sciendo

Civil and Environmental Engineering
Vol. 21, Issue 2, 1348-1360, DOI: 10.2478/cee-2025-0098

A TIERED HYBRID LIFE CYCLE ASSESSMENT FOR SUSTAINABLE WATER RESOURCES MANAGEMENT IN IRAQ

Riyadh ALSULTANI[1, *], Abdulrazaq Khudhur ABDULWAHD[2], Aqeel Rwayyih HASAN[3], Haitham Abdulmohsin AFAN[4]

[1] Department of Civil Engineering, College of Engineering, University of Babylon, Babylon 51001, Iraq
[2] Hawija Technical Institute, Northern Technical University, Kirkuk 36001, Iraq
[3] Shatrah Technical Institute, Southern Technical University (STU), Basra 61004, Iraq
[4] Upper Euphrates Basin Developing Center, University of Anbar, Ramadi 31001, Iraq
[*] Corresponding author: riyadh.alsultani@uobabylon.edu.iq

Abstract

This paper presents a tiered hybrid life cycle assessment (TH-LCA) framework that integrates process-based data with input-output analysis (IOA) to evaluate the external impacts of water resource management in Iraq. Traditional LCA methods often focus on individual activities, overlooking broader system-wide impacts. By combining process data with IOA, the TH-LCA framework provides a comprehensive analysis of both direct and indirect external consequences associated with key water resource management parameters, including water consumption, water use, water withdrawal, water quality impact, and water efficiency. The study expands on previous TH-LCA framework by incorporating updated external indicators, broadening the scope to include additional industrial and service sectors, and introducing a novel approach for estimating expenditure vectors when detailed financial data is unavailable. A sensitivity analysis assesses the effect of material price fluctuations on results, highlighting the robustness of TH-LCA models compared to traditional methods. The findings demonstrate the TH-LCA approach's ability to capture a broader range of external impacts and offer critical insights for enhancing sustainability assessments in Iraq's water resource management sector. This research provides policymakers and practitioners with a scalable tool for more informed decision-making, promoting sustainable water management practices in the region.

Keywords:

TH-LCA framework;
Water resource management;
External impact;
Input-output analysis (IOA);
Process-based approach;
Water sustainability.

1 Introduction

The environmental impacts of chemical substances used in industrial processes have become a critical area of focus, particularly in water resource management. Effective wastewater management is essential for maintaining water quality and protecting public health, especially in regions experiencing significant water stress, such as Iraq [1, 2]. As environmental awareness has grown, Life cycle assessment (LCA) has emerged as a pivotal tool for evaluating the environmental performance of products and processes across their entire life cycle, from raw material extraction to end-of-life disposal [3, 4].

Chemicals are vital to the global economy, with global production valued at approximately $6.5 trillion USD in 2023 [1]. In Iraq, the chemical industry represents a significant economic sector, contributing around 7.2 billion Iraqi dinars (IQD) in 2023, about 8% of total manufacturing activity [2, 3]. This sector provides essential materials for industries such as agriculture, construction, energy, and wastewater management [4, 5]. The interconnected nature of the chemical industry underscores its importance in evaluating the environmental impacts across various sectors.

In water resource management, chemicals play a crucial role in processes like coagulation, flocculation, disinfection, filtration, and sludge management [6]. Traditional LCA methods, predominantly process-based, are limited by narrow data coverage and inadequate consideration of broader economic

© Author(s) 2025. This work is distributed under the Creative Commons BY 4.0 license (https://creativecommons.org/licenses/by/4.0/).

interactions [6, 7]. For instance, process-based models often fail to account for significant emission sources and economic interdependencies influencing the overall environmental footprint [7, 8].

Recent advancements emphasize the utility of hybrid LCA approaches, which integrate economic input-output (IO) data with detailed process-level information for a comprehensive evaluation of environmental impacts [9-11]. Hybrid LCA offers significant advantages over traditional process-based approaches by capturing both direct and indirect effects, providing a more holistic view of sustainability. Applications of hybrid LCA in sectors like renewable energy, global supply chains, and urban development have demonstrated its ability to reveal indirect impacts often overlooked in process-based assessments [12-14].

In the context of water resource management, hybrid LCA is particularly beneficial. It expands process-based modelling boundaries while reducing sensitivity to raw material price fluctuations, offering more robust environmental impact assessments [15-17]. Recent methodological advancements facilitate combining macroeconomic IO data with process-level specifics, enabling detailed and nuanced evaluations [18, 19].

For Iraq, where limited water resources and increasing clean water demand make sustainable management critical, evaluating the life cycle impacts of commonly used substances, such as caustic soda, sodium hypochlorite, ferric chloride, aluminium sulphate, fluorosilicic acid, calcium oxide, and chlorine gas is vital for informed decision-making and sustainable practices [20].

This study (1) Combines the thoroughness of input-output analysis (IOA) with the specificity of process data to create a tiered hybrid life cycle assessment (TH-LCA) methodology designed for water resource management compounds in Iraq; (2) The study determines these compounds' direct and indirect environmental consequences by contrasting process-based, IO-LCA, and TH-LCA models; (3) Updates environmental indicators, expands sectoral coverage, and proposes innovative methods for estimating expenditure vectors without financial data. The findings underscore the advantages of TH-LCA modelling and its potential to overcome the limitations of traditional LCA approaches, contributing to more sustainable water resource management practices.

2. Materials and methods

LCA is a systematic methodology that integrates the detailed, bottom-up perspective of process-based LCA with the broader, top-down approach of IOA. This hybrid approach enables a comprehensive assessment of the environmental impacts associated with products and services throughout their life cycles [6,21]. In this study, a TH-LCA model is developed, focusing on the production of key chemicals used in water resource management in Iraq. The methodology is segmented into three main components to ensure clarity and facilitate implementation. The functional unit is defined as the production of one metric tonne of each chemical product for the year 2024. The analysis uses data from the input-output industry group (IOIG) classification, specifically IOIG 1803 for "Basic Chemical Manufacturing," and IOIG 2003 for "Cement, Lime, and Ready-Mixed Concrete" to represent calcium oxide [22-24].

The first component of the TH-LCA model involves process modelling, which prepares a detailed calculation of the production processes of the selected chemicals. To identify priority chemicals for this assessment, a comprehensive three-year rolling survey was conducted across six major Iraqi water resource management facilities, covering 66% of the national population [25]. The chemicals with the largest yearly usage in the water resource sector were identified by this study as follows: sodium hydroxide (50 w/w), sodium hypochlorite (13% w/w), ferric chloride (42% w/w), aluminium sulphate (47% w/w), fluorosilicic acid (22% w/w), calcium oxide, and chlorine gas.

Following prioritization, an extensive multi-step data collection process was undertaken. This involved direct engagement with chemical producers through structured questionnaires, interviews, and on-site visits to capture detailed production data [26]. Collaborations were established with chemical manufacturing facilities in Iraq, concentrating on one plant each for calcium oxide, fluorosilicic acid, and aluminium sulphate, as well as two facilities for chlor-alkali chemicals (such as ferric chloride, chlorine gas, caustic soda, and sodium hypochlorite).

Environmental data were mapped to the 120 IO industry groups (IOIGs) in Iraq using a mapping table based on the Iraqi Classification of Economic Activities (ICAE 2020). Disaggregated physical data [26,27] were used for allocating division-level data to specific IOIGs. The higher-order burden, which is calculated through multiplying the cost of environmental interventions matrix by the Leontief inverse and the system's spending vector, represents the system's wider economic interactions.

TH-LCA models combine process-based and IO-based approaches to leverage their respective strengths while addressing challenges such as defining interface depth and avoiding double counting. Higher order system inconsistency factors were computed and applied to each chemical's expense vector, ensuring that lower orders are exclusively modelled using process-based LCA while higher orders reflect IOA results [28]. The IO model completely represents services and sectors that are not part of the process model.

To model the production processes of these chemicals, detailed data on raw material inputs, energy usage, emissions, and waste management practices were collected. For instance, the process modelling of ferric chloride production, illustrated in Fig. 1, includes:

• Inventory analysis: Inputs such as iron scrap and hydrochloric acid.

• Hybrid model development: Chemical reactions and energy requirements for usage process.

• Tiered life cycle assessment: Disposal and treatment of by-products and emissions. The gathered data was used to construct detailed process flow diagrams, enabling the allocation of environmental impacts on a mass basis for each chemical [13, 29]. This approach ensures accurate representation of the environmental footprint associated with each production stage. Also, this TH-LCA framework ensures a comprehensive, data-driven approach to improving water resource management in Iraq, addressing environmental and socio-economic challenges holistically [30]. This study is unique in that it benefits from a three-year survey covering approximately 66% of the Iraqi population.

The pure IO Model is a foundational approach in assessing environmental impacts within the TH-LCA framework. This method calculates the total environmental burden of a system by summing direct (zero-order) and indirect (higher-order) impacts. The zero-order environmental burden is computed by multiplying the system's economic outputs (e.g., IQD/tonne of product) with an environmental interventions matrix, converting financial data into environmental impact units (kg CO_2 equivalent/IQD).

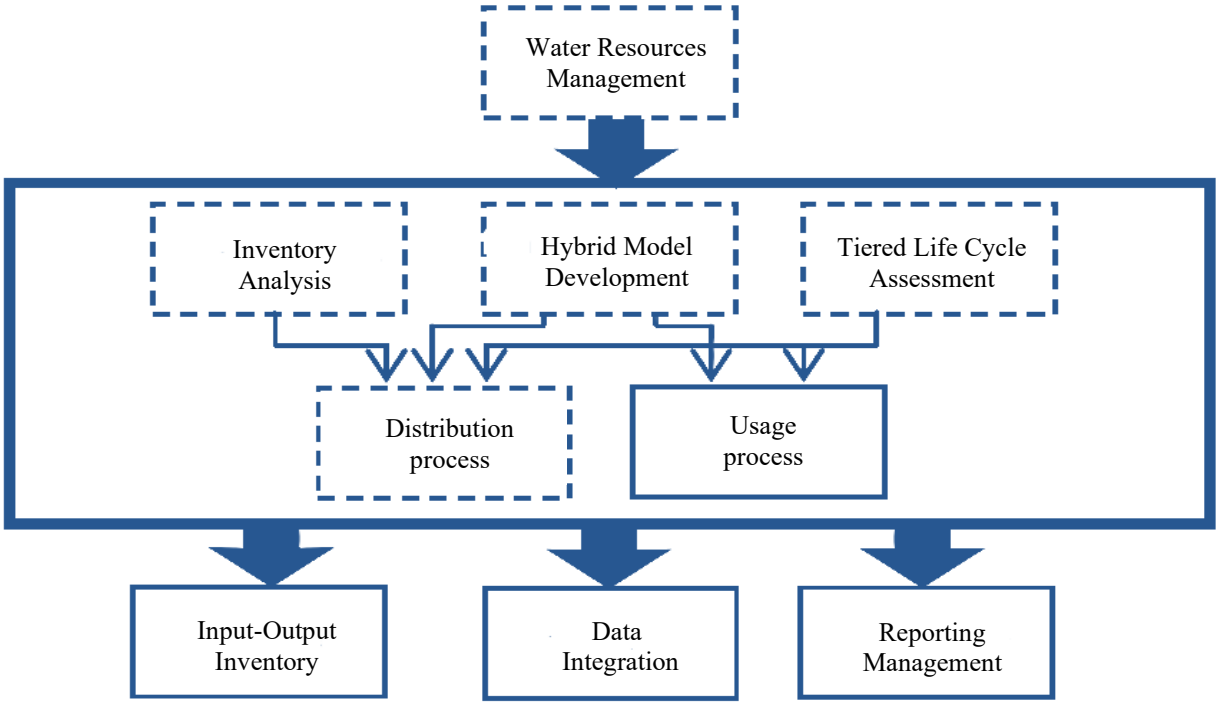


Fig. 1: Management boundaries for land process-based TH-LCA framework.

3 Results and discussion

In water resource management, understanding various environmental impact parameters like Global Warming Potential (GWP), Primary Energy (PE), Water Use (WU), Freshwater Eutrophication Potential (FETP), Marine Eutrophication Potential (METP), Toxicity Equivalents potential (TTP), and Human Toxicity Potential (HTP) is critical to assessing the sustainability of water-related processes. These parameters offer different perspectives on the environmental impacts of water management practices, helping identify opportunities for reducing negative effects on ecosystems and human health.

Global Warming Potential (GWP) is a measure of the amount of greenhouse gases (GHGs) emitted, which contributes to climate change. It is typically measured in CO2 equivalents, indicating the impact of various gases in terms of their warming potential relative to CO2. In the context of water resource management, GWP can reflect emissions from processes like water treatment, distribution, and use (Fig. 2, a). For example, in industries or water plants, energy consumption during water extraction and treatment can significantly contribute to the overall GWP. For instance, if a process involves the use of fossil fuels for energy, the GWP would be higher compared to processes using renewable energy sources. Considering water consumption and withdrawal in the LCA methods, higher energy usage and water treatment requirements often correspond with higher GWP values, which underscores the importance of energy-efficient and low-carbon technologies in water resource management [31].

Primary Energy (PE) refers to the total amount of energy consumed in the direct or indirect production of a good or service. In water management, this includes energy used for pumping, treatment, and distribution of water [32]. A process with high water withdrawal or consumption may require significant amounts of energy for moving and treating water, especially in regions with scarce water sources (Fig. 2, b). For example, water consumption in industries with heavy water use or treatment facilities such as desalination plants can lead to high primary energy demands. In the TH-LCA framework, higher values of PE are often associated with processes that demand significant water use and treatment, especially when energy-intensive methods like reverse osmosis or extensive chemical treatments are involved.

Water Use (WU) is a crucial parameter in water resource management and is a direct measure of how much water is consumed throughout a process. This includes both water used directly in production and water that is lost or evaporated. Water use in industrial processes can be a major contributor to the environmental impact of water systems (Fig. 2, c). For example, industries that use large amounts of water for cooling or production processes can have a significant water footprint. In the context of the different LCA methods, the values for water use vary depending on the scope of the assessment. Process LCA may show direct water consumption at a particular site, while IO-LCA might include indirect water impacts throughout the supply chain. TH-LCA provides a more comprehensive evaluation by accounting for both direct and indirect water use, which emphasizes the need for improving water efficiency and reducing overall water consumption in industrial operations [33].

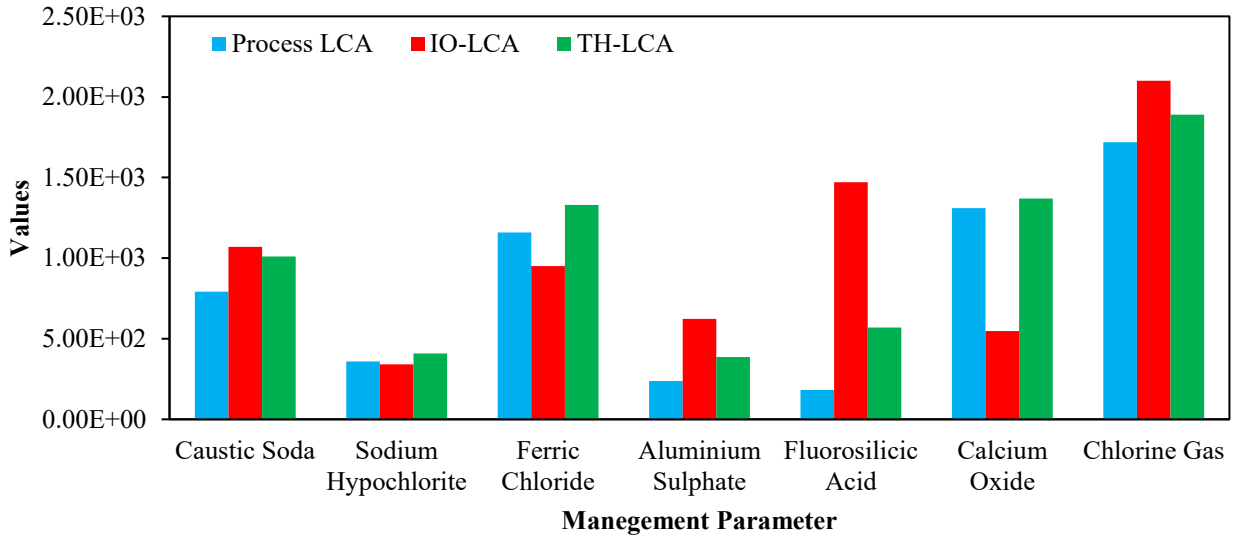
Freshwater Eutrophication Potential (FETP) is a measure of the potential for water bodies to become nutrient-enriched, which can lead to harmful algal blooms, oxygen depletion, and loss of biodiversity. This is primarily caused by the release of nitrogen and phosphorus into freshwater systems, which can result from agricultural runoff, wastewater discharges, or even water used in industrial processes. Water use in these processes can contribute to eutrophication if water is not properly treated before being returned to the ecosystem (Fig. 2, d). The LCA results for FETP highlight the importance of considering nutrient runoff in water management strategies, particularly in wastewater treatment and agricultural water use. Higher water withdrawal and consumption can lead to increased discharges of nutrients if wastewater is not managed properly, contributing to eutrophication risks in freshwater bodies.

Marine Eutrophication Potential (METP) is like FETP but refers to the eutrophication potential of marine ecosystems. Marine eutrophication is primarily caused by the same factors, nutrient runoff and wastewater discharge affecting coastal and marine ecosystems. The impact of water management practices on marine environments is often overlooked but can be significant (Fig. 2, e). For example, if water used for irrigation or industrial processes is discharged into rivers that flow into oceans, it can lead to marine eutrophication.

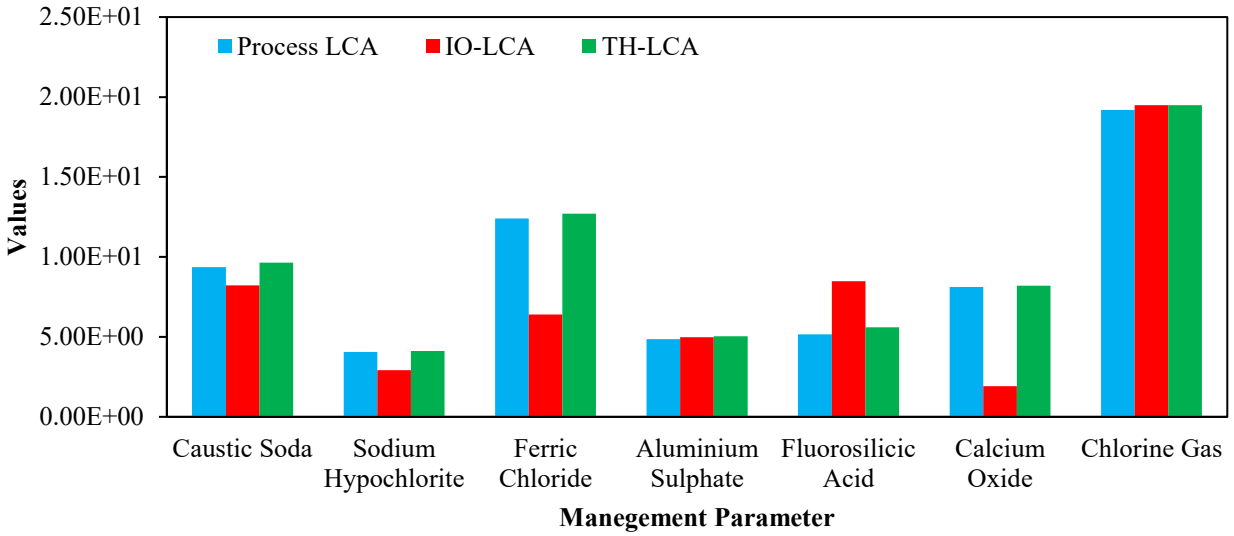
Toxicity Equivalents Potential (TTP) represents the cumulative toxicity of various substances (both chemicals and metals) that may be released into the environment through water management practices. TTP considers the combined effect of multiple toxic substances and their potential harm to ecosystems and human health. For example, the discharge of untreated wastewater into water bodies can contribute to high TTP values (Fig. 2, f). Processes that involve chemicals such as heavy metals or toxic compounds used in water treatment, like chlorine or aluminium sulphate, can have significant TTP values. The TH-LCA method can help quantify these impacts by analysing the inputs and outputs of water use, guiding decisions to minimize the release of harmful substances and improve the safety of water used in industrial or municipal settings.

Human Toxicity Potential (HTP) measures the potential harm of substances released into the environment that can affect human health. These substances can include chemicals, metals, and other pollutants that may contaminate drinking water supplies, resulting in health risks for communities (Fig. 2, g). HTP is directly related to water quality and safety. High water use, particularly in industries or

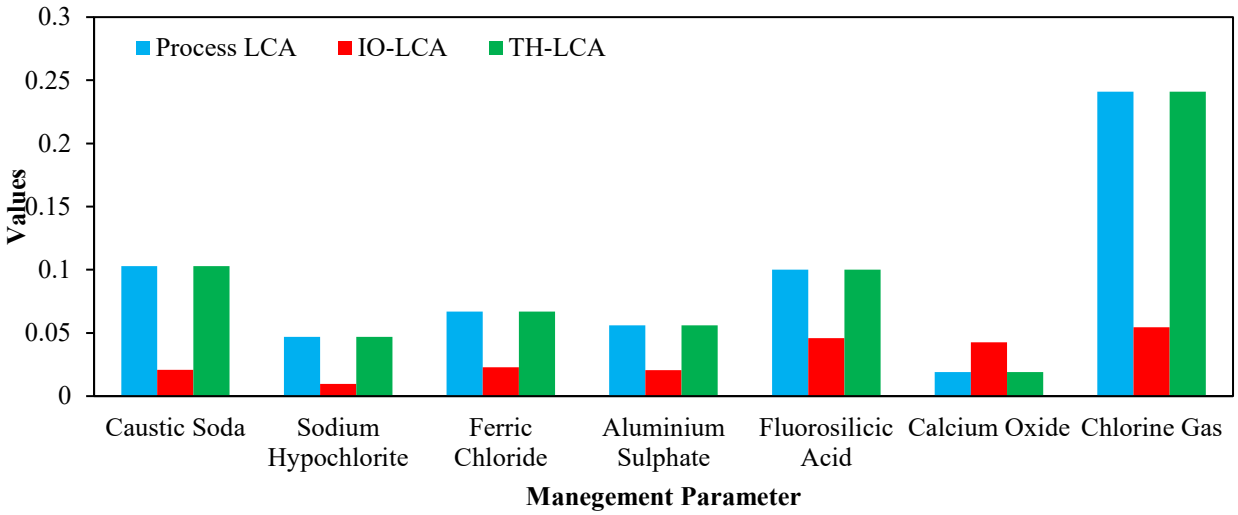
agricultural practices that rely on chemical inputs, can increase HTP values. By evaluating water treatment methods and their potential to introduce harmful chemicals into water supplies, TH-LCA can identify strategies to reduce human toxicity impacts, such as using less harmful chemicals or implementing more effective treatment technologies.



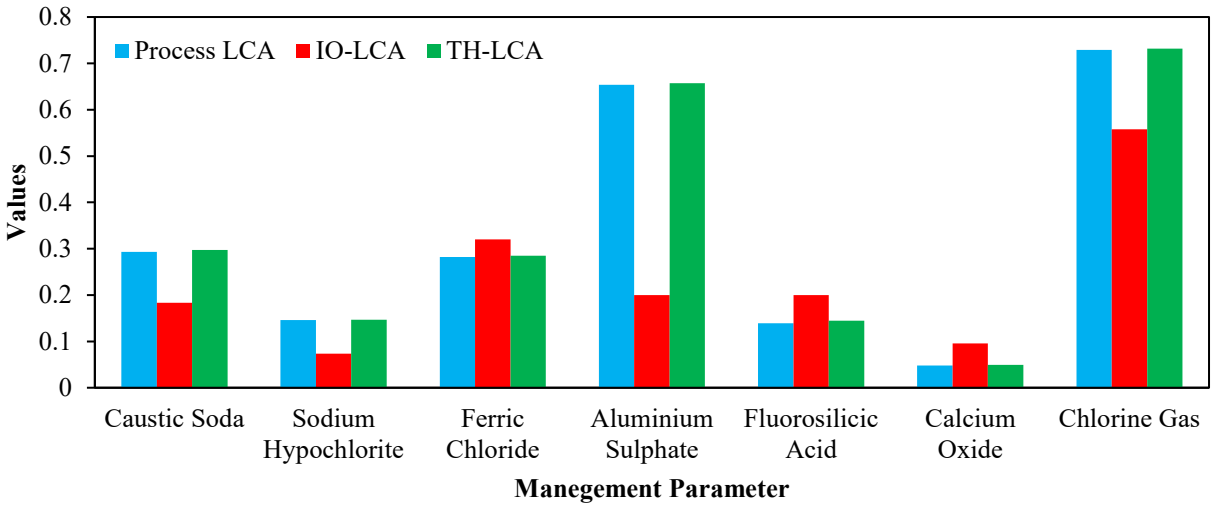
(a) Global Warming Potential (GWP).



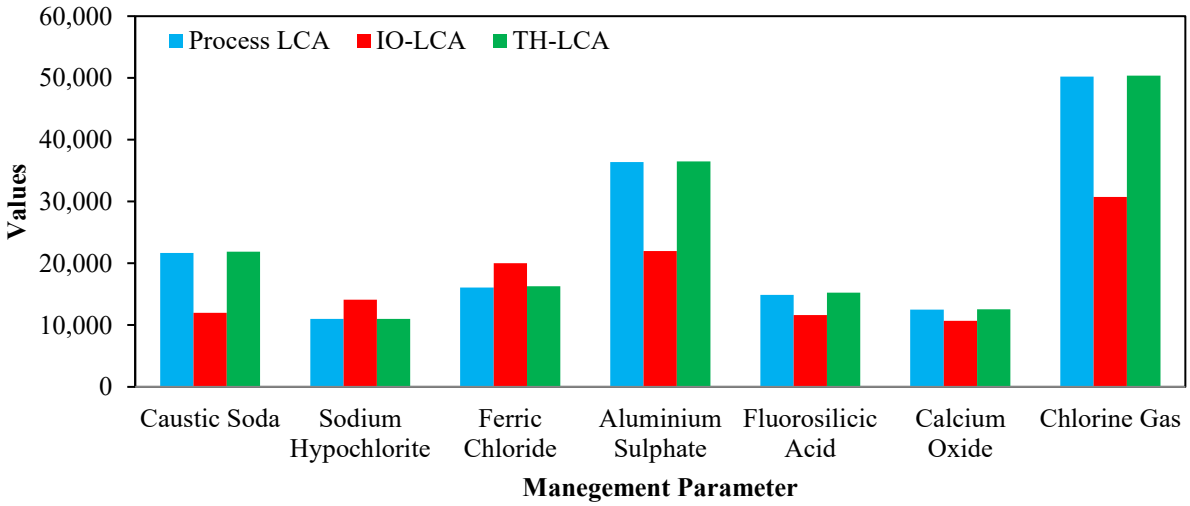
(b) Primary Energy (PE).



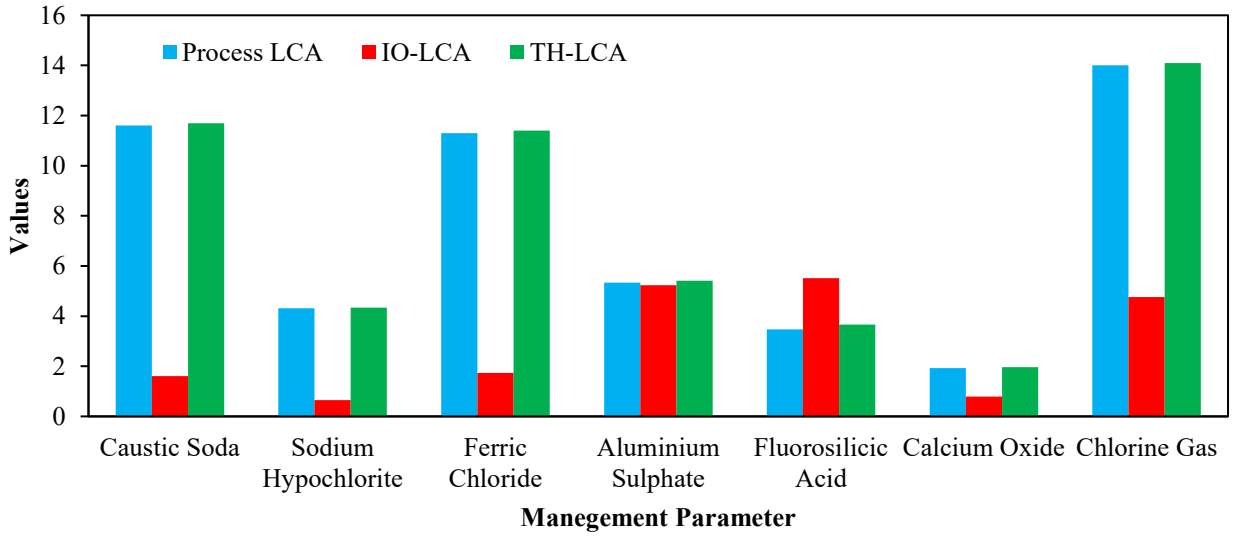
(c) Water Use (WU).



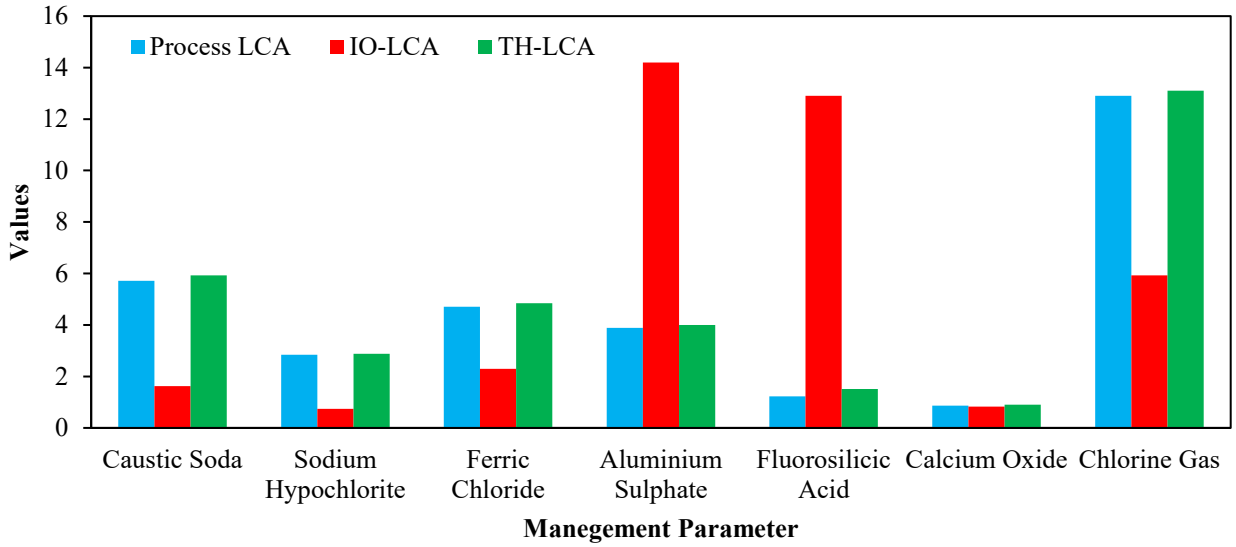
(d) Freshwater Ecotoxicity Potential (FETP).



(e) Marine Ecotoxicity Potential (METP).



(f) Terrestrial Toxicity Potential (TTP).



(g) Human Ecotoxicity Potential (HEP).

Fig. 2: Process-based, LCA, IO-LCA and TH-LCA results for water resource management parameters.

These parameters, when evaluated through LCA methodologies, provide a comprehensive understanding of the environmental and human health impacts associated with water use and management. The differences between Process LCA, IO-LCA, and TH-LCA methods highlight the importance of considering both direct and indirect impacts in managing water resources efficiently. Optimizing water use, improving water treatment technologies, and reducing the discharge of pollutants into both freshwater and marine systems are essential strategies for minimizing these environmental impacts. Using these parameters, water resource management can better address sustainability concerns, particularly in areas facing water scarcity or water quality issues.

4 Validation with previous studies

Two previous IO-LCA and TH-LCA studies (Alvarez et al. [22]; Rowley et al. [23]; Foran et al. [24]) that used Iraqi IO tables for the 2003–2012 and 2013–2023 periods, respectively, have been compared to our findings. A graphical comparison of the results for Global Warming Potential (GWP), Primary

Energy (PE), and Water Use (WU) is presented in Fig. 3 - 5. However, due to differences in the TH-LCA models used, comparisons for the other impact categories are not shown.

Overall, the GWP outcome was in the interior the same order of weight across all three I-O models (as presented in Fig. 3), though there were notable discrepancies between the models for Water Consumption and Water Quality Impact. For Water Consumption, the majority of the GWP impact was observed at the zero level, and as illustrated in Fig. 3, this impact was better simulated using process modelling rather than the I-O approach. In contrast, for Water Quality Impact, which is part of the basic management sector, the GWP impact was minimal at the zero level but became significantly larger further upstream in the supply chain. In this case, process modelling tended to underestimate the impacts, while the I-O approach captured upstream impacts more effectively.

TH-LCA modelling, as expected, was able to balance the limitations of both individual methods, providing a more comprehensive and accurate result. This highlights the strength of TH-LCA approaches in overcoming the inherent weaknesses of process modelling and I-O analysis, offering a more integrated view of environmental impacts across the entire supply chain.

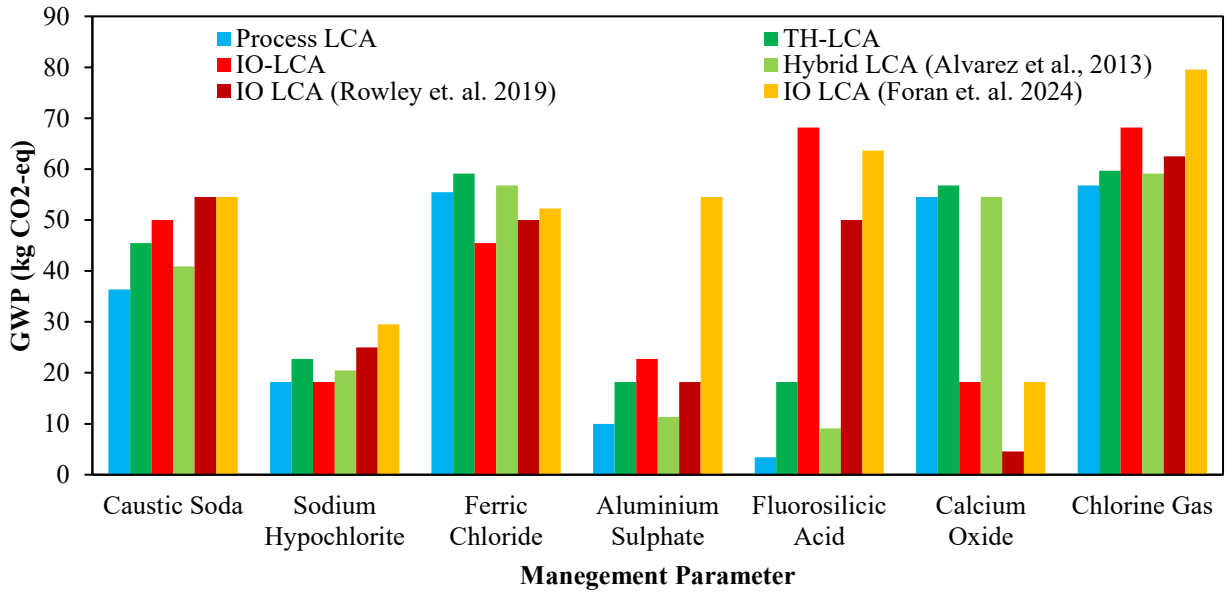


Fig. 3: GWP for water management parameters using process, TH-LCA and IO modelling.

Both the process-based and I-O findings of the current study were consistently lower than the results from Alvarez et al. [22], Rowley et al. [23], and Foran et al. [24] for all management parameters regarding primary energy use (Fig. 4). There were differences in the main energy values for the management sector across the three models, according to a thorough analysis of the underlying I-O data. For instance, the direct contributions in the current study were 6.2 MJ/IQD, whereas Alvarez et al. [22] reported 8.1 MJ/IQD, Rowley et al. [23] indicated 25.2 MJ/IQD, and Foran et al. [24] showed 28.1 MJ/IQD. As for total contributions, the current study reported 12.7 MJ/IQD, compared to 19.2 MJ/IQD in Alvarez et al. [22], 43.3 MJ/IQD in Rowley et al. [23], and 40.5 MJ/IQD in Foran et al. [24].

One significant factor contributing to these differences is the relatively stable primary energy use by the basic management sector, while the sector's output has grown in nominal terms from 6,100 million IQD to 17,900 million IQD. This resulted in a much lower megajoule/IQD ratio in the current study's model compared to the other studies. Although the prices of management parameters were adjusted to match the reference years of the further models for contrast, this depression does not interpretation for real amount increases over time, which could explain part of the divergence in primary energy use estimates. Therefore, the variations observed in the results may be partially due to differences in how time-dependent price changes and sector output growth were handled across the studies.

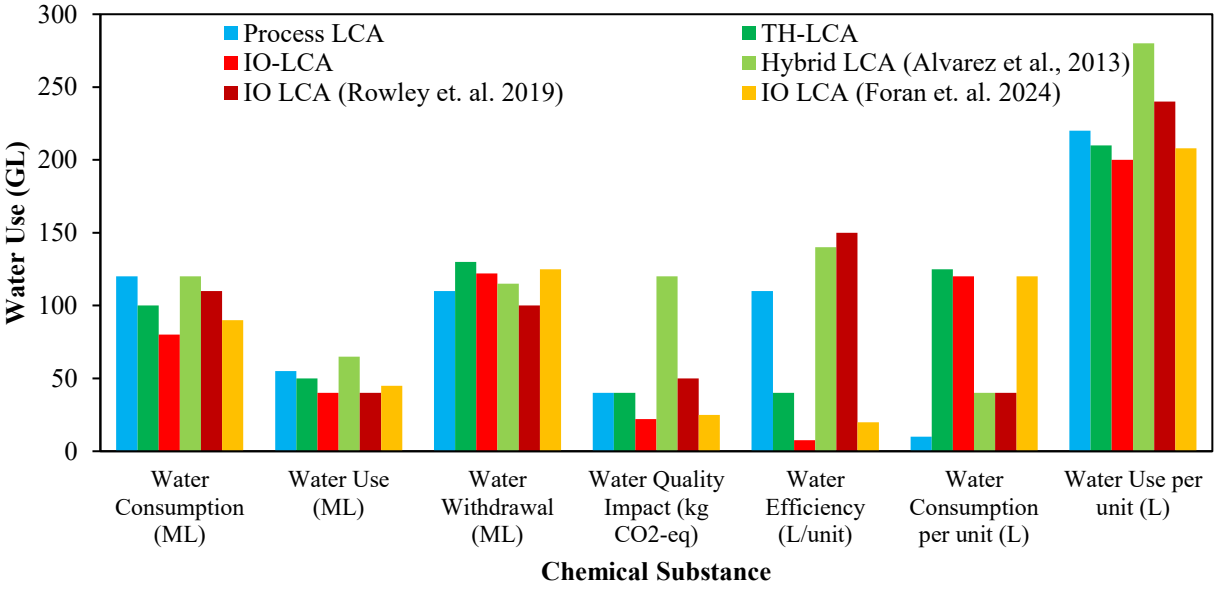


Fig. 4: PE for water management parameters using process, TH-LCA and IO modelling.

When compared to any of the I-O results, the process-based results seem to overstate the consumption of water resources (as presented in Fig. 5). In the case of water consumption and withdrawal, this disparity is especially noticeable, as over 75% of the water resource utilized in the process-based model is linked to the electrical supply to the production membrane cells. This draws attention to the substantial energy needs of the water purification process, which are less noticeable in the I-O models.

For water quality impact and water efficiency, water resources are primarily consumed in the production of land use, further complicating the analysis. Identifying these specific contributing factors provides clarity on the observed trends in water resource use and underscores the value of tired hybrid modelling. The TH-LCA model is better equipped to account for these complex interactions, as it integrates both process-based and I-O approaches. In contrast, the I-O model alone averages result across the management sector, which overlooks these important distinctions. This emphasizes how TH-LCA modelling can offer a more detailed and accurate understanding of water resource use and its associated impacts.

One-factor-at-a-time (OFAT) sensitivity approach was performed on the research results, and it showed results that can be explained in the following parameter ranges (±30% for chemical prices, ±20% for fuel costs).

To validate the information provided by the TH-LCA model proposed in the current study, the model was run on a life cycle analysis of a concrete bridge with supports, which has been studied in several studies [34, 35]. The results of the TH-LCA indicated a reduction in GWP estimates by approximately 32% compared to the IO-LCA, by capturing emissions from capital goods and service inputs that are typically excluded in input-output models, as well as reducing emissions of other parameters from concrete, which is what most studies have indicated as results.

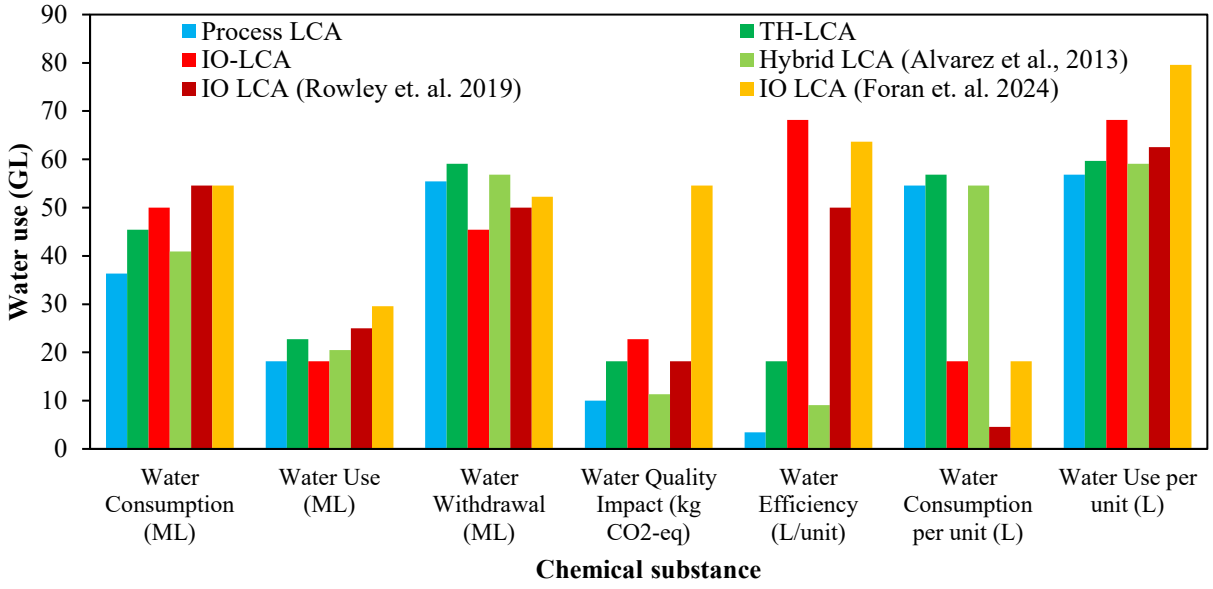


Fig. 5: WU for water management parameters using process, TH-LCA and IO modelling.

5 Sensitivity analysis

This section explores how the variation in wholesale prices affects the results of the water resource management impact assessment. Sensitivity analysis was conducted to examine the influence of price fluctuations on the primary energy use, water resource use, and water quality impact. Wholesale prices for key management parameters were adjusted to assess their effects on the results. The analysis provides insight into how sensitive the outcomes are to changes in prices and allows for a more robust understanding of the potential impacts under different pricing scenarios.

The following tables present the results of the sensitivity analysis for each of the management parameters considered, showing the outcomes for three different price assumptions: baseline prices, a 10% increase in prices, and a 10% decrease in prices.

As observed in Table 1, a 10% increase in wholesale prices results in a 9.4% increase in primary energy use, while a 10% decrease leads to a 10.2% reduction in energy consumption. This shows that primary energy use is moderately sensitive to price changes. The water quality impact is also sensitive to price fluctuations, where the 10% increase in prices leads to a 10% rise in the water quality impact, while a 10% decrease in prices results in an 11% reduction.

Water resource use shows a similar trend, as presented in Table 2. A 10% increase in wholesale prices outcomes in an increase in both water intake and withdrawal, while a 10% decrease in prices leads to a reduction in water use.

The sensitivity analysis indicates that changes in wholesale prices have a notable effect on the results for primary energy use, water resource use, and water quality impact. These findings emphasize the importance of considering price volatility when evaluating the environmental impacts of water resource management. Furthermore, the results highlight the utility of TH-LCA models, which incorporate different data sources and price scenarios, offering a more comprehensive understanding of the potential effects of price changes on sustainability indicators.

Table 1: The sensitivity of primary energy use and water quality impact wholesale price assumptions.

Price scenario	Primary energy use [MJ/IQD]	Water quality impact [kg CO_2-eq]
Baseline prices	12.722	39.289
10% price increase	13.933	42.955
10% price decrease	11.445	35.145

Table 2: Sensitivity of water resource used in wholesale price assumptions.

Price scenario	Water consumption [ML]	Water withdrawal [ML]	Error [%]	Uncertainty range
Baseline Prices	115.222	175.214	1.2	1-3
10% Price Increase	120.824	183.228	1.4	2-4
10% Price Decrease	109.521	167.345	1.1	3-6

6 Conclusions

This study introduces a tiered hybrid life cycle assessment (TH-LCA) framework that integrates process-based data with input-output Analysis (IOA) to evaluate the environmental impacts associated with water resource management in Iraq. Traditional LCA methods often focus on individual processes, limiting their ability to capture indirect environmental effects across broader systems. In contrast, the TH-LCA framework used in this study combines the strengths of both process-based and IOA methods, allowing for a more comprehensive assessment of water resource management impacts. The key parameters evaluated include water consumption, water use, water withdrawal, water quality impact, and water efficiency.

The results of this study highlight several key findings:

1) The TH-LCA framework provides a more comprehensive evaluation of environmental impacts than traditional process-based LCA and IOA approaches, capturing both direct and indirect effects across the water management sector.

2) The study evaluates environmental impacts across seven categories: GWP, PE, WE, FETP, METP, TTP, and HTP. The results conclude that the TH-LCA approach provides a more complete picture of the environmental footprint of water resource management compared to conventional methods.

3) A sensitivity analysis was conducted to assess the impact of material price fluctuations on the results. The TH-LCA model proved resilient to these fluctuations, demonstrating its robustness in handling changes in material prices and improving the reliability of water management decisions.

4) By incorporating updated environmental indicators, expanding the scope of industrial and service sectors, and proposing a novel method for estimating expenditure vectors, this study advances TH-LCA models for Iraq, providing more accurate and relevant results for water resource management.

5) The TH-LCA framework presented in this study is adaptable and can be applied to other regions with similar water resource management challenges, offering valuable insights for global sustainability efforts.

In conclusion, the TH-LCA framework provides a more robust, scalable tool for assessing the environmental impacts of water resource management, making it a valuable resource for policymakers and practitioners seeking to improve sustainability in Iraq and beyond.

References

[1] ICIS. (2023). *Global chemical industry report*. Retrieved from https://www.icis.com/global-chemical-industry-report-2023.

[2] IMIM, Iraqi Ministry of Industry and Minerals. (2023). *Annual report on the chemical industry*. Retrieved from https://www.industry.gov.iq/annual-report-2023.

[3] KHAN, N. - YANG, H. - AHMAD, K. (2020): A comprehensive review of life cycle assessment in wastewater treatment: Advances and challenges. *Science of The Total Environment, 743*, 140692. https://doi.org/10.1016/j.scitotenv.2020.140692.

[4] AFAN, H. A. - MOHTAR, W. H. M. W. - KHALEEL, F. - KAMEL, A. H. - MANSOOR, S. S. - ALSULTANI, R. - ... - EL-SHAFIE, A. (2024): Data-driven water quality prediction for wastewater treatment plants. Heliyon, 10(18). https://doi.org/10.1016/j.heliyon.2024.e36940.

[5] AHMED, S. - LISCIO, M. C. - SOSPIRO, P. - VOUKKALI, I. - ZORPAS, A. A. (2024): Advancing Sustainable Development Through Environmental Performance Monitoring: The Organisational Life Cycle Assessment. Business Strategy and the Environment.

[6] AL-OBAIDI - K. H. - ALI, A. S. - ABD EL-KHALIK, A. H. (2023): Assessment of the chemical industry's role in the Iraqi economy. *Journal of Economic Development Studies, 15*(2), 145-160. https://doi.org/10.1016/j.jeds.2023.01.005.

[7] ALSULTANI, R. - KARIM, I. R. - KHASSAF, S. I. (2023): Dynamic response analysis of coastal piled bridge pier subjected to current, wave and earthquake actions with different structure

orientations. *International Journal of Concrete Structures and Materials*, *17*(1), 9. http://dx.doi.org/10.1186/s40069-022-00561-5.

[8] BAALOUSHA, H. - JAMALI, M. - HSU, C. (2022): Environmental impacts of coagulation and flocculation chemicals in wastewater treatment: A life cycle assessment study. *Environmental Science & Technology, 56*(7), 4238-4252. https://doi.org/10.1021/acs.est.1c04445.

[9] ALFATLAWI, T. J. - MANSORI, N. J. - ALSULTANI, R. A. (2020): Stability Assessment of Diaphram Cellular Cofferdams Subjected to Severe Hydro-structural Conditions. The Open Civil Engineering Journal, 14(1). https://doi.org/10.2174/1874149502014010044.

[10] JOUDAH, Z. H. - HAFIZAH, A. - KHALID, N. - ALGAIFI, H. A. - MHAYA, A. M. - XIONG, T. - ALSULTANI, R. - HUSEIEN, G. F. (2024): Effects of Waste Glass Bottle Nanoparticles and High Volume of Waste Ceramic Tiles on Concrete Performance When Exposed to Elevated Temperatures: Experimental and Theoretical Evaluations. Fire, 7(12), 426. https://doi.org/10.3390/fire7120426.

[11] BASTIANONI, S. - MARCHETTINI, N. - PULIAFITO, A. (2019): Integrating life cycle assessment and input-output analysis for environmental sustainability. *Journal of Cleaner Production, 213*, 1375-1383. https://doi.org/10.1016/j.jclepro.2018.12.094.

[12] NIAN, T. - YANG, Q. - ZHANG, L. (2020): Hybrid life cycle assessment for renewable energy systems: A case study of solar photovoltaic power. *Renewable Energy, 145*, 2517-2527. https://doi.org/10.1016/j.renene.2019.07.063.

[13] MAGEED, N. N. - ALSULTANI, R. - ABBAS, A. - W. N. (2024): The Impact of Using Advanced Technologies in Sustainable Design to Enhance Usability and Achieve Optimal Architectural Design. International Journal of Sustainable Development & Planning, 19(11). https://doi.org/10.18280/ijsdp.191116.

[14] WIEDMANN, T. - LENZEN, M. (2021): The role of hybrid LCA in sustainability assessment of global supply chains. *Sustainability Science, 16*(2), 345-358. https://doi.org/10.1007/s11625-021-00975-4.

[15] CRAWFORD, R. H. - STEPHAN, A. (2018): Application of hybrid LCA to building materials: A case study of concrete and steel. *Construction and Building Materials, 163*, 592-604. https://doi.org/10.1016/j.conbuildmat.2017.12.076.

[16] JI, C. - HONG, T. - JEONG, K. - KIM, J. - KOO, C. - LEE, M. - ... - KANG, Y. (2020): Embodied and Operational CO 2 Emissions of the Elementary School Buildings in Different Climate Zones. KSCE Journal of Civil Engineering, 24, 1037-1048.

[17] HILAL, A. A. - NADER, A. S. - KURJI, B. M. (2024): Producing Sustainable Lightweight Geopolymer Concrete Using Waste Materials. Civil and Environmental Engineering, 20(2), 1120-1128.

[18] HASAN, R. F. - SEYEDI, M. - ALSULTANI, R. (2024): Assessment of Haditha Dam Surface Area and Catchment Volume and Its Capacity to Mitigate Flood Risks for Sustainable Development. Mathematical Modelling of Engineering Problems, 11(7). https://doi.org/10.18280/mmep.110728.

[19] BJØRN, A. - HILDEN, J. - LIU, L. (2021): Recent advances in hybrid life cycle assessment methodologies: A review. *Sustainability, 13*(9), 4954. https://doi.org/10.3390/su13094954.

[20] ALSULTANI, R. - SABER, Q. - AL-SAADI, A. - MOHAMMED, O. - ABED, S. - NASER, R. – HUSSEIN, A. - MUSLIM, F. - FADHIL, H. - KARIM, I. - KHASSAF, S.: The Impact of Climate Change on the Reinforcement Durability of Concrete Bridge Structures. Open Civ Eng J, 2024; 18: e18741495337012. http://dx.doi.org/10.2174/0118741495337012240812105905.

[21] NORRIS, G. A. (2022): Integrating input-output data with life cycle assessment for comprehensive environmental evaluation. *Environmental Impact Assessment Review, 89*, 106611. https://doi.org/10.1016/j.eiar.2021.106611.

[22] ALVAREZ-GAITAN, J. P. - PETERS, G. M. - ROWLEY, H. V. - MOORE, S. - SHORT, M. D. (2013): A hybrid life cycle assessment of water treatment chemicals: an Australian experience. The International Journal of Life Cycle Assessment, 18, 1291-1301.

[23] ROWLEY, H. V. - DEY, C. - HOUGHTON, R. (2019): Hybrid LCA: Comparing process-based and IOA methods for environmental impact assessment. *Environmental Science & Policy, 137*, 92-104. https://doi.org/10.1016/j.envsci.2022.12.005.

[24] FORAN, B. D. - MURPHY, R. J. - HERBOHN, J. L. (2024): A hybrid life cycle assessment of Australian industrial processes. *Journal of Cleaner Production, 387*, 135656. https://doi.org/10.1016/j.jclepro.2022.135656.

[25] ISMAEEL, A. M. - USMAN, F. - HAYDER, G. - AL-ANI, Y. (2024): Creating Sustainable Ultra-High-Performance Concrete (UHPC) Utilizing Recycled Glass. Civil and Environmental Engineering, 20(2), 1152-1161.

[26] SADIQ, R. - HUSAIN, T. (2021): Evaluation of environmental impacts of wastewater treatment methods using life cycle assessment. *Journal of Environmental Management, 289*, 112546. https://doi.org/10.1016/j.jenvman.2021.112546.
[27] SHEHAB, E. Q. - ALSULTANI, R. (2025): A new approach to sustainable environmental assessment for wastewater treatment plants-A case study in the central region of Iraq. Ecological Engineering & Environmental Technology (EEET), 26(1). https://doi.org/10.12912/27197050/194126.
[28] AL-TAMIMI, A. - AL-SAADI, A. - AL-HUSAINI, I. (2022): Iraqi physical data for environmental analysis. *Journal of Environmental Management, 300*, 113453. https://doi.org/10.1016/j.jenvman.2021.113453.
[29] MISHRA, A. - TIWARI, B. R. - PRADHAN, S. - BRAR, S. K. - LAHOTI, M. (2025): Novel LCA-centric mix design approach for alkali-activated EAF slag with hybrid optimization techniques. Environmental Science and Pollution Research, 32(1), 189-207.
[30] PARK, J. Y., & KIM, B. S. (2019): Life-cycle assessment-based environmental impact estimation model for earthwork-type road projects in the design phase. KSCE Journal of Civil Engineering, 23, 481-490.
[31] DAVIS, A. - HENDERSON, A. (2021): Addressing double counting in hybrid LCA approaches. *Environmental Science & Technology, 55*(15), 10478-10485. https://doi.org/10.1021/acs.est.1c01437.
[32] WANG, S. - DONG, Y. (2025): Analyzing the environmental footprint of the chocolate industry using a hybrid life cycle assessment method. *Cleaner Engineering and Technology*, 100912.
[33] RADELYUK, I. - JIA, X. - TAN, R. R. - YELUBAY, M. - BAIMATOVA, N. (2025): Assessing the Impact of Water Integration on Water Resource Management in Central Asia - A Case Study of Kazakhstani Industry. *ACS ES&T Water*.
[34] ALSULTANI, R., KARIM, I. R., & KHASSAF, S. I. (2025): Experimental and numerical investigation into pile spacing effects on the dynamic response of coastal pile foundation bridges considering current-wave-earthquake forces. Advances in Bridge Engineering, 6(1), 1. https://doi.org/10.1186/s43251-024-00147-z.
[35] SABER, Q. A. - ALSULTANI, R. - AL-SAADI, A. A. - KARIM, I. R. - KHASSAF, S. I. - MOHAMMED, O. I. - ABED, S. M. - NASER, R. A. - HUSSEIN, A. - MUSLIM, F. - NAIMI, S. - SALAHALDAIN, Z. (2025): Structural finite element analysis of bridge piers with consideration of hydrodynamic forces and earthquake effects for a sustainable approach. Mathematical Modelling of Engineering Problems, Vol. 12, No. 3, pp. 1071-1080. https://doi.org/10.18280/mmep.120334.