman and other cities in Iran? To address this question, the study employs the Life cycle assessment methodology to evaluate the environmental, economic, and social impacts of various scenarios. The LCA methodology is a holistic and quantitative approach that assesses the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction to disposal and recycling.

LCA has become a powerful tool for assessing the sustainability of wastewater reuse systems, particularly in industrial applications (Bender and Farach-Colton, 2000). The approach enables the identification of critical environmental trade-offs and optimization of resource use across different stages of the water treatment and reuse process. In the context of steel production, the LCA framework provides a valuable platform for assessing the environmental impacts of using treated municipal wastewater compared to conventional water sources, such as groundwater and surface water (Burchart-Korol, 2013). Although the water-saving benefits of wastewater reuse are well-documented, there are several associated factors that must be carefully evaluated, including energy consumption for pumping and advanced treatment processes, chemical use, and emissions, to quantify the net environmental benefits of treated wastewater reuse (Suer *et al*., 2022).

While several studies have examined the environmental impacts of wastewater reuse in agriculture and urban applications, however, to date, no comprehensive study has been conducted on the environmental impacts of using municipal wastewater in industry, especially in developing countries facing water crises. This knowledge gap necessitates a detailed environmental impact assessment of the water consumption lifecycle in industry, using scientifically validated methods, models, and databases. Such an assessment will provide a comprehensive scientific perspective on the environmental effects at intra-plant, regional, and national scales. Furthermore, this study will serve as a foundation for policymakers and industry experts, guiding the development of sustainable wastewater management projects across Iran and potentially other regions facing similar challenges.

LCA has become an essential tool in evaluating the environmental performance of various wastewater treatment technologies. Banti *et al*. (2020) compared membrane bioreactors and activated sludge systems for municipal wastewater treatment. The study highlighted the benefits of membrane bioreactors, which offer more efficient removal of pollutants with a relatively lower environmental impact in terms of energy consumption and operational costs. However, membrane bioreactors can be more resource-intensive in terms of membrane replacement and fouling issues, which can elevate their environmental burden. In contrast, activated sludge systems, though less efficient, generally have a lower initial environmental impact but struggle with long-term operational efficiency (Banti *et al*., 2020). Recent research highlights the growing importance of Life cycle assessment as a comprehensive methodology for evaluating the environmental sustainability of wastewater treatment and reuse systems.

The primary focus of these studies has shifted toward understanding not just energy consumption, but also broader environmental trade-offs such as chemical use, resource depletion, and long-term ecological impacts (Corominas *et al*., 2020, Tayyebi *et al*., 2023, Li *et al*., 2021, Zhang *et al*., 2020). LCA is increasingly recognized as an effective decision-support tool, especially when applied with a systems-thinking approach that accounts for local energy sources, available technologies, and socio-environmental contexts (Corominas *et al*., 2020).

A key theme emerging from the literature is the role of wastewater recycling and reuse in addressing water scarcity. Studies suggest that decentralized and low-complexity treatment systems—particularly in developing regions—can reduce environmental burdens significantly by substituting freshwater use with treated wastewater, particularly for non-potable purposes such as irrigation and industrial operations (Lopes *et al*., 2020, Dominguez *et al*., 2018, Maeseele and Roux, 2021). However, practical implementation challenges remain, especially regarding infrastructure costs and public acceptance.

Energy efficiency is another dominant concern in wastewater treatment assessments. Although advanced biological and membrane-based treatment technologies offer better pollutant removal, they are often associated with higher energy demand, emphasizing the need for optimized energy management strategies (Li *et al*., 2021, Zhang *et al*., 2020). In this context, the integration of renewable energy sources and biological nutrient removal systems is proposed as a path toward more sustainable operation. Some studies have also advocated for a broader perspective in LCA by incorporating ecosystem services. This approach considers the ecological value of actions such as habitat restoration and water cycle support, enabling a more holistic assessment of wastewater management interventions (Zhang *et al*., 2010). Despite these advancements, several methodological challenges remain. Variability in data quality, assumptions in impact modeling, and regional inconsistencies often hinder cross-comparison of LCA results. To address these uncertainties, recent studies recommend the use of tools such as Monte Carlo simulations and fuzzy logic to enhance model robustness and improve the reliability of LCA outcomes (Alemam *et al*., 2018, Sheikholeslami *et al*., 2023).

The results of this study will provide much-needed clarity on the environmental and socio-economic trade-offs involved in the current water management practices in Kerman. By comparing different water management scenarios and their associated impacts, this research will offer valuable insights into the sustainability of the steel industry's reliance on treated wastewater. It will also provide recommendations for optimizing water use, reducing environmental impacts, and ensuring long-term water security for both the urban population and industrial sectors in Kerman and other regions in Iran.

This study focuses on the comprehensive environmental evaluation of the water and wastewater management in Kerman, with a particular emphasis on wastewater collection, treatment, and reuse compared to conventional water use practices under different scenarios. Using advanced analytical tools, the study aims to assess the environmental performance of the reuse system by analysing key parameters such as energy consumption, infrastructure requirements, and pollutant emissions. The analysis will also identify potential trade-offs between the various water management scenarios and provide actionable insights for policymakers and industry stakeholders to enhance the sustainability of water management practices in the steel sector.

2. Materials and methods

The Life cycle assessment conducted in this study followed the standardized four-step framework defined by ISO 14040 and ISO 14044. First, in the Goal and Scope Definition phase, the purpose of the assessment, system boundaries, functional unit (1 m³ of urban wastewater in Kerman), and assumptions were clearly defined. Second, in the Life Cycle Inventory phase, data on inputs (e.g., energy, materials) and outputs (e.g., emissions, waste) were collected for all processes within the system boundaries, drawing from technical reports and the Ecoinvent v3.7.1 database. Third, during the Life Cycle Impact Assessment step, the collected inventory data were translated into environmental impact indicators using the ReCiPe 2016 midpoint method. Finally, in the Interpretation phase, results were analyzed to identify trade-offs, uncertainties, and the most environmentally favorable scenario, providing clear recommendations for sustainable water management strategies in Kerman. In this study, the ReCiPe 2016 Midpoint (H) method was selected as the impact assessment methodology due to its comprehensive and widely accepted framework for evaluating a broad range of environmental impact categories. ReCiPe integrates both midpoint and endpoint indicators, allowing for detailed analysis while maintaining interpretability across different environmental dimensions (Huijbregts *et al*., 2017). Moreover, it is particularly well-suited for urban water systems, as it captures impacts relevant to energy use, emissions, and resource depletion associated with wastewater treatment and reuse processes. Its compatibility with the normalization and weighting set of "World (2010) H" also enhances comparability of results across global contexts.

2.1. Goal and scope definition

The primary objective of this study is to assess the environmental impacts associated with the management of urban water and wastewater systems in Kerman, with the aim of identifying strategies for their improvement. Data and information for this analysis were obtained from official documents provided by the Water and Wastewater Company. Currently, Kerman's water and wastewater management system comprises a drinking water treatment plant, a wastewater sludge treatment facility.

Prior to the establishment of the steel Industry, due to the incomplete development of the sewage collection network, approximately 25% of the wastewater was directed to the wastewater treatment plant, while the remaining 75% was discharged into absorption wells. The treated wastewater was primarily used for agricultural purposes. However, since the construction of the steel plant, as well as further development of wastewater collection infrastructure, approximately 40% of the treated wastewater has been diverted to the steel company, while the remaining effluent continues to be directed to the absorption wells. The volume of treated wastewater transferred to the steel plant exceeds its actual demand, and the surplus is sold to other industries. It is estimated that approximately 50% of the transferred treated wastewater surpasses the steel plant's requirements.

The water and wastewater management system of Kerman city is divided into two main sectors: the potable water Sector (PWS) and the wastewater treatment sector (WWTS). In the PWS, groundwater is extracted from 51 wells and, after being transferred to storage reservoirs, undergoes filtration, aeration, and disinfection processes before being pumped into the water distribution network. Water loss in the distribution network is estimated at approximately 15%. Additionally, in the domestic sector, about 10% of the water is considered lost due to evaporation or garden irrigation. In the WWTS, municipal wastewater is collected through a sewage network consisting of concrete pipelines and pumping stations and is conveyed to the Sharfabad wastewater treatment plant, located in the northern part of Kerman. The treatment process at this facility includes preliminary (bar screens and grit removal), primary (sedimentation and chemical coagulation/flocculation), secondary (activated sludge), and tertiary (filtration and disinfection) treatment stages (Fig. 1). Currently, there is no management of the sludge produced, and it is improperly disposed of in the vicinity of the treatment plant.

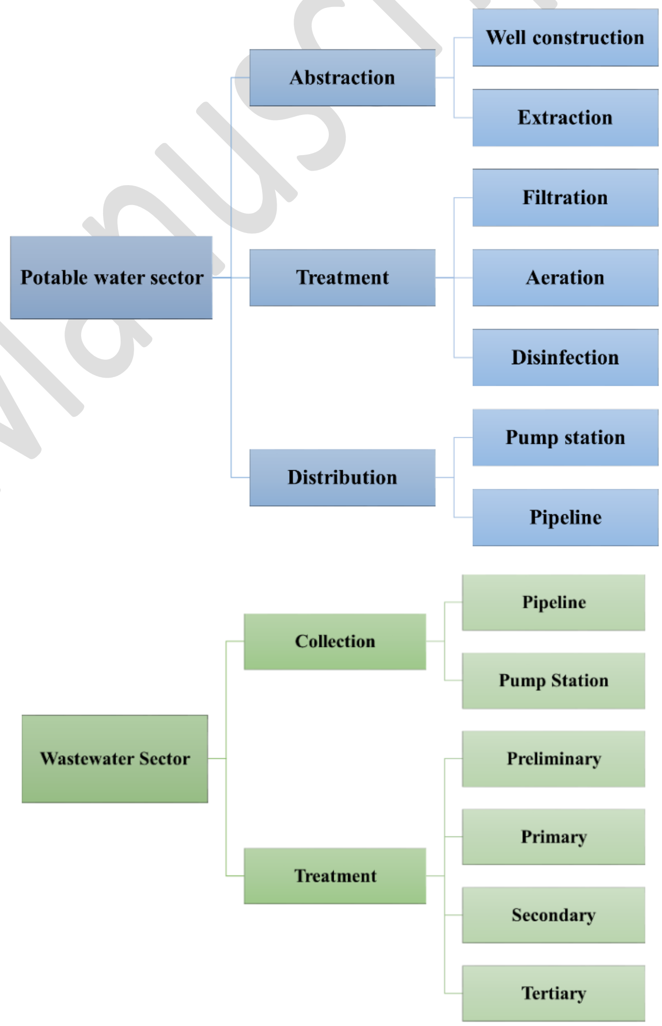


Fig. 1. PWS and WWTS processes in Kerman.

This study evaluates four distinct scenarios for water and wastewater management in Kerman, including two representing conditions before and after the expansion of the sewage collection network, and two proposed alternatives aimed at reducing environmental impacts. The objective is to identify the most sustainable and environmentally sound strategy for the region. The analysis is based on a functional unit of managing one cubic meter of urban wastewater, corresponding to the city's average flow rate of approximately one cubic meter per second. Scenario 1 reflects the pre-industrial system, prior to the establishment of the steel plant and sewer network expansion. Scenario 2 represents the current situation, in which a significant share of treated wastewater is diverted to the steel industry.

Scenario 3 recommends partially reallocating this wastewater for urban green space irrigation to enhance sustainability. Scenario 4 suggests replacing most of the municipal wastewater currently sent to the steel plant with desalinated seawater (0.1 m³), using infrastructure connected to pipelines from the Persian Gulf. Table 1 and Fig. 2 provide a detailed overview of the system boundaries and the configuration of each scenario. In this study, OpenLCA version 2.4.1 was employed for the life cycle assessment. This software utilizes an attributional approach to evaluate the potential environmental impacts across the entire life cycle of a system (Ciroth *et al*., 2014). It relies on historical, fact-based, and measurable data, incorporating defined uncertainties, and considers all processes that significantly contribute to the studied system (Ramakrishna and Ramasubramanian, 2024). OpenLCA is an open-source tool designed to support LCA, enabling users to assess the environmental impacts of products, processes, and systems in alignment with ISO 14040 and ISO 14044 standards (Pamu *et al*., 2022).

OpenLCA allows for the modeling of material and energy flows throughout the life cycle of a product or service, offering a comprehensive analysis of environmental impacts (Ciroth *et al*., 2014). Users can import data from established databases such as Ecoinvent, Agribalyse, and USLCI, utilizing these datasets for detailed and accurate assessments (Fritter *et al*., 2020, Kuczenski, 2015). The software supports various impact assessment methodologies, including ReCiPe, CML, and Impact 2002+, providing flexibility in evaluating a range of environmental categories (Ciroth *et al*., 2014).

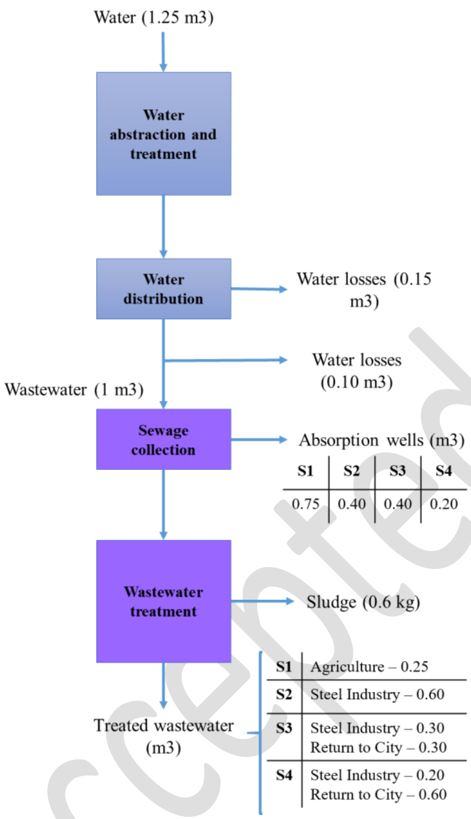


Fig. 2. System boundaries and the four proposed water and wastewater management scenarios for Kerman.

2.2. Life Cycle Inventory (LCI)

The Life cycle assessment analysis of these scenarios encompasses all stages of the treatment process, considering both construction and operational phases. This includes the materials and energy consumed during these phases, with an emphasis on identifying the environmental impacts generated by the system. The primary environmental outputs include secondary effluent discharge, unusable sludge produced during the operational phase, and emissions such as CO_2 from both construction and operation. Except for the first scenario, treated water is considered a product in all other scenarios.

The Life Cycle Inventory focuses on material and energy consumption throughout the construction and operational phases. Data related to material and energy use were collected through technical visits and consultations with managers and technicians at the treatment facilities. During the construction phase, the main materials used in building the treatment plants were concrete and steel. The inventory of construction materials for the plants is shown in Table 2. The data collected for the construction phase covers the entire 30-year design period of the treatment plants. In the operational phase, key factors include energy consumption and the characteristics of the effluent produced. All treatment plants in the study operate using electricity derived from non-renewable sources, specifically the local power grid. According to the collected data, the wastewater treatment plant generates approximately 0.6 kg of sludge for every cubic meter of wastewater it treats. The most significant output of the treatment processes is treated water, which is intended for reuse in agricultural and non-potable domestic applications. The characteristics of the treated effluent are assumed based on the efficiencies reported in similar treatment systems, as described in the scientific literature.

Effluents and emissions produced by the treatment plants are considered outputs for all scenarios. Solid waste and gaseous emissions, including greenhouse gases (GHGs) such as CO_2, CH_4, and N_2O, were calculated based on relevant reports from the scientific literature. These emissions were taken into account in assessing the environmental performance of each scenario. Effluents from all scenarios are eventually discharged into natural water streams, potentially causing environmental impacts such as nutrient enrichment (eutrophication). However, the reuse of treated wastewater for industrial and non-potable purposes may mitigate these impacts by reducing the consumption of freshwater and potable water. Table 3 presents the characteristics of the wastewater discharged into the absorption wells. Energy consumption for auxiliary units, such as pumps and other treatment plant infrastructure, was assumed based on relevant data from scientific literature. The effluent characteristics resulting from the treatment process are assumed to meet the U.S. Environmental Protection Agency (EPA) guidelines for water reuse. Scenarios that involve water reuse are expected to offer both economic and environmental benefits, as they reduce the demand for freshwater while promoting sustainability in water use. The data related to background processes extracted from the ecoinvent V3.7.1 database.

2.3. Life Cycle Impact Assessment (LCIA) Methodology

The environmental impacts associated with the Life cycle assessment of the wastewater management scenarios were evaluated using the ReCiPe 2016 methodology (Huijbregts *et al*., 2016b). ReCiPe is widely recognized as one of the most comprehensive and commonly used impact assessment methods in LCA studies, especially in the absence of primary or localized data (Huijbregts *et al*., 2016a). This methodology offers quantitative metrics for environmental impacts and supports a multi-layered analysis, divided into two evaluation levels (Rybaczewska-Błażejowska and Jezierski, 2024): midpoints and endpoints.

Table 1. Description of the water and wastewater management scenarios evaluated in Kerman.

Scenario	Title	Description
Sc. 1	Pre-industry Conventional System	Represents the water and wastewater management system before the steel plant was established; wastewater was mostly discharged into infiltration wells.
Sc. 2	Current Allocation to Industry	Reflects the current system in which a large share of treated wastewater is allocated to the steel industry, based on a long-term contract.
Sc. 3	Partial Reallocation to Urban Use	Proposes reducing the volume of wastewater sent to the steel plant, redirecting some of it for irrigating urban green spaces and non-potable uses.
Sc. 4	Seawater Desalination for Industry	Suggests replacing most of the wastewater supplied to the steel plant with desalinated seawater via existing pipelines from the Persian Gulf.

Table 2. Life cycle inventory of construction materials for the plants.

Item	Unit	Drinking water treatment plant	Wastewater sludge treatment facility	Desalination plant
Sand	Ton	17.9	8134	4376
Gravel	Ton	26.8	12250	7875
Cement	Ton	122.4	3038	11870
Steel	Ton	17.9	2315	4560
Land occupation	m2	43749.5	77246	66875

Table 3. Specifications of urban wastewater discharged into absorption wells.

Item	Emission to groundwater, mg/L
Ammonia	20
BOD_5	230
COD	400
Nitrogen, total	35
Phosphorus, total	6

At the midpoint level, environmental impacts are categorized into 18 distinct impact groups. These groups address the direct environmental consequences of various activities and processes, providing insights into specific environmental areas. Key impact categories include (Huijbregts *et al*., 2016b):

- Climate change
- Ozone depletion
- Acidification
- Habitat destruction
- Human toxicity
- Natural resource depletion

At the endpoint level, the midpoints are aggregated into three broader categories that reflect the overall effects on human and ecological systems (Huijbregts *et al*., 2016b):

1. Human health
2. Ecosystem degradation
3. Resource scarcity

The ReCiPe 2016 method, an updated version of the ReCiPe 2008 methodology, integrates newer data and more advanced techniques (Dekker *et al*., 2020). Given the lack of detailed local data for LCA evaluations in Iran, the environmental impacts of the wastewater management scenarios were analysed using the midpoint categories within the ReCiPe methodology. This approach provides a robust and scientifically backed framework for evaluating the environmental consequences of the scenarios under study. Normalization factors used in the ReCiPe 2016 method help standardize the results and facilitate comparison across different studies and geographical contexts (Crenna *et al*., 2019).

2.4. uncertainty analysis

The data used in this study exhibit varying degrees of quality. A fundamental categorization of these quality levels was conducted by distinguishing among three classifications: “high” (data acquired through the verification of invoices in the organizational archives or through the examination of organizational reports), “medium” (data supplied by the organizations as an average of total consumption divided by total flow, encompassing municipalities rather than Kerman), and “low” (data sourced from the existing ecoinvent database and literature) (Ziyadi and Al-Qadi, 2019, Guo and Murphy, 2012). The distribution was as follows:

High quality data: water and wastewater fluxes, electricity consumption by PWS and WWTS stages, data related to the construction phase, fuel consumption in various treatment and pumping sections, water loss, and sludge production.

Medium quality data: fuel consumption and martials of water well drilling and water pumping from the well, water transmission to reservoirs, the distribution and collection pipeline network, and methane production in the wastewater treatment plant.

Low quality data: emissions from sludge disposal and the treatment process, fuel and electricity consumption for seawater pumping, and emissions resulting from fuel and electricity use and background processes.

A simplified sensitivity analysis was conducted to assess how data quality affects the results. Data classified as high quality were assumed to have a 10 % margin of error, while medium and low quality data were assigned error margins of 20% and 30%, respectively. To determine the range of possible impacts, input and output values were adjusted according to these error margins, generating both minimum and maximum impact estimates (Hung and Ma, 2009). Impact data sourced from databases remained unchanged throughout the analysis. The value related to emissions from electricity and fuel consumption follow a lognormal distribution in the ecoinvent database. To determine the uncertainty range, Monte Carlo simulations were carried out using 10,000 iterations at a 90% confidence interval in the openLCA software.

3. Results and discussion

This section presents the results of the Life cycle assessment conducted on the four water and wastewater management scenarios for Kerman, focusing on their environmental, economic, and social impacts. The comparative analysis highlights the key findings from each scenario, examining the trade-offs between water resource utilization, environmental sustainability, and system efficiency. The results are interpreted in the context of their implications for Kerman's water management strategy, offering insights into the potential benefits and challenges associated with each scenario. By exploring the impacts across various environmental categories, this section aims to provide a comprehensive understanding of the sustainability of each scenario and to inform decision-making processes for the future development of water management practices in the region.

In this study, four distinct scenarios for water and wastewater management in Kerman were evaluated using the Life cycle assessment methodology. The results of this comparative analysis are presented in Table 1. Among the scenarios analysed, Scenario 3, which prioritizes the use of treated wastewater for urban management, emerged as the most sustainable and environmentally favourable option. In contrast, Scenario 4, which involves the transfer of seawater, was identified as the least favourable scenario, exhibiting the highest environmental impacts across several key categories.

In the water consumption category, Scenario 4 achieved the most favourable results, followed closely by Scenarios 1 and 3, which showed nearly identical performance. Scenario 2 performed the worst in this category. Regarding freshwater eutrophication, the best management scenarios were, in order, Scenario 4, Scenario 3, Scenario 2, and Scenario 1. For global warming potential, Scenario 1 demonstrated the best performance, while Scenario 4 exhibited the highest impact. A relative comparison of the scenarios across all impact categories is shown in the Fig. 3.

This section provides a detailed analysis and discussion of these results, emphasizing the trade-offs between water usage, energy consumption, environmental degradation, and resource conservation. Each scenario offers a unique approach to managing Kerman’s water resources, with varying implications for sustainability and environmental performance. Fig. 4 presents the comparative life cycle environmental impacts of the four evaluated water and wastewater management scenarios in Kerman, with uncertainty ranges illustrated by error bars derived from Monte Carlo simulations.

Among the four assessed scenarios for water and wastewater management in Kerman, Scenario 1 demonstrated the lowest water consumption at 0.08454 m^3, indicating its relatively modest demand on freshwater resources. This scenario primarily involves conventional drinking water production and wastewater treatment without the added complexity of water reuse or desalination. While efficient in water use, it lacks the long-term resilience needed for water-scarce regions.

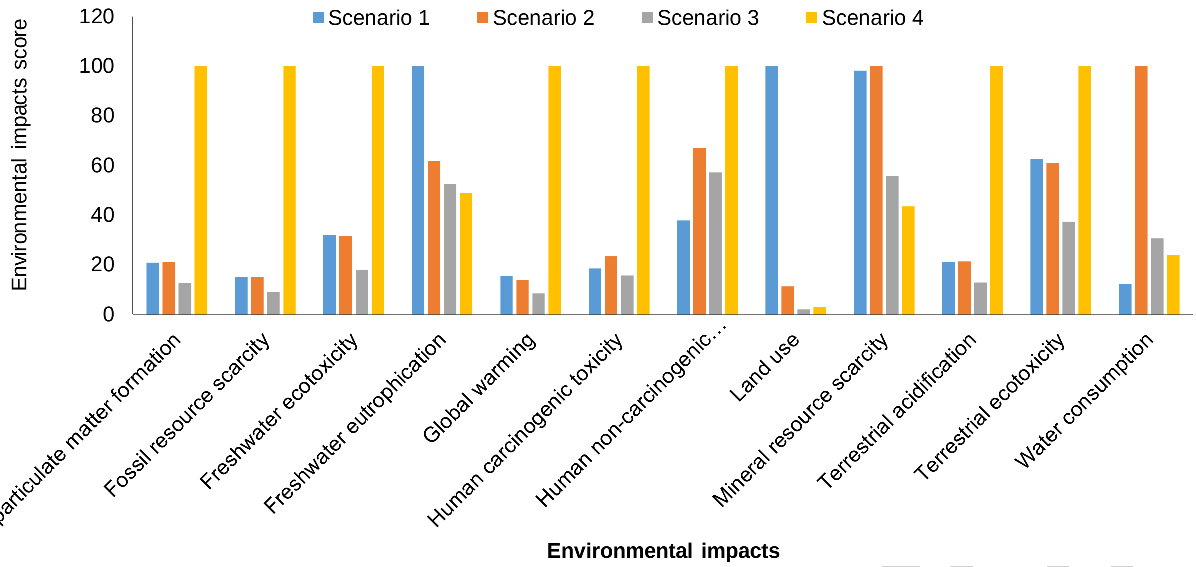
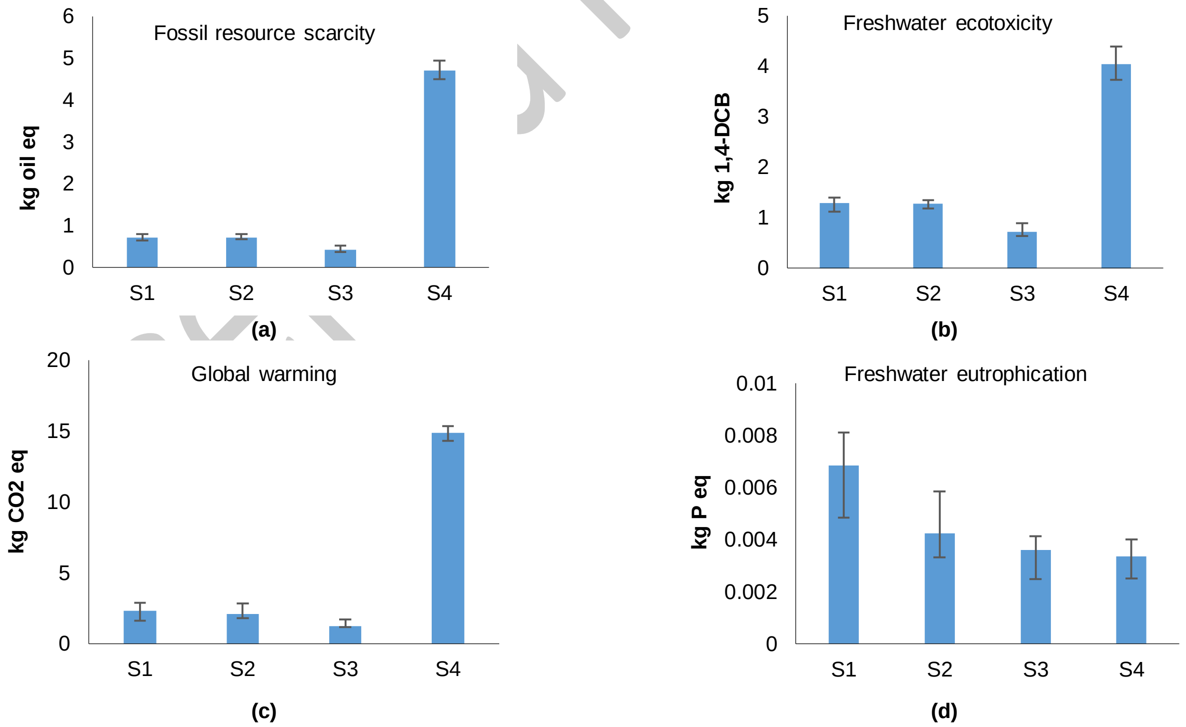


Fig. 3. Comparative environmental impacts based on Life cycle assessment results.

Table 4. Comparative environmental impacts of the four water and wastewater management scenarios for Kerman, based on Life cycle assessment results.

Impact Category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Fine particulate matter formation	kg PM2.5 eq	0.00427	0.00429	0.00259	0.020473
Fossil resource scarcity	kg oil eq	0.70535	0.71533	0.42134	4.69349
Freshwater ecotoxicity	kg 1,4-DCB	1.28678	1.28018	0.72014	4.03487
Freshwater eutrophication	kg P eq	0.00686	0.00423	0.00360	0.00335
Global warming	kg CO2 eq	2.30466	2.06688	1.24399	14.87236
Human carcinogenic toxicity	kg 1,4-DCB	0.33262	0.42126	0.28249	1.79688
Human non-carcinogenic toxicity	kg 1,4-DCB	5.72505	10.17135	8.66326	15.19109
Land use	m2a crop eq	0.15225	0.01724	0.00315	0.00474
Mineral resource scarcity	kg Cu eq	0.67499	0.68838	0.38191	0.29847
Terrestrial acidification	kg SO2 eq	0.01	0.01006	0.00612	0.04741
Terrestrial ecotoxicity	kg 1,4-DCB	24.85153	24.2155945	14.81921	39.66591
Water consumption	m3	0.08454	0.6858	0.20899	0.16456



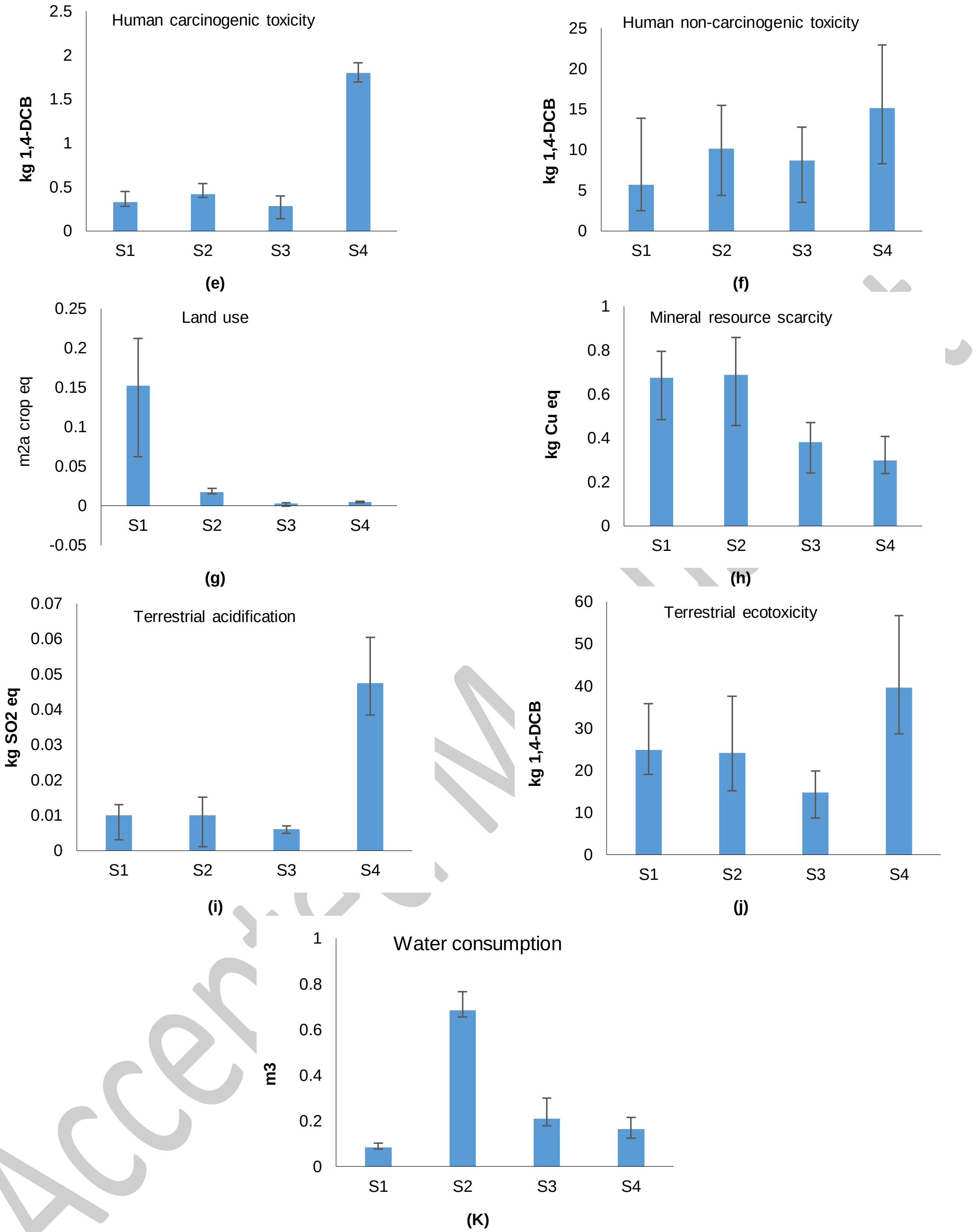


Fig. 4. Comparative environmental impacts based on Life cycle assessment results; a-j are key impact environmental categories based on Life cycle assessment (Error bars represent uncertainty ranges derived from Monte Carlo simulations) (10,000 iterations, 90% confidence interval).

Scenario 3, which promotes wastewater recycling for industrial and municipal non-potable uses, recorded a water consumption of 0.20899 m³. Although slightly higher than Scenario 1, this approach significantly contributes to sustainability by substituting freshwater with treated wastewater. It represents a balanced trade-off, offering environmental benefits while reducing stress on groundwater and surface water resources. In contrast, Scenario 2—which relies on groundwater extraction—exhibited substantially higher consumption at 0.6858 m³, raising concerns about aquifer depletion and long-term viability in arid regions. However, Scenario 4, which incorporates seawater desalination, displayed a lower water consumption (0.16456 m³) than Scenario 2, but this comes with higher environmental trade-offs in energy use and emissions.

3.4.1. Freshwater eutrophication

Freshwater eutrophication refers to the enrichment of water bodies with nutrients—particularly phosphorus and nitrogen—which can lead to algal blooms, oxygen depletion, and ecosystem degradation. Among the four evaluated scenarios, Scenario 4 demonstrated the lowest eutrophication potential (0.00335 kg P eq), followed closely by Scenario 3 (0.0036 kg P eq). Both scenarios involve the reuse of treated wastewater—either for industrial or non-potable urban purposes—thus significantly reducing nutrient discharges into natural water bodies.

These scenarios suggest that redirecting treated effluent toward beneficial reuse instead of environmental discharge can mitigate eutrophication risks.

In contrast, Scenario 1, which relies on conventional wastewater discharge into infiltration wells, exhibited the highest eutrophication impact (0.00686 kg P eq). This result underscores the environmental cost of unmanaged nutrient loading from untreated or partially treated effluents. Scenario 2, which incorporates groundwater abstraction and conventional treatment, also performed better than Scenario 1 but not as effectively as Scenarios 3 and 4. The findings indicate that without a robust strategy for nutrient recovery or effluent reuse, conventional disposal methods continue to pose eutrophication threats. Therefore, policies favouring wastewater recycling—especially in water-stressed urban-industrial contexts—offer dual benefits: alleviating freshwater scarcity and protecting aquatic ecosystems.

3.4.2. Global warming potential

Global warming potential, typically measured in kilograms of CO_2 equivalent, represents the contribution of a process or system to climate change. According to Table 3, Scenario 3—which emphasizes the reuse of treated wastewater for industrial and municipal applications—demonstrated a moderately low GWP of 1.24399 kg CO_2 eq, making it one of the most environmentally balanced approaches.

This reduction in emissions is attributed to the localized reuse of treated water, which limits the need for energy-intensive processes such as pumping from distant sources or desalination. By contrast, Scenario 4, which includes seawater desalination, exhibited the highest global warming potential at 14.87236 kg CO_2 eq, primarily due to the substantial energy requirements of desalination technologies and associated emissions from fossil-fuel-based electricity. Scenario 1, involving only drinking water production and basic wastewater treatment, had the lowest GWP at 2.30466 kg CO_2 eq, benefitting from minimal process complexity and infrastructure. Scenario 2, based on groundwater extraction and conventional treatment, yielded a GWP of 2.06688 kg CO_2 eq, slightly better than Scenario 1. However, these two scenarios fall short in long-term sustainability. Overall, Scenario 3 offers the most practical compromise, achieving meaningful emission reductions while promoting efficient and circular water use.

2.4.3. Fine particulate matter formation and fossil resource scarcity

Fine particulate matter formation (PM2.5 eq) is a critical environmental concern, as these particles contribute to air pollution and have direct health implications. In the comparison of the four scenarios, Scenario 3 showed the lowest PM2.5 formation impact at 0.00259 kg, reflecting its efficiency and reduced reliance on energy-intensive or combustion-based processes. This indicates that water recycling not only contributes to water security but also minimizes secondary air pollutant formation. Scenario 1 and Scenario 2 reported similar values (~0.00427–0.00429 kg), suggesting comparable impacts likely due to their conventional processes. In stark contrast, Scenario 4 had the highest PM2.5 emissions (0.020473 kg), a result of the energy-intensive nature of desalination processes and their associated combustion emissions.

Regarding fossil resource scarcity, which reflects the depletion of non-renewable energy sources like oil and natural gas, Scenario 3 again demonstrated the lowest impact (0.42134 kg oil eq), reinforcing its environmental efficiency. Scenario 1 and Scenario 2 followed with moderate impacts (~0.705–0.715 kg oil eq), due to conventional treatment operations. However, Scenario 4 stood out with a dramatically higher impact at 4.69349 kg oil eq, underscoring the unsustainable fossil fuel dependency of desalination technologies. These findings collectively affirm that Scenario 3 not only conserves water resources but also mitigates fossil energy dependency and air pollution, making it the most environmentally integrated and sustainable option.

3.4.4. Human toxicity and ecotoxicity

Human toxicity, both carcinogenic and non-carcinogenic, reflects the potential health risks posed by exposure to harmful substances released throughout the water management lifecycle. In the carcinogenic category, Scenario 3 demonstrated the lowest impact (0.28249 kg 1,4-DCB eq), followed by Scenario 1 (0.33262 kg) and Scenario 2 (0.42126 kg). Scenario 4 showed the highest carcinogenic toxicity (1.79688 kg), likely due to the increased use of chemicals and energy in the desalination process, which leads to emissions of hazardous substances during both construction and operation phases. In terms of non-carcinogenic toxicity, the trend was consistent: Scenario 3 again showed a lower impact (8.66326 kg), whereas Scenario 2 and Scenario 4 exhibited significantly higher values (10.17135 kg and 15.19109 kg, respectively). These figures highlight the environmental and public health risks of energy-intensive and chemically demanding technologies, emphasizing the need for cleaner and more controlled reuse pathways, such as those in Scenario 3. As for ecotoxicity, measured across freshwater and terrestrial systems, Scenario 3 consistently outperformed other scenarios, particularly with lower freshwater ecotoxicity (0.72014 kg 1,4-DCB) and terrestrial ecotoxicity (14.81921 kg 1,4-DCB). In contrast, Scenario 4 recorded the highest impacts (4.03487 kg freshwater and 39.66591 kg terrestrial), reinforcing the substantial ecological burden of desalination. These results collectively underscore the importance of considering toxicity metrics in water governance decisions and position Scenario 3 as the most health- and ecosystem-friendly strategy.

2.4.5. Land use and mineral resource scarcity

Land use and mineral resource scarcity are two important indicators within the Life cycle assessment framework, reflecting the extent of land occupation and the pressure on finite mineral resources due to water and wastewater management activities. In terms of land use, Scenario 3 had the lowest impact at 0.00315 m²a crop eq, closely followed by Scenario 4 (0.00474 m²a crop eq) and Scenario 2 (0.01724 m²a crop eq). Interestingly, Scenario 1 exhibited the highest land use impact (0.15225 m²a crop eq), likely due to reliance on infiltration wells and larger spatial infrastructure footprints for conventional systems. The reduced land footprint in Scenario 3 highlights the spatial efficiency of integrated reuse systems, which often utilize existing networks without expanding land occupation.

As for mineral resource scarcity, which is measured in kg Cu eq, Scenario 3 again performed favourably (0.38191 kg Cu eq), indicating less dependency on scarce materials in construction and operation. Scenario 4, despite its high impacts in most other categories, showed the lowest mineral resource use (0.29847 kg Cu eq), perhaps due to technological design choices with lower copper demand. However, Scenarios 1 and 2 had higher impacts (0.67499 kg and 0.68838 kg, respectively), suggesting inefficiencies in material utilization. These findings reinforce Scenario 3's balanced profile in both land conservation and resource efficiency.

The comparative analysis of the four water and wastewater management scenarios for Kerman reveals complex trade-offs across various environmental impact categories. Scenario 1, which focuses on conventional water treatment and wastewater discharge, consistently performed well in minimizing carbon emissions, particulate matter formation, and fossil resource depletion. However, it struggled with freshwater eutrophication due to the discharge of wastewater into natural water bodies. A qualitative comparison of the four water and wastewater management scenarios for Kerman in terms of environmental sustainability, highlighting the strengths and weaknesses of each scenario across key categories: Scenario 3 (Water Recycling) stands out as the most balanced and sustainable approach for Kerman's water management challenges. It offers a practical solution by effectively minimizing freshwater consumption, reducing eutrophication, and maintaining environmental impacts within acceptable limits. While Scenario 1 performs well in terms of carbon emissions and human toxicity, it fails to address the long-term issue of water scarcity, making it less viable for sustainable water management. Scenario 4, despite offering the best reduction in freshwater consumption, introduces significant environmental trade-offs, particularly in global warming potential and resource depletion, which must be carefully managed.

Lastly, Scenario 2 is the least favourable due to its heavy reliance on groundwater resources and conventional treatment methods, which exacerbate water scarcity and lead to further environmental degradation. Ultimately, Scenario 3 provides a comprehensive, sustainable solution for Kerman's water needs, prioritizing water recycling while minimizing adverse environmental consequences, and offering a path toward long-term water security and ecological balance. Based on the challenges, concerns raised, and the results of the Life cycle assessment model, the recommended policy for the use of urban wastewater in the steel industry should focus on promoting water recycling and sustainable wastewater reuse while minimizing the environmental trade-offs associated with energy-intensive processes like seawater desalination. Here's a structured suggestion for such a policy:

3.4.6. Prioritize water recycling and wastewater reuse

The results of the LCA clearly indicate that Scenario 3 (Water Recycling) is the most balanced and sustainable approach, reducing freshwater consumption, mitigating eutrophication, and lowering global warming potential. The policy should focus on encouraging the steel industry to invest in advanced wastewater treatment technologies that allow for effective reuse within industrial processes. This would reduce the dependency on freshwater sources and mitigate the environmental risks posed by wastewater discharge. To facilitate this, the policy could provide incentives for the steel industry to collaborate with urban water authorities, ensuring that treated wastewater is appropriately sourced and recycled for industrial use. Such incentives could include tax rebates, subsidies for infrastructure development, and funding for research into more efficient wastewater treatment and reuse technologies.

Table 5. Qualitative comparison of the four water and wastewater management scenarios.

Impact category	Scenario 1 (conventional treatment)	Scenario 2 (groundwater + conventional)	Scenario 3 (water recycling)	Scenario 4 (seawater desalination)
Water consumption	Very low water use due to limited treatment operations; efficient but lacks reuse integration.	Very high water use; heavy dependence on groundwater exacerbates depletion and scarcity.	Low water use through effective wastewater recycling; reduces pressure on freshwater sources.	Moderate water use; seawater desalination reduces freshwater demand but is energy-intensive.
Freshwater ecotoxicity	High ecotoxic impact from untreated discharge and low-level treatment.	Similar high impact due to chemical use and pollution from groundwater pumping.	Moderate impact; recycling reduces ecotoxic discharges compared to conventional pathways.	Very high impact; brine discharge and chemical residues from desalination pose ecological threats.
Freshwater eutrophication	Very high nutrient discharge into infiltration wells causes major eutrophication risks.	High eutrophication from insufficient control of nutrient outflows.	Low nutrient discharge due to improved treatment and reuse; significantly mitigates eutrophication.	Very low eutrophication risk; seawater pathway limits nutrient return to freshwater systems.
Global warming potential	Low GHG emissions due to simple, low-energy processes.	Moderate emissions from groundwater pumping and treatment operations.	Low emissions; recycling reduces energy use and GHGs compared to seawater desalination.	Very high GHG emissions due to energy-intensive desalination technology.
Human carcinogenic toxicity	Moderate toxicity; limited chemical input in basic treatment.	High toxicity; chemical-intensive treatment and groundwater handling increase exposure risks.	Low toxicity; chemical use is managed within advanced recycling frameworks.	Very high toxicity due to advanced infrastructure and chemical demands in desalination.
Human non-carcinogenic toxicity	Low exposure risk in conventional systems.	Very high non-carcinogenic risk; increased contamination from deep groundwater and chemical use.	High risk due to treatment chemical residues, although lower than desalination.	Very high toxicity impact due to widespread chemical usage and process complexity.
Land use	High land demand for infiltration and dispersed infrastructure.	Moderate land use with combined extraction and treatment facilities.	Very low land use; compact design of recycling units reduces spatial footprint.	Low land use but requires dedicated coastal infrastructure for desalination.
Mineral resource scarcity	High resource demand due to conventional plant materials and outdated technology.	High material consumption from extraction wells and pipe networks.	Moderate resource use; less infrastructure expansion needed for centralized recycling.	Low relative material use but high total due to technological intensity and system complexity.
Stratospheric ozone depletion	Low ozone impact; conventional systems emit negligible ozone-depleting substances.	Moderate ozone impact from pumping and treatment emissions.	Moderate impact; treatment chemicals may contribute to ozone effects if unmanaged.	High impact; energy and chemical processes in desalination contribute significantly to ozone depletion.
Terrestrial scidification	Low acidification risk due to minimal energy input and emissions.	Moderate emissions result in some acidification, particularly from energy use.	Low risk; emissions from treatment processes are relatively controlled.	Very high acidification potential due to energy consumption and combustion by-products.
Terrestrial ecotoxicity	High risk from discharge to land and infiltration systems.	High risk from contamination of soil due to extraction and treatment residues.	Moderate risk; controlled outputs but some effect on surrounding ecosystems.	Very high impact; industrial construction and chemical discharges affect soil and biodiversity.

3.4.7. Regulate the volume of wastewater allocation

Given the concerns regarding the monopolization of treated wastewater by the steel industry, the policy should establish clear regulations on the volume of wastewater allocated to the industry, ensuring a fair share for municipal uses, including irrigation and public services.

This would help balance the needs of both urban and industrial sectors, preventing the potential negative impacts on urban water supply and green spaces. A tiered allocation system based on demand forecasting and water availability can be implemented to ensure equitable access to treated wastewater. Additionally, periodic reviews of the allocation system should be part of the policy to adapt to changing urban needs and industrial growth.

3.4.8. Incorporate sustainable energy sources in water treatment

As seen in Scenario 4, the environmental costs associated with seawater desalination, particularly in terms of energy consumption and greenhouse gas emissions, are considerable. Therefore, a policy that encourages the integration of renewable energy sources (such as solar or wind energy) into wastewater treatment and desalination processes would significantly reduce the carbon footprint of the steel industry's water supply. Providing financial and technical support for renewable energy integration would help make the reuse of wastewater more environmentally sustainable. Moreover, it is essential to establish environmental standards for the steel industry, mandating the adoption of low-emission technologies and energy-efficient processes in wastewater treatment and recycling. These measures can be gradually implemented with incentives for industries that adopt greener practices.

3.4.9. Monitor and manage environmental impacts

While water recycling significantly reduces pressure on freshwater resources, it is not without its challenges, including potential risks associated with ecotoxicity and carcinogenic toxicity from chemicals used in wastewater treatment. A policy should be implemented that requires continuous monitoring of the ecological impacts of wastewater treatment and reuse processes. Regular environmental assessments and reporting can help mitigate unforeseen consequences, such as harmful chemical discharges or contamination from wastewater effluent. The establishment of a comprehensive regulatory framework would ensure that wastewater treatment and reuse processes adhere to environmental safety standards. Additionally, the policy should promote research and development of green chemicals and biological treatment methods that reduce harmful emissions and improve the safety of reused water.

3.4.10. Encourage multi-stakeholder collaboration

To address the uncertainties and conflicting interests between urban planners, environmentalists, and industrial stakeholders, the policy should promote multi-stakeholder collaboration. This could be achieved through the creation of an advisory board that includes representatives from the municipal government, the steel industry, environmental NGOs, and academic experts.

The role of this advisory board would be to oversee water allocation decisions, ensure environmental standards are met, and facilitate knowledge sharing on best practices for wastewater management.

This collaborative approach would help balance economic, environmental, and social considerations, leading to more informed decision-making that takes into account both immediate and long-term impacts.

3.4.11. Adaptive management and policy flexibility

Given the rapidly changing nature of both water availability and industrial water demands, the policy should be designed with flexibility in mind. It should incorporate adaptive management strategies that can be adjusted based on new data, technological advancements, and shifts in environmental conditions. For example, if a new treatment technology emerges that significantly improves water recycling efficiency or reduces environmental impacts, the policy should allow for its rapid adoption and integration into the existing framework.

Additionally, scenario-based planning can help policymakers anticipate future challenges and adjust their strategies accordingly. For instance, projections of urban growth and water demand could be incorporated into the policy to ensure that treated wastewater is allocated in the most sustainable and equitable manner.

4. Conclusions

Based on the comparative analysis of the four water and wastewater management scenarios for Kerman, it is evident that Scenario 3 (Water Recycling) offers the most sustainable and balanced approach for addressing the city’s water management challenges. By focusing on recycling treated wastewater for industrial and urban uses, Scenario 3 effectively reduces freshwater consumption, mitigates eutrophication, and minimizes the overall environmental impact, particularly in terms of global warming potential and resource depletion. This scenario not only addresses Kerman’s immediate water needs but also provides a long-term solution that promotes resource efficiency and environmental protection. In contrast, Scenario 1, while effective in reducing carbon emissions and human toxicity, fails to adequately address the pressing issue of water scarcity, as it continues to rely heavily on conventional water sources. Scenario 4, which incorporates seawater desalination, offers a substantial reduction in freshwater consumption but at the cost of significant environmental trade-offs, including high greenhouse gas emissions, resource depletion, and toxicity risks. Scenario 2, reliant on groundwater and conventional treatment, is the least favorable, exacerbating water scarcity and contributing to environmental degradation. The findings from this analysis underscore the importance of adopting Scenario 3 as the preferred policy for Kerman’s water management. By promoting water recycling and the reuse of treated wastewater, this scenario not only alleviates the pressure on freshwater resources but also supports a more sustainable and resilient urban-industrial water system. The policy should focus on advancing recycling technologies, regulating wastewater allocation, and ensuring that environmental impacts are continuously monitored, creating a path toward a sustainable water future for Kerman.

Author Contributions

Payam Salajegheh: Contributed to data collection, model development, and LCA analysis. Participated in the interpretation of the results and took part in drafting and revising the manuscript.
Mohammad Hossein Niksokhan: Involved in the design of the study, data collection, and model development. Contributed to the analytical interpretation of LCA results and participated in writing and critical revision of the manuscript.
Hossein Vahidi: Collaborated in data collection, LCA modeling, and validation of analytical results. Participated in result interpretation, manuscript writing, and final editing.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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