Optimizing the Nonconventional Water Supply across the Water-Energy-Food Nexus for Arid Regions Using a Life Cycle Assessment

Esra Aleisa, Ph.D.[1]; and Sara Al-Haddad, Ph.D.[2]

Abstract: The escalating global water scarcity crisis has propelled an increasing dependence on nonconventional water sources, particularly desalination and treated wastewater. Assessments of the United Nations' water-related sustainable development goals on a global scale have brought to light a paradoxical trend of localized water decisions that have exacerbated long-term water scarcity issues. This study employs a water-energy-food (WEF) nexus framework to evaluate nonconventional water resources, fostering an understanding of interconnected water dynamics and promoting enhanced resource utilization and sustainability. Utilizing a multicriteria mathematical model grounded in life cycle assessment (LCA), this study optimizes water usage across the WEF nexus. The augmented simplex lattice mixture (ASLM) design is employed to identify WEF optimal frontiers under varying priorities within the hyperarid region of Kuwait. The findings underscore the significant influence of hidden virtual water on overall outcomes. Specifically, for wastewater permeate treated by reverse osmosis (WWROP), each cubic meter of permeate utilizes 1.78 m^3, with 90% consumed virtually for chemical production. Within the water-for-food nexus, the results reveal that tertiary-level treated wastewater (WWTTE) contains 67% of the required phosphate for fodder cultivation, leading to an additional 24.89 t/ha of fodder compared with WWROP and desalinated water. An evaluation of the energy-for-water nexus indicates that WWTTE and WWROP exhibit the lowest cumulative energy demand. Consequently, these results advocate for the utilization of WWTTE over WWROP and desalinated water to enhance the overall WEF nexus. **DOI: 10.1061/JWRMD5.WRENG-6103.**

Practical Applications: Research suggests that a misrepresentation of the local context in WEF solutions may contribute to the slow adoption of WEF concepts in governance and political reform. This study addresses the pressing issue of water scarcity through the application of LCA. This analysis involves the evaluation of commercially available nonconventional water technologies concerning demand requirements across municipal, agricultural, and industrial sectors. A mathematical model is employed to assess and optimize the demand and supply assignment problem considering various impacts associated with WEF frontier priorities. The primary focus of this research is on the critical water scarcity challenges faced by hyperarid regions. Specifically, this study delves into the interrelationships among water, energy, and food consumption and their collective impact on these precious resources. Employing LCA, sensitivity analysis, and optimization models, this research scrutinizes the existing state of water, energy, and food in Kuwait. The aim is to provide specific recommendations that contribute to enhancing the equilibrium among these three vital resources.

Author keywords: Water-energy-food (WEF) nexus; Life cycle assessment (LCA); Optimization; Wastewater treatment; Desalination; Kuwait.

Introduction

The World Economic Forum has expanded its understanding of the water-energy-food (WEF) nexus by studying the interrelationships of "sustainability, the green economy, trade-offs, livelihoods, climate, optimization, modeling, or scarcity" and the sustainable management of resources (Simpson and Jewitt 2019a). Synergies and trade-offs are among the aspects of the WEF nexus that have always been a point of debate and that significantly impact systems at the local level (Terrapon-Pfaff et al. 2018). A study by Gai et al. (2022) underscored significant gaps in addressing ecosystems while integrating social, economic and political dynamics in WEF nexus studies. The WEF nexus priorities vary considerably based on local policies. A salient example is the supply priorities of scarce water to the agricultural sector in hyperarid regions for similar socioeconomic conditions. Gulf Cooperation Council (GCC) countries, including Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE), are among the top 30 countries facing water stress. Although global averages indicate that the agricultural sector consumes 71% and 30% of the produced water and electricity, respectively (Simpson and Jewitt 2019b), the water consumed in agriculture accounts for 49% of the water supply in Bahrain, 54% in Kuwait, 89% in Oman, 83% in Saudi Arabia, and 89% in the UAE (Aleisa 2024; Aleisa and Al-Zubari 2017; Aleisa and Alshayji 2019). Given low precipitation rates (117.9–215 Mm^3/year in Kuwait) (FAO-AQUASTAT 2019) coupled with high evaporation (9.5 Mm^3/year) (SCPD 2019) and consumption rates, total renewable water resources has dropped sharply since

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1962 (Mukhopadhyay and Akber 2018; Worldometer 2017). This drop is also reflected in water stress levels, thus demonstrating the lack of sustainability of natural freshwater resources and underscoring the importance of effective water management policies (Mateo-Sagasta et al. 2016).

Additionally, energy and water are highly interrelated in the GCC region because most desalinated water production is cogenerated with energy production. The development and use of nonconventional water resources are extremely advantageous for hyperarid regions, such as the Arab Peninsula, where freshwater resources are scarce. To combat water scarcity, GCC countries and other hyperarid regions are becoming increasingly dependent on nonconventional water resources, such as seawater desalination (Al-Shayji and Aleisa 2018; Aleisa and Al-Shayji 2018; Aljuwaisseri et al. 2023; Alrashidi et al. 2024) and treated wastewater (Aleisa et al. 2022a). Currently, nonconventional water resources, including desalination technologies and advanced wastewater treatment systems, contribute to more than 78% of water resources in Kuwait, which indicates the need to rely on these nonconventional systems to satisfy increasing urban requirements (Aleisa 2024).

The adoption of desalination and wastewater technology primarily aims to manage the ever-growing demand for potable and nonpotable water. Monocentric decision making focusing on these challenges but considering only energy efficiency or food security has resulted in a paradox of considerable variations in SDG 6 targets (clean water and sanitation) within individual nations. A salient example is the notable achievement of almost 100% of the water-related SDG of "accessibility to clean water and sanitation services," whereas the long-term water sustainability scores are almost nil. One reason for this dilemma is the need for an overall WEF assessment that highlights the complex interlinkages among the factors involved in integrated water management.

This paper presents a comprehensive life cycle assessment (LCA) of water resources within the WEF nexus, demonstrating the current state of the system. This study introduces a mathematical model for optimizing the water budget across the three frontiers of the WEF nexus. The model uses LCA models to derive scores, employing impact methods such as cumulative energy demand (CED) and water footprint (WF). Sensitivity analysis employs the augmented simplex lattice mixture (ASLM) method and provides valuable insights into the impact of prioritizing different WEF frontiers, thereby enhancing our understanding of their interrelationships.

Although the study is applied to a specific case, its findings have global implications, especially for hyperarid regions. The research contributes to the broader goals related to water, energy, and food security, and its implications extend beyond the immediate context, making it a valuable resource for trade-offs for policymakers and researchers worldwide.

Literature Review

The key concepts driving the WEF nexus have evolved over time since this nexus was first proposed by the World Economic Forum and the Bonn 2011 Conference (Hoff 2011). Despite the growing literature, knowledge gaps and critiques exist regarding the application of nexus frameworks for policy recommendations (Abdi et al. 2020; Bhaduri et al. 2015; Cai et al. 2018; Lazaro et al. 2022; Olawuyi 2020; Pahl-Wostl 2019; Purwanto et al. 2021; Silalertruksa and Gheewala 2018). In their current form, the findings of Simonovic and Breach (2023) suggest that a more comprehensive structure for the global change WEF models should replace the nexus approach. WEF formulations are multidimensional and apply a spectrum of qualitative and quantitative methods (Fernandes Torres et al. 2019; Ramirez et al. 2022) to decrease the uncertainty and increase the robustness of the models (Kang et al. 2020). A qualitative assessment focuses on policy coherence (Bao et al. 2018; Yang et al. 2016; Yuan et al. 2018) and mostly applies questionnaires, interviews, workshops, focus groups, etc. Jander et al. (2023) showed that the multiobjective WEF approach has the potential to enhance the effectiveness of climate change mitigation measures while simultaneously incorporating the diverse interests of numerous stakeholders when implementing regulations. Quantitative approaches to the WEF nexus predominantly involve LCA, multicriteria mathematical models (MCMMs), input–output (IO) models (Ju 2019; Tian et al. 2022; Wang et al. 2021; Zhao et al. 2021), and simulations (Arfelli et al. 2022; Bian and Liu 2021; Dawoud 2018; Fernandes Torres et al. 2019; Hejnowicz et al. 2022; Yuan et al. 2018).

Although no standardized application exists for studying the WEF nexus, LCA has been a consistent enabler for measuring WEF impacts (Mannan et al. 2018) at different geographical scales and under different sector classifications (Arfelli et al. 2022; Ding et al. 2020; Mannan et al. 2018; Pausta et al. 2020; Salmoral and Yan 2018; Yuan et al. 2018). Most applications have been associated with water supply (Arfelli et al. 2022; Dawoud 2018; Ramirez et al. 2022), food and animal feed production (Fernández-Ríos et al. 2022; Ju 2019; Rogy et al. 2022; Silalertruksa and Gheewala 2018), and bioenergy or food trade-offs (Gazal et al. 2022; Hiloidhari et al. 2017; Pahl-Wostl 2019; Yuan et al. 2018). In addition, WEF analysis has been repeatedly applied to address transboundary water issues (Elsayed et al. 2020; Jalilov 2021; Zhang et al. 2021a), including dam specifications and hydropower generation (Carravetta et al. 2022; Gao et al. 2021). Despite the abundance of research that applies LCA for WEF nexus analysis, few studies have focused on quantitatively assessing the interlinkages and trade-offs or objectively assigning WEF frontier weights. Research efforts addressing this integration have applied multicriteria optimization and mathematical models to assimilate WEF interrelationships (Lazaro et al. 2022; Li et al. 2022; Pahl-Wostl 2019; Sharifzadeh et al. 2019; Wang et al. 2020; Weitz et al. 2017; Yang et al. 2023; Yuan et al. 2018; Zhang et al. 2022; Zhao et al. 2021). The literature review indicates a considerable lack of literature that objectively assigns and analyzes the impact of weight assignments to WEF nexus frontiers, which is crucial for WEF interlinkage trade-off analysis (Fernandes Torres et al. 2019; Pausta et al. 2020; Yang et al. 2023; Zanghelini et al. 2018).

In addition, the literature review emphasizes the impact of local context on WEF priorities (Abulibdeh et al. 2019; Bao et al. 2018; Bian and Liu 2021; Carmona-Moreno et al. 2021; Dawoud 2018) (see Table 1). Only 30% of WEF tools are applicable at local scales (Taguta et al. 2022). Based on a case study of Ethiopia, Stein et al. (2014) indicated that WEF solutions that address local preferences produce better outcomes than general solutions at a broader scale (Weitz et al. 2017). The misrepresentation of the local context has been argued to be a reason for the slow traction of WEF concepts in governance and political reform (Hejnowicz et al. 2022; Olawuyi 2020; Purwanto et al. 2021; Siderius et al. 2019). Researchers have concluded that to convince the public and policy-makers of necessary changes that will have a long-term impact, WEF analysis should address the local vulnerability to the impacts and challenges related to resource scarcity (Boluwade 2021; Ding et al. 2020; Khorrami and Malekmohammadi 2021; Siderius et al. 2019). Addressing WEF challenges at the microscale will result in transboundary impacts and will achieve global goals (Purwanto et al. 2021).

Table 1. Literature on WEF nexus with specific geographic context

Literature	W	E	F	Model	Geographic region
Li et al. (2022)	x	x	x	Multi-Objective Linear Programming Optimization Model - Biochar Model Function and Hydrological and Socioeconomic Data	Northeastern China
Anser et al. (2020)	x	x	x	WEF - Tapio's Elasticity of Decoupling	Pakistan
Rogy et al. (2022)	x	x	x	Water Energy Infrastructure Nexus - AgricultureIMPACT World + Method AWARE Model	Southern France
Boluwade (2021)	x	x	x	Multidisciplinary Database Platform on WEF Nexus Modeling Using the Unified Modeling Language (UML)	North–South Al-Batinah, Sultanate of Oman
Ju (2019)	x	x	x	WEF Nexus - IO-Based Model (Input–Output Based Model)	Japan and China
Karabulut et al. (2018)	x	x	x	Ecosystem -Water-Food-Land-Energy Nexus - Synthesis Matrix LCA - Synthesis Matrix	
Tian et al. (2022)	x	x		WEC Nexus - Multi-Regional Input–Output Analysis (MRIO)	China
Fan et al. (2022)	x	x		WEC Nexus - Dietary Consumption Using EE-MRIO Analysis	Global
Wang et al. (2021)	x	x		WEC Nexus Multi-Regional Input–Output (MRIO) Model	European Union (EU27)
Sharifzadeh et al. (2019)	x	x		Optimization FrameworkElectricity-Water Nexus for Greenhouse Gas Emissions in Renewable Resources and Carbon Capture and Storage	China
Arfelli et al. (2022)	x	x		Water-Energy Nexus and LCA using the Recipe Method, Cumulative Energy (CED) Method, Monte Carlo Simulation. For regional water supply.	Romagna Region, Italy
Wang et al. (2020)	x	x		Large-Scale WEF Nexus OptimizationUrban Energy Systems (UES) Optimization Model Using a Flexible Clustering Approach	Shanghai, China
Zhang et al. (2022)	x			Environ-Economic Tax Management PolicyUrban Energy Systems (UES) Optimization Model Using a Flexible Clustering Approach	Shanxi Province, China
Zhao et al. (2021)	x			Water NexusMixed Multi-Regional Input–Output (MRIO) Model	Capital Region of China - Beijing, Tianjin, Hebei

Materials and Methods

Data Collection

The data used in this research were collected from local governments, plants, reports, and published literature (see Table 2). Additional information on the assumptions made during the data collection is included in the Supplemental Materials.

Water Flow Analysis

WEF nexus assessments involving measurements of nonconventional water production systems are mainstream in arid countries. The predominant desalination systems currently used in the GCC are multistage flash distillation (MSF), multieffect distillation (MED), and seawater reverse osmosis (SWRO) systems. The wastewater treatment plants in the GCC treat wastewater to the tertiary level by producing tertiary treated effluent (WWTTE), and to the advanced level using reverse osmosis and ultrafiltration (WWROP). In this study, GW includes brackish water, which is abstracted for irrigation and mixed with distilled water produced from desalination plants.

The methodology conducts a water flow analysis by constructing a Sankey diagram of water accounts that contribute to the municipal, agricultural, and industrial sectors while visualizing the nexus frontiers in terms of water, energy, and food production. Then, a water flow analysis is used to assess the water-for-food, water-for-water, and energy-for-water nexuses.

Life Cycle Assessment

An LCA-based framework (see Fig. 1) is employed to optimize the performance among nexus frontiers ($j = 1, 2, 3$) to find the optimal nonconventional water source ($i = 1, 2, \ldots, 6$) and sector ($k = 1, 2, 3$) assignment. The sources include desalination systems, wastewater treatments, and GW. Let s_{ij} denote the normalized (0–1)

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Table 2. Process inventories for nonconventional water sources per Mm^3

Inventory	Unit	WWTTE[a,b]	WWRO[a,c]	MSF[d,e]	MED[f]	SWRO[g]
Caustic soda	g	1.096	4.80×10^{-2}	3.0187×10^{6}	12.95×10^{6}	56.03×10^{6}
Sodium hypochlorite 12.5%	g	2.740	2.69×10^{-8}			20.14×10^{6}
Activated carbon	g	3.044×10^{2}				
Cationic polymer	g	1.461				3.25×10^{5}
Anionic resin	g					0.09×10^{6}
Chlorine liquid	g	3.288	1.00×10^{-5}			
Ferric chloride 40%	g		9.00×10^{-2}			41.88×10^{6}
Ethylenediaminetetraacetic acid (EDTA)	g		5.00×10^{-4}			1.003×10^{6}
Sulfuric acid	g		0.048	7.331×10^{6}		108.31×10^{6}
2,2-Dibromo-2-cyanoacetamide (DBNPA)	g		1.36×10^{-2}	7.546×10^{6}		
Sodium metabisulfite (SMBS)	g		3.76×10^{-6}		5.345×10^{5}	2.236×10^{6}
Citric acid	g		1.20×10^{-3}			5.81×10^{6}
Sodium dodecyl sulfate (SLS)	g		3.76×10^{-6}			
Hydrochloric acid 32%	g		0.022	3.74×10^{3}		
Ferric sulfate	g		4.00×10^{-3}			
Sodium nitrite	g			1.33 E $\times 10^{2}$		0.056×10^{6}
Propylene glycol	g			4.312×10^{5}	6.78×10^{5}	
Polyphenylene sulfide	g					2.23×10^{6}
Phosphoric acid	g			2.52×10^{2}	11.718×10^{6}	6.699×10^{6}
Tri(sodium phosphate)	g				5.1395×10^{4}	
Limestone	g				82.23×10^{6}	
Glass fiber-reinforced plastic, polyamide	kg					1.65×10^{3}
Electricity high voltage fossil fuels	kWh	3.95×10^{-1}	3.14×10^{-1}	4.0×10^{6}	8.63×10^{4}	5.2×10^{6}
Natural gas	kg			8.44×10^{5}		
Thermal energy					61.1×10^{6}	

Note: All processes were obtained from Ecoinvent (2007).
[a]Data from Aleisa et al. (2022a).
[b]Data from Lee et al. (2012).
[c]Excludes WWTTE.
[d]Data from Aleisa and Al-Shayji (2018).
[e]Data from Al-Shayji and Aleisa (2018).
[f]Data from Aljuwaisseri et al. (2022).
[g]Data from Aljuwaisseri et al. (2023) and Aldei et al. (2023).

impact of water produced from source i on nexus j. The calculations for each WEF nexus frontier are explained in the following sections. The indices are found in Table 3. The scores and their associated normalization are explained in the following sections.

Water-for-Food Scores

The water-for-food ($j = 1$) nexus scores, s_{i1} ($i = 1, 2, \ldots, 6$), are used to assess the impacts of different water resources on agriculture, particularly to account for the amount of water and nutrients recirculated through treated wastewater to complement conventional fertilizers (Aleisa and Heijungs 2022). The functional unit (FU) is defined in terms of the fodder yield (t/ha) of limited irrigation based on Volesky and Berger (2010) using open-loop modeling (JRC 2010). Open-loop modeling is used because recycled water is used for an activity outside the water network, i.e., agriculture. As in many LCA studies, fodder plants are chosen to represent agricultural sector water requirements as a simplification assumption. First, Kuwait environmental law No. 42/2014 (KEPA 2014) and its amendment No. 99/2015 have placed considerable emphasis on treated wastewater uses. Fodder plants can be irrigated with all conventional and nonconventional water sources considered in this study, including tertiary treated wastewater ($i = 1, 2, \ldots, 6$) (Allnqawi 2018; MPW 2021). Fodder plants can be harvested all year long and require average irrigation and fertilizer requirements that can represent average crop irrigation (Aleisa et al. 2022a, b; Aleisa and Heijungs 2022; Johar and Al-Alawi 2008; Karam 2015).

The FU application is examined regarding the impact of the growth of fodder plants (forage) over one year. According to Haitsma Mulier et al. (2022), the food component in the WEF nexus is best understood when represented by constituent nutrients. Recirculating wastewater can provide the required nutrients for irrigation, thus reducing the need for synthetic fertilizer and all associated mineral mining, manufacturing, and transport. The benefit is amplified if sewage sludge nutrients are recovered and used to further minimize the need for synthetic soil enhancers (Aleisa et al. 2021a).

Water-for-Water Scores

The water-for-water ($j = 2$) nexus scores, s_{i2} ($i = 1, 2, \ldots, 6$), are used to assess the impacts of generating and consuming water from different sources. Water efficiency is assessed in terms of the water footprint (WF) (WFN 2015) of nonconventional water sources because they both replenish and consume water (Zhang et al. 2021b). This study uses the Boulay et al. (2011) method to measure both the direct and indirect water use of water production throughout its lifecycle. The water circle is modeled as an open loop system through LCA using an FU of a cubic meter of water produced. Open-loop recycling is used to model the recirculation of treated wastewater into the water cycle in accordance with ISO 14040/4 (ISO 2006a, b). In addition, according to ILCD (JRC 2010), treated wastewater belongs to an open-loop system with different primary routes per clause 4.3.4.3 or "Allocation procedures for reuse and recycling standards" from ISO 14044 (ISO 2006b) to account for saved virgin materials, in our case, desalinated water and GW.

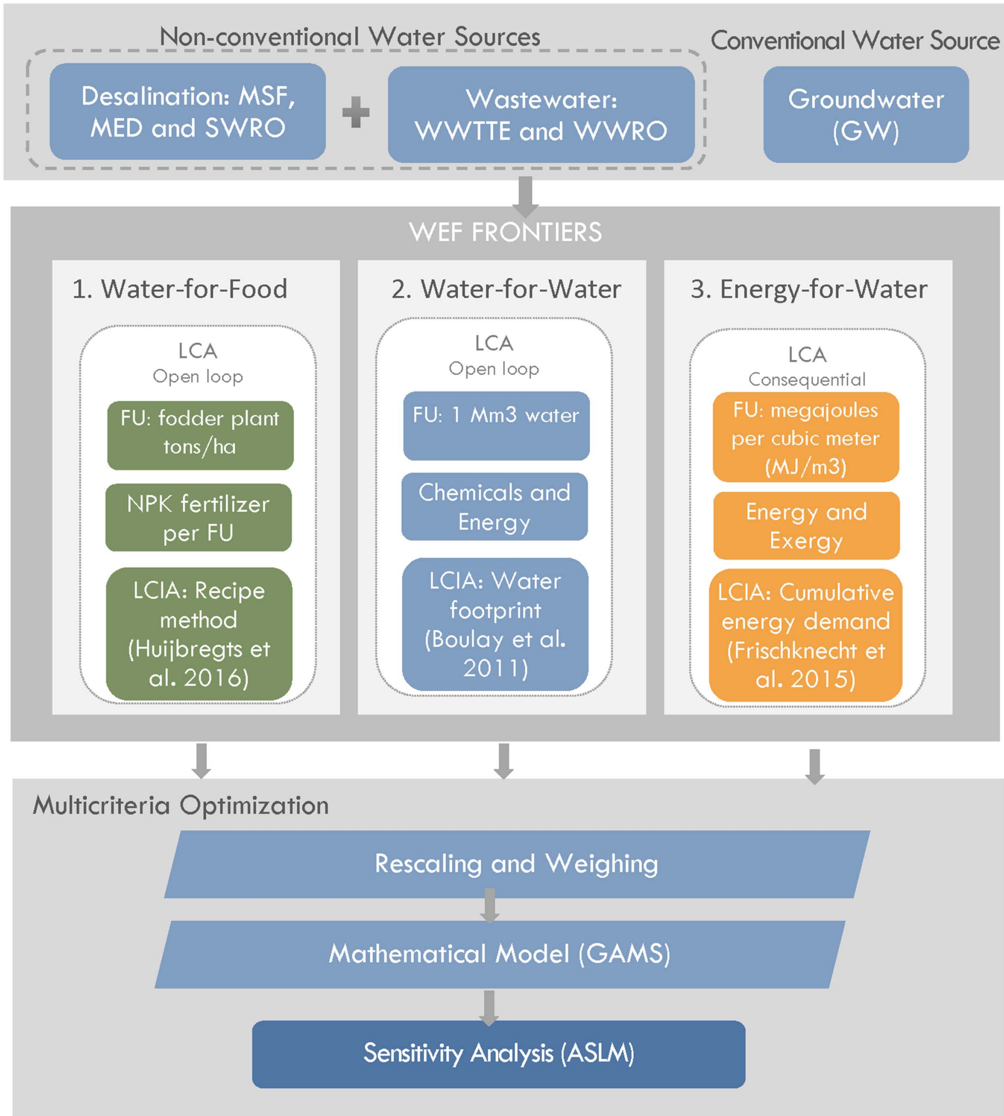

Fig. 1. Framework for optimizing WEF frontiers through multicriteria mathematical modeling.

Table 3. LCA-based multicriteria mathematical model indices

Forefront	Identification	Index
Water source (i)	WWTTE	1
	WWRO	2
	MSF	3
	SWRO	4
	MED	5
	GW	6
Nexus front (j)	Food/nutrients	1
	Water	2
	Energy	3
Sector (k)	Municipal	1
	Agricultural	2
	Industrial	3

Energy-for-Water Scores

The energy-for-water ($j = 3$) nexus scores, s_{i3} ($i = 1, 2, \ldots, 6$), are used to assess the amount of energy required for water production using energy and exergy calculations based on the consequential modeling concept [ISO 14044 (ISO 2006b)]. The cumulative energy demand (CED) by Frischknecht et al. (2015) quantifies the embedded energy of the system in the foreground and background processes. The CED indicator computes the primary energy consumption per FU of megajoules per cubic meter (MJ/m^3) of water production. The CED method applied is v.1.8 based on Ecoinvent V.2.0 (Ecoinvent 2007).

Multicriteria Mathematical Model

An LCA-based multicriteria mathematical model optimizes the performance among nexus fronts, food/nutrients ($j = 1$), water ($j = 2$), and energy ($j = 3$) to find the optimal source for each sector. The model indices are provided in Table 3. The decision variable x_{ik} is the fraction of water produced from source i to satisfy the demand of sector k. Let w_j denote the weight of front $j\,\{0 \leq w_j \leq 1; j = 1, 2, 3\}$ such that $\sum_{j=1}^{3} w_j = 1$. Let z indicate a composite index of nexus frontiers that need to be simultaneously optimized. Let d_k be the proportion of water demand per sector k. The objective function [Eq. (1)] minimizes a composite value, z, across the three WEF fronts of normalized impacts, s_{ij}. Eq. (2) implies that the agricultural sector demand, $\boldsymbol{d_2}$, can be satisfied from any water source. However, Eq. (3) indicates that as per local regulations (KEPA 2014, 2017), the municipal ($\boldsymbol{d_1}$) and industrial ($\boldsymbol{d_3}$) sectors' demand cannot be satisfied from tertiary treated wastewater ($\boldsymbol{i \neq 1}$). Eq. (4) imposes an upper limit on the availability amounts of WWTTE and WWROP because they cannot exceed source water arriving from municipal sources.

Min z

$$z = \sum_{i=1}^{6}\sum_{j=1}^{3}\sum_{k=1}^{3} w_j s_{ij} x_{ik} \tag{1}$$

such that

$$\sum_{i=1}^{6} x_{i2} \geq d_2 \tag{2}$$

$$\sum_{i=2}^{6} x_{ik} \geq d_k \quad (k = 1, 3) \tag{3}$$

$$\sum_{i=1}^{2}\sum_{k=1}^{3} x_{ik} \leq \sum_{i=3}^{6} x_{i3} \tag{4}$$

$$\sum_{j=1}^{3} w_j = 1; \quad w_j \in \{0 \leq w_j \leq 1; j = 1, 2, 3\} \tag{5}$$

$$x_{ij} \geq 0 \tag{6}$$

The nexus frontier scores, $\boldsymbol{s_{ij}}$, are normalized to a 0–1 scale using the equation found in Table S2. Normalization to a [0–1] range ensures that each WEF front is scaled to the same range, preventing any single front from dominating the analysis simply due to its original values. The 0–1 is compatible with ASLM weight priorities as $\boldsymbol{w_j} \in \{\boldsymbol{0} \leq \boldsymbol{w_j} \leq \boldsymbol{1}\}$, which is used to investigate the sensitivity discussed in the next section.

Uncertainty and Sensitivity Analysis

Uncertainty analysis of different WEF parameters is conducted and simulated in LCA using Monte Carlo simulation. The sensitivity analysis of weight priorities assigned is conducted by applying the ASLM design (Cornell 2002) to examine the solution space for the different nexus frontier weights. The ASLM was created using the Minitab software (v. 21) mixture design model to satisfy the Eq. (5) constraint (see Fig. 2). The sensitivity analysis of nexus weight combinations includes investigating vertices, centroid, and inner axial points (Smith 2005) to test the influence of the robustness of the weight assumptions of each nexus frontier. The sensitivity of local meteorological conditions and the impact of geographic conditions on water quality intake for desalination are also investigated.

Results and Analysis

A water flow analysis was first performed by using a Sankey diagram to visualize the nexus frontiers, nonconventional water sources, and sectors. An LCA was performed to assess the relationship between the water-for-food (nutrients) nexus, water-for-water nexus, and energy-for-water nexus. The last step of the analysis consisted of optimizing the results and investigating the sensitivity of the weights per the nexus frontier.

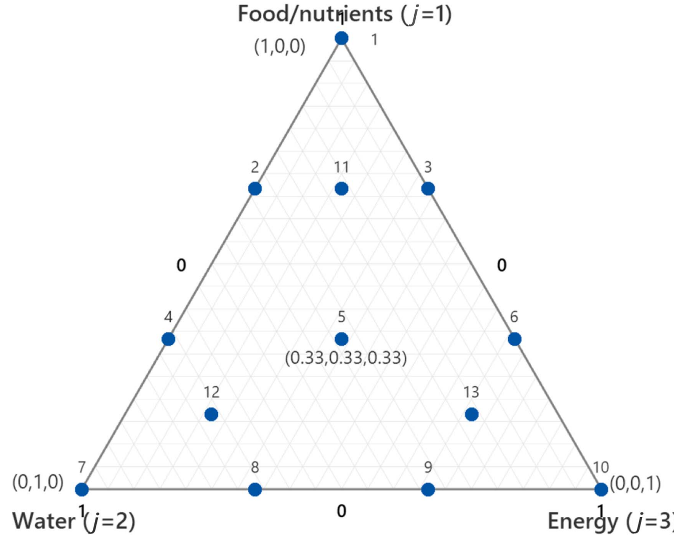

Fig. 2. ASLM simplex design plot of nexus inner sectoral weights (Lattice 3) generated using Minitab v.21.

Sankey Diagram

Fig. 3 presents a Sankey diagram that illustrates the primary water resources, their flows, and their uses at a national scale in Kuwait. The flow data used for the Sankey diagram are shown in Table S3. Seawater desalination is conducted using three technologies—MSF (65%), MED (23%), and SWRO (12%) systems. Most of them contribute to the provision of potable water in the municipal sector, which accounts for 44% of the water budget, whereas 2% of desalinated water is consumed in electricity cogeneration. An 8%–11% leakage occurs in the freshwater distribution system depending on network efficiency, distance, or illegal connections to end use. Additional data on leakage can be obtained from Al-Khalid et al. (2013) and Akber and Mukhopadhyay (2021).

Most municipal wastewater is treated (90.3%), and 43% of which is treated using advanced tertiary wastewater treatment, whereas 47% is treated to reach potable quality for nonpotable use through WWROP facilities. The remaining 9.7% is disposed of as untreated into the sea (Aleisa et al. 2022a). GW is mixed with distilled water in electricity-water cogeneration plants (33%), and the remaining water is used to produce crops. The manufacturing sector is a subset of the industrial sector that also includes desalination, electricity cogeneration, and wastewater facilities. These entities are segregated to avoid looping in the Sankey diagram.

On average, the agricultural sector consumes 54% of the total water budget and is irrigated by both treated wastewater arriving from the municipal sector and GW (Aleisa and Alshayji 2019). In 2018, approximately 62% of GW withdrawn in Kuwait was for agriculture. The agricultural sector in Kuwait consumed an average of 775 Mm^3 of GW, 2.9 Mm^3 of brackish water, and 6.4 Mm^3 of purchased water (Central Statistical Bureau 2019). The water required for landscaping in Kuwait is approximately 48 MIG/d (PAAF 2020). Landscaping and crops also belong to the agricultural sector and are segregated only when irrigation wastewater is used for irrigation.

Water-for-Food (Nutrients) Nexus

The water-for-food nexus was calculated based on the FU in Table 4. The LCIA characterized and normalized results are provided in Table S4 and Fig. S1. WWTTE can yield an additional

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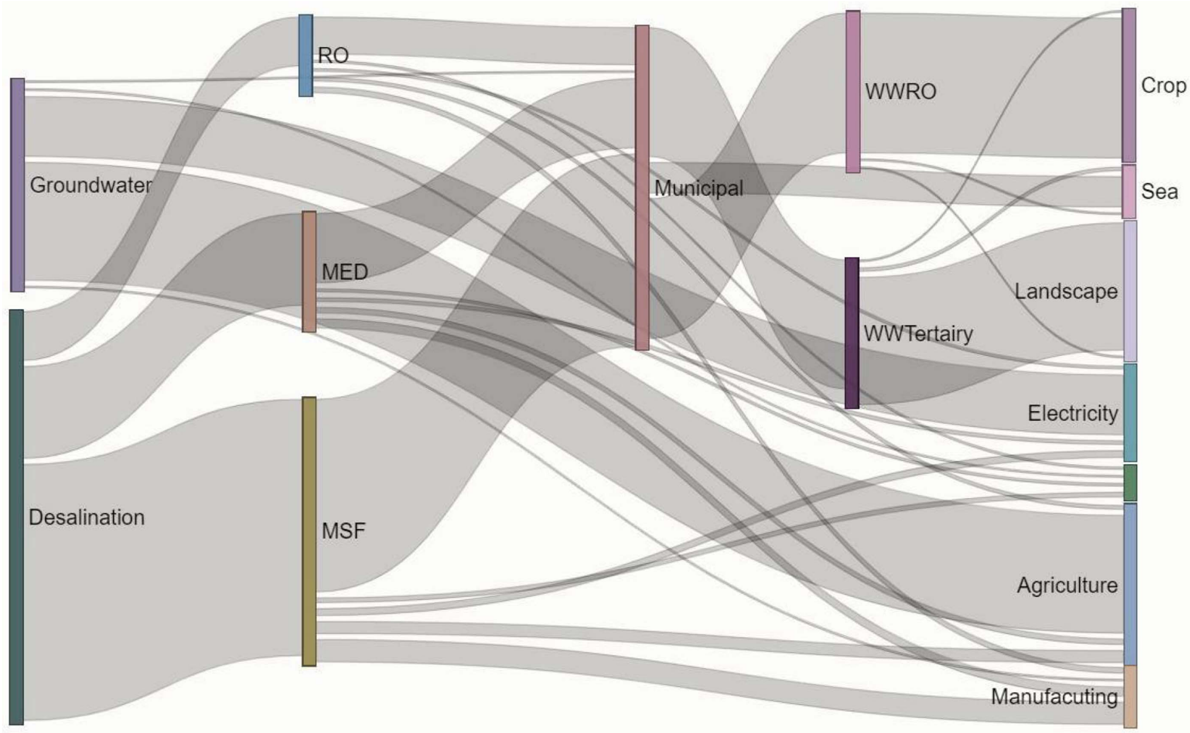

Fig. 3. Sankey diagram of major water flows and utilization of water resources across various sectors in Kuwait water management system (refer to the Supplemental Materials section for additional Sankey Diagram information).

Table 4. Saved virgin NPK equivalent of WWTTE efferent when used for irrigating one hectare of fodder plant

	Per unit	Per FU			
Measure	WWTTE (g/ml)	NPK in WWTTE (kg/ha)	NPK required (kg/ha)	Difference (kg/ha)	Shipping (sea) (tkm)
Nitrogen (N)	12.7	112.65	180	67.351	391.3
Phosphate (PO_4)	8.35	74.06	110	35.935	208.8
Potassium (K_2O)	20.5	181.8	180	−1.835	0

Source: Data from Aleisa and Alshayji (2019).

24.89 t/ha of fodder compared with the yield of WWROP and desalinated water, provided that the same synthetic nitrogen, phosphorus, and potassium (NPK) fertilizer ratio of 60:36:60 kg/ha is used. Supplying WWTTE to irrigate fodder emits 1.02×10^3 kg of CO_2 equivalent (eq)/ha compared with the 2.76×10^3 kg CO_2 eq/ha emitted by MED, MSF, and WWROP systems, which results in a 63% reduction in CO_2 emissions based on the IPCC 2013 method (Stocker et al. 2014). This reduction is because of the conservation of virgin NPK counterparts in the production and shipping systems. The WWTTE, WWROP, MSF, SWRO, and MED carbon footprints are 0.108, 0.405, 1.79, 1.0, and 1.62 kg CO_2 eq/kg fodder, respectively.

A substance analysis performed using the Recipe method (Huijbregts et al. 2016) indicates that virgin N production in synthetic fertilizer contributes to more than 95% of the overall environmental burden. For the climate change category, the nitrous oxide (N_2O) used in N production is responsible for 58% of the impact because it has a global warming potential that is 298 times that of CO_2 (Aleisa et al. 2021a).

Water-for-Water Nexus

The water-for-water nexus impact is calculated using the WF method developed by Boulay et al. (2011) with the inventories found in Table 2. The LCIA results indicate that the SWRO and WWROP methods have the highest water footprints due to the extensive amount of chemicals consumed to prepare water for ultrafiltration (UF)/RO treatment (Aljuwaisseri et al. 2022). Ferric chloride (Fe_3Cl) was used as a flocculant in sewage and was dispensed at a rate of 9.0×10^{-2} g/Mm^3 of WWROP. However, it contributes to 90% of the WWROP WF, requiring 1.6 m^3 of water per cubic meter of WWROP. The WF of Fe_3Cl is 8.94 m^3. Hydrochloric acid (HCl) and citric acid ($C_6H_8O_7$) are applied to UF/RO to adjust the pH and remove the metal deposits in WWROP. They are responsible for 11% (0.195 m^3) and 3% (0.0489 m^3) of the WWROP WF, respectively. All chemical WFs are virtual (The Water Footprint Calculator 2019) and occur in the country of origin; their impacts in Kuwait, for instance, are not calculated in the typical anthropogenic WFs.

For SWRO, the LCIA indicates that 81% of the WF is attributed to the dissolved air flotation (DAF) system in which Fe_3Cl is injected. In the DAF system, for every cubic meter of treated seawater, 0.937 m^3 of water is consumed in Fe_3Cl production (119.98 g/m^3). For WWTTE, 20% of the WF is attributed to electricity, and the rest is attributed to chemical use. Fig. 4 visualizes the calculated virtual WF for these nonconventional water sources.

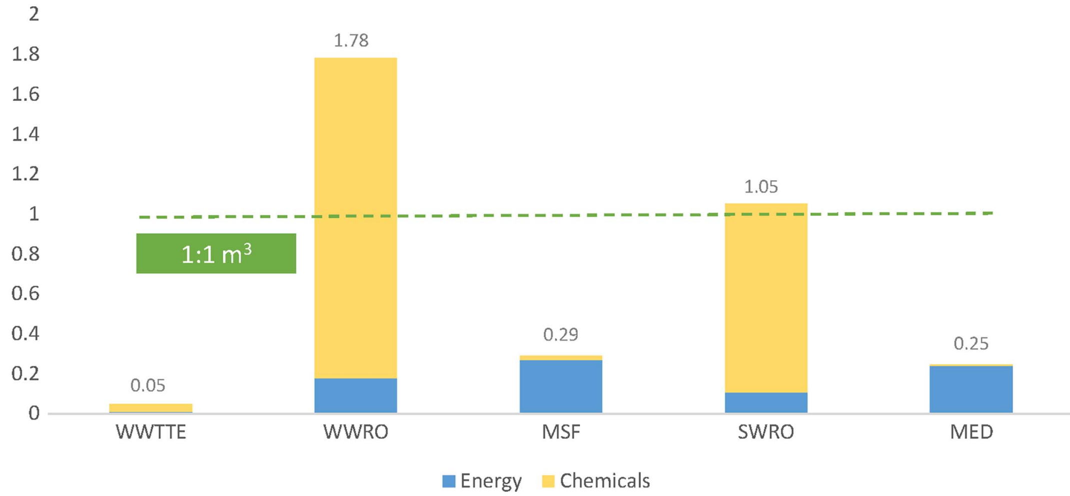

Fig. 4. WFs of nonconventional water resources derived using method in Boulay et al. (2011).

Energy-for-Water Nexus

The energy-for-water nexus impacts are calculated using the CED method. The analysis indicates that desalinating water consumes considerably more energy than recycling water. The CEDs of the MSF, MED, and SWRO desalination systems are 136.516 MJ/m^3, 122.437 MJ/m^3, and 70.159 MJ/m^3. The CEDs of the WWTTE and WWROP wastewater systems require 5.1344 MJ/m^3 and 15.844 MJ/m^3, respectively. These CEDs, in MJ/m^3, against the maximum allowable irrigation limits from the local Kuwait Environmental Authority (KEPA) are provided in Fig. 5. The permissible ranges and maximum value standards of irrigation water are compiled as per Annex I of Decree No. 12 of 2017 (KEPA 2017) with Articles 88, 90, 92, and 94–99 of Law No. 42/2014 (KEPA 2014), which are more conservative than those of the World Health Organization (WHO) (Aleisa and Alshayji 2019; WHO 2012). Fig. 5 also shows the maximum allowable limits for irrigation and potable water provisions in terms of total dissolved solids $(TDS)/m^3$, and the remaining properties reference KEPA (2017).

Multicriteria Optimization Results

The optimization model is modeled as a linear program using the general algebraic modeling system (GAMS) to minimize z using the CPLEX solver. The model is solved for all nexus weight combinations generated using the ASLM; hence, the multicriteria optimization model was run at each point of the ASLM. The optimal proportions of the source for the sector water assignment, $\boldsymbol{x_{ik}}(\boldsymbol{i}=\mathbf{1},\mathbf{2},\ldots,\mathbf{6};\boldsymbol{k}=\mathbf{1},\mathbf{2},\mathbf{3})$, across the WEF nexus are provided in Table 5. The weights assigned to the nexus frontier $(\boldsymbol{w_j})$, are neither the MSF technology for desalination $(\boldsymbol{i}=\mathbf{3})$ nor the WWROP technology for wastewater treatment $(\boldsymbol{i}=\mathbf{2})$ where ever part of the optimal solution, i.e., $\boldsymbol{x_{3k}}=\mathbf{0}$ and $\boldsymbol{x_{2k}}=\mathbf{0}$ for all $\boldsymbol{k}=\mathbf{1},\mathbf{2},\mathbf{3}$, and is thus omitted from Table 5. Tracing the results back to the substance contributions shows that the

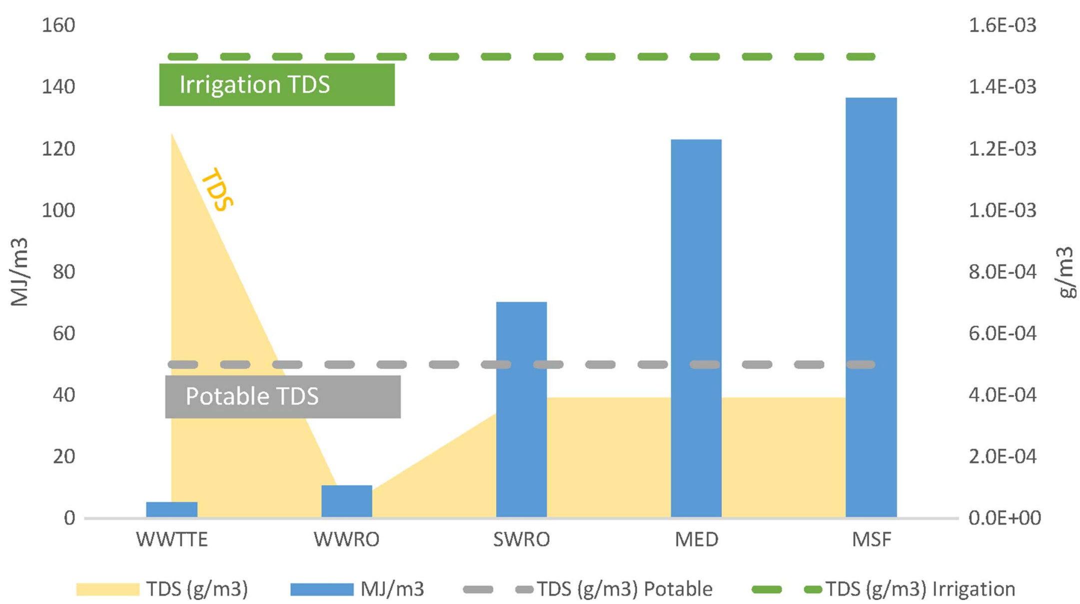

Fig. 5. CEDs obtained for water production systems (CED v1.8).

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Table 5. Optimization model results derived using ASLM sensitivity for nexus frontier weights

Input: Frontier weights, w_j — Food w_1	Water w_2	Energy w_3	ASLM Solution node	From: WWTTE ($i=1$) To: AGRI ($k=2$) x_{12}	From: SWRO ($i=4$) To: MCPL ($k=1$) x_{41}	To: AGRI ($k=2$) x_{42}	To: INDST ($k=3$) x_{43}	From: MED ($i=5$) To: MCPL ($k=1$) x_{51}	To: AGRI ($k=2$) x_{52}	To: INDST ($k=3$) x_{53}	From: GW ($i=6$) To: AGRI ($k=2$) x_{62}
1.00	0.00	0.00	1	81.5%	100%	—	18.5%	—	—	—	18.5%
0.67	0.33	0.00	2	81.5%	—	—	—	100%	18.5%	100%	—
0.67	0.00	0.33	3	81.5%	100%	—	100%	—	—	—	18.5%
0.33	0.67	0.00	4	81.5%	—	—	—	100%	18.5%	100%	—
0.33	0.33	0.33	5	81.5%	—	—	—	100%	18.5%	100%	—
0.33	0.00	0.67	6	81.5%	100%	—	100%	—	—	—	18.5%
0.00	1.00	0.00	7	81.5%	—	—	—	100%	18.5%	100%	—
0.00	0.67	0.33	8	81.5%	—	—	—	100%	18.5%	100%	—
0.00	0.33	0.67	9	81.5%	100%	18.5%	100%	—	—	—	—
0.00	0.00	1.00	10	—	100%	—	100%	—	—	—	100%
0.67	0.17	0.17	11	81.5%	—	—	—	100%	18.5%	100%	—
0.17	0.67	0.17	12	81.5%	—	—	—	100%	18.5%	100%	—
0.17	0.17	0.67	13	81.5%	100%	18.5%	100%	—	—	—	—

Note: Only nonzero x_{ij} columns are shown; therefore, none of the optimal solutions that used MSF or WWROP as source are shown. Optimal solutions only used WWTE and GW sources for the agricultural sector.

excessive energy use in MSF and the WF of WWROP are not justified across any of the WEF frontiers.

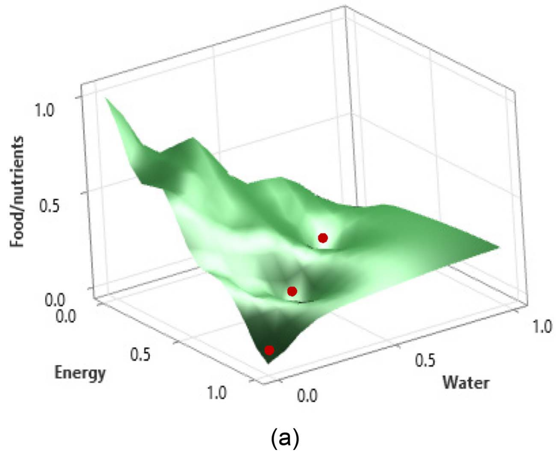
As previously indicated, the ASLM results show the robustness of the weight assignments to nexus frontiers within the optimization model. As shown in Table 5, the vertex points in ASLM, nodes 1, 7, and 10, show the results from a single WEF perspective, i.e., food, water, or energy. While prioritizing the food nexus at node 1, with $\boldsymbol{w_1} = \mathbf{1}$, the optimal solution indicates that all municipal and industrial water demand should be supplied using SWRO. In addition, 81.5% of the water demand in the agricultural sector should be supplied by WWTTE, and 18.5% should be supplied by GW. On the other hand, when prioritizing the water frontier in WEF (node 7 in Table 5), the optimal results indicate that all municipal and industrial water demands are best produced by MED. For this solution, 81.5% of agricultural water demand should be supplied by WWTTE and, again, 81.5% by MED. A focus on the energy frontier of WEF (node 7 in Table 5) leads to the recommendation of using GW for irrigation. This result presents salient evidence for the need to collectively consider the WEF nexus given the severe state of depleting GW aquifers in Kuwait (Aleisa et al. 2022a; Aleisa and Al-Zubari 2017; Aleisa and Alshayji 2019).

At the WEF core, the centroid point (node 5) of the balanced WEF score card (see Fig. 2) indicates that the entire capacity of WWTTE should be used for irrigation, whereas the remaining agricultural capacity should be supplied by MED. At the centroid point, MED should also supply the entire water demand of the municipal and industrial sectors. In general, more than half of the optimal solutions exclude GW as part of the water supply.

Fig. 6(a) shows a visual representation of the composite index value, $\boldsymbol{z}$, for all solutions' corresponding output response in a mathematical model. In other words, regardless of the weight assigned to the nexus frontiers, WWTTE ($\boldsymbol{i} = \mathbf{1}$) for agricultural use and MED ($\boldsymbol{i} = \mathbf{5}$) or SWRO ($\boldsymbol{i} = \mathbf{4}$) for municipal use have predominantly been part of the optimal solution. These three technologies will always minimize the composite impact, $\boldsymbol{z}$, as shown in the three valleys in the response surface optimization plot in Fig. 6(a). The Pareto front shown in Fig. 6(b) indicates a nondominated solution that comprises the best trade-offs among the WEF nexus. The Pareto front shows source-sector assignments that are also inferior to all other solutions in all WEF-ASLM optimizations. These are WWRO and MSF. However, as previously indicated, there is a substantial contrast between the present state of the water supply and the technologies recommended by the WEF framework (Aleisa 2024). Specifically, the predominant method (65%) for supplying desalinated water is MSF, and the primary choice for wastewater treatment is WWROP (Aleisa et al. 2022a). Neither of these technologies is represented on the Pareto frontier illustrated in Fig. 6(b). Therefore, considering the consistent optimization observed for WWTTE in agricultural use and either MED or SWRO in municipal use, policy makers are encouraged to explore a technology shift toward these solutions. These technologies consistently demonstrate the ability to minimize the composite impact, as evident in the valleys of the response surface optimization plot.

Interpretation and Discussion

Sensitivity and uncertainty analyses investigate the impact of model assumptions or variability in the model data or randomness that is inherited naturally in the system (Loucks and Bee 2005). This section discusses significant parameter uncertainty and model sensitivity, as well as other externalities through which the results need to be interpreted.



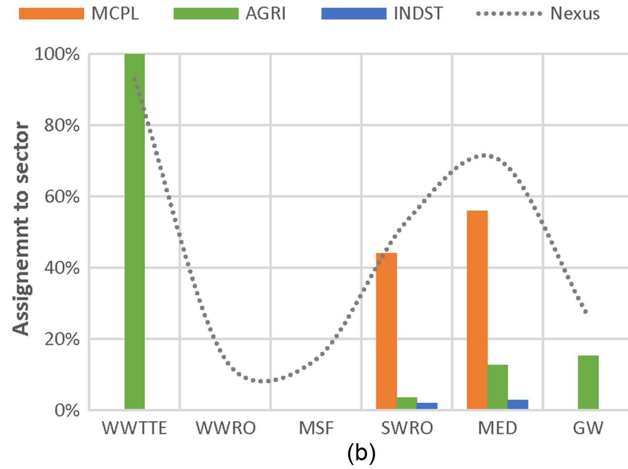


Fig. 6. (a) Response surface plot for three nexus fronts; and (b) Pareto-efficient points for WEF nexus framework.

Model Parameter Uncertainty

An uncertainty analysis attempts to describe the set of possible outcomes using the associated probability distributions. Sensitivity analysis identifies the uncertainty in the model output (z) and how it could be apportioned to model inputs (Saltelli et al. 2004). For the water-for-food (nutrients) nexus, the inventory values rely on multiple assumptions that build the FU of the study. These assumptions include the NPK concentration in tertiary treated wastewater, the amount of NPK required per hectare to irrigate groups for one year, the source of fertilizer used, the amount of irrigation required, and the annual yield per hectare, among others. For our study, the inventory of the water-for-food nexus is calculated with the assumption of low irrigation water levels (12.4 cm). This assumption includes scarce rainfall, which is equivalent to an average of 8.877 $\mathrm{K\,m^3}$ of water for irrigation requirements averaged over the data reported in Singh et al. (2014), Chowdhury and Al-Zahrani (2015), and Mekonnen and Hoekstra (2010). The expected yield is 40 t/ha (dry matter 10–15 t/ha) based on Draycott and Hollies (2018) and Volesky and Berger (2010). The NPK fertilizer ratios are calculated using FAO (2002) average standard rates of fertilizer application for the main agricultural crops (kg nutrient/ha) and based on Warman and Termeer (2005) for forage plants. Inorganic commercial fertilizer with a concentration ratio of 110 N:60 P:110 K is equivalent to applying 180 kg of N and K and 110 kg of P (total of both applications) (Aleisa et al. 2021a). The use of WWTTE decreases the amount of fertilizer needed to grow crops because it is rich in macronutrients (NPK), given that WWROP and desalinated water lack these nutrients. Based on the effluent specification of WWTTE found in Aleisa and Alshayji (2019), the NPK nutrient complements are calculated per FU, as provided in Table 4. These essential nutrients can be harnessed to create fertilizer that can be credited to the LCA model. The transoceanic shipping for NPK fertilizer is calculated from Jordan to Kuwait and is estimated at 3,137 nautical miles, equivalent to 2,730.57 tkm (t/km) of shipped NPK for the entire FU. Most of these variables are regional, and investigating their impact boundary should be addressed on a case-by-case basis. However, the amount of NPK nutrients in tertiary treated wastewater effluent and the amount of NPK required per hectare require a closer look at the input data variability and associated uncertainty. The NPK requirements for different agricultural crops are obtained from FAO (2002) (see Table 6).

The statistical probability distributions associated with the NPK requirements were investigated using the Arena Input Analyzer software (by Rockwell). For N, a uniform distribution [$X \sim \mathbf{UNIF}(\mathbf{55}, \mathbf{240})$ kg/ha] produces the least square error (0.0551). For P, the data are fit to a normal distribution [$X \sim \mathbf{NORM}(\mathbf{110}, \mathbf{30.1})$ kg/ha] because it has the least square error, $\boldsymbol{e}$ (0.0261). For K, the triangular distribution [$X \sim \mathbf{TRIA}(\mathbf{0}, \mathbf{57.9}, \mathbf{165})$ kg/ha] has the least, $\boldsymbol{e}$ (0.0136). All distributions have corresponding p values greater than 0.15 using the Kolmogorov–Smirnov test.

Table 6. Average NPK applications for main agricultural crops (kg/ha)

Crop	Nitrogen (N)	Phosphorus (P_2O_5)	Potash (K_2O)
Cereals (irrigated land)	150 to 200	100 to 120	50
Cereals (arid land)	50 to 60	40 to 50	0
Cereals (for seed)	180 to 220	120 to 140	85 to 90
Cereals (rice)	200 to 220	140 to 145	150 to 180
Cotton (average fibers)	215 to 240	145 to 165	95 to 110
Cotton (fine fibers)	230 to 250	155 to 165	100 to 110
Kenaf	160 to 180	130 to 140	80 to 90
Potatoes	120 to 150	85 to 100	60 to 75
Vegetables	145 to 200	100 to 110	70 to 75
Gourds	50 to 75	100 to 110	45 to 80
Fodder roots	220	90	60
Maize for silage	200	90	60
Established alfalfa	100	90 to 100	50 to 60
Orchards and vineyards	120 to 130	85 to 90	65

Source: Data from FAO (2002).

On the other hand, the NPK found in WWTTE varies by season and region. Available data for some countries were found in Wong et al. (1998) and Mtshali et al. (2014) and are used to fit the NPK tertiary sewage concentrations for the uncertainty analysis (see Table 7).

For the N concentration in WWTTE, the statistical analysis failed to reject the concept that the data are drawn from a Weibull distribution [$X \sim \mathbf{WEIB}(\mathbf{85.3}, \mathbf{0.399})$ g/kg], with $\boldsymbol{e}$ equal to 0.00564 with a reasonable $\boldsymbol{p}$ value of 0.0626 using the Kolmogorov–Smirnov test. The P concentration in WWTTE is found to follow a triangular distribution [$X \sim \mathbf{TRIA}(\mathbf{0}, \mathbf{14.7}, \mathbf{49})$ g/kg] with a square error of 0.09704 and a $\boldsymbol{p}$ value greater than 0.15. The test statistic for K in WWTTE was insufficient to confirm its statistical distribution at $\boldsymbol{\alpha} = 0.05$. Randomly generated values from these distributions were simulated using Monte Carlo simulation to measure uncertainty (Ciroth et al. 2004; Khang et al. 2017). Importantly, the underlying

Table 7. NPK concentrations in WWTTE (g/kg)

Literature	Nitrogen (N)	Phosphorus (P_2O_5)	Potash (K_2O)
Wong et al. (1998)	70.443	18.89	0
Lombardi et al. (2017)	17	5	1
Sampson (2016)	0.005	0.03	0.696
Wierzbowska et al. (2016)	61.69	34.7	0
Tontti et al. (2017)	34	49	1.4
Mtshali et al. (2014)/Ireland	70	19.5	—
Mtshali et al. (2014)/Turkey	60.3	10.45	—
Mtshali et al. (2014)/Turkey	30	10.3	—
Mtshali et al. (2014)/US	30.3	23	—
Mtshali et al. (2014)/Spain	20.42	16.4	—
Mtshali et al. (2014)/Spain	20.63	18.1	—
Mtshali et al. (2014)/Russa	20.1	18	—
Mtshali et al. (2014)/Poland	30.07	—	—
Mtshali et al. (2014)/Spain	10.5	—	—

distributions adhere to Monte Carlo assumptions for this specific case. The convergence criteria in our Monte Carlo analysis were based on a predetermined number of iterations, in our case 1,000 runs on characterizing the carbon footprint of IPCC using a 95% confidence level. The results are provided in Fig. 7. In Fig. 7, the dark shade bar represents the number of times WWTTE (B) had lower carbon footprint emissions than MSF, MED, or WWROP (A) when used for irrigation. With 95% confidence, it can be concluded that in 91.7% of cases, carbon emissions are lower only when WWTTE is used, which means that it is better.

Regarding the water and energy nexus frontiers, in our case, 78% of water resources are produced nonconventionally through mass production either through desalination or wastewater treatment (Aleisa 2024). The effluent of these treatments is strictly regularized by law [see articles 35, 38, 40, 42, 66, 70, 72–74, and 108 of KEPA (2014)]. Since 2008, the data records of the Kuwait wastewater plant and the desalination plant effluent properties have been consistent on average (Abusam and Al-Haddad 2016; Al-Shammari 2018; Al-Shayji and Aleisa 2018; Aleisa et al. 2011; Aleisa and Al-Zubari 2017; Aleisa and Alshayji 2019; Hamoda 2013; Kuwait News 2015; MEW 1998) for water properties measured over 27 parameters [see the Drinking Water Quality Index (KDWQI) and National Drinking Water Quality Standards (KDWQS) in MEW (2019)]. Hence, the variability of the effluent is not sufficient to describe a hypothetical or an empirical distribution from which data can be drawn and uncertainty analysis could be conducted.

Model Sensitivity

A model sensitivity analysis is applied to investigate the impact of the sensitivity of frontier priorities.

The steepness of the curve slopes in the Cox response trace plots [shown in Fig. 8(a)] serves as a visual indicator of the degree of sensitivity in the ASLM methodology. Steeper slopes suggest higher sensitivity, implying that changes in the priority of the corresponding nexus frontier significantly influence the overall performance of the WEF nexus. Fig. 8(b) provides a quantitative representation of the responsiveness of the ASLM model to varying priorities. The darker the blue is, the higher is the sensitivity. Fig. 8 indicates a steep ascent in the curve associated with the food nexus, which reflects higher sensitivity on the overall composite index. The Water Nexus Sensitivity curve shows a steeper downward slope toward the lower values, which indicates that the results are more sensitive for lower weights assigned to the water frontier. A gradual slope in the energy nexus [Fig. 8(a)] curve implies lower sensitivity to changes in the priority of the energy frontier. A less steep slope indicates that alterations in the priority of the energy nexus have a comparatively minor effect on the overall composite index, z.

Sensitivity to Regional Factors

The meteorological conditions of Kuwait, which has a hyperarid climate characterized by irregular, sparse rainfall (121 mm/y) (FAO-AQUASTAT 2019) and high evaporation rates (>3,000 mm/y) (Al-Zubari 1998), impact irrigation requirements. Irrigation water requirements were adapted from Volesky and Berger (2010), Singh et al. (2014), Chowdhury and Al-Zahrani (2015), and Mekonnen and Hoekstra (2010). The irrigation requirements listed in Table 4 can be adjusted based on the meteorological conditions of a specific country using data found in FAO-AQUASTAT (2021) for wider implications of the results.

Another regionally significant factor is the location of the desalination plants in Kuwait. Kuwait is in the northern part of the shallow waters of a semiclosed body of water, the Arabian/Persian Gulf. It is considered one of the warmest sea basins worldwide (Charles 2019; Karam 2023). The high feedwater temperatures of the Arabian/Persian Gulf promote biological activities such as red tide phenomena and jellyfish swarms (Saeed et al. 2019). The intake areas of the desalination plants are characterized by high salinity due to lower water circulation (Lattemann and Höpner 2008; Saeed et al. 2019) and high turbidity due to sediment flow

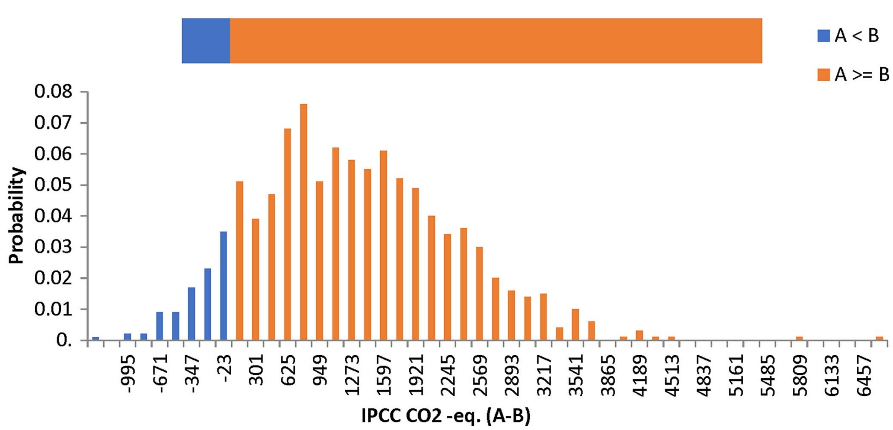


Fig. 7. Uncertainty analysis for comparing NPK values of WWTTE (B) with other water resources (A) when used for irrigation using characterized results produced using IPCC method at a 95% confidence interval.

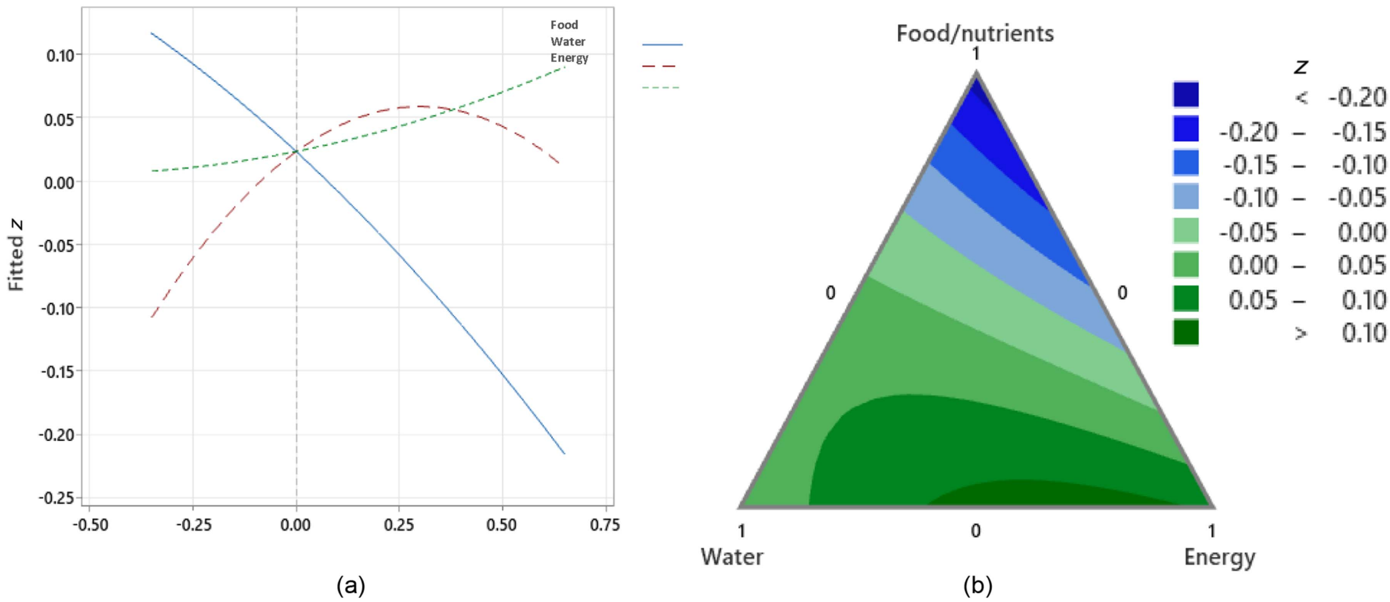


Fig. 8. (a) Cox response trace plot for nexus fronts weights sensitivity; and (b) contour plot for three nexus fronts generated by ASLM sensitivity using Minitab 21.

from the Tigris and Euphrates River systems to the Kuwait marine area (Karam 2023). Research showed that these parameters increase the amount of chemicals required in the pretreatment and dissolved air flotation (DAF) unit of SWRO and increase RO membrane replacement (Aljuwaisseri et al. 2022; Ettouney et al. 2002). The increase in higher chemical and membrane use is reflected in the cost of SWRO desalination (see Fig. 9). The higher cost of SWRO desalination is due to the additional chemicals required in the DAF system (Aljuwaisseri et al. 2023). Hence, the chemical inventories for SWRO in Table 2 could be adjusted by region.

Additional Externalities Associated with the Country Context

The optimization model built in this study was based on LCA, which is superior in identifying impacts across single or multiple categories, including the impacts of WFs, energy, and many other factors. However, LCA does not normalize impacts or resource depletion based on resource scarcity. The elemental material flows from inventories are characterized and normalized based on the effect and propagation of pollutants per subcomponent. Because competition over multiple resources is at the heart of the WEF nexus, material or commodity scarcities must be factored in within the analysis by giving such dimensions increased weights or impacts. Within the LCA interpretation, this requirement could be translated to optimizing the considered factors, with a higher priority allocated to the dimension with the farthest distance to the target (Muhl et al. 2021). For instance, Kuwait's water stress index reached 3,850% in 2021, with Kuwait having the worst ranking among 177 nations (Mateo-Sagasta et al. 2016). Such scarcity should encourage the application of higher weights to the water nexus frontier ($w_2 \geq 0.67$) to provide region-specific optimal solutions, wherein water sustainability is ultimately the greatest challenge.

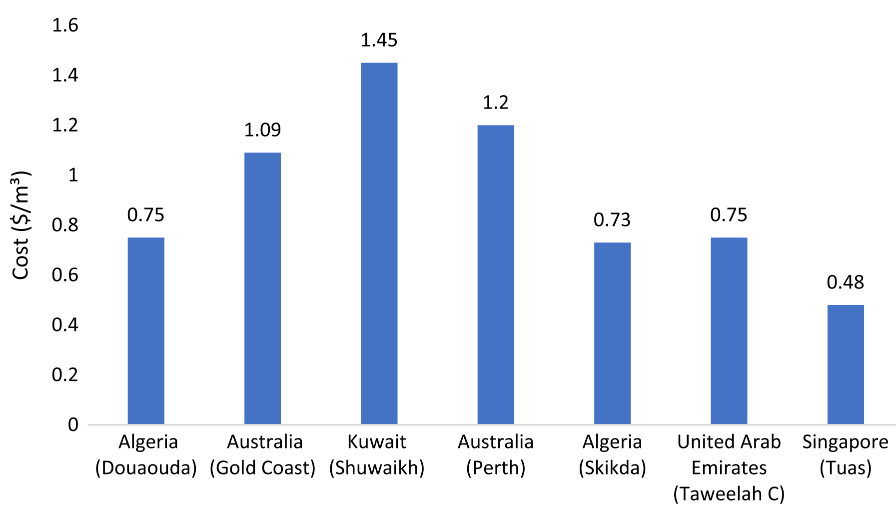


Fig. 9. Cost of desalinating water using SWRO in different geographic locations as a reflection of increased chemical and membrane requirements. (Data from Aljuwaisseri et al. 2022; Huehmer 2011; Ghaffour et al. 2013.)

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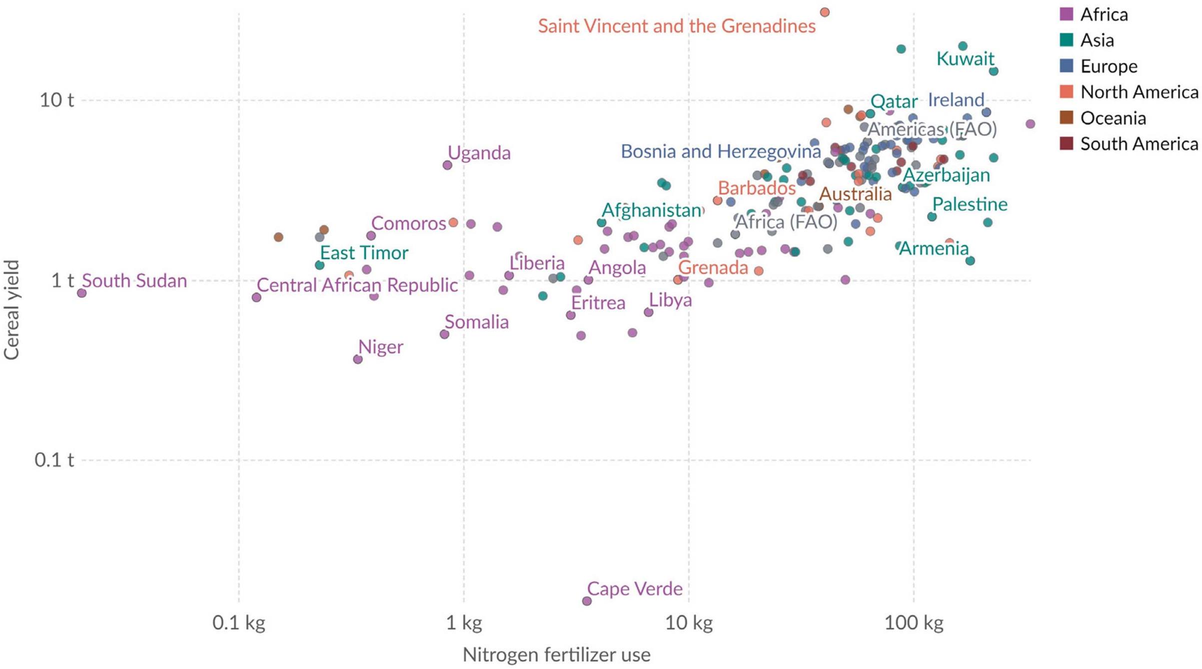

Fig. 10. Cereal yield versus fertilizer use, 2021 (latest available). Yields measured in tons per hectare. Fertilizer use is measured in kilograms of nitrogenous fertilizer applied per hectare of cropland. (Data from OECD/FAO 2023.)

Another externality associated with commodity scarcity is the excessive use of phosphorus (P) as a macrocomponent in NPK fertilizers. P, which is essential for soil fertility and agricultural productivity (Cordell and White 2015), is being depleted at an alarming rate (Aleisa et al. 2021b; Alewell et al. 2020; Walker 2021) and is now listed among the critical substances in the EU [COM No. 297 (CEN 2013); EC 2017]. P scarcity is not emphasized in LCA because the high environmental impact of N production masks the depletion of this vital nutrient (Aleisa et al. 2021a). N production consumes considerable amounts of copper and is responsible for 38% of the burden within the metal depletion midpoint category. N has a global warming potential that is 298 times that of CO_2 (Aleisa et al. 2021a). Approximately 90% of mined P is used in agriculture (Smol et al. 2020). WWTTE includes considerable amounts of NPK nutrients for crop irrigation, including vegetables and fruits that are consumed raw (Al-Khamsi 2013; Al-Shammiri et al. 2005; Aleisa et al. 2021a; Alhumoud et al. 2003; MPW 2021). For fodder crops, WWTTE can supply up to 67% of the required P (see Table 4).

Local regulations in Kuwait prohibit the use of WWTTE for irrigating crops (KEPA 2014, 2017). Hence, because WWROP is used instead, a considerable amount of synthetic fertilizer is applied (see Fig. 10), thus increasing the risk of plant resilience and soil erosion and inhibiting crop growth (Townsend et al. 2003). Fig. 4 shows that per TDS needed, the energy embodied in desalination and WWROP is not justified for irrigation purposes. As per international and local standards (KEPA 2014, 2017), irrigation requires a maximum amount of 1,500 mg/L, which could be achieved by the WWTTE system (1,247 mg/L), consuming 47% of the energy required for WWROP and 7% of the energy required for average desalination technologies, both thermal and membrane based. A WWTTE system is not suitable for potable or industrial uses. WWROP (10.71 MJ/m^3) consumes less than 15.3% of the energy consumed in SWRO desalination (70 MJ/m^3), and the water produced by WWROP (37.97 mg/L) is 10.3 times lower in TDS (better) than the desalinated water specification (392 mg/L). However, the provision of WWROP can satisfy only 30.15% of the municipal potable water demand (see Fig. 3) and may entail public opposition (Aleisa and Alshayji 2019). Arfelli et al. (2022) found that renewable energy sources can compensate for the energy demands of water production by scaling up to meet water demands but reported that the benefits seen in their study are on a local level that does not translate to larger regional levels. Their results indicate that policy-makers should focus on smaller local areas to promote optimized sustainable long-term solutions. In Kuwait, renewable energy resources could be used to supplement the high energy demands of water production. Since local regulation highly prioritizes water source safety and not efficiency, an opportunity exists to enhance the current laws and regulations.

Conclusions

This study develops a multicriteria mathematical model to optimize the allocation of water demand across municipal, agricultural, and industrial sectors and addresses the intricate trade-offs among water, energy, and food (WEF) using the analytic sensitivity-based linearization method (ASLM). The environmental impacts for each nexus frontier are quantified through life cycle assessment (LCA). Specifically, the food frontier within the WEF nexus is evaluated by assessing nutrient-food impacts. The functional unit is defined as the annual fodder yield irrigated by conventional and nonconventional water sources. The findings reveal that WWTTE can yield an additional 24.89 t/ha of fodder compared with WWROP and desalinated water, assuming a consistent synthetic NPK fertilizer ratio of 60:36:60 kg/ha. When WWTTE is used for fodder irrigation, the carbon footprint is 1.02×10^3 kg CO_2 eq/ha compared with the emissions of 2.76×10^3 kg CO_2 eq/ha produced by MED, MSF, and WWROP. Hence, the carbon footprint is reduced by approximately 63% of that based on the IPCC. Consequently, the carbon footprint is expected to decrease by approximately 63% compared with the baseline established by the IPCC. This outcome can be attributed to the preservation of virgin NPK counterparts during production and shipping processes, which are present in acceptable quantities in water-wastewater treatment efficiency (WWTTE). The carbon footprints per unit of fodder for WWTTE, WWROP, MSF, SWRO, and MED are 0.108, 0.405, 1.79, 1.0, and 1.62 kg of CO_2 eq/kg fodder, respectively.

In the outcomes of the WEF study, the water nexus frontier highlights that the foremost contributor to the water footprint is the quantity of virtual water utilized in the manufacturing of chemicals, particularly prevalent in reverse osmosis (RO)-based technologies such as seawater desalination (SWRO) and wastewater treatment (WWROP). Ferric chloride (Fe_3Cl) alone contributes to more than 90% and 80% of the water footprints in WWROP and SWRO, respectively.

The energy frontier in the WEF is calculated using the cumulative energy demand (CED). The analysis results indicate that desalinated water consumes considerably more energy than does recycled wastewater. The CEDs of the MSF, MED, and SWRO desalination systems are 136.516 MJ/m^3, 122.437 MJ/m^3, and 70.159 MJ/m^3, respectively. The wastewater CEDs of WWTTE and WWROP systems require 5.1344 MJ/m^3 and 15.844 MJ/m^3, respectively.

The WEF nexus optimization model is constructed under various scenarios of component weights systematically assigned through ASLM. The optimization outcomes suggest that the prevalent practice of employing MSF desalination and reverse osmosis (RO) for wastewater treatment lacks justification and should be discouraged. In contrast, the optimal approach, as indicated by the model, advocates for tertiary wastewater treatment and desalination using MED and seawater reverse osmosis (SWRO) across the entire WEF nexus.

Conducting sensitivity and uncertainty analyses entails exploring the repercussions of model assumptions, variations in model data, or inherent randomness within the system. Within the water-for-food nexus, these assumptions encompass factors such as the NPK concentration in tertiary treated wastewater, the required amount of NPK per hectare for one year of irrigation, and the fertilizer source, irrigation needs, and annual yield per hectare, among others. The findings, with a 95% significance level, reveal that irrigating crops with WWTTE statistically demonstrate a significantly lower impact in 91.7% of instances compared with utilizing water MSF, MED, or WWRO. Additionally, this study delves into the influence of local meteorological and geographical conditions on the results, emphasizing the necessity to adjust inventories for SWRO desalination based on the characteristics of regional water intake areas.

The optimization outcomes challenge the efficiency of current practices, indicating that reliance on MSF for desalination and WWROP for wastewater treatment is suboptimal. The expansion of the water network is advocated to incorporate WWTTE, MED, and SWRO. One limitation acknowledged in this study is the omission of groundwater (GW) recharge as a water demand source. Future research should address this by considering GW recharge in terms of depletion rates and seawater intrusion. This approach aims to bolster a circular economy and rectify the disrupted water cycle, fostering sustainability for generations to come.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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Supplemental Materials

Tables S1–S4 and Fig. S1 are available online in the ASCE Library (www.ascelibrary.org).

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