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Towards Environmentally Sustainable Water Management in Iraq: A Review of Life Cycle Assessment Studies for Water Treatment Plants with Identification of Critical Cases

Mustafa Abdulameer[1], Ahmed Samir Naje[2,*], K. Pradeep[3], K. Saranya[4]

[1,2]Department of Water Resources Engineering Management, College of Engineering, Al-Qasim Green University, Al-Qasim, Babylon, Iraq.
[3]Department of Petroleum Engineering, Dhaanish Ahmed College of Engineering, Chennai, Tamil Nadu, India.
[4]Department of Earth and Environmental Sciences, Indian Institute of Science (IISc), Bengaluru, Karnataka, India.
mustafaabd957@gmail.com[1], ahmednamesamir@gmail.com[2], kpradeep@dhaanishchennai.in[3], saranyak@iisc.ac.in[4]

*Corresponding author

Abstract: The main purpose of water treatment is to give customers access to high-quality drinking water. Making drinking water from fresh surface water requires several steps, consumes energy, and uses chemicals, all of which affect ecosystems worldwide. When choosing how to treat water, it's crucial to consider these factors. This paper provides an overview of different types of water treatment and the plants that perform them. This study also examines how well environmental analysis methods perform in determining whether water treatment plants affect the ecosystems around them. Following this, a detailed overview of the fundamentals of Life Cycle Assessment (LCA) will be provided. The last part of the study will outline how life cycle assessment (LCA) can be applied to water systems. At the end of the paper, there is a summary of how LCA can be used in water systems. To sum up, researchers discussed a comprehensive review of this investigation and the problems encountered in the current study's contribution.

Keywords: Environmentally Sustainable; Water Management; Life Cycle Assessment (LCA); Water Treatment Plant (WTP); Weighted Arithmetic Method; Environmental Analysis.

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1. Introduction

Because many nations face water shortages that hinder social and economic growth, water is becoming a more pressing global issue. This subsection starts by elucidating the supply and demand of water in Iraq [32]. To close this gap, several important tactics have been outlined [3]. Lastly, a succinct overview of the global water treatment situation is provided. Through evaporation, condensation, precipitation, and transpiration, water moves through the Earth and its atmosphere in a continuous, intricate cycle known as the natural water cycle [4]. The water cycle comprises the collection of water in watersheds, its use, and its eventual return to the natural water cycle as clean water [5]. When water is gathered from natural systems such as rivers, dams, wells, or canals and supplied to homes via pipes, the water cycle begins [12]. In many nations, drinking water treatment

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facilities use a combination of chemical and physical processes to treat collected water initially [17]. After treatment, the water is sent to communities via the distribution network, where it is used for domestic purposes, industrial processes, garden irrigation, and other uses [28]. Following use, the now-contaminated water, also referred to as wastewater, is collected and sent via the sewer system to a treatment facility, where solids, organics, pathogens, and nutrients are removed through physical and biological treatment processes before the wastewater is released into receiving bodies of water [30]; [24]; [31]. This study aims to present and describe the concept of water treatment plant life-cycle assessment in general and how it can be applied in Iraq (Figure 1).

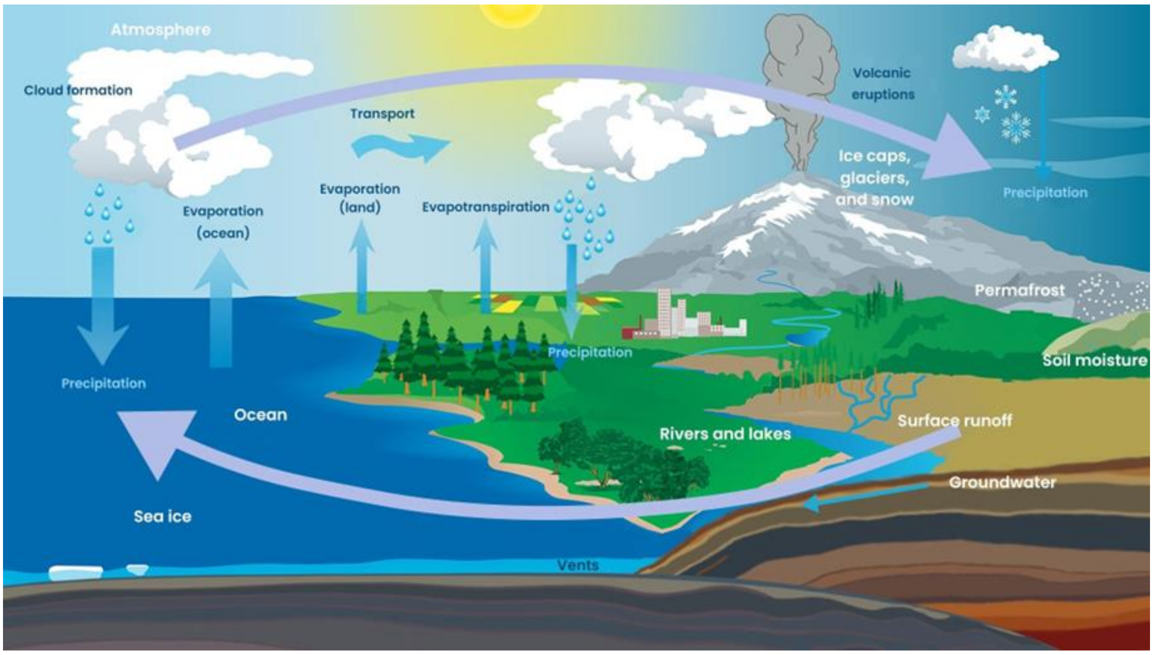


Figure 1: Urban water cycle

2. Unit of Processing in Water Treatment Plants

Life requires water, and everyone must have access to a sufficient, secure, and safe supply. To safeguard human health, improving the quality of drinking water is a top global priority. The public's awareness of and discrimination against drinking water quality have increased over the past few decades, along with the severity of water quality regulations. Water for human consumption is defined as "all water, whether in its original state or after treatment, intended for drinking, cooking, food preparation or other domestic purposes, regardless of its source" by European Directive 98/83/CE on drinking water quality. This definition applies regardless of whether the water is supplied from a distribution network, a carrier, or in bottles or containers. This regulation outlines the microbiological, chemical, and sensory factors that comprise drinking water quality requirements. Water has to be treated and/or treated to meet the precise goals and requirements outlined in the rule. Even if tap water meets regulatory requirements, most European nations have seen a growing trend in recent years to switch from tap to bottled water. Two primary reasons impact consumer preferences and are responsible for the rising usage of bottled water: (1) Dissatisfaction with the flavour and other sensory aspects of tap water; and (2) Health-related concerns.

Coagulation, flocculation, sedimentation, filtration, adsorption, and disinfection are steps in the conventional water treatment process. These physicochemical processes eliminate turbidity, organic debris, and pathogens. Reverse osmosis may also be used to improve water quality by using membranes to remove dissolved materials. Reverse osmosis is now accessible in homes and is mostly used to treat drinking and cooking water. This is due to technological advancements. Reverse osmosis at home enhances the sensory qualities and purity of water, which might boost consumer trust in tap water. Moreover, it can reduce the negative environmental impacts of bottled water. Because the bottle production process requires significant energy and resources, it is commonly believed that the bottled water business has a detrimental impact on the environment. For a very long time, only glass bottles were used to package bottled water; nowadays, polyethene terephthalate is commonly used. Accordingly, the manufacture of bottles, their transportation, and the removal of solid waste resulting from packaging are responsible for the greatest effects.

Even for highly energy-intensive drinking water treatment technologies (such as reverse osmosis), tap water from conventional treatment has consistently demonstrated the best environmental performance, according to prior studies comparing the environmental impacts of tap water and bottled water. Fallah et al. [30]; Tarpani et al. [31]; Usman et al. [32]. As far as researchers are aware, no research has been conducted to compare home RO systems with treatment plants, conventional water treatment systems, or bottled mineral water. In addition to removing harmful compounds and natural organic matter, water treatment also preserves the visual quality of the water and guards against corrosion and recontamination of the distribution network. Physical and chemical procedures, including coagulation, flocculation, sedimentation, granular filtration, and chemical disinfection, make up the majority of conventional water treatment systems. The water sector has recently adopted UV disinfection and pressure-activated membranes more and more [2]. Since membrane operations primarily require energy to filter water, they offer an appealing alternative to traditional methods (Figure 2).

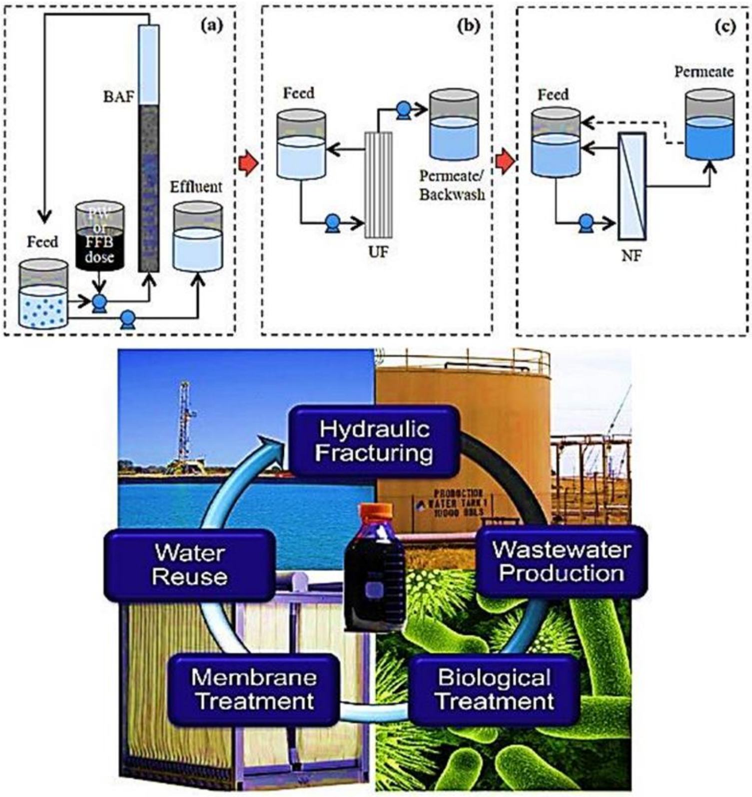


Figure 2: Membrane processes [1]

Generally speaking, the most important factors in determining the "best" water treatment system are the financial and technological limitations. However, the depletion of natural resources and the indirect release of pollutants into water, land, and air through the use of chemicals and energy consumption are the most prevalent environmental consequences that the water treatment business may be accountable for on a worldwide scale. There is currently limited knowledge of these effects, particularly regarding Iraq and novel water-treatment methods such as membranes.

2.1. Environmental Analysis Tools

Water treatment facilities have a significant influence on the environment during construction and operation, even if they treat water before releasing it back into receiving bodies of water and remove contaminants. These days, there are several approaches for evaluating the potential environmental impacts of specific technologies, products, communities, and manufacturing processes. To identify potential environmental impacts resulting from commodity processing plants, researchers have used a variety of environmental analysis tools, including Material Flow Analysis (MFA), Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), and Life Cycle Assessment (LCA). An overview of the aforementioned techniques is provided in Amaryllis et al. [7].

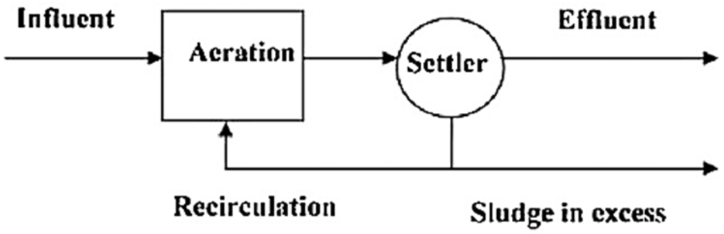
2.2. Basic Concepts of LAC

The environmental impacts of water treatment systems can be assessed using life-cycle assessment (LCA). A "cradle to grave" method is used in life cycle assessment (LCA) to evaluate potential worldwide environmental harm from a product, process, or service [11]. According to McNamara et al. [20], there are four essential steps in conducting a life cycle assessment: defining the objective, scope, and functional units; creating a life cycle inventory (LCI); evaluating the life cycle impact assessment (LCIA); and creating a life cycle interpretation. LCA is a useful tool for comparing and analysing systems or processes based on their environmental impacts. One crucial aspect that enables fair comparison of systems using life cycle assessment (LCA) is the definition of a functional unit. A life cycle inventory (LCI) is a flowchart that includes every step necessary to manufacture, ship, use, and discard the designated product. For any important process, the inflows (raw materials, energy, other processes, etc.) and outflows (emissions, wastewater, etc.) are provided.

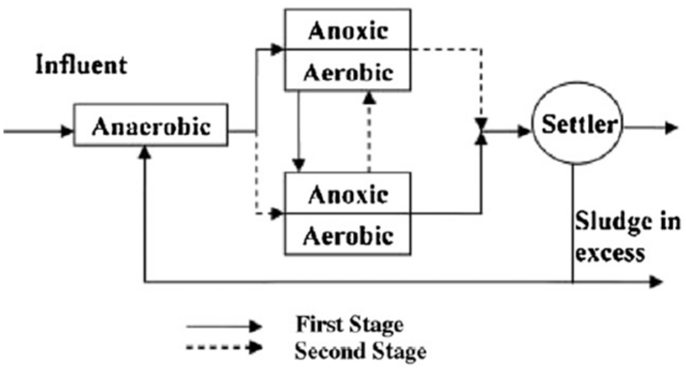
2.3. History of LCA

According to Corominas et al. [10], life cycle assessment (LCA) is a method used to assess the effects of a process, product, or service at every step of its life cycle, or "from cradle to grave." Numerous industries and products, including combined-cycle power plants, solid waste disposal, the fishing industry, the construction industry, and artichoke production, have been the subject of life-cycle assessment studies [27]; [7]. Numerous life-cycle assessment (LCA) studies have been conducted to assess the environmental impacts of wastewater treatment plants [8]. LCA assesses the environmental impacts of inputs and outputs, including resource depletion and climate change. Software such as GaBi or SimaPro must be used to conduct a life cycle assessment [9]. Numerous inventory databases (such as the US Life Cycle Inventory Database, Ecoinvent, and European Reference Life Cycle Data System) and impact assessment techniques (such as Impact 2002+, Traci, and Ecoindicator) are commonly included in these software solutions [14]. Databases must often be modified for use in different contexts because they are predominantly built in the European setting [16]; [23]. The fact that many of the water treatment procedures are not included in current databases is another significant obstacle [19].

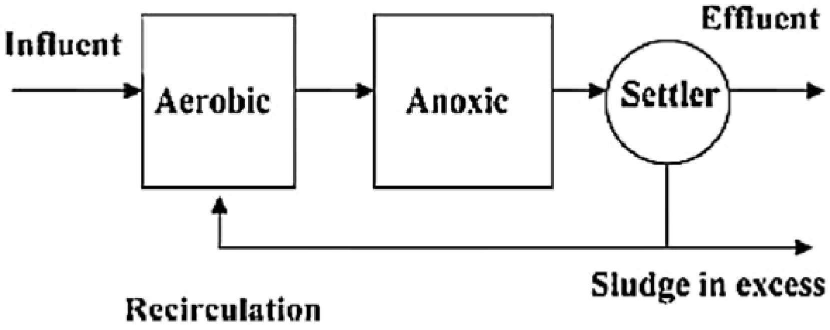
This might make it more difficult to perform effective LCA water treatment. Ortiz [22] demonstrated how LCA performs better than other techniques in many areas by comparing various environmental analysis tools. The most complete and integrated technique for addressing all upstream and downstream consequences associated with WTP projects is Life Cycle Assessment (LCA), a step-by-step approach guided by ISO standards. Houillon and Jolliet [15] conducted an LCA study to compare six wastewater sludge treatment scenarios applied to a wastewater treatment plant serving 300,000 residents, with an emphasis on energy and emissions that contribute to global warming throughout the overall life cycle of treatment. The study used average data obtained from wastewater treatment plants in France and Switzerland. The findings indicated that the least amount of non-renewable primary energy is consumed in agriculture during sawing and burning. Gallego et al. [13] used life-cycle assessment (LCA) to compare the environmental performance of 13 wastewater treatment plants serving small communities in Galicia, northwest Spain. The results indicated that extended aeration had a lower environmental impact than biodynevo and anoxic aerobic treatment, two secondary treatment techniques (Figure 3).



(a) Extended Aeration



(b) Biodenipho Treatment



(c) Aerobic-Anoxic Treatment

Figure 3: Secondary treatments available at the WWTPs [13]

Applying life cycle analysis (LCA) to a water treatment facility in Xi'an, China, Zhang et al. [33] demonstrated that the advantages of recycling treated wastewater outweighed the energy consumption during the process. In a Spanish wastewater treatment facility in the Mediterranean, Pasqualino et al. [24] used life cycle assessment (LCA) to examine several urban wastewater reclamation and reuse options (Figure 4). They observed that substituting potable water saves 1.1 cubic meters of fresh water, while substituting desalinated water saves substantial energy.

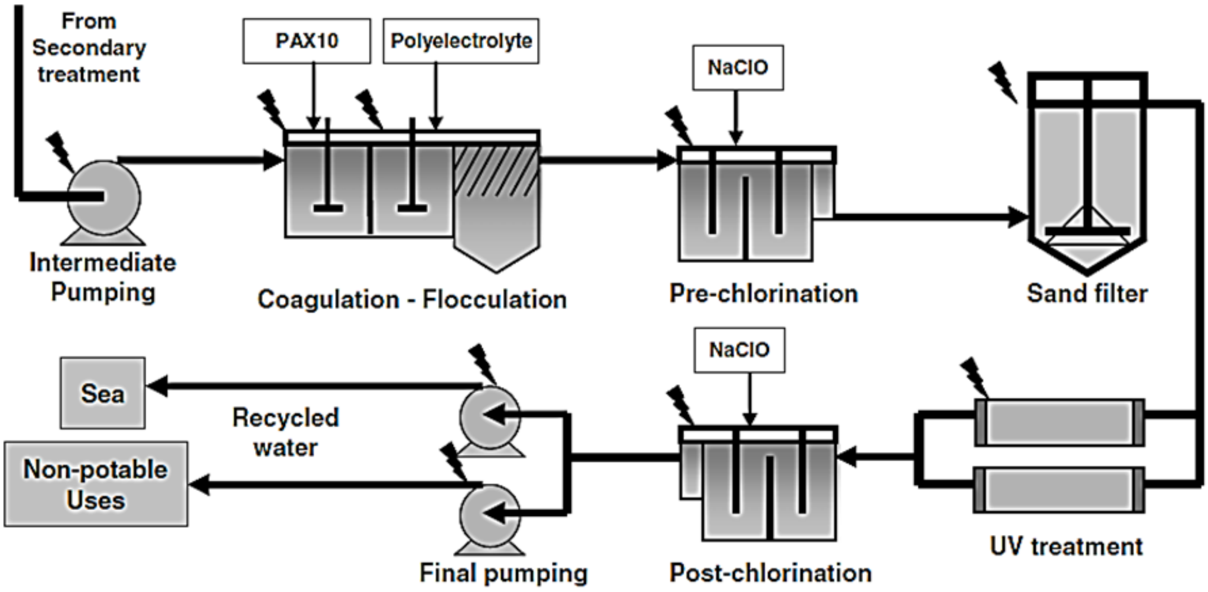


Figure 4: Flow diagram for the operation of the tertiary treatment of a wastewater treatment plant [23]

In a water treatment facility in China, Corominas et al. [10] assessed the environmental impacts of water treatment using life-cycle assessment (LCA). Their study's objective was to compare this water treatment plant's environmental advantages and disadvantages to those of other water treatment plants that used various advanced treatment units.

In a separate study, the environmental costs of two plants differing in size and location were examined. The findings demonstrated that the two main factors influencing the environmental effects of wastewater treatment are energy use and the use of sludge for agricultural purposes [20]. Remy et al. [26] used life-cycle assessment (LCA) to compare the environmental impacts of several tertiary wastewater treatment systems (Figure 5).

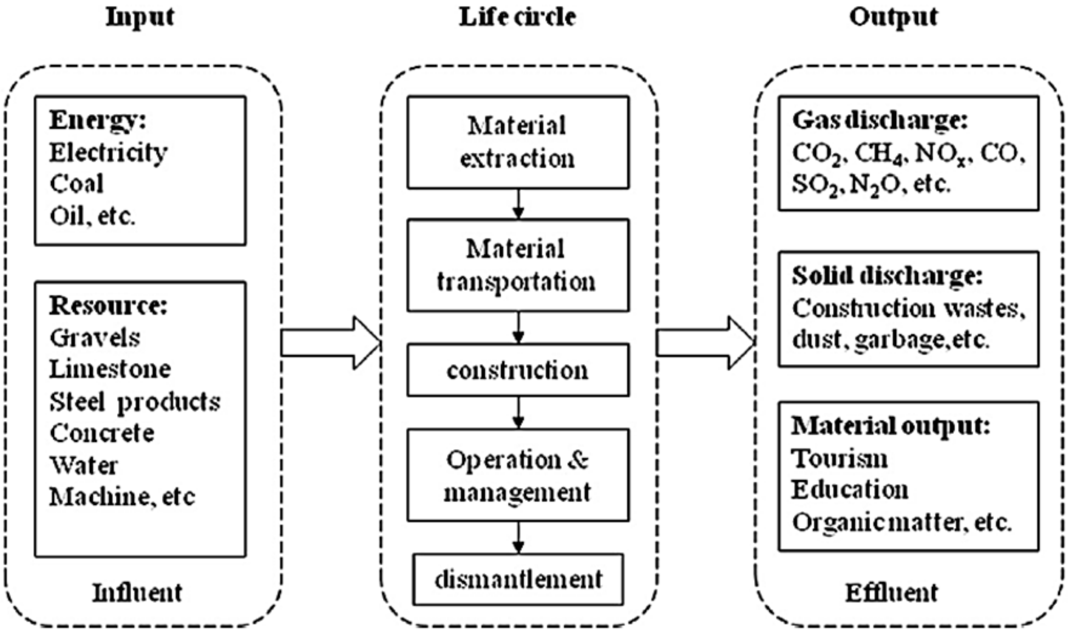


Figure 5: Scope of the LCA of GCW [18]

The results are displayed in Figure 6. According to them, life cycle assessment is a useful tool for assessing the direct and indirect environmental impacts of tertiary processing.

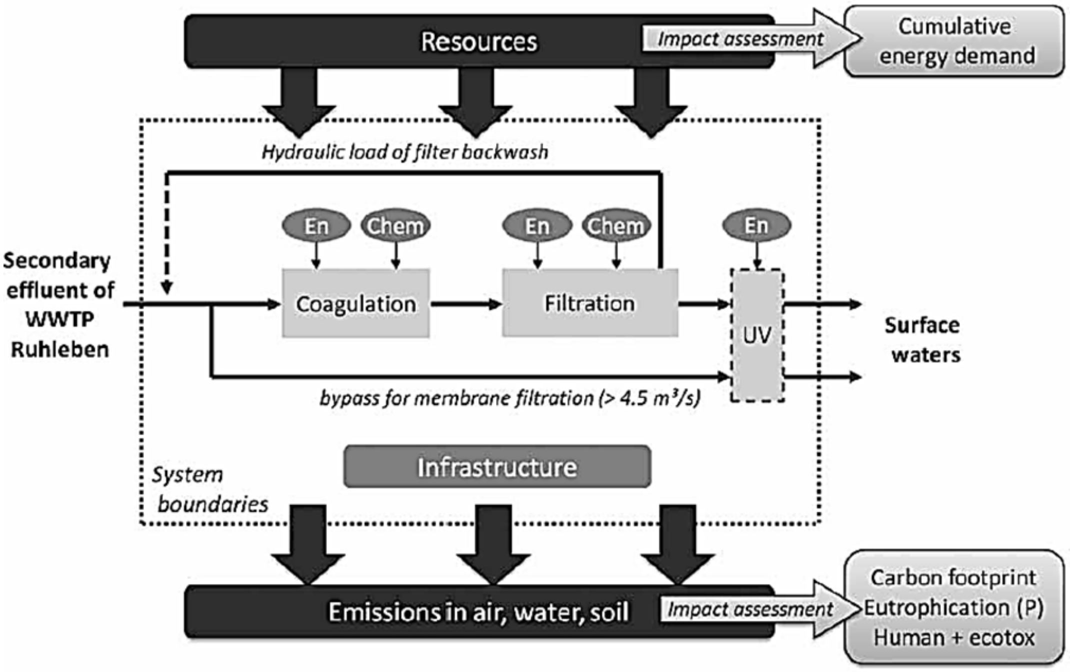


Figure 6: System boundaries for LCA (En: Energy, Chem: Chemicals, Final UV disinfection or bypass depending on treatment technology) [26]

Additionally, Sapkota [29] found that the configuration of treatment units affected environmental performance by analysing small-scale decentralised water treatment units; this suggests that the more units there are, the higher the environmental load during the construction phase. On the other hand, adding more units, modules, or processing stages will improve system performance and reduce the system's overall environmental impact (Figure 7).

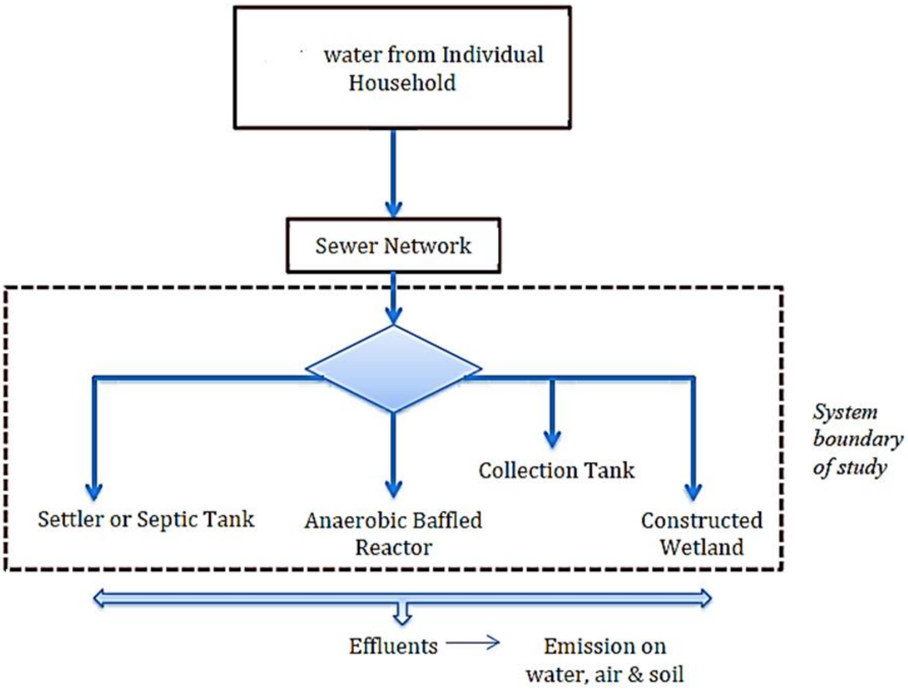


Figure 7: General system boundaries of the study [29]

An LCA assessment of an existing wastewater treatment facility on an Indian university campus was conducted by Raghuvanshi et al. [25]. They utilised the Eco-invent v3.0 database with LCA Umberto NXT Universal software. The outcomes showed that the evaluated groups benefited from recycled water from the station. Additionally, across other categories such as particle matter creation, terrestrial ecotoxicological potential, and global warming potential, the treatment system's consequences are considerably greater than those of recycled water. Note that their research did not account for the environmental effects of the compost produced by the system or the social repercussions of untreated wastewater (Figure 8).

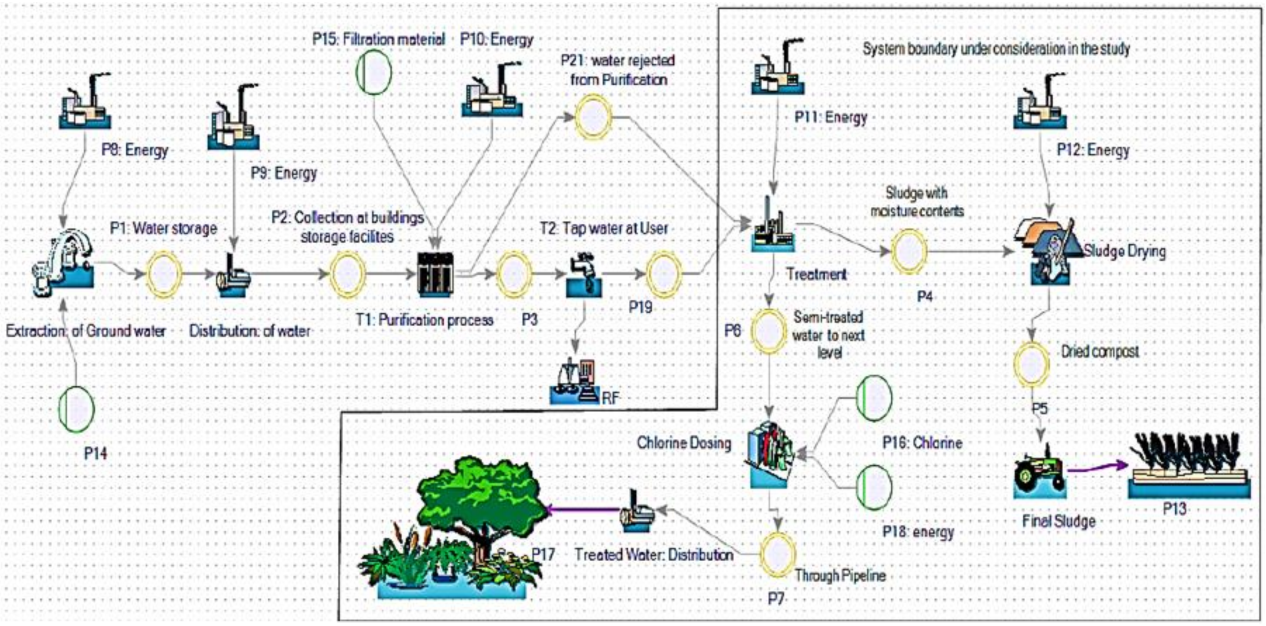


Figure 8: Water supply and sewage treatment process with the system boundary of the study [25]

On an Indian university campus, Raghuvanshi et al. [25] recently conducted an LCA of an existing wastewater treatment facility. Using the Ecoinvent v3.0 database, they employed the LCA Umberto NXT Universal software. The findings demonstrated the benefits of the station's recycled water on the groups under evaluation. In addition, the treatment system's impacts on other categories, such as particulate matter generation, terrestrial ecotoxicological potential, and global warming potential, far exceed those of recycled water. Remarkably, their research did not include the environmental effects of the compost generated by the system, nor the social effects of untreated wastewater (Figure 8). Using life cycle assessment (LCA), Morelli and Cashman [21] investigated options to modernise a New York wastewater treatment facility while recovering energy for heating and electricity, nutrients for fertiliser, and water for irrigation. The findings demonstrated that a 20–30% increase in global warming, particulate matter production, smog formation, fossil fuel depletion, and acidification potential is associated with improved effluent quality. Additionally, the percentage of incoming carbon and nitrogen lost as greenhouse gases during end-of-life therapy affects potential greenhouse impacts. Water-related LCA research is mostly conducted in industrialised nations, with very little involvement from developing nations. The 2015 scholarly publication by Al-Anbari et al. is one of the few investigations on LCA in poor nations. They examined the environmental impacts of the wastewater treatment facility in Hilla (Figures 9 and 10). For this, the SimaPro software suite was utilised.

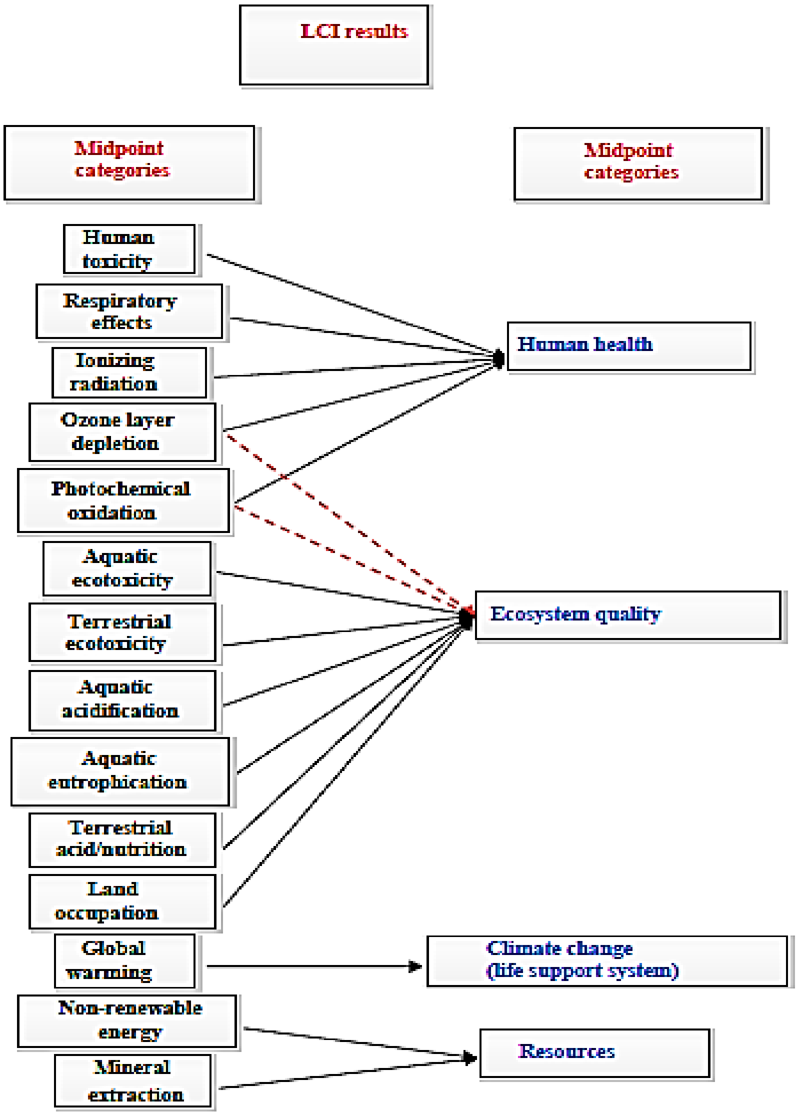


Figure 9: Overall scheme of the IMPACT 2002+ framework, linking LCI results via the midpoint categories to damage categories [4]

The findings indicated that non-renewable energy, inorganic respiratory chemicals, and global warming are responsible for the majority of environmental effects. Furthermore, the use of steel, cement, and electricity has even greater detrimental consequences for the environment.

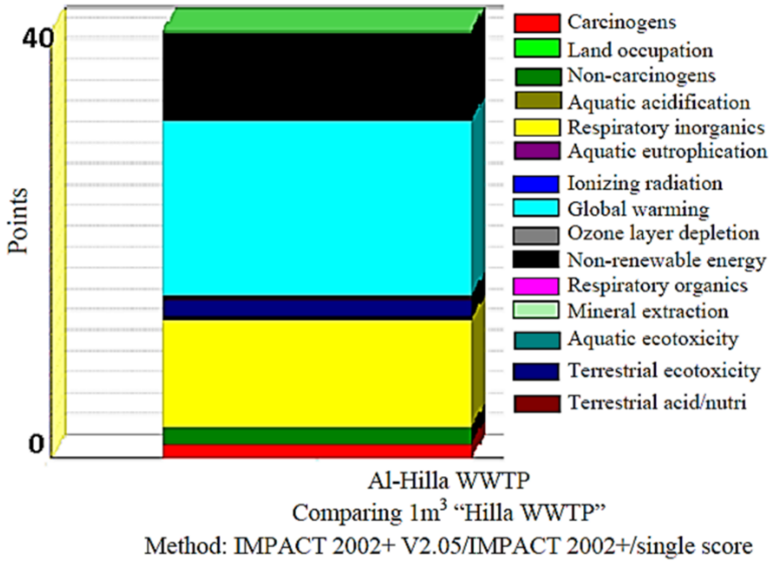


Figure 10: Global eco-score of damage categories [4]

An overview of the use of life cycle assessment (LCA) for wastewater was provided by Ahmed [2], who also discussed the challenges associated with its use in underdeveloped nations. The following are the primary barriers to using LCA in poor nations:

- Policy makers are not well informed about the advantages of this instrument.
- Industry and government lack internal capability, and fundamental data is not easily available.
- Ensuring quality.
- The need for relevant effect categories.
- A lack of coordination among local LCA specialists.

Iraq is one of the emerging nations with a deficiency of operational water treatment facilities. Efficient water treatment plants help around 40% of Iraq's entire population. Approximately 30 million people are served by these plants, and less than 40% of the total domestic sludge is fully treated. Seepage pits have been the most common means of disposing of wastewater in most Iraqi cities for the past few decades, contaminating the aquifer and soil. The primary reason for the current acceleration in the construction of contemporary wastewater collection and treatment systems in Iranian cities is the rise in groundwater contamination in cities like Tehran. Life cycle assessment studies conducted on Iraqi water treatment plants are entirely novel, as the country's domestic water treatment business is not unique. Urban water managers in Iraq are particularly interested in the environmental impacts of water treatment facilities throughout their life cycles. Consequently, life cycle assessment (LCA) can serve as a useful decision-making tool by providing insights into the advantages and disadvantages of various options for reusing household wastewater.

2.4. LC Impact Assessment (Impact Assessment Methodology and Impact Assessment Categories)

Classification and characterisation are required aspects in the third phase of an LCA research, but normalisation and weighting are optional, according to the ISO standard.

2.4.1. Classification and Characterisation

The majority of LCA studies for water have advanced to the effect assessment phase from the inventory stage. Of the 45 studies reviewed, 26 reported the impact evaluation methodology applied: 1 EPS, 2 Ecopoint 97, 1 ReCiPe, 7 EDIP 97, 3 Eco-indicator 99, and 19 selected CML studies. The remaining references did not specify the selected approach or the mix of agents utilised for profiling. To the best of our knowledge, only three studies, Ortiz [22], Cooper et al. [9], and Al-Anbari et al. [6], have looked at the potential impact of selecting one of the currently available LCIA methodologies on LCA outcomes. Three techniques were employed in Ortiz's [22] study to evaluate life-cycle effects. In contrast to the findings from CML 2000, the results for EcoScore97 and EcoIndex99 were highly comparable, despite this issue not being specifically discussed in that study. According to research by Tarpani et al. [31], the chosen technique for effect assessment is not crucial for impact categories such as resource depletion, eutrophication, acidification, or global warming because the outcomes are similar.

Significant differences were nonetheless observed in human toxicity, as reported earlier by Zhang et al. [39], who compared nine approaches for determining how metals affect human health.

Al-Anbari et al. [6] assessed the quality of the environmental categorisation acquired for four MBRs by contrasting three impact assessment techniques. The primary distinctions between the four effect categories (eutrophication, acidification, terrestrial and freshwater ecotoxicity) were discovered in relation to eutrophication potential. These disparities were caused by the varying weights assigned by various impact assessment techniques to P-related emissions. The potential for eutrophication, acidification, and global warming were the indicators that attracted the most attention within the set of impact categories evaluated (rated 38, 27, and 28 out of 45 studies, respectively). Subsequently, the concerns were photochemical oxidation (17 studies) and toxicity-related features (18 human toxicity studies, 17 terrestrial ecotoxicity studies, 15 freshwater ecotoxicity studies, and only 9 marine ecotoxicity research). When assessing sludge disposal possibilities and accounting for heavy metals or micropollutants, terrestrial ecotoxicology was crucial. Lastly, as only 14 and 20 publications, respectively, evaluated ozone depletion and abiotic depletion (including fossil energy and material depletion), it was determined that these factors were not significant in the decision-making processes of these studies.

2.4.2. Normalisation and Weighting

In 18 of the analysed studies, normalisation, which enables comparison of all environmental factors on an equal scale, was applied. Regional and international datasets (e.g., PE, 1990s Denmark; SCB, Statistics Sweden; EU15 World 1994; Western Europe 90s) provided the normalisation factors. Just five studies employed weighting, a technique for combining indicator data across many effect categories into a single indicator. The rationale is that determining the relative environmental sustainability of a set of design options is less important to decision-making than assigning weights based on subjective value judgments. The EPS method weighted the environment. theme and scarcity of the environment, a hierarchical perspective with a weighing of the environment. Indicator 99, using the weights offered by the CML methodology 2001, or decision makers using a cardinal or ordinal scale based on their preferences or the importance of various attributes, were the approaches employed in the five studies to calculate the weights.

2.5. Challenges

The constraints of current procedures restrict the validity of the outcomes of the evaluated investigations. As research advances, some results could be proven false (e.g., by adding more contaminants, discovering new factors to assess possible consequences, accounting for the particular characteristics of the local environment, environmental dynamics, or other time horizons). LCA users are aware of the unsolved problems with this analytical technique. The purpose of this work is to identify the difficulties LCA methodology faces when used in WWT, rather than to fix them.

2.5.1. Use of LCA to Address the Change of Paradigm in Wastewater Treatment

The objectives of surface water treatment facilities must transcend safeguarding the health of people and surface waters to include reducing resource loss, limiting energy and water use, minimising waste output, and protecting the environment in light of the long-term requirements of environmental sustainability. recycling of nutrients. A paradigm shift has occurred from waste to resource recovery and water reuse, which may be effectively managed through Life Cycle Assessment (LCA) during the development phase of new technologies or throughout their full-scale implementation.

2.5.2. Adaptation of LCA Methodologies to New Target Compounds

Heavy metals and priority pollutants are the major subjects of developments in toxicity-related impact categories. Life-cycle techniques are being revised to incorporate the influence of PPs on ecotoxicology, despite significant gaps in knowledge about their impacts on human health. To determine more practical parameters for heavy metal release into soil, research is required. More study is required to precisely identify the quantities (bioavailable percentages) and amounts of heavy metals that plants and crops efficiently absorb, as the actual levels of their persistence in the environment are quite high. As leachate, it is moved to a new stage. Moreover, the most recent research has taken into account organic micropollutants. When it comes to sludge disposal, heavy metals continue to outweigh organic micropollutants. This is also true of wastewater treatment plant effluents, where micropollutants greatly increase the toxicity to aquatic life. USEtox is perhaps the finest practice technique available right now for ecotoxicology and human toxicity. a consensus model created as part of the UNEP/SETAC Life Cycle Initiative by a group of LCIA method developers. Because heavy metals in soil can more easily be transferred to crops and from there to humans, either directly or through meat and milk, USEtox believes that all metals (apart from nickel) are more dangerous to human health when released into soil than when released into fresh water. A greater understanding of the environmental implications of micropollutants would come from full life-cycle assessment studies that measure their fate not only in wastewater but also in excess sludge and sludge treatment.

3. Conclusion

Life cycle thinking is a broad approach that looks at all the effects a product or service has on the environment, the economy, and society over its entire life cycle, from the extraction of raw materials to production, use, and final disposal. Life Cycle Assessment (LCA) has become a well-established field in the last 27 years in the context of water treatment. Since 1995, many studies have used LCA methods to assess the environmental performance of various water treatment systems worldwide. A thorough analysis of these studies reveals considerable discrepancies in methodological frameworks, especially in the delineation of functional units and system boundaries. There are significant differences in how impact assessment methodologies are chosen and how results are interpreted. These variations persist even with standardised rules, showing how hard it is to get studies to agree on everything. This kind of heterogeneity might make it hard to compare and trust the results, hindering generalisations and the adoption of best practices on a larger scale. So, it is important to establish uniform, standardised rules in the water treatment industry to ensure that LCA methods are used correctly and of high quality. The current study aims to assess and enhance the environmental performance of the Al-Hashimiya water treatment station to address this necessity. The study evaluates operational efficiency while also analysing raw and processed water quality metrics. This research presents a newly defined functional unit spanning 25 months, from March 2023 to March 2025, to facilitate a more precise, context-specific evaluation, enabling a detailed, temporally constrained review of system performance and environmental implications.

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Ethics and Consent Statement: This study was carried out in accordance with established ethical standards. Necessary permissions were obtained from relevant institutions, and informed consent was secured from all participants involved in data collection where applicable.

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