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Life Cycle Assessment of Wastewater Treatment Plants in Saudi Arabia

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Abstract:

Saudi Arabia is a water-scare nation with high population growth rate. Agriculture accounts for 80% of total water usage in Saudi Arabia [1]. Climate change is expected to have a significant impact on water availability, particularly in arid regions [1,2]. The discharge of untreated wastewater results in the pollution of surface water, soil, and groundwater as well as pose risks to human health [3]. As part of Vision 2030, Saudi Arabia has prioritized wastewater management as a strategic response to regional water scarcity, targeting near-total reuse of treated urban wastewater. Membrane Bioreactors (MBRs) offers several advantages over Activated sludge processes like excellent effluent quality and lower environmental footprint. However, MBRs have several drawbacks, like membrane fouling and high energy consumption [4]. In this study, Life Cycle Assessment is used to evaluate the environmental performance of Activated sludge treatment plant(s) to Membrane Bioreactors systems.

Introduction:

Water scarcity is the small volumetric abundance of water for human use [1]. The Kingdom of Saudi Arabia is classified by the United Nations as water-scare nation [1] where it's the largest country without any rivers [7]. Saudi has higher than average annual rate of population growth (2.5%), which increase the water requirement by 8.8%. [1]. KSA heavily relies on desalination and non-renewable groundwater resources to meet the daily water requirements [7]. Agricultural sector is the largest consumer of water in Saudi; consuming more than 80% [1] of total water demands and it heavily relies on non-renewable groundwater [7]. Climate change is going to have significant impact on water availability, especially in arid and semi-arid regions [1,2] Rising temperatures and changes in precipitation intensity, annual totals, and seasonal distribution as well as changes in atmospheric water vapor and soil moisture, are projected to increase agricultural evapotranspiration. Consequently, this will significantly impact irrigation water requirements [2].

The discharge of untreated or inadequately treated wastewater can lead to the pollution and degradation of receiving water bodies, soil, and groundwater, thereby affecting the aquatic ecosystems [8]. Municipal wastewater contains a wide range of contaminants, such as pathogenic microorganisms, nutrients, organic matter, heavy metals and emerging pollutants. The release of these contaminants can lead to adverse human health effects [8]. Diseases caused by bacteria, viruses, and protozoa are the most common health hazards associated with untreated drinking and recreational waters. Wastewater treatment aims to reduce the biodegradable organic matter and nutrients in the environment, eliminate the pathogens, as well as recycling of water [3].

Wastewater (WW) reclamation has become a critical focus area in the Kingdom of Saudi Arabia, driven by rapidly increasing urban water demand and the pressing need to conserve scarce freshwater resources [9]. As part of Vision 2030, the Kingdom has prioritized wastewater management as a strategic response to regional water scarcity,

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targeting near-total reuse of treated urban wastewater. To this end, substantial investment has been directed toward expanding sewage networks and treatment facilities nationwide, enabling reclaimed water to be repurposed for agriculture, industrial processes, and urban landscaping [10]. Wastewater treatment specially for water scare countries like Saudi Arabia can reduce their dependence on groundwater and desalination [11]. Wastewater treatment and recycling minimize the pollution released into the environment which lower the environmental footprint of water management making water use more sustainable and eco-friendly [11]. Using treated wastewater for agriculture can reduce the use of untreated or saline water, which often results in soil degradation and land erosion. This approach also provides a sustainable and reliable source for agriculture which enhances food security [11]. In conclusion, wastewater recycling offers multiple benefits, like saving water resources, supporting agricultural needs, and enhancing water resilience [11].

Since the development of modern sanitation systems, large-scale municipal wastewater treatment has been predominantly based on the aerobic activated sludge (AS) process. In this system, microorganisms biologically degrade dissolved organic matter and nutrients present in wastewater, converting them into insoluble biomass (activated sludge) and gaseous by-products such as CO_2 and N_2. The resulting activated sludge is then separated from the treated effluent through gravitational settling in a conventional clarifier [12].

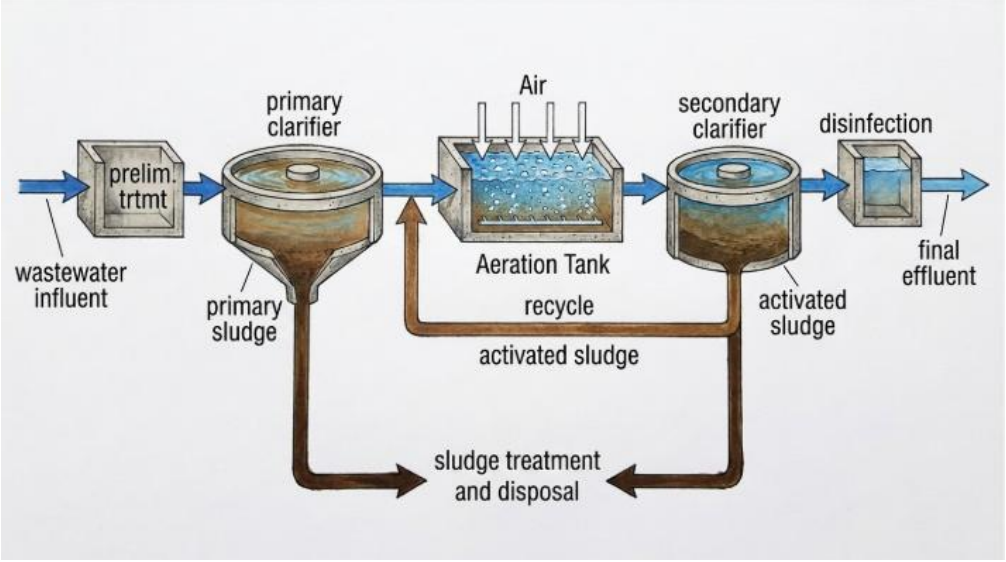


Figure [1]: Conventional Activated Sludge Process

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Extending the aeration period is a typical example of the modifications of the activated sludge process s, which was explored through local experience and found beneficial under diverse conditions [13]. The main difference between Conventional Activated Sludge (CAS) and Extended Aeration Activated Sludge (EA-AS) is the absence of a primary clarifier in the EA-AS process. Instead, employs a longer hydraulic retention time and solids retention time in the aeration tank, allowing settleable and suspended organic matter entering with the influent to undergo biological oxidation together with the dissolved and fine suspended organic matter. This extended aeration also promotes greater stabilization of the biomass and reduces the amount of primary sludge generated compared with CAS [14].

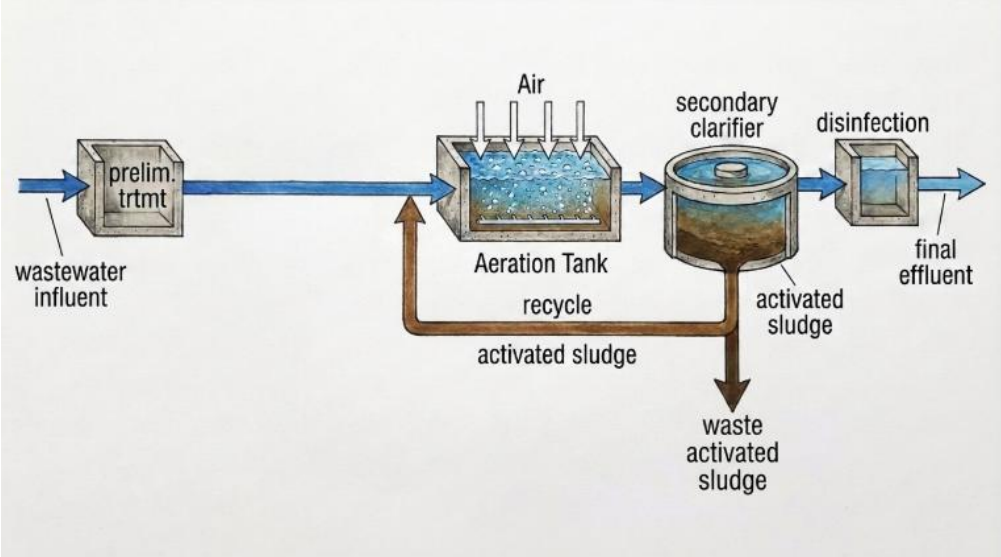
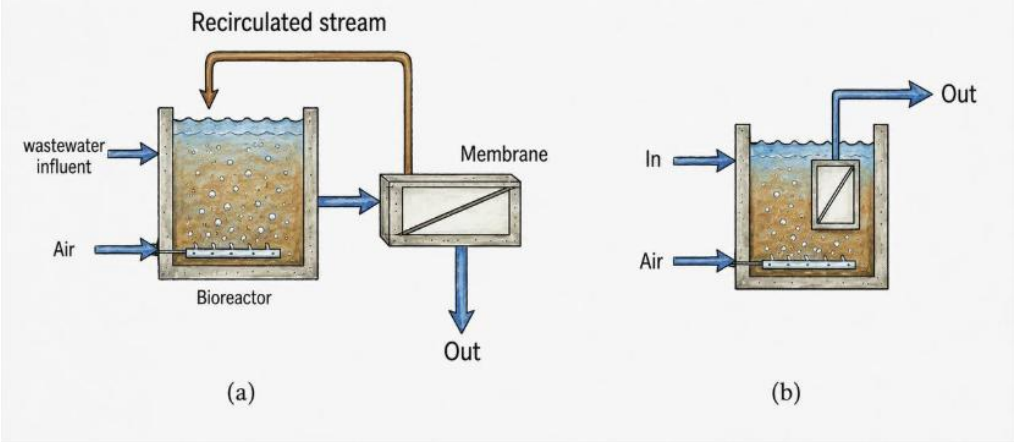


Figure [2]: Extended Aeration Activated sludge

An alternative to the conventional AS process is the membrane bioreactor (MBR), which replaces the gravity-based clarifier with a membrane separation process for biomass retention. Compared with the AS system, MBR technology generally requires a smaller physical footprint and can produce effluent of higher and more consistent quality [12].



Figure[3]: (a) side stream MBR (b) submerged MBR

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Background:

-LCA for Wastewater Treatment Plants:

Wastewater treatment plants (WWTPs) can contribute to environmental burdens through several aspects of their operation, including energy consumption, chemical use, land occupation, and sludge generation. For this reason, Life Cycle Assessment (LCA) has become a valuable framework for evaluating the environmental impacts associated with wastewater treatment systems in a comprehensive manner. LCA is an environmental assessment tool used to examine the entire life cycle of a process, product, or system, considering potential impacts from raw material extraction and resource use to operation, end-of-life treatment, recycling, and final disposal [5].

Methodology:

A reliable LCA study is generally conducted through four main stages. The first stage is goal and scope definition, where the purpose of the study is established and key methodological choices are determined, including the functional unit (FU), system boundaries, and level of analysis. The second stage is the life cycle inventory (LCI), which involves collecting all relevant input and output data for the system under study. The third stage is the life cycle impact assessment (LCIA), in which the inventory data are translated into potential environmental impacts. Finally, the life cycle interpretation stage is carried out to analyse and discuss the LCI and LCIA results, draw conclusions, and support decision-making [6].

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-Goal and scope:

The study covers the operational phase of the Wastewater Treatment Plants (WWTPs), focusing on the environmental impacts associated with their operation.

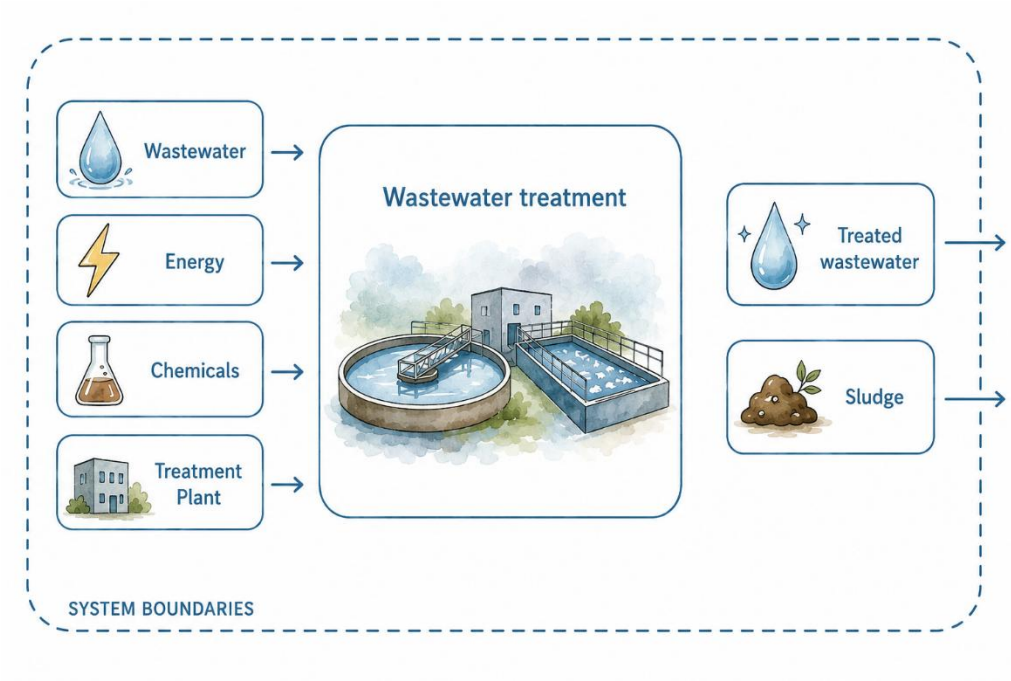


Figure [3]: system boundaries

-Functional Unit:

The functional unit of the study is defined as 1 m^3 of treated effluent, and all input and output data are normalized accordingly.

-Life Cycle Inventory (LCI):

The life cycle inventory (LCI) data including electricity and chemical consumption were compiled from relevant scientific literature and obtained from multiple peer reviewed studies.

Systems included:

In this study, the environmental impacts of two activated sludge systems (Extended Aeration and Conventional) were evaluated and compared alongside two membrane bioreactor systems (Aerobic and Anaerobic MBRs).

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Results:

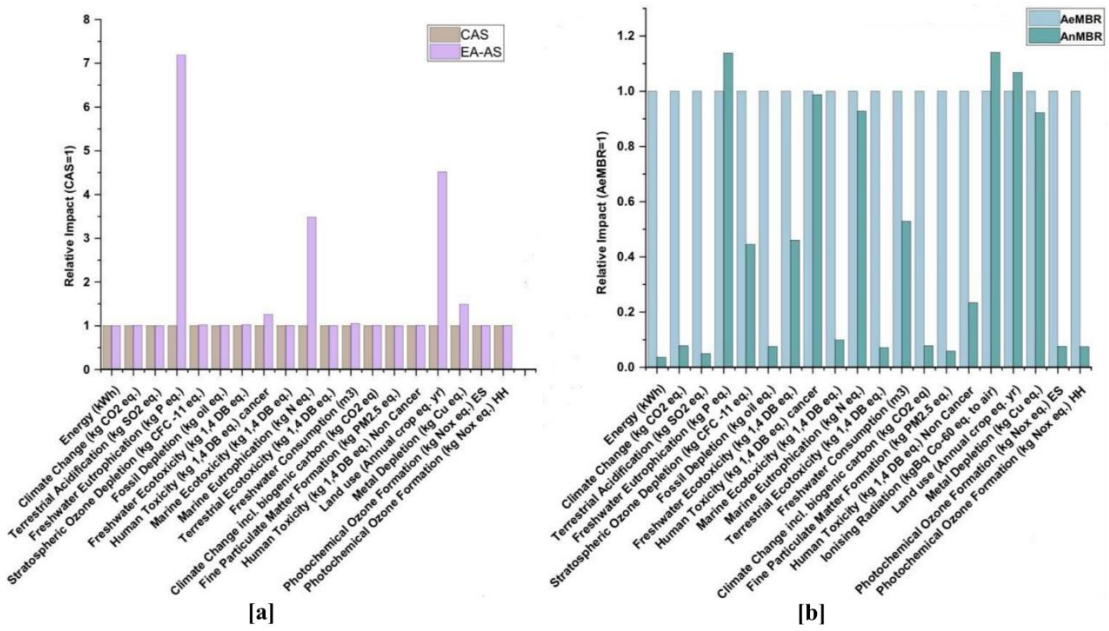


Figure [4]: (a) comparison of the LCIA of CAS and EA-AS (b) comparison of the LCIA of CAS and EA-AS

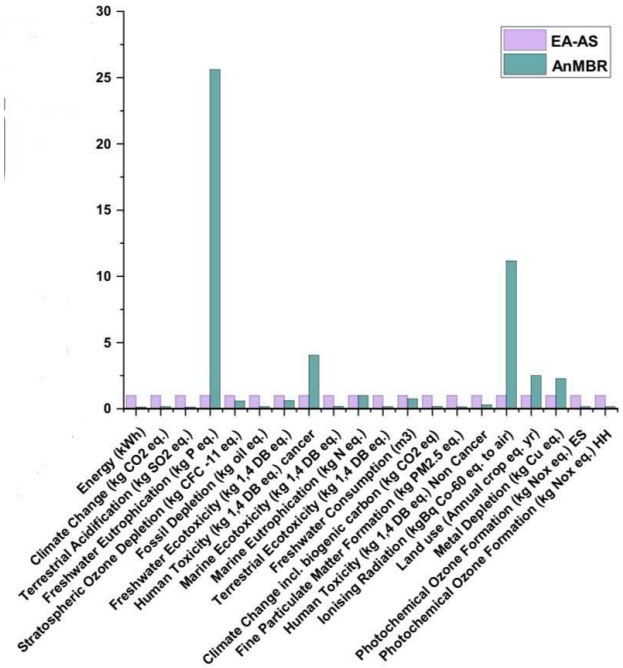


Figure [5]: comparison of the LCIA of EA-AS and AnMBR

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Discussion:

The comparison between Conventional Activated Sludge (CAS) and Extended Aeration Activated Sludge (EA-AS) shows that the two processes are environmentally comparable across most of the assessed impact categories, with values close to a 1:1 ratio in categories such as climate change, terrestrial acidification, fossil depletion, and human toxicity. However, EA-AS has clear drawbacks in freshwater eutrophication, metal depletion, marine eutrophication, and land use. This trend matches the operational differences between Conventional Activated Sludge (CAS) and Extended Aeration Activated Sludge (EA-AS): Extended Aeration Activated Sludge (EA-AS) runs with longer hydraulic and solids retention times and usually needs tank construction and more aeration equipment per unit of wastewater treated which probably explains the higher metal depletion. The eutrophication issue might be from chemicals or effluent nutrient levels in Conventional Activated Sludge (CAS), versus Extended Aeration Activated Sludge (EA-AS) but more study using plant-specific effluent data would help to clarify.

The comparison between Aerobic MBR (AeMBR) and Anaerobic MBR (AnMBR) reveals a much larger difference. AnMBR achieves lower impacts up to 5 to 20 times lower. across nearly all energy-linked categories, including climate change, fossil depletion, terrestrial acidification, and particulate matter formation. This happens duo to the absence of aeration in anaerobic treatment, which removes the single largest energy demand in aerobic membrane systems. However, AnMBR shows clear drawbacks in land use, ionizing radiation, and freshwater eutrophication relative to AeMBR. The land use and radiation penalties are probably linked to the larger reactor footprint and the additional infrastructure associated with energy recovery in anaerobic systems, while the elevated freshwater eutrophication likely reflects lower residual nutrient removal in anaerobic treatment compared to an aerobic process.

these results show that environmental performance in wastewater treatment technology selection cannot be simplified into a better" or worse decision. Each technology pair has its trade-off: EA-AS The EA-AS technology has penalties that are mostly focused on eutrophication and resource depletion. The AnMBR has advantages in energy-linked categories come at the cost of land use, radiation, and eutrophication impacts.

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Conclusion:

This study demonstrates that the environmental performance of activated sludge and membrane bioreactor wastewater treatment technologies is highly dependent on which impact category is given priority than following one fixed ranking. EA-AS performs similarly to CAS overall but EA-AS has significant penalties in eutrophication and metal depletion. AnMBR offers reductions, in energy-related impacts compared to AeMBR mainly because it eliminates aeration demand, but this advantage is balanced by increased land use, ionizing radiation and freshwater eutrophication.

These findings show that choosing the technology for treating wastewater in Saudi Arabia should depend on the most important environmental problem in a specific situation.

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