

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

**EVALUATING ENVIRONMENTAL EFFECTS OF DIFFERENT ANAEROBIC  
WASTEWATER TREATMENT SYSTEMS BY USING LCA APPROACH**



**Ph.D. THESIS**

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**Department of Environmental Engineering**

**Environmental Biotechnology Programme**

**JUNE, 2025**



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**Thesis Advisor: Prof. Dr. Ismail KOYUNCU**

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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ**

**FARKLI ANAEROBİK ATIKSU ARITMA SİSTEMLERİNİN ÇEVRESEL  
ETKİLERİNİN LCA YAKLAŞIMI İLE DEĞERLENDİRİLMESİ**

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**JUNE, 2025**



Merve YILMAZ, a Ph.D. student of ITU Graduate School student ID 501172805, successfully defended the thesis/dissertation entitled “EVALUATING ENVIRONMENTAL EFFECTS OF DIFFERENT ANAEROBIC WASTEWATER TREATMENT SYSTEMS BY USING LCA APPROACH”, which she prepared after fulfilling the requirements specified in the associated legislation, before the jury whose signatures are below.

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*To my daughters,*



## FOREWORD

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June 2025

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## ABBREVIATIONS

|                         |                                                 |
|-------------------------|-------------------------------------------------|
| <b>AP</b>               | : Acidification potential                       |
| <b>An</b>               | : Anaerobic                                     |
| <b>AnFO</b>             | : Anaerobic forward osmosis                     |
| <b>AnFOMBR</b>          | : Anaerobic forward osmosis membrane bioreactor |
| <b>D-CH<sub>4</sub></b> | : Dissolved methane                             |
| <b>CAS</b>              | : Conventional activated sludge                 |
| <b>EP</b>               | : Eutrophication potential                      |
| <b>FE</b>               | : Freshwater eutrophication                     |
| <b>FET</b>              | : Freshwater ecotoxicity                        |
| <b>FETP</b>             | : Freshwater ecotoxicity potential              |
| <b>FOMBR</b>            | : Forward osmosis membrane bioreactor           |
| <b>GHG</b>              | : Greenhouse gas emissions                      |
| <b>GWP</b>              | : Global warming potential                      |
| <b>HH</b>               | : Ozone formation, human health                 |
| <b>HCT</b>              | : Human carcinogenic toxicity                   |
| <b>HNCT</b>             | : Human non-carcinogenic toxicity               |
| <b>IRP</b>              | : Ionizing radiation                            |
| <b>LCA</b>              | : Life cycle assessment                         |
| <b>LCC</b>              | : Life cycle cost analysis                      |
| <b>LCI</b>              | : Life cycle inventory                          |
| <b>LCIA</b>             | : Life cycle impact assessment                  |
| <b>LU</b>               | : Land use                                      |
| <b>ME</b>               | : Marine eutrophication                         |
| <b>MET</b>              | : Marine ecotoxicity                            |
| <b>METP</b>             | : Marine ecotoxicity potential                  |
| <b>MBR</b>              | : Membrane bioreactor                           |
| <b>NF</b>               | : Nanofiltration                                |
| <b>ODP</b>              | : Ozone depletion potential                     |
| <b>PMFP</b>             | : Fine particulate matter formation             |
| <b>RO</b>               | : Reverse osmosis                               |

|             |                                     |
|-------------|-------------------------------------|
| <b>WWT</b>  | : Wastewater treatment              |
| <b>WWTP</b> | : Wastewater treatment plant        |
| <b>TA</b>   | : Terrestrial acidification         |
| <b>TE</b>   | : Terrestrial ecosystems            |
| <b>TET</b>  | : Terrestrial ecotoxicity           |
| <b>TETP</b> | : Terrestrial ecotoxicity potential |



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# **EVALUATING ENVIRONMENTAL EFFECTS OF DIFFERENT ANAEROBIC WASTEWATER TREATMENT SYSTEMS BY USING LCA APPROACH**

## **SUMMARY**

Enhancing effluent quality has been the primary goal of wastewater treatment (WWT) since the invention of the activated sludge technique in 1914. As stricter discharge limitations are enforced to save the environment and public health, this focus has changed. One potential way to mitigate the environmental implications of WWT systems, including energy consumption, solid waste creation, and greenhouse gas emissions, is to implement a better method that includes the recovery of resources obtained from wastewater. However, the environmental implications and advantages of enacting such a significant shift remain unclear and require extensive examination. By eliminating contaminants, the discipline of WWT is thus evolving into a phenomenon that encompasses the pursuit of resource recovery and a circular economy. By assessing the environmental sustainability of novel technologies and procedures, life cycle assessment, or LCA, is vital to this developing phenomenon.

As the first step of this thesis, a comprehensive literature review was conducted. Although numerous LCA studies on wastewater treatment systems have been published in recent years, none of the existing reviews have focused specifically on anaerobic treatment applications. In this section, LCA studies addressing anaerobic wastewater treatment were examined, with the structure organized as follows: first, publication trends in LCA and wastewater treatment were summarized, highlighting the increase in studies since 2000. Subsequently, the reviewed studies were analyzed according to the methodological stages of LCA, namely goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. Thereafter, existing LCA studies and economic assessments of anaerobic treatment systems were discussed, followed by perspectives for future research in this field.

The reviewed studies indicate that anaerobic wastewater treatment systems exhibit lower environmental impacts in most categories compared to conventional systems. Owing to their energy recovery mechanisms, anaerobic systems generally require less energy than aerobic systems. However, if dissolved methane in anaerobic effluents is not captured, it significantly contributes to global warming potential (GWP) and increases toxicity. Similarly, if nutrient recovery is not implemented following anaerobic treatment—for instance through aeration systems or alternative methods—eutrophication potential (EP) may rise. Another contributor to increased EP is the direct discharge of anaerobic effluents into receiving waters without reuse. While most existing LCA studies compare a particular anaerobic process with conventional activated sludge (CAS) systems, studies comparing anaerobic technologies with each other remain scarce. Furthermore, integrating LCA with additional tools such as techno-economic analysis (TEA) and social assessments is considered essential for more comprehensive evaluations. The detailed literature review also revealed a lack

of LCA studies on anaerobic forward osmosis (AnFO) systems, which have gained prominence in recent years. For this reason, the second part of the thesis focuses on these systems.

In the second part of the thesis, a comprehensive life cycle assessment (LCA) was performed for an Anaerobic Forward Osmosis Membrane Bioreactor (AnFOMBR) treating municipal wastewater. The main objective of this study was to evaluate the environmental impacts of different draw solution (DS) types and concentrations and to determine the optimal operating conditions that balance treatment efficiency with environmental sustainability. Conducted in accordance with ISO 14040 and 14044 standards, this LCA aimed to quantify the environmental burdens associated with different DS scenarios and to provide insights into the design and operation of forward osmosis (FO)-based wastewater treatment systems. The impact categories assessed included global warming potential (GWP), ozone depletion potential (ODP), terrestrial acidification (AP), freshwater and marine eutrophication (FEP and MEP), human toxicity (HT), and ecotoxicity.

The first comparative analysis in this section examined the environmental performance of NaCl and MgCl<sub>2</sub> at 0.5 M and 1 M concentrations. The results showed only minor differences between these draw solutions. In terms of GWP, MgCl<sub>2</sub> consistently exhibited slightly higher values than NaCl, primarily due to its more energy-intensive production and transportation; however, the differences were negligible. This finding suggests that draw solution choice exerts little influence on GWP, while factors such as sludge management, membrane production and disposal, and energy demand are more decisive. Regarding ODP, both solutions had minimal and comparable impacts, indicating that the chemicals used in the AnFOMBR system do not significantly contribute to stratospheric ozone depletion. By contrast, terrestrial acidification effects were more pronounced, with MgCl<sub>2</sub> showing slightly higher values due to its greater energy requirements during production. Differences became more evident in eutrophication categories: high-concentration NaCl (1 M) resulted in the highest freshwater and marine eutrophication impacts, whereas NaCl at 0.5 M had the lowest. While biogas recovery partially mitigated these effects by offsetting synthetic fertilizer use, phosphorus and nitrogen release remained critical concerns. In the human toxicity categories, MgCl<sub>2</sub>—particularly at 1 M—caused the highest impacts in both carcinogenic and non-carcinogenic toxicity, followed by MgCl<sub>2</sub> at 0.5 M, whereas NaCl at 0.5 M showed the lowest impact. These differences were linked to the resource- and emission-intensive production processes of MgCl<sub>2</sub>. Overall, the choice of draw solution (NaCl vs. MgCl<sub>2</sub>, 0.5 M vs. 1 M) was found to influence certain categories such as eutrophication and human toxicity, while exerting negligible effects on GWP and ODP.

In the second analysis of this section, the comparison was expanded to four draw solutions: NaCl, MgCl<sub>2</sub>, sodium sulfate (Na<sub>2</sub>SO<sub>4</sub>), and monoammonium phosphate (MAP, NH<sub>4</sub>H<sub>2</sub>PO<sub>4</sub>). Results showed that MgCl<sub>2</sub> use led to approximately 6.5% higher GWP than NaCl (increasing from 0.492 to 0.527 kg CO<sub>2</sub>-eq), whereas NaCl showed a 2.7% decrease across concentrations. ODP values remained consistently low across all scenarios, with no significant differences. Acidification potential (AP) was 28–40% higher for MgCl<sub>2</sub> and Na<sub>2</sub>SO<sub>4</sub> compared to MAP, primarily due to sulfur-related emissions and fossil fuel-based energy use. Nutrient-related impacts were most pronounced in MAP and MgCl<sub>2</sub> scenarios, driven by phosphorus and nitrogen concentrations in the effluent; among NaCl and MgCl<sub>2</sub>, NaCl at 1 M yielded the highest eutrophication potential. Furthermore, MgCl<sub>2</sub> presented 15–20% higher human

toxicity impacts than NaCl, linked to its resource-intensive production processes and the chemical use (e.g., EDTA, acetonitrile) in membrane cleaning. Energy consumption emerged as a critical factor: for most draw solutions, system energy demand was 2.43 kWh/m<sup>3</sup> due to regeneration, while MAP required only 0.4 kWh/m<sup>3</sup>, eliminating the need for regeneration and thereby lowering GWP. However, this advantage came at the expense of 25–30% higher human toxicity and freshwater ecotoxicity, attributable to nutrient-related effects. These results highlight the trade-off between energy efficiency and environmental health risks in draw solution selection.

The third part of the thesis presents a comparative LCA of three anaerobic wastewater treatment technologies—AnMBR, AnFOMBR, and UASB—using the ReCiPe midpoint method. Operational inputs, emissions, waste generation, and credits from energy and nutrient recovery were assessed. The results demonstrated that AnFOMBR achieved the best overall performance, with the lowest impact scores in 9 out of 11 categories. In terms of GWP, AnFOMBR (8.49 kg CO<sub>2</sub>-eq) performed 33.7% better than AnMBR (12.8 kg CO<sub>2</sub>-eq) and 10.5% better than UASB (9.49 kg CO<sub>2</sub>-eq), owing to lower electricity consumption (0.34 kWh vs. 0.865 kWh in AnMBR) and high nutrient removal efficiencies. In freshwater eutrophication, AnFOMBR (1.63 kg P-eq) reduced impacts by 67.7% compared to AnMBR and by 76.8% compared to UASB, correlating with its 85% phosphorus removal efficiency versus 30% in AnMBR and 10% in UASB. For marine eutrophication, AnFOMBR (1.24 kg N-eq) performed 90% better than AnMBR and 83% better than UASB, emphasizing the crucial role of nutrient removal in mitigating aquatic ecosystem impacts. AnFOMBR also exhibited the lowest ODP values and ozone formation impacts affecting human health, attributed to reduced fossil fuel use and chemical demand. For fine particulate matter formation and terrestrial acidification, AnFOMBR achieved 45% and 36.5% lower impacts than AnMBR, respectively. Although differences in ecotoxicity and human toxicity were smaller, AnFOMBR consistently demonstrated the lowest impacts. In human health, expressed in Disability-Adjusted Life Years (DALYs), AnFOMBR reduced impacts by 42% compared to AnMBR, while UASB showed intermediate performance. In ecosystem quality, AnFOMBR yielded 67% lower species loss than both UASB and AnMBR. Finally, in resource depletion, AnFOMBR incurred the lowest additional cost (0.76 USD), outperforming both UASB (0.77 USD) and AnMBR (0.89 USD).

These results demonstrate that AnFOMBR not only reduces environmental burdens across multiple categories but also minimizes long-term resource use, positioning it as the most sustainable option among the three anaerobic technologies. In conclusion, this LCA study shows that while the type and concentration of draw solution exert a measurable influence on certain impact categories, the overall environmental footprint of AnFOMBR systems is more strongly shaped by factors such as energy consumption, chemical cleaning, membrane materials, and sludge management. The findings provide valuable insights for the sustainable design and optimization of next-generation anaerobic wastewater treatment systems. Moreover, the results highlight that system-level improvements, combined with the use of environmentally advantageous draw solutions such as MAP and comprehensive LCA-based evaluations, could significantly reduce the ecological footprint of AnFOMBR, positioning it as a promising alternative for sustainable wastewater treatment in the future.



## **FARKLI ANAEROBİK ATIKSU ARITMA SİSTEMLERİNİN ÇEVRESEL ETKİLERİNİN LCA YAKLAŞIMI İLE DEĞERLENDİRİLMESİ**

### **ÖZET**

1914 yılında aktif çamur prosesinin icadından bu yana, atıksu arıtımının temel amacı, arıtılmış suyun kalitesini artırmak olmuştur. Ancak, çevrenin ve halk sağlığının korunmasına yönelik daha katı deşarj limitlerinin uygulanmasıyla birlikte, bu odak yön değiştirmiştir. Atıksu arıtma sistemlerinin enerji tüketimi, katı atık oluşumu ve sera gazı emisyonları gibi çevresel etkilerini azaltmanın potansiyel bir yolu, atıksudan elde edilen kaynakların geri kazanımını içeren daha gelişmiş bir yöntemin uygulanmasıdır. Bununla birlikte, bu denli önemli bir dönüşümün çevresel etkileri ve potansiyel avantajları henüz tam olarak netlik kazanmamış olup, kapsamlı bir şekilde incelenmesi gerekmektedir. Kirleticilerin uzaklaştırılmasının ötesine geçen atıksu arıtımı, kaynak geri kazanımı ve döngüsel ekonomi hedeflerini kapsayan bir disipline dönüşmektedir. Bu gelişen olguda, yeni teknolojilerin ve süreçlerin çevresel sürdürülebilirliğini değerlendirmek adına yaşam döngüsü değerlendirmesi (LCA) önemli bir rol oynamaktadır. Bu bağlamda, verilen tez üç ana başlıktan oluşmaktadır: (i) anaerobik atıksu arıtma sistemlerine yönelik LCA uygulamalarının sistematik bir değerlendirmesi, (ii) Anaerobik İleri Ozmotik Membran Biyoreaktör (AnFOMBR) sistemlerinde farklı tür ve konsantrasyonlarda çekme çözeltilerinin (draw solution, DS) ayrıntılı çevresel karşılaştırması, ve (iii) AnMBR, AnFOMBR ve UASB olmak üzere üç farklı anaerobik arıtma teknolojisinin karşılaştırmalı LCA analizi.

Bu tez çalışmasının ilk adımı olarak kapsamlı bir literatür taraması gerçekleştirilmiştir. Son yıllarda atıksu arıtma sistemlerine ilişkin birçok LCA incelemesi yayımlanmış olsa da, bu derlemeler arasında özellikle anaerobik arıtma uygulamalarına odaklanan bir çalışma bulunmamaktadır. Bu bölümde, anaerobik atıksu arıtımına yönelik LCA çalışmalarına odaklanılmış olup, yapı şu şekilde düzenlenmiştir: Öncelikle, LCA ve atıksu arıtımı konularındaki yayın eğilimleri özetlenmiş, 2000 yılından itibaren çalışmalarda artış ortaya konulmuştur. Ardından, incelenen çalışmalar LCA'nın metodolojik adımları çerçevesinde; amaç ve kapsam tanımı, yaşam döngüsü envanteri (LCI), yaşam döngüsü etki değerlendirmesi (LCIA) ve yaşam döngüsü yorumlama (LCI) aşamalarına göre analiz edilmiştir. Daha sonra, mevcut anaerobik arıtma sistemlerine yönelik LCA çalışmaları ve ekonomik değerlendirmeler incelenmiş, son olarak bu alandaki geleceğe yönelik perspektifler detaylandırılmıştır.

Analiz edilen çalışmalara göre, anaerobik atıksu arıtma sistemlerinin birçok çevresel etki kategorisinde konvansiyonel sistemlere kıyasla daha düşük çevresel etkilere sahip olduğu görülmektedir. Enerji geri kazanım mekanizmaları sayesinde, anaerobik atıksu arıtma sistemlerin toplam enerji gereksinimi aerobik atıksu arıtma sistemlerine göre daha düşüktür. Ancak, anaerobik çıkış suyunda çözünmüş halde bulunan metan gazı geri kazanılmadığı takdirde, sera gazı etkisini artırmakta ve toksisite seviyelerini yükseltebilmektedir. Ayrıca, anaerobik ünite sonrasında besin maddelerinin geri kazanımı gerçekleştirilmezse – örneğin havalandırma sistemleri ya da alternatif yöntemlerle – ötrofikasyon potansiyelinde (EP) artış meydana gelebilmektedir.

Mevcut LCA çalışmalarının çoğunlukla belirli bir anaerobik prosesi konvansiyonel aktif çamur (CAS) sistemi ile karşılaştırdığı, farklı anaerobik teknolojilerin birbiriyle karşılaştırıldığı çalışmaların ise oldukça sınırlı olduğu görülmüştür. Ayrıca, LCA çalışmalarının maliyet ve sosyal değerlendirmeler gibi ek araçlarla bütünleştirilmesi, daha kapsamlı analizler yapabilmek için önemli adımlardır. Bu nedenle, bu alandaki boşluğun giderilmesi adına LCA ve atıksu arıtımı alanındaki araştırmacıların daha fazla çalışmasına ihtiyaç duyulmaktadır. Detaylı literatür incelemesi sonucunda, son yıllarda kullanımı artan anaerobik ileri ozmoz (AnFO) sistemlerine ilişkin LCA çalışmalarının eksik olduğu tespit edilmiştir. Bu nedenle, tezin ikinci bölümünde bu sistemler üzerine odaklanılmıştır.

Tezin ikinci bölümünde, evsel atıksuyun arıtımı amacıyla uygulanan bir Anaerobik İleri Ozmoz Membran Biyoreaktörü (AnFOMBR) sistemine ilişkin kapsamlı bir Yaşam Döngüsü Değerlendirmesi (LCA) sunulmuştur. Çalışmanın temel amacı, farklı çekme çözeltisi (DS) türleri ve konsantrasyonlarının çevresel etkilerini değerlendirerek, arıtım verimliliği ile çevresel sürdürülebilirlik arasında denge kuran en uygun işletme koşullarını belirlemektir. ISO 14040 ve 14044 standartları doğrultusunda yürütülen bu LCA çalışması, farklı DS senaryolarına bağlı olarak ortaya çıkan çevresel yükleri nicel olarak ortaya koymayı ve ileri ozmoz (FO) tabanlı atıksu arıtım teknolojilerinin tasarım ve işletimine katkı sağlamayı amaçlamaktadır. Analiz edilen etki kategorileri arasında küresel ısınma potansiyeli (GWP), ozon tabakası incelmesi potansiyeli (ODP), kara asidifikasyonu (AP), tatlı su ve deniz ötrofikasyonu (FEP, MEP), insan toksisitesi (HT) ve ekotoksisite yer almaktadır.

İkinci bölümün kapsamında ilk karşılaştırma 0.5 M ve 1 M konsantrasyonlarında NaCl ve MgCl<sub>2</sub>'nin çevresel performansları üzerine yapılmıştır. LCA sonuçları, AnFOMBR sisteminde kullanılan NaCl ve MgCl<sub>2</sub> çekme çözeltilerinin çevresel etkilerinde yalnızca sınırlı farklılıklar olduğunu ortaya koymaktadır. Küresel ısınma potansiyeli (GWP) açısından MgCl<sub>2</sub>, üretim ve taşımadaki daha yüksek enerji gereksinimleri nedeniyle her zaman NaCl'den biraz daha yüksek değerler göstermektedir; ancak bu farkın ihmal edilebilir düzeyde olduğu görülmüştür. Bu durum, GWP üzerinde DS seçiminin etkisinin düşük olduğunu ve çamur yönetimi, membran üretimi ve bertarafı ile enerji tüketimi gibi diğer faktörlerin daha belirleyici olduğunu göstermektedir. Ozon tabakası incelmesi (ODP) açısından ise her iki çözelti de oldukça düşük ve birbirine yakın etkiler sergilemiş, bu da AnFOMBR sisteminde kullanılan kimyasalların stratosferik ozon tabakasının incelmesine önemli bir katkı yapmadığını göstermektedir. Buna karşılık, karasal asidifikasyon etkisi daha belirgin olup MgCl<sub>2</sub>, daha yüksek üretim enerjisi gereksinimleri nedeniyle NaCl'ye kıyasla biraz daha yüksek değerlere sahip olduğu görülmüştür. Ötrofikasyon kategorilerinde ise farklar daha dikkat çekicidir. Yüksek konsantrasyondaki NaCl (1 M), hem tatlı su hem de denizel ötrofikasyonda en yüksek etkiyi gösterirken, düşük konsantrasyondaki NaCl (0.5 M) en düşük etkiye sahiptir. Biyogaz geri kazanımı, sentetik gübrelerin yerini alarak kısmen bu etkileri azaltabilse de fosfor ve azot salınımı riski önemli bir sorun olmaya devam etmektedir. İnsan toksisitesi kategorilerinde ise MgCl<sub>2</sub>, özellikle 1 M konsantrasyonda, hem kanserojen hem de kanserojen olmayan toksisite açısından en yüksek değerlere sahiptir; bunu MgCl<sub>2</sub> 0.5 M izlerken, en düşük etki NaCl 0.5 M senaryosunda gözlenmiştir. Bu farklılık, MgCl<sub>2</sub> üretiminde kullanılan enerji yoğun süreçler ve buna bağlı kirletici emisyonlarla ilişkilendirilmektedir. Genel olarak, çekme çözeltisi seçiminin (NaCl – MgCl<sub>2</sub>, 0.5 M – 1 M) ötrofikasyon ve insan toksisitesi gibi belirli kategorilerde etkili olduğu, ancak GWP ve ODP üzerindeki etkisinin ihmal edilebilir düzeyde kaldığı görülmüştür.

İkinci bölümün kapsamında ikinci olarak, karşılaştırılma yapılan çekme çözeltisi sayısı genişletilerek NaCl, MgCl<sub>2</sub>, sodyum sülfat (Na<sub>2</sub>SO<sub>4</sub>) ve monoamonyum fosfat (MAP, NH<sub>4</sub>H<sub>2</sub>PO<sub>4</sub>) değerlendirmeye alınmıştır. Çalışma sonuçlarına göre, MgCl<sub>2</sub> kullanımı GWP açısından NaCl'ye kıyasla yaklaşık %6,5 oranında daha yüksek bir etki göstermiştir (0.492'den 0.527 kg CO<sub>2</sub>-eq'e artış), NaCl senaryosunda ise %2,7 oranında azalma gözlenmiştir. Tüm senaryolarda ODP değeri düşük düzeyde kalmış, çekme çözeltileri arasında önemli bir fark oluşmamıştır. Asidifikasyon potansiyeli, MgCl<sub>2</sub> ve Na<sub>2</sub>SO<sub>4</sub> senaryolarında MAP'e kıyasla %28–40 oranında daha yüksek çıkmıştır; bu farkın, sülfür kaynaklı emisyonlar ve fosil yakıt kullanımıyla ilişkili olduğu düşünülmektedir. Besin maddesi kaynaklı etkiler, özellikle çıkış suyu fosfor ve azot konsantrasyonları nedeniyle MAP ve MgCl<sub>2</sub> senaryolarında en yüksek seviyelerde gözlenmiştir; NaCl (1 M) senaryosu ise NaCl ve MgCl<sub>2</sub> kıyaslamasında en yüksek ötrofikasyon potansiyeline sahip olmuştur. Ayrıca, MgCl<sub>2</sub>'nin insan toksisitesi (kanserojen ve kanserojen olmayan) NaCl'ye göre %15–20 oranında daha yüksek olup, EDTA ve asetonitril gibi temizlik işlemlerinde kullanılan kimyasalların üretimindeki enerji yoğunluğu ve emisyonların bu duruma neden olduğu düşünülmektedir. Enerji tüketimi kritik bir unsur olarak öne çıkmaktadır: çoğu çekme çözeltisi için enerji tüketimi 2.43 kWh/m<sup>3</sup> iken, rejenerasyon gerektirmemesi nedeniyle MAP için bu değer yalnızca 0.4 kWh/m<sup>3</sup>'tür. Ancak bu enerji avantajı, içerdiği besin maddeleri nedeniyle %25–30 oranında daha yüksek insan toksisitesi ve tatlı su ekotoksitesi ile birlikte gelmektedir; bu da enerji verimliliği ile çevresel sağlık riskleri arasında bir denge kurulması gerektiğini göstermektedir.

Tezin üçüncü bölümünde ise, üç anaerobik atıksu arıtma teknolojisinin — AnMBR, AnFOMBR ve UASB — karşılaştırmalı LCA analizi yapılmıştır. ReCiPe midpoint yöntemi kullanılarak işletme girdileri, emisyonlar, atık oluşumu ve enerji/besin geri kazanım kredileri değerlendirilmiştir. Sonuçlar, Küresel ısınma potansiyeli (GWP) açısından AnFOMBR, 8.49 kg CO<sub>2</sub>-eq ile AnMBR'den %33,7 ve UASB'den %10,5 daha düşük değer göstermiştir. Bu fark, daha düşük elektrik tüketimi (0.34 kWh; AnMBR'de 0.865 kWh) ve yüksek besi maddesi giderim verimliliğine bağlanmıştır. Tatlı su ötrofikasyonu kategorisinde AnFOMBR, 1.63 kg P-eq değeri ile AnMBR'den %67,7 ve UASB'den %76,8 daha düşük etki göstermiştir. Bu sonuç, %85'lik fosfor giderim verimliliğinin, AnMBR (%30) ve UASB (%10) sistemlerine kıyasla belirgin bir üstünlük sağladığını göstermiştir. Denizel ötrofikasyon açısından da AnFOMBR, 1.24 kg N-eq ile AnMBR'ye göre %90 ve UASB'ye göre %83 daha düşük etki yaratmıştır. Bu durum, sucul ekosistemlerin korunmasında besi maddesi gideriminin kritik önemini bir kez daha ortaya koymaktadır. Stratosferik ozon incelmesi (ODP) ve insan sağlığını etkileyen ozon oluşumu kategorilerinde de AnFOMBR en düşük değerlere sahiptir. Bu sonuç, fosil yakıta dayalı enerji kullanımının ve kimyasal ihtiyacının azaltılmasıyla ilişkilendirilmiştir. İnce partikül madde oluşumu ve karasal asidifikasyon kategorilerinde de AnFOMBR, AnMBR'ye kıyasla sırasıyla %45 ve %36,5 daha düşük değerler göstermiştir. Ekotoksite ve insan toksisitesi kategorilerindeki farklar daha sınırlı olmakla birlikte, AnFOMBR tüm toksite kategorilerinde en düşük etki değerlerini korumuştur. İnsan sağlığı üzerindeki etki (DALY cinsinden ölçülen) açısından AnFOMBR, AnMBR'ye kıyasla %42 daha düşük zarar vermektedir; UASB ise orta düzeyde bir performans göstermektedir. Bu bulgu, çevresel emisyonların halk sağlığı üzerindeki risklerinin AnFOMBR ile önemli ölçüde azaltılabileceğini göstermektedir. Ekosistem kalitesi kategorisinde (yıllık tür kaybı), AnFOMBR  $1.13 \times 10^{-6}$  species·yr değeri ile hem UASB'den hem de AnMBR'den %67 daha düşük etki yaratmıştır. Bu sonuç, biyolojik çeşitlilik ve ekosistem işlevleri üzerindeki tehditlerin azaltıldığını göstermektedir. Son olarak,

kaynak tükenmesi kategorisinde (2013 USD cinsinden kaynak kıtlığına bağlı ek ekonomik maliyet), AnFOMBR 0.76 USD ile en düşük değere sahip olduğu gözlemlenmiştir. Bu bulgular, AnFOMBR sisteminin yalnızca çoklu kategorilerde çevresel yükleri azaltmakla kalmayıp, aynı zamanda uzun vadeli kaynak kullanımını da en aza indirdiğini ve üç anaerobik atıksu arıtım teknolojisi arasında en sürdürülebilir seçenek olabileceğini göstermiştir.

Sonuç olarak, bu LCA çalışması, çekme çözültisi türü ve konsantrasyonunun çevresel performans üzerinde ölçülü bir etkisi olsa da, enerji kullanımı, kimyasal temizlik, membran malzemeleri ve çamur yönetimi gibi diğer faktörlerin AnFOMBR sisteminin genel çevresel ayak izinde daha belirleyici olduğunu ortaya koymuştur. Bulgular, gelecek nesil anaerobik atıksu arıtma sistemlerinin sürdürülebilir tasarımı ve optimizasyonu için önemli bilgiler sunmaktadır. Ayrıca, elde edilen bilgiler enerji verimliliği, yüksek giderim verimi, MAP gibi çevresel açıdan daha avantajlı çekme çözültülerin kullanımının AnFOMBR sistemlerinin ekolojik ayak izini önemli ölçüde azaltabileceğini ortaya koymaktadır. Dolayısıyla, sistem düzeyindeki iyileştirmeler ve bütüncül LCA temelli değerlendirmelerle desteklendiği takdirde, bu teknolojinin gelecekte sürdürülebilir atıksu arıtım uygulamaları için tercih edilebilir bir alternatif olabileceği öngörülmüştür.

## **1. INTRODUCTION**

One of the most widely used methods in recent times is Life Cycle Assessment (LCA), which comprehensively examines all inputs and outputs, emissions, and their effects on the environment, human health, and natural resources. The anaerobic treatment of wastewater is known for its importance in energy recovery due to the opportunity for biogas production. However, the extent of the environmental impacts of these systems has only recently begun to be examined using approaches like LCA. With advancing technologies, anaerobic wastewater systems have also evolved, and the use of osmosis systems has started to become widespread. Since there are not many examples of their use in domestic WWT and large-scale operations in the literature, studies that thoroughly examine the environmental impacts of these systems are almost non-existent. This thesis aims to fill this gap in the literature and provide wastewater stakeholders with information on the environmental impacts of anaerobic systems.

### **1.1 Purpose of Thesis**

The purpose of this PhD thesis is to evaluate the environmental sustainability of anaerobic wastewater treatment technologies using a comprehensive Life Cycle Assessment (LCA) approach. Anaerobic systems are increasingly acknowledged for their low energy requirements and potential for energy recovery, yet there remains a significant lack of comparative LCA studies—particularly those that assess different system configurations and forward osmosis draw solution (DS) scenarios. This thesis aims to fill this research gap by conducting two independent but complementary LCA studies.

The first study focuses specifically on the Anaerobic Forward Osmosis Membrane Bioreactor (AnFOMBR) system and investigates the environmental implications of various draw solutions used in full-scale applications. Two levels of comparison were conducted: (i) NaCl and MgCl<sub>2</sub> at two different concentrations (0.5 M and 1 M), and (ii) four distinct draw solutions—MAP, NaCl, MgCl<sub>2</sub>, and Na<sub>2</sub>SO<sub>4</sub>. The analysis

integrated multiple midpoint indicators such as global warming potential (GWP), ozone depletion potential (ODP), acidification (AP), freshwater and marine eutrophication (FEP, MEP), and human toxicity (HT), offering a comprehensive evaluation of each DS scenario. The findings revealed that MAP-based draw solutions provided the most favorable environmental performance due to reduced energy demand and the elimination of reconcentration requirements when MAP is reused as fertilizer, thereby enhancing both environmental and resource efficiency.

The second study expands the scope to a broader system-level comparison by assessing three anaerobic treatment technologies: Anaerobic Membrane Bioreactor (AnMBR), Anaerobic Forward Osmosis Membrane Bioreactor (AnFOMBR), and Upflow Anaerobic Sludge Blanket (UASB). This comparative LCA was performed using both midpoint and endpoint indicators to quantify the systems' impacts on human health, ecosystems, and resource depletion. The AnFOMBR system emerged as the most environmentally sustainable option among the three, achieving the lowest impacts in 9 out of 11 midpoint categories. It showed a 33.7% reduction in global warming impact compared to AnMBR, up to 77% lower freshwater eutrophication than UASB, and over 90% reduction in marine eutrophication relative to AnMBR. At the endpoint level, AnFOMBR caused 42% less damage to human health (in DALYs) and 67% less damage to ecosystems (in species.yr), while also demonstrating the lowest resource depletion cost (0.76 USD). These advantages were primarily driven by its high nutrient removal efficiency and low electricity demand, despite the absence of methane recovery in this particular configuration.

By integrating findings from both draw solution optimization and system-level comparisons, this thesis offers a robust and multidimensional understanding of the environmental trade-offs in anaerobic wastewater treatment. The results highlight the AnFOMBR system's potential as a next-generation solution for sustainable and circular wastewater management, and aim to guide policymakers, engineers, and researchers in developing low-impact, resource-efficient treatment strategies.

## **1.2 Research Questions**

Taking all this into account, the following objectives in a form of research questions have been developed:

- How do different draw solutions and their concentrations influence the environmental performance of AnFOMBR systems as assessed through LCA?
- What are the comparative environmental impacts of four distinct draw solutions (MAP, NaCl, MgCl<sub>2</sub>, and Na<sub>2</sub>SO<sub>4</sub>) in AnFOMBR systems about critical LCA impact categories?
- What are the key environmental trade-offs between energy recovery, toxicity, and eutrophication when employing AnFOMBR systems for municipal wastewater treatment?
- How do the inclusion of sludge treatment processes and the presence or absence of regeneration units affect the overall sustainability performance of AnFOMBR systems?
- How do AnMBR, AnFOMBR, and UASB systems compare in terms of environmental impact when evaluated using midpoint and endpoint LCA indicators?
- What are the key environmental trade-offs between energy recovery, greenhouse gas emissions, nutrient removal efficiency, and toxicity among different anaerobic wastewater treatment systems?

### 1.3 Hypothesis

This study hypothesizes that the type and concentration of draw solutions (NaCl, MgCl<sub>2</sub>, Na<sub>2</sub>SO<sub>4</sub>, and MAP) used in AnFOMBR systems significantly influence their environmental performance, with higher concentrations expected to increase impacts due to greater energy and material demands. Among these, NaCl and MAP are anticipated to perform better overall; however, MAP may result in higher eutrophication despite its energy efficiency and potential for reuse as fertilizer. It is further hypothesized that, compared to AnMBR and UASB systems, AnFOMBR will demonstrate the lowest environmental burdens across most LCA categories due to its enhanced nutrient removal and low electricity demand, even in the absence of methane recovery. Regardless of system type or DS used, sludge treatment is expected to remain a major contributor to global warming and toxicity-related impacts. By integrating both midpoint and endpoint LCA indicators, this research is expected to

provide a more holistic understanding of the sustainability trade-offs associated with anaerobic wastewater treatment technologies.

#### **1.4 General Overview**

In recent years, research on integrating forward osmosis (FO) membranes into membrane bioreactor (MBR) systems has garnered significant attention due to the high rejection capacity of FO membranes. The primary aim of these technologies is the effective removal of small-sized contaminants that are not efficiently retained by conventional membrane processes. The aerobic osmotic membrane bioreactor (OMBR) was the first system developed in this field, created by integrating an FO membrane into an MBR. Compared to conventional MBR technologies, OMBR systems offer several advantages, including reduced membrane fouling, lower energy consumption, and improved treatment efficiency (Arhilli et al., 2010; Bacaksız A. 2019; Wang et al., 2016).

FOMBRs can be considered an extension of conventional MBRs, which typically employ porous microfiltration (MF) or ultrafiltration (UF) membranes to separate biomass from the treated effluent. While these porous membranes can effectively retain suspended solids, they generally exhibit limited removal efficiency for soluble organic matter, nutrients, and dissolved contaminants such as heavy metals and trace organics. In contrast, FOMBRs replace porous, pressure-driven membranes with dense, osmotically driven FO membranes, which provide superior retention of dissolved and colloidal pollutants. The FO membrane's high salt rejection, lower fouling propensity, ability to generate water flux through osmotic driving forces, and potential for producing high-quality permeate have expanded its application areas beyond seawater desalination and water purification to include advanced wastewater treatment (Chen et al., 2014).

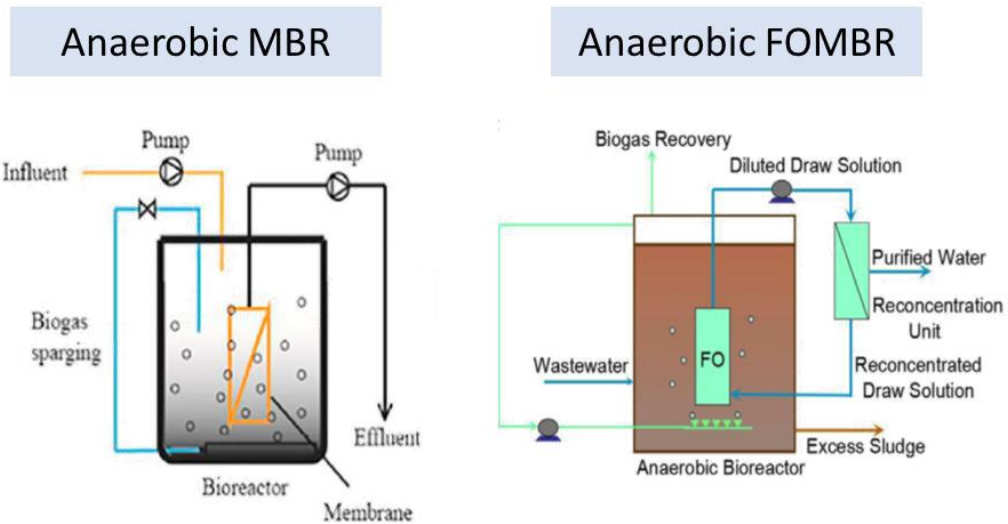


**Figure 1.1 :** The figure of conventional AnMBR and AnFOMBR ( Al-Asheh et al., 2021; Wang et al., 2016).

The selection of draw solution critically influences AnFOMBR operation by affecting water flux, reverse salt flux (RSF), membrane fouling, biological performance, and system sustainability. Draw solutes with high osmotic pressure enhance water flux ( $J_w$ ), but internal concentration polarization (ICP) can diminish this benefit. RSF, driven by concentration gradients, leads to salt accumulation in the bioreactor, which can inhibit microbial activity and reduce methane production. Biological performance, particularly methane yield, is sensitive to RSF-induced salinity changes, with some solutes (e.g., MAP) enhancing biogas production and others (e.g.,  $\text{NaNO}_3$ ) inhibiting it. From a sustainability perspective, draw solution recovery (e.g., via RO or NF) is essential for economic feasibility. Ultimately, optimal draw solution selection requires balancing hydraulic performance, microbial stability, fouling control, recovery feasibility, and environmental impact (Achilli et al., 2010; Giognorio et al., 2021; Kim et al., 2016). The illustration of the conventional AnMBRs and AnFOMBRs is given in Fig. 1.1.



## **2. THE APPLICATION OF LIFE CYCLE ASSESSMENT (LCA) TO ANAEROBIC TECHNOLOGIES FOR THE TREATMENT OF MUNICIPAL WASTEWATER: A REVIEW<sup>1</sup>**

### **2.1 Introduction**

Water and energy depletion have been among the most critical resource issues in the world in recent years. With rapid population growth, the consumption of water resources and wastewater generation accelerate. 380 billion m<sup>3</sup> of wastewater is produced worldwide, estimated to increase by 24% in 2030 (Qadir et al., 2020). Meanwhile, resource consumption has also kept up with economic development, infrastructure aging, and more strict regulations. It is necessary to take a broad view of WWT systems to create sustainable WWT. When considering the sustainability of a WWT system and selecting an appropriate design for a given condition, recycling, and social issues are essential in addition to cost and treatment performance. Thus, sustainable WWT technologies have become a significant topic of interest since the 2000s. (Mo and Zhang, 2013). There are practical approaches for sustainable WWT plants; (i) energy efficiency achieved by diminishing consumption, (ii) resource recovery; nutrient recovery, and water reuse options, (iii) reduction in chemical use, (iv) energy recovery; generation from the treatment system for heat, electricity, fuel, etc. providing a decrease in energy cost (Güven et al., 2019; McCarty et al., 2011; Mo and Zhang, 2013). If energy and resource recovery is achieved efficiently, wastewater treatment plants (WWTPs) may become energy-neutral or even energy-positive systems. To provide this, selecting suitable technology with lower energy consumption in all treatment units is one of the most important tasks in WWTPs.

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<sup>1</sup> This chapter is based on “Yilmaz, M., Güven, H., Ozgun, H., Ersahin, M. E., & Koyuncu, I. (2024). The application of Life Cycle Assessment (LCA) to anaerobic technologies for the treatment of municipal wastewater: A review. *Process Safety and Environmental Protection*, 182, 357-370.”

Even though aerobic treatment ensures high-quality effluent, it has huge energy demand attributed to intensive aeration and sludge handling processes. To solve these problems, employing anaerobic treatment technologies seems like an attractive option as they are energy-saving, allowing biogas recovery, lower sludge production, and lower cost for domestic WWT (Gomec, 2010; Stazi and Tomei, 2018). At first, anaerobic treatment technologies were applied in tropical regions at temperatures above 20-25 °C for high-strength wastewater, such as industrial wastewater. However, developing new technologies has recently become applicable for low or medium-strength wastewater at lower temperatures (Stazi and Tomei, 2018). Over the past four to five decades, several anaerobic treatment configurations have been developed. These configurations include the anaerobic filter (AF), (UASB) reactor, anaerobic fluidized-bed reactors (AFBR), expanded granular sludge bed (EGSB) reactor, and anaerobic baffled reactor (ABR). The most commonly used is anaerobic MBR with recent novel configurations (Hu et al., 2022; Van Lier et al., 2020; Shoener et al., 2014). Despite the advantages of anaerobic technologies, some challenges must be overcome, such as the dissolution of the produced methane, which leads to more greenhouse emissions, low biogas recovery, and potentially explosive effects (Centeno Mora and Chernicharo, 200). The post-treatment requirement for the effluent to meet discharge standards is another difficulty for anaerobic technologies.

To achieve sustainable development, the potential environmental impact of all stages from cradle to grave (energy and material inputs and outputs including raw material extractions, energy acquisition, production, manufacturing, use, recycling, ultimate disposal, etc.) product, service, or process should be quantified. The LCA technique has become one of the well-known methods to evaluate and discuss environmental effects (e.g., climate change (CC), eutrophication potential (EP), etc.) on the ecosystem, human health, and natural resources of the entire product or process (Corominas et al., 2013; Rebitzer et al., 2004). Firstly, the LCA was improved from energy analysis to comprehensive environmental burden analysis in the 1970s. After introducing the holistic life cycle impact assessments and life cycle cost models in the 1980s and 1990s, the demand for the standardization of LCA methodologies increased. Therefore, the LCA was standardized in the International Standards Organization (ISO) 14000 series (The ISO 14040 and 14044) and is now identified as a general methodology, but it is not defined in detail for each field in which the method used has

developed. The rapid increase in LCA publications showed that LCA had become one of the most used environmental burden assessment methods. To make economic and social assessment successful, the LCA framework can be integrated with; life cycle cost analysis (LCC), which is the most commonly accepted economic assessment method, and TEA (techno-economic analysis), which is focused on a product or process sale prices and potential revenue relatively, and SCLA (social life cycle assessment), which influences decision-making via public acceptance and stakeholder participation variables (Byrne et al., 2017; Corominas et al., 2020; Guinée et al., 2011).

LCA is crucial for assessing how new technologies and processes behave environmentally concerning different environmental concern categories (Corominas et al., 2020). Remarkably, the published studies about WWT technology LCAs from different locations have been growing rapidly since the 1990s, along with rapid urbanization and population growth, to determine a good level of environmental sustainability. While some LCA studies are conducted to evaluate the overall environmental consequences of WWT operations, others were specifically carried out as tools to aid in decision-making for WWTP management. In addition, LCA studies have examined a wide range of scales and levels, such as nutrient removal, different configurations (primary, secondary, or tertiary processes), integrated resource recovery, and water reuse technologies. On the other hand, some studies have not taken into account the management and disposal of solid waste, which is important for assessing the harmful effects of heavy metals (Foley et al., 2010; Rahman et al., 2016). Municipal wastewater may lead to many diseases worldwide, spreading direct and indirect emissions from WWT processes. These emissions have become difficult to ignore and have played a significant role in some environmental impact categories like CC. The environmental loads of these processes can be reduced through LCA, helping to select alternative processes and distribution patterns. In general, LCA studies on WWT offer numerous benefits. These include enhancing our comprehension of environmentally and economically viable alternatives, identifying strategies for reducing contamination, and aiding in the decision-making process regarding water reusability while ensuring process safety and environmental security (Parra-Saldivar et al., 2020; Sabeen et al., 2018).

Many reviews regarding WWT LCAs that applied physical and biological WWT technologies like nutrient removal systems, biofilm systems, etc., have been published

in past years (Corominas et al., 2013; Gallego-Schmid and Tarpani, 2019; Rebello et al., 2021). However, none of the LCA reviews focused on the opportunities and drawbacks of anaerobic WWT applications. This review article serves as a compilation of existing LCA studies that explore the treatment of municipal wastewater using anaerobic treatment systems in mainstream applications. This paper's primary goals are to: (1) provide a critical analysis of the published LCA studies assessing the environmental, energy, and cost analyses of different anaerobic treatment systems, and (2) to support the extension of LCA applications on anaerobic treatment technologies used for municipal wastewater, and (3) to guide researchers and practitioners studying anaerobic WWT and LCA for future studies. The format of this paper is as follows: First, a brief presentation of the LCA and WWT publication statistics demonstrates how the amount of research has varied since 2000. After that, the reviewed studies are analyzed following the LCA phases step by step: (i) goal and scope, (ii) life cycle inventory, (iii) impact assessment, and (iv) interpretation in the methodology section. Then, the reviewed current LCA studies on anaerobic WWT and their economic evaluations are analyzed, and future perspective in LCA studies on anaerobic WWT is given in detail.

## **2.2 Publication Pattern**

A systematic literature review is required to understand important flaws in earlier efforts that can be addressed in future ones. Scanning should be done correctly and systematically to ensure scanning results would not be misleading and would illustrate the best articles. For this purpose, the literature scanning was conducted by one of the leading scientific databases, the Scopus Database, to present adequate information.

Firstly, the keywords 'life cycle assessment' and 'wastewater treatment' were searched (1686 document results) from 2000 until 2023. After that, the 'anaerobic' keyword filter was used, with 277 results of which 218 were research articles, 29 review articles, 12 conference papers, and 14 book chapters; the rest were conference reviews, books, and notes. When 277 articles were examined, it was found that there are studies on both anaerobic sludge treatment and side-stream treatment, besides anaerobic WWT in the mainstream. 20 LCA studies, including an anaerobic WWT system of municipal wastewater in the mainstream, were analyzed using the LCA methodology.

The number of LCA studies applied to WWT and anaerobic WWT systems has been increasing dramatically daily. Based on the literature studies, it was seen that there are more performed LCA studies using anaerobic municipal WWT systems compared to LCA studies on anaerobic sludge treatment, side-stream treatment, industrial WWT systems, etc. When the LCA studies that used anaerobic municipal WWT systems were investigated, it was found that 16% of them were within the scope of this review. The distribution of research and review articles, anaerobic treatment methods with municipal wastewater and other wastewater types, and anaerobic system types used in the evaluated LCA studies are presented in Fig. 2.1.

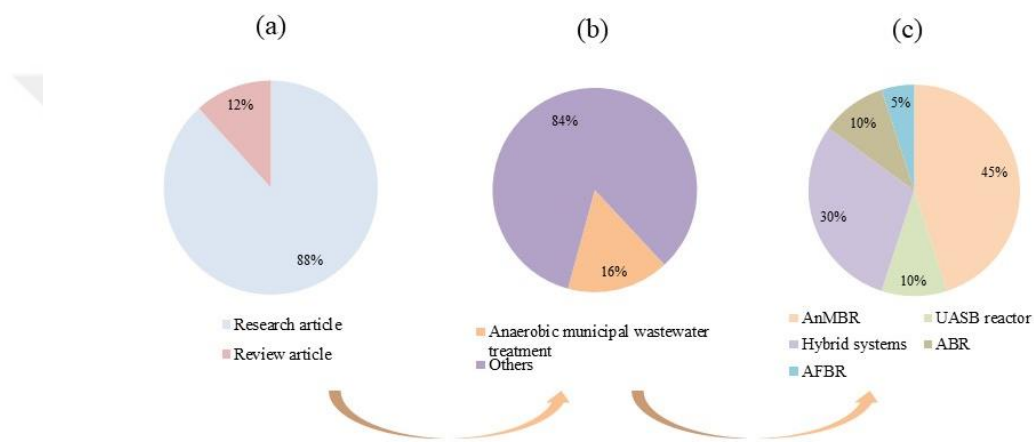


**Figure 2.1 :** a) Distribution of research and review articles about LCA studies about anaerobic WWT (published between 2000 and 2023), (b) Distribution of LCA studies evaluated anaerobic treatment methods with municipal wastewater and other wastewaters (published between 2000 and 2023), (c) Distribution of anaerobic system types used in the LCA studies evaluated in this review.

When further screened, of the 20 LCA studies that used anaerobic systems of the WWT method, which is applied in the mainstream, AnMBR has been studied in most cases (45%). Additionally, it was seen that UASB reactors with hybrid systems or solely were used predominantly. ABR and AFBR systems were used in the rest of the LCA studies analyzed. While giving the information about the studies, CAS refers to conventional activated sludge. The distribution of LCA studies on anaerobic technologies all over the world is shown in Fig. 2.2.



**Figure 2.2 :** The distribution of the studies reviewed in this study.

## **2.3 Methodology**

### **2.3.1 Goal and scope definition**

The scope definition should involve system boundary, functional unit (FU), data parameters, target for data quality, and impact assessment methods. To achieve a proper goal definition and aims of performing the study, the application areas of the LCA results should be explained adequately (ISO, 2006). Almost all articles reviewed in this study defined their goal and scopes clearly. In most studies, the purpose of the study was based on the lifecycle comparison of the different treatment system scenarios in many aspects. For instance, the life cycle comparison of different process configurations such as AnMBR vs. aerobic MBR (AeMBR) (Cashman et al., 2018) and AFBR vs. conventional activated sludge (CAS) treatment systems (Alvarado et al., 2019) was investigated in the previous studies. On the other hand, some studies also compared the effect of operating conditions or influent characterization on the system performance in the same treatment system (Pretel et al., 2013, 2015, 2016).

#### ***Functional unit***

The FU representing all functional outputs, such as flows and emissions, must be selected properly to conduct the LCA studies. A WWTPs or resource recovery

facility's primary job is to treat wastewater, and how well either performs is dependent on how much pollution is eliminated. The widely used FUs in WWT LCAs are the volume of treated wastewater, person equivalent (p.e.), and pollutant loads in the effluent (kg PO<sub>3</sub><sup>4-</sup> eq. removed, kg N removed, etc.) and other units. These units were similar to those in the reviewed LCAs, where the volume-based ones were the most commonly used FU. Although the volume of treated wastewater is defined as the FU in most articles, person-equivalent units were also useful (Kalbar et al., 2013; Lijó et al., 2017). Different FUs could be used in the same study to check the robustness of the results. For instance, two different FUs were selected to see the performance of biomethane produced in the study of Maga (2017); one is 1 m<sup>3</sup> treated wastewater, and the other is 1 MJ compressed natural gas (CNG) used in a gas engine. Additionally, to properly evaluate the contribution of the energy produced from the system in the study of Arias et al. (2020), the volume units of treated wastewater and 1 kWh of energy-produced units were used as a FU). To better understand the comparisons in all studies, the FU volume was selected as m<sup>3</sup> and converted to it if other volume units were used in Table 1.

Based on the selected FU, results might be critically affected when WWTPs receive fluctuated influent loads, which can cause high variations in effluent characteristics. Moreover, if only the volumetric FU is chosen, individual changes in wastewater quality and quantity, which vary from region to region, would be disregarded (Corominas et al., 2020). Although WWT plants connected to combined sewerage systems had greater impact exposure per m<sup>3</sup> treated than plants connected to separated systems, the impact value per capita might be lower.

### ***System boundary***

The system boundary defines which technical systems will be used in the assessment (Yoshida et al., 2013). One of the most critical steps in an LCA practice is defining the system boundary covering all processes from start to end. The most commonly used method, which illustrates each unit in the system in LCAs, is a box or schema that clearly shows the various interrelationships. System boundaries must be specified in several dimensions: Boundaries between the technological system and nature, limitation of the geographical area, time horizon, production of capital goods, boundaries between the studied life cycle of the product, and related life cycles of other

products (Tillman et al., 1994). System boundaries could follow the exact path for selecting environmental processes, like WWTPs.

The system boundaries in wastewater LCAs cover generally; treatment, system maintenance, sludge management, energy production and consumption, and the options for treated wastewater effluent end uses. The system boundaries in wastewater LCAs usually exclude the construction, collection, and transportation of wastewater by sewer lines to WWTPs, and plant demolition due to data inaccessibility. Regarding WWTPs and the exclusion of the construction period, Corominas et al. (2020) highlighted that it might have an impact on the change on the final impact if considered, therefore its exclusion should not be taken for granted. To better conceive the processes' interrelationships and how these affected the environment, commonly used processes to draw system boundaries in anaerobic wastewater LCA studies are given in Fig. 2.3.

The system boundaries were clearly defined, and all units, possibilities, and scenarios were shown as schemes in most reviewed studies. In recent WWT LCA cases, the system boundary included not only wastewater line but also sludge handling, water reuse, and energy generation options and was shown as process flow diagrams (Cashman et al., 2018; Foglia et al., 2021; Harclerode et al., 2020; Lijó et al., 2017; Pfluger et al., 2018; Pretel et al., 2015; Rebello et al., 2021; Tian et al., 2020).

The inclusion of constructing inside of the system boundaries has been a topic of debate when examining the life cycle processes. The construction and demolition phase of infrastructure was not involved in most of the analyzed studies because this data is generally unavailable. When articles were analyzed, only 41 % of studies included the construction part in the system boundary. The negative effect of the construction phase can be considered negligible; however, some studies included construction costs in the LCC assessment (Arias et al., 2020). In the study of Pretel (2015), the construction and demolition parts were included. Still, the pre-treatment (screening, degritter, and grease removal) part is excluded from the system boundary of the study. Besides, it was seen that the construction phase stands out as one of the most variable factors influencing environmental impact results in Jimenez's study (2023). Some operational periods and/or impact categories were found to have a considerable contribution from the building phase to the cumulative LCA. These include 8-13% GWP, 51-71% mineral resource scarcity, 18-27% fossil resource

scarcity and 21-28% water use (Jiménez-Benítez, Vázquez, et al., 2023). Considering these examples, careful consideration should be given to the exclusion of the construction phase from the system boundary.

The energy recovery from anaerobic systems (wastewater systems or anaerobic sludge digestion) reduces energy consumption in WWT systems and may convert the system into energy-neutral or even energy-positive systems. To find out the effect on the environment, biogas and energy production processes were also included in system boundaries in 45.3% of the reviewed studies (Arias et al., 2020; Maga, 2017; Pretel et al., 2013; Rebello et al., 2021; Sills et al., 2016; Tian et al., 2020). In addition, one of the essential parts of the overall impact of WWTPs is associated with sludge management. For this reason, 46.2% of studies involved sludge management parts in their system boundaries (Arias et al., 2020; Hospido et al., 2012; Kalbar et al., 2013; Maga, 2017; Pfluger et al., 2018; Pretel et al., 2013; Rebello et al., 2021). Although some papers used the “Gate to Gate” approach due to lack of information, most studies assessed in this study focused on the “Cradle to Grave” approach because of better understanding of the impacts of all stages.

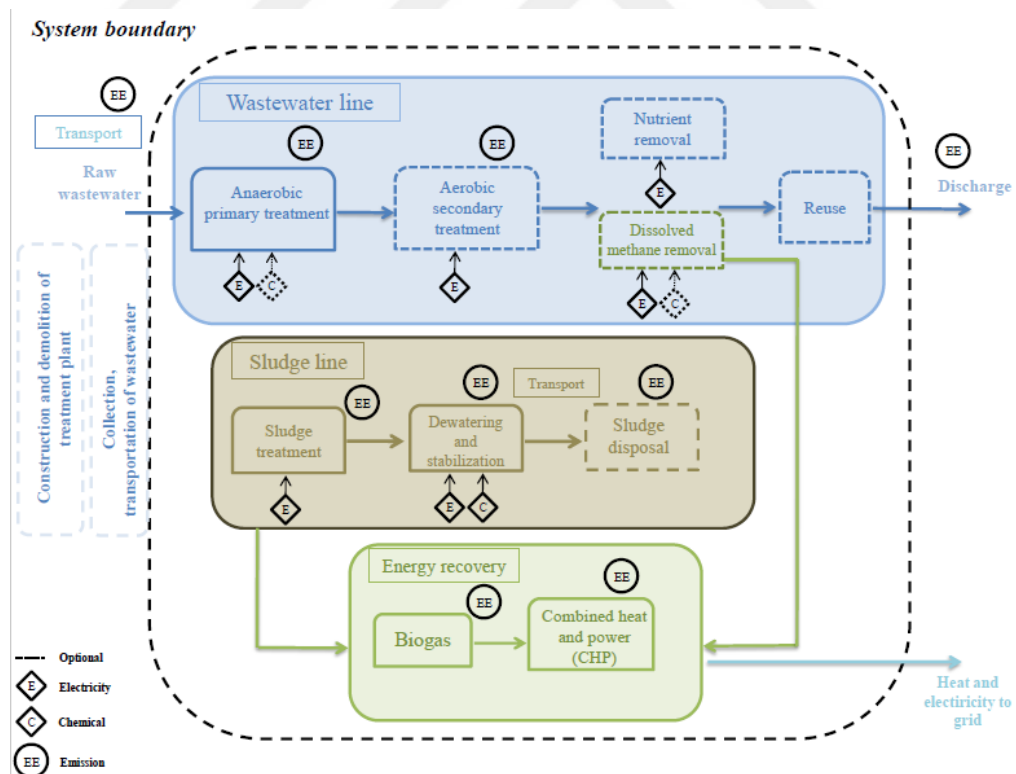


**Figure 2.3 :** Commonly used processes to draw system boundary anaerobic wastewater LCA studies used in this review.

### 2.3.2 Life cycle inventory analysis (LCI)

LCI encompasses data collection and calculation to measure the system's inputs and outputs of materials and energy. According to data quality requirements, several data types can be collected, such as on-site, literature, or database data (ISO, 2006). The data in LCI is often categorized as “foreground data” collected directly from measurements and detailed design reports and “background data” provided by LCI databases. Of the 20 reviewed studies, 88% used Ecoinvent with different versions as the database. 53% of the analyzed papers comprehensively give LCI data, while others just include partial information (34%), and approximately half do not include inventory data. Some studies mentioned built-in databases within LCA software packages such as SimaPro, Biowin, Stepwise, Umberto, and CapdetWorks in Table 1.

The inventory step of LCA studies is an essential issue because it directly governs LCA results. Studies have used both literature or on-site data and database data. For instance, in the study of Harclerode et al. (2020), primary data related to energy and material consumption were taken from pilot test results, full-scale treatment plant data, engineering calculations, and vendor specifications. Additionally, the Life Cycle Inventory (LCI) data for the treatment system was derived from the Ecoinvent unit process database version 3. In the study of Hospido et al. (2012), real and database data were used for the inventory collected from on-site measurements. Regarding the background data, the Ecoinvent database was also used. On the other hand, different databases could be used in the same study, like Xu et al. (2020) and Mohammed et al. (2022), which used Ecoinvent and U.S. LCI databases simultaneously.

Each study has individual inventory classification depending on its goal and scope. For instance, for Cashman et al. (2018), all pre and post-treatment steps, aerobic and anaerobic MBR parts, wastewater collection, and recycled water distribution parts were included in the LCI phase of the study. Some data were taken from previous studies, but some were from LCI data previously developed by the U.S. EPA. On the other hand, in the study of Hospido et al. (2012), information about wastewater, sludge, and biogas was used as LCI data obtained from on-site measurements in pilot systems; some estimations have also been made.

### **2.3.3 Life cycle impact assessment (LCIA)**

According to the ISO 14040 standard, the LCIA is the third phase of the LCA applied to convert data input into LCI results. There are three crucial steps in the LCIA phase: The process of choosing and identifying relevant impact categories, classifying and allocating inventory data for the impact categories that have been chosen, and characterizing the potential effects by assumptions and the application of certain scientific characterization variables (ISO, 2006). The impact categories are selected based on data availability and the significance of a particular impact category regarding the study's goal.

Although CML can be used to compare findings to earlier research that has been published generally, TRACI (midpoint analysis) and ReCiPe (midpoint and endpoint analysis) are reported as the most appropriate ones for impact assessment methodologies (Corominas et al., 2020). The ReCiPe methodology was first developed in 2008 and created by the inventor of CML 2001 and Ecoindicator 99. It is a combination of CML and Ecoindicator methodologies and has remarkable growth according to the findings of previous review articles. It contains 18 midpoint indicators and three endpoint indicators based on which software interface the operators use (Rebello et al., 2021). Among the 20 studies reviewed in this study, 19 of the papers mentioned the methodology used; the distribution of LCIA methods used in the reviewed studies is given in Fig 2.4.

Of the 20 investigated articles, 19% did not state which software was used, and 60% used the SimaPro software, 10% used CapdetWorks, other studies used Umberto, Open LCA, and GREET software. Most of the studies stated that the software version deeply influenced the LCIA results, primarily for the database and methodology assessment tools, such as SimaPro. A summary of FUs, LCI database, LCA modeling tool, and LCAI methods of the analyzed studies are given in Table 2.1.

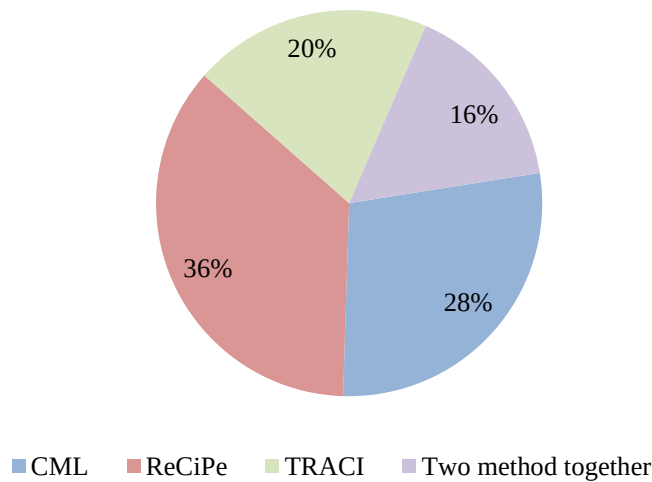


**Figure 2.4 :** LCIA methodologies used in evaluated studies.

According to the LCIA methodologies used, the impact categories can differ from each other. Each assessed study used various impact categories depending on its goal and scope. Midpoint indicators are generally preferred in wastewater systems; nevertheless, if these indicators are not sufficiently precise for decision-making, endpoint indicators should be considered (Corominas et al., 2020). On occasion, the same impact category could be referred to as different names according to impact category methodologies (CML, ReCiPe, etc.), even if they are the same unit. For instance, the CML methodology's GWP impact category is kg CO<sub>2</sub>-eq, like the CC impact category in the ReCiPe methodology. Additionally, some impact categories are not included by all methodologies, such as agricultural land occupation potential (LOP) and ionizing radiation potential (IRP) (existing in ReCiPe but not CML). On the other hand, some categories are divided into subcategories like ecotoxicity: METP, FETP, and TETP.

Concerning the set of impact categories evaluated, CC, AP, and EP were the most common impact categories considered in the reviewed studies. Subsequently, fossil depletion (FD), toxicity-related aspects, TETP, marine ecotoxicity (METP), and freshwater ecotoxicity (FETP), were the subjects of concern. Additionally, ozone depletion potential (ODP), photochemical oxidation potential (POP), and various impact categories were evaluated in these studies. A summary of impact categories used in investigated studies is given in Fig. 2.5.

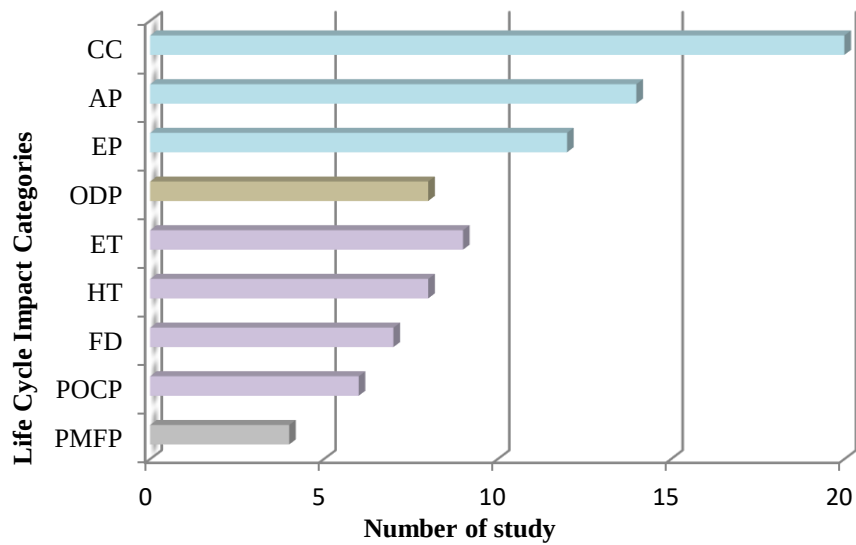


**Figure 2.5 :** Commonly used impact categories in the reviewed anaerobic municipal WWT LCAs: CC, Climate change; AP, acidification potential; EP, eutrophication potential; ODP, ozone depletion potential; ET, ecotoxicity; HT, human toxicity; FD, fossil depletion; POCP, Photochemical oxidation potential; PMFP, Particulate matter formation.

**Table 2.1** : FUs, LCI database, LCA modeling tool, and LCAI methods of the analyzed studies.

| Functional unit (FU)                                                                    | LCI database                     | LCIA methods                                     | LCA software used  | Reference                      |
|-----------------------------------------------------------------------------------------|----------------------------------|--------------------------------------------------|--------------------|--------------------------------|
| 1 m <sup>3</sup> of permeate produced                                                   | Ecoinvent                        | CML 2001 v.2.05                                  | SimaPro v.7.3      | Hospido et al. (2012)          |
| 1 p.e / year                                                                            | Ecoinvent v.2.1                  | CML 2000 v.2                                     | -                  | Kalbar et al. (2013)           |
| 1 m <sup>3</sup> of treated wastewater                                                  | Ecoinvent v.2.2                  | CML 2000 v.2                                     | SimaPro v.7.3      | Pretel et al. (2013)           |
| 5 MGD <sup>b</sup> (MGD, 18 950 m <sup>3</sup> /d)                                      | Ecoinvent, US LCI, and ELCD      | TRACI                                            | Capdet Works       | Smith et al., (2014)           |
| 1 m <sup>3</sup> of treated wastewater                                                  | Ecoinvent v.3                    | CML 2000 v.2                                     | SimaPro v.8.01     | Pretel et al. (2015)           |
| 1 m <sup>3</sup> of treated wastewater                                                  | Ecoinvent v.3.1                  | CML 2000 v.2                                     | SimaPro v.8.02     | Pretel et al. (2016)           |
| 2 MGD <sup>c</sup> of domestic wastewater over 30 years                                 | Ecoinvent v.3.2                  | IMPACT 2002+                                     | SimaPro v.8.1      | Sills et al. (2016)            |
| DOW <sup>c</sup> is produced by 2000 inhabitants per day                                | Ecoinvent v.3.1                  | ReCiPe Midpoint (H <sup>a</sup> )                | -                  | Lijó et al. (2017)             |
| FU1: 1 m <sup>3</sup> of treated wastewater<br>FU2: 1 MJ CNG (LHV) used in a gas engine | Ecoinvent v.2                    | Recipe 2008                                      | Gabi               | Maga (2017)                    |
| 1 m <sup>3</sup> of municipal wastewater                                                | -                                | TRACI v.2.1                                      | SimaPro v.8.0      | Pfluger et al. (2018)          |
| 1 m <sup>3</sup> of treated wastewater                                                  | Ecoinvent v.2.2                  | TRACI v.2.1                                      | Open LCA v.1.4.2   | Cashman et al. (2018)          |
| 1 m <sup>3</sup> of treated wastewater                                                  | Ecoinvent v.3.2                  | ReCiPe Endpoint and CML 2000 v.2                 | SimaPro v.8.0      | Alvarado et al. (2019)         |
| 1m <sup>3</sup> of treated wastewater                                                   | Ecoinvent v.3.5                  | Recipe and CML 2001                              | SimaPro v.9.0      | Arias et al. (2020)            |
| 5 MGD of medium-strength wastewater                                                     | Ecoinvent v.3                    | TRACI v.2.1                                      | SimaPro v.8.5      | Harclerode et al. (2020)       |
| 1 MGD of municipal wastewater                                                           | Ecoinvent v.3.6                  | Recipe 2008                                      | Capdet Works v.4.0 | Tian et al. (2020)             |
| 5 MGD of treated wastewater                                                             | Ecoinvent and U.S. LCI database  | TRACI v.2.1                                      | SimaPro v.8.0      | Xu et al. (2020)               |
| 1 m <sup>3</sup> of treated wastewater                                                  | Ecoinvent v.3.6                  | Recipe 2008 Midpoint (H) v.1.13                  | Umberto LCA v.10.0 | Foglia et al. (2021)           |
| 1 m <sup>3</sup> of pre-treated wastewater                                              | Ecoinvent v.3.5                  | Recipe 2008 Midpoint (H) v.1.13                  | Open LCA v.1.9     | Rebello et al. (2021)          |
| 2 MGD <sup>c</sup> of domestic wastewater over 30 years                                 | Ecoinvent v.3.4, US LCI          | IMPACT 2002+, and IPCC 2017, ReCiPe Midpoint (H) | Simapro 8.5.2      | Mohammed and Sills, (2022)     |
| 1 kg of removed COD                                                                     | Ecoinvent 3.0, Industry data 2.0 | ReCiPe 2016 Midpoint (H), Endpoint               | SimaPro            | Jiménez-Benítez et al., (2023) |

#### **2.3.4 Interpretation**

The important results arising from the previous phases are discussed and checked for consistency in the interpretation, followed by limitations and recommendations based on the findings (ISO, 2006). A final synthesis of the LCA results is necessary to assure clarity and enhance communication to make decisions. The three primary phases of the LCA interpretation phase are urged to be standardized by ISO 14044: (i) Significant issues are identified (e.g., considering contributions of the construction and operation parts of the WWT, (ii) Evaluation is performed along with assessments for sensitivity and uncertainty. (iii), Recognizing constraints allows for the formulation of conclusions and suggestions. When conducting LCA for wastewater, it is essential to follow these stages in order to undertake an extensive evaluation that can have significant consequences for making decisions. Checks for reliability, sensitivity, and validity are required by ISO (ISO, 2006). It is essential to examine for any weaknesses in the LCA that might affect the result. Results on sensitivity should be considered during interpretation since they might encourage the collecting of further data in the future.

#### ***Sensitivity analysis***

Sensitivity analysis is an essential step for the interpretation of LCA results. Applying uncertainty and sensitivity analysis ensures understanding of the impact of any uncertainty on the results and determining the main points for improvement through inventory data collection or impact assessment (Hauschild et al., 2017). Sensitivity analysis often involves changing selected input parameters one at a time to examine how sensitive the LCA results are to each change.

As critical parameters, such as prices, are volatile in most circumstances or show wide variation in the existing literature based on case-specific assumptions, it is worth investigating how these parameters could affect the economic and environmental performances of the WWT pathways. When analyzing reviewed studies, 35 % of them did not present sensitivity or uncertainty analysis. In the study of Pretel (2015), sensitivity analysis was conducted in two stages: The first stage was an evaluation of the entire decision space, and the second one was restricted to the designs that managers seemed likely to accept. The findings demonstrated that even while the model results were not certain, and alternative values for the microturbines,

transportation distances, and stirring energy, parameters would not have altered the narratives and trends around the sustainable design of submerged AnMBRs that have been identified.

In addition, Harclerode et al. (2020) conducted sensitivity studies on the LCC. The LCA aims to assess the financial and environmental effect factors related to the removal of sulfide and phosphorus. This includes three components: (i) Elimination of the sulfide and phosphorus removal process, (ii) Utilization of coagulants for sulfide and phosphorus removal, and (iii) Biological removal of sulfide.

Besides, the sensitivity analysis was carried out on all variables and constants considered for modeling the projected full-scale AnMBR system in Jimenez's study (2023b). The pivotal midpoint identified in this study served as the foundation for the key impact parameters within the impact categories (CHP electrical efficiency; dissolved methane recovery efficiency; total filtration time).

### ***Uncertainty analysis***

If utilities require complete transparency from suppliers regarding emissions emitted and resources spent while producing chemicals, equipment, and energy, the uncertainty in LCA results will be reduced (Corominas, 2020). Unfortunately, this is not a common application in LCA studies compared to sensitivity analysis. For this reason, only five studies evaluated in this review conducted it. Sills et al. (2016) and Mohammad et al. (2022) conducted an uncertainty analysis. When the results are examined, the anaerobic treatment option applied to remove dissolved methane gave the most beneficial impact results for CC. On the other hand, a Monte-Carlo analysis was performed to evaluate the uncertainty of the data in the study of Arias et al.(2020).

## **2.4 Current LCA Studies on Anaerobic Wastewater Treatment**

Although anaerobic technology presents huge opportunities, it negatively affects the environment like CC and EP. A detailed assessment of the environmental impacts and consequences of the anaerobic treatment technologies' construction and operation phases, reuse, and recovery processes should be done. Even though there are numerous LCA studies about WWT plants or systems, the number of LCA studies using anaerobic treatment systems with municipal wastewater is limited. In this section, 20 studies were analyzed to understand these systems' environmental impact. A summary

of the approach for sensitivity analysis, the goal, and the results of the analyzed studies are given in Table 2.2.

#### **2.4.1 LCA studies on ABRs**

As mentioned before, the LCA studies using different anaerobic technologies exist in this article, such as UASB, AnMBR, ABR, and AFBR systems. Firstly, Sills et al. (2016) discussed the environmental performance of an ABR and system alone and with different assemblies in their investigation. The study results showed that if dissolved methane is captured as gaseous methane and converted to heat and power, the beneficial impacts on resources, ecosystem quality, and human health will increase for all ABR options used in this study. In Mohammed's 2022 study, environmental performances were contrasted across different scenarios, specifically involving both the ABR system and the Rotating Biological Contactor (RBC) simultaneously. Within the modeled ABR - Rotating Biological Contactor (RBC) system, where 80% of the dissolved methane undergoes oxidation in the RBC, there is an 87% reduction in CC impact compared to the ABR system.

A reduction in the formation of biosolids has a positive effect on ecosystems and human health. This is because, aside from the dissolved methane issue, biosolids disposal was approximately five times more detrimental to the trickling filter (TF) assembly than ABR. TF and ABR-TF assemblies have smaller contributions on CC compared to conventional systems operated with anaerobic digestion; this indicated that using a fixed film, low-energy aerobic processes like TF or ABR-TF instead of a CAS has an advantage in most environmental impact categories ((Sills et al., 2016). In the case of three other environmental damage categories considered in the study of Mohammed and Sills (2022) (ecosystem quality, resource depletion, and human health), the assemblies of ABR, RBC - Anaerobic Digestion (AD), and ABR - RBC demonstrated overall beneficial life cycle impacts or neutral impacts. Notably, both the ABR and ABR-RBC systems exhibited more overall beneficial impacts than the RBC-AD system across these three categories, primarily attributed to the positive impact of bioelectricity generated by the ABR (Mohammed and Sills, 2022).

Pfluger et al. (2018) evaluated the life cycle impacts of primary anaerobic treatment of municipal wastewater using ABRs with aerobic secondary treatment compared with CAS. On the other hand, when looking into the study by Pfluger et al. (2018), ABR-

aerobic treatment scenarios had lower environmental impacts for most of the impact categories, including AP, ODP, and ecotoxicity, but also generated more on-site electricity in comparison with baseline CAS scenarios. Also, it was seen that the ABR-aerobic treatment scenarios with dissolved methane removal reduced GWP dramatically.

#### **2.4.2 LCA studies on AFBRs**

Alvarado et al. (2019) used LCA to compare a CAS and AFBR, followed by a partial nitrification/anammox fluidized-bed membrane bioreactor (PN/A-FMBR). Study results showed that AFMBR systems had better energy performance than the activated sludge process. The CO<sub>2</sub> and CH<sub>4</sub> biogenic emissions suggested as GHG-neutral and direct emissions were used in this study. In this context, the biogenic CO<sub>2</sub> emission of the AFBR-PN/A-FMBR option had the lowest value in CH<sub>4</sub> biogenic emissions due to assumed leakage from the anaerobic digesters. Conversely, the direct CH<sub>4</sub> is closely related to the water effluent quality, unlike biogenic emissions. Therefore, the conventional system reduced direct CH<sub>4</sub> emissions in comparison to AFBR-PN/A-FMBR. The AFBR-PN/A-FMBR had lower impacts in almost all impact categories assessed in this study (CC, EP, HT, etc.). Still, when looking at ODP values, the results were comparable in AFBR-PN/A-FMBR and conventional systems.

#### **2.4.3 LCA studies on UASB reactors**

Because of their potential for energy recovery and comparatively cheap operating costs, UASB reactors have emerged as a critical technology for the anaerobic treatment of municipal wastewater. To understand how the UASB systems are affecting the ecosystem or human health, the LCA studies have found essential room in the last decades. The study by Maga et al. (2017) established the feasibility and viability of the sustainable generation of biomethane based on cheap microalgae cultures cultivated in urban wastewater with the UASB configuration as an anaerobic wastewater pre-treatment technology, taking into account the LCA researches evaluated. It was found that using the UASB reactor as a pre-treatment of wastewater contributes to 16% of the total cumulative energy demand (CED) using UASB sludge disposal and the pre-desulphurization of biogas produced by the UASB reactors.

UASB reactors were used as a primary treatment method in 25% of reviewed LCA studies. For instance, Hospido et al. (2012) operated four MBR configurations, one is coupled with the UASB system. They found that the UASB-MBR configuration has more EP than other MBR configurations because of ammonium concentrations, which have high concentrations in the effluent due to poor nitrification capacity under anaerobic conditions and high phosphate concentration. In contrast, the energy production from the biogas generated in the UASB-MBR configuration is the reason behind the negative values in GWP. Moreover, when looking into ecotoxicity potential, the UASB-MBR configuration has one of the lowest values compared with other MBR configurations (Hospido et al., 2012). Another LCA study that used a UASB reactor as a primary treatment was performed by Kalbar et al. (2013). They assessed the environmental footprints of India's widely used sewage treatment technologies, including UASB with facultative aerobic lagoons (FAL). When comparing the UASB-FAL system with the CAS, for all impact categories, it was concluded that the UASB option had lower values than CAS except EP. UASB-FAL system had the highest EP value due to insufficient nutrient removal. On the contrary, when looking into other impact categories, the UASB-FAL system had higher ecotoxicity values than the sequencing batch reactor (SBR) and constructed wetlands (CWs) systems used in the study. In the study of Arias et al. (2020), the environmental and economic perspectives of three different WWT configurations were compared with CAS; one of the configurations is UASB reactors with integrated fixed-film activated sludge (IFAS) used as primary treatment. The UASB-IFAS scenario gave the best results regarding environmental impacts using more electricity production than the other systems and no chemical use. Moreover, the UASB-IFAS system had lower EP than the other configurations because it had better effluent quality. When looking into all impact categories, it was seen that the IFAS unit is the main contributor to all impact categories.

Additionally, the improvement of WWTPs with anaerobic technologies can also be considered within the scope of LCA and LCC. For this purpose, Tian et al. (2020) study evaluated three proposed retrofits of WWTFs; one is the UASB reactor replacing the primary settling tank. The LCA results showed that the retrofitted design considering slow/fast pyrolysis with a primary UASB reactor had higher effects on ecosystem quality and human health. The retrofitted systems, including the primary

UASB reactor, had worse environmental performance than reference system aspects of all impact categories. In the study of Rebello et al. (2021), the UASB reactor was also used as a primary treatment. In that study, 10 WWT plants were evaluated based on UASB followed by a high-rate aerobic pond. When examining the impact results like EP and HT, the UASB system with thermal hydrolysis, biomass recirculation, and CO<sub>2</sub> recirculation from biogas-electricity and heat conversion presented the best results compared with other systems that significantly outperformed the CAS scenario. Furthermore, the highest environmental gain identified was an 80% decrease in the UASB system with biomass and CO<sub>2</sub> circulation and another scenario similar to the UASB scenario, including thermal hydrolysis, biomass, and CO<sub>2</sub> recirculation. Still, there was a difference in the sludge handling part.

On the other side, the UASB reactor was used as a secondary treatment in the study of Foglia et al. (2021), which assessed the environmental impacts of existing WWTPs in Italy in terms of possible reclaimed water reuse scenarios. The results showed that the UASB reactor coupled with AnMBR showed much higher benefits in CC at 28% and FETP at 35% than the baseline scenario (CAS), which used biological oxidation as a secondary treatment. Additionally, the effluent of the UASB reactor coupled with AnMBR is not reused and is directly discharged into a water body. Effluent discharge to the receiving water body contributes to eutrophication considerably by 23%, compared to the baseline. Also, it was realized that if the dissolved methane in the permeate is not recovered, the GWP increases by 28%.

#### **2.4.4 LCA studies on AnMBRs**

In addition to UASB systems, AnMBRs have been widely applied in anaerobic WWT. High effluent quality can be obtained regarding COD, SS, and pathogens compared to conventional anaerobic processes using AnMBRs (Ozgun et al., 2013). With the increasing number of AnMBR applications at WWT, it has become crucial to investigate how it affects environmental and human health or resources. In this review, 35% of studies used AnMBR as an anaerobic treatment method for municipal wastewater. Two of these studies compared the environmental and economic impacts of AeMBRs and AnMBRs for municipal WWT using LCA and LCC under different operation conditions (Cashman et al., 2018) and different effluent end-use scenarios (X. Xu et al., 2020). When the results were examined, operating the reactor at ambient

temperatures rather than mesophilic ranges (35 °C) provided notable CED and GWP savings in the study of Cashman et al. (2018). Also, methane recovery in reactor headspace provided the largest CED gain and GHG emission decrease. On the other hand, in the study by Xu et al. (2020), 42% more energy was recovered from AnMBR than the AeMBR. An AnMBR scenario without a reuse application had much greater impact in almost every impact category than an AeMBR scenario without any reuse application. Furthermore, AnMBR with a reuse option had less impact than AeMBR with a reuse option for the EP category because of nutrient recovery from the AnMBR effluent. Another study that used AnMBR in their LCA study belongs to Harclerode et al. (2020), in which multiple AnMBR trains were compared to CAS treatment. When the results were examined, AnMBR treatment of municipal wastewater with sulfide removal could exhibit a lower environmental footprint compared to traditional treatment methods. Furthermore, all AnMBR scenarios that included primary sedimentation were either energy-neutral or even produced more energy than they consumed. Furthermore, the use of chemicals to remove sulfide and phosphorus resulted in a decrease of over 70% in all measured environmental effect categories for the seven AnMBR scenarios that were assessed.

In addition to the AnMBR studies mentioned previously, three LCA studies were conducted by Pretel et al. (2013; 2015; 2016); the first one is the evaluation of the environmental impact of a submerged AnMBR (SAnMBR) system at various temperatures (2013), the second one is the evaluation of the effects of design and operational measures on SAnMBRs in terms of technological, environmental, and economic sustainability (2015), and the third one is the evaluation of the economic and environmental sustainability of a SAnMBR co-treating municipal wastewater and the organic fraction of municipal solid waste (OFMSW) (2016). When the results are examined, it is found that nearly all impact categories showed a positive environmental impact (negative LCA scores) from the reuse of SAnMBR wastewater. Conversely, it was found that impact categories related to toxicity are negatively affected, such as HT, FETP, TETP, and METP, if dissolved methane is not captured from effluent. Also, the environmental benefits of operation at 33 °C were greater than those at 20 °C since methane production is higher at 33 °C. Based on the LCA data obtained from the studies, it was seen that the system can achieve carbon offsets through resource

recovery and decrease the EP (by around 50%), GWP, and AD impact categories if nutrients, biogas, and soluble methane are recovered.

Similarly, at 25°C the positive net energy balance (NEB) of HRAS-AD declined by 13% as an effect of the temperature change. The negative NEB of AnMBR decreased by 21%, mainly attributed to lower methane solubility, resulting in an increased collection of biogas in Smiths's study (2014). These benefits should be considered in comparison to the installation of smaller-scale combined heat and power (CHP) systems, which may be less economical and efficient than bigger CHP systems located in centralized WWTPs.

The reduction of environmental impacts related to avoiding mineral fertilizer production (ODP, TETP, land use, etc.) is significantly contributed to by the direct reuse of phosphorus and nitrogen from sludge for fertilization purposes. Additionally, the environmental benefits derived from nitrogen recovery in agriculture through sludge spreading counterbalance the drawbacks linked to N<sub>2</sub>O emissions (GWP and ODP), resulting in positive net balances and emphasizing the environmental sustainability of this agricultural practice. Moreover, the EP results emphasize the importance of incorporating nutrient recovery strategies in later post-treatment stage or through enhances the sustainable viability using AnMBR for urban wastewater (UWW) treatment. This strategic approach is intended to maximize the potential for the recovery of resources from the AnMBR effluent. Importantly, it was seen that the implementation of nutrient recovery measures has the potential to mitigate environmental impacts in other categories associated with avoiding mineral fertilizer production in Jimenez's study (2023).

In the study of Lijo et al. (2017), the environmental performance of AnMBR and UASB with SBR configurations was evaluated for the combined treatment of wastewater and domestic organic waste (DOW). When the results were examined, the AnMBR option had a larger environmental effect in terms of CC, ODP, TA, POF, and FD impact categories but a lower environmental effect for FE and ME (related to effluent quality) impact categories than the UASB-SBR option. Also, the UASB-SBR option consumes more electricity than AnMBR because of the aerobic phase of the SBR. Similarly, with the addition of OFMSW to AnMBR influent, membrane cleaning frequency has increased. Therefore, the system's energy demand increased (about 50%) for all scenarios in (2016).

**Table 2.2 : Summary of the goal and results of the analyzed studies.**

| <b>Goal of the study</b>                                                                                                                                    | <b>The main results of the study</b>                                                                                                                                                                                                                                                                                                                                                                                        | <b>Reference</b>      |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| Evaluation of four MBR configurations                                                                                                                       | According to the evaluated five environmental impact categories (EP, CC, ADP, FETP, TETP), the UASB-MBR scenario showed better environmental performance than other MBR configurations (activated sludge-MBR, UCT <sup>a</sup> -MBR, anoxic-aerobic-MBR).                                                                                                                                                                   | Hospido et al. (2012) |
| Evaluation of environmental footprints of most commonly used sewage treatment technologies in India (ASP, SBR, UASB-FAL, CWS).                              | UASB-FAL system showed lower environmental burdens than CAS in all impact categories except EP due to low nutrient recovery. The GWP of UASB-FAL was lower than the ASP and SBR options.                                                                                                                                                                                                                                    | Kalbar et al. (2013)  |
| Assessment of the environmental impact of an SAnMBR system at different operational temperatures.                                                           | The environmental benefits when operating the system at 33 °C were greater than the operation at 20°C due to higher methane production. The toxicity impact category values were increased when the methane dissolved in the effluent was not captured.                                                                                                                                                                     | Pretel et al. (2013)  |
| Evaluation of emerging AnMBR technology in comparison with conventional wastewater energy recovery technologies                                             | AnMBR featured the highest global warming (GWP) impact compared with all other systems. AnMBR had greater environmental impacts in all other categories relative to HRAS-AD.                                                                                                                                                                                                                                                | Smith et al., (2014)  |
| Assessment of design and operational decisions of SAnMBRs technological, environmental, and economic sustainability across its life cycle.                  | The nutrient recovery reduced EP by approximately 50% and significantly reduced METP, GWP, and AD due to the avoided fertilizer use.<br>If nutrients, biogas, and soluble methane are recovered, the system under study achieves carbon offsets through resource recovery (up to -0.059 kg CO <sub>2</sub> /m <sup>3</sup> for methane recovery and up to -0.067 kg CO <sub>2</sub> /m <sup>3</sup> for nutrient recovery). | Pretel et al. (2015)  |
| Evaluation of the economic and environmental sustainability of a SAnMBR co-treating MWW and OFMSW <sup>b</sup> at ambient temperature in mild/hot climates. | Increasing the SRT (e.g., from 40 to 70 days) and co-treating MWW and OFMSW enhanced the environmental performance of AnMBR systems: the environmental impact through GWP, AP, and METP was considerably reduced.                                                                                                                                                                                                           | Pretel et al. (2016)  |
| Comparing the environmental and economic performances for treatment of dilute MWW at low temperatures with ABR and TF-AD technologies.                      | For all impact categories, disposal of biosolids was more harmful (5 times) for the TF assembly compared to the ABR system due to the bioenergetics of anaerobic versus aerobic processes. ABR treatment (at 15–20°C) was not beneficial for CC unless a post-treatment was used.                                                                                                                                           | Sills et al. (2016)   |
| Assessment from an environmental perspective of two different configurations (AnMBR, UASB-SBR) for the co-treatment of wastewater and DOW <sup>c</sup> .    | AnMBR had a larger environmental effect in CC, ODP, TA, POF, and FD impact categories but vice versa for FE and ME (related to effluent quality) than the UASB-SBR system.                                                                                                                                                                                                                                                  | Lijó et al. (2017)    |

**Table 2.2 (Continued) : Summary of the goal and results of the analyzed studies.**

| Goal of the study                                                                                                                                                                                                               | The main results of the study                                                                                                                                                                                                                                                                                                                                | Reference                |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| Assessment of the environmental performance of; (i) WWT-applied algae biorefinery compared to CAS, (ii) biomethane production from microalgae compared to CNG <sup>d</sup> used as automotive fuel.                             | The anaerobic pre-treatment (UASB) contributed 16 % of the CED.<br>FWEP and MEP are driven by phosphate, ammonia, and nitrate emissions attributed to sludge treatment and disposal of the UASB reactor.                                                                                                                                                     | Maga (2017)              |
| Evaluation of the lifecycle impacts of primary anaerobic treatment of MWW using ABRs coupled with aerobic secondary treatment compared to CAS.                                                                                  | ABR-aerobic treatment system reduced environmental impacts by comparing CAS scenarios, including AP, fossil fuel depletion, ODP, respiratory effects, ecotoxicity, and smog.                                                                                                                                                                                 | Pflugger et al. (2018)   |
| Determining the impact of population density, scale, and climate factors on the environmental and cost performance of AnMBR and AeMBR systems and reusing water for non-potable purposes by performing an LCA and LCC analysis. | When AnMBRs were operated at psychrophilic conditions (20°C) in warmer climates, they represented a promising technology for decreasing the environmental impacts of WWT systems. Potential CED and GWP benefits of the AnMBR operation under psychrophilic conditions increased in warmer climates and when dissolved methane in permeate was recovered.    | Cashman et al. (2018)    |
| Evaluation of methodological development of the LCI with the standardization of data collection and processing with CAS and AFBR, followed by PN/ AFMBR.                                                                        | AFMBR systems had better energy performance than the CAS option.<br>The AFBR-PN/AFMBR system had lower environmental impacts in almost all categories assessed in this study (CC, EP, HT, etc.), except ODP, compared to the CAS.                                                                                                                            | Alvarado et al. (2019)   |
| Evaluation from an environmental and economic perspective of three different WWT configurations (UASB-IFAS, HRAS-IFAS-RBF, and CEPT-IFAS) compared to CAS.                                                                      | UASB-IFAS and HRAS-IFAS treatment options were the best in energy production and effluent quality compared to CAS. The CAS system was the worst option regarding environmental impact in almost all categories compared to the UASB system.                                                                                                                  | Arias et al. (2020)      |
| Comparing multiple AnMBR-based MWW trains to the CAS system.                                                                                                                                                                    | AnMBR treatment system of MWW had the potential to have a less environmental impact than CAS, provided sulfide removal, and was conducted using a sustainable process (biological sulfide oxidation).<br>From an energy point of view, scenarios with primary sedimentation before AnMBR treatment were preferable though the LCC might be slightly greater. | Harclerode et al. (2020) |

**Table 2.2 (Continued) : Summary of the goal and results of the analyzed studies.**

| Goal of the study                                                                                                                                                                        | The main results of the study                                                                                                                                                                                                                                                                           | Reference                      |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|
| Assessment of economics and life cycle environmental impacts of three proposed retrofits of WWTFs.                                                                                       | The environmental impacts of the retrofitted with HTL <sup>f</sup> are close to that of CAS, while the retrofits with pyrolysis induce higher impacts.<br>The retrofitted system with UASB had higher than CAS with tertiary treatment for all impact categories.                                       | Tian et al. (2020)             |
| Comparing environmental and economic impacts of full-scale aerobic and anaerobic MBRs for MWWT under different end-use scenarios using LCA and LCC.                                      | 42% more energy was recovered from AnMBR than AeMBR (also from CAS).<br>AnMBR with direct discharge had much greater impacts in almost every category than AeMBR with direct discharge AnMBR with reuse had less environmental impact than AeMBR with reuse due to nutrient recovery, especially in EP. | Xu et al. (2020)               |
| Comparing environmental and economic impacts of full-scale aerobic and anaerobic MBRs for MWWT under different end-use scenarios using LCA and LCC.                                      | The UASB-AnMBR scenario showed much higher relative benefits than CC (-28%), FD (-31%), mineral resource depletion (-52%), and FWET (-35%) compared to the CAS.                                                                                                                                         | Foglia et al. (2021)           |
| Investigate the environmental and economic impacts of existing conventional WWTPs in Peschiera (Italy) and possible upgrading scenarios to enable reclaimed water reuse for agriculture. | Regarding AP, EP, and most other impact categories, the UASB system with biomass and CO <sub>2</sub> recirculation had the lowest environmental impact values compared with CAS.                                                                                                                        | Rebello et al. (2021)          |
| Comparison with the environmental performance of three treatment scenarios: ABR system, RBC-AD system, and ABR-RBC system.                                                               | The ABR treatment has the lowest NPV and the most negative environmental consequences, whereas the ABR-RBC treatment has the highest NPV and the most positive environmental consequences.                                                                                                              | Mohammed and Sills, (2022)     |
| Assessment of the environmental performance of a projected full-scale AnMBR treating UWW at ambient temperature                                                                          | Recovering the D-CH <sub>4</sub> with efficiencies of 80–84% led AnMBR to act as carbon sink (emissions avoidance up to 0.223 kgCO <sub>2</sub> eq/kgCODrem)<br>AnMBR performed as an energy producer (NED between -0.277 and -0.688 kWh/kg CODrem)                                                     | Jiménez-Benítez et al., (2023) |

<sup>a</sup> University of Cape Town modified configuration, <sup>b</sup> high rate activated sludge <sup>c</sup> organic fraction of municipal solid waste, <sup>d</sup> domestic organic waste, <sup>e</sup> compressed natural gas, <sup>f</sup> combined heat and power, <sup>g</sup> hydrothermal liquefaction, <sup>h</sup> Net present value

## 2.5 Energy Assessment

The advantages of anaerobic systems are closely tied to the transformation of gaseous methane into valuable energy forms, such as electricity, and the oxidation or valorization of dissolved methane. Moreover, in certain regions, integrating this energy recovery with water-reuse technologies has the potential to boost overall energy yields and improve access to clean water (Mo and Zhang, 2013). The anaerobic primary treatment scenarios demonstrated a reduced Net Energy Balance (NEB) compared to baseline CAS-AD scenarios; the scenario with anaerobic digestion of sludge utilized only 34-53% of the energy required for CAS-AD operation, (Pfluger et al., 2018). This indicates a potential energy efficiency improvement in anaerobic primary treatment configurations relative to the CAS baseline scenarios. In Alvarado et al.'s study, it is given information that the AFMBR systems had better energy performance than the activated sludge process.

One of the most important factors determining the energy demand in both aerobic and anaerobic WWT systems is sludge production. Due to issues such as dewatering, treatment, and disposal of this sludge, sludge production accounts for a significant proportion of the overall energy demand in the entire treatment plants. As an example, one can refer to the study conducted by Smith and colleagues (2014) comparing the life cycle of AnMBR with HRAAS-AD systems. According to the data obtained from this study, the energy demand for sludge thickening and dewatering in the HRAAS-AD system is approximately three times that of the AnMBR system. However, the energy expended by the AnMBR system is mainly due to gas recirculation, making it four times that of the HRAAS-AD system. It's worth noting that the gas scouring method employed to prevent membrane fouling plays a substantial role in the energy demand of treatment systems utilizing membranes; it accounts for about 50 % of energy demand in Pretel's study (2016), 86% of the total energy demand in Smith's study (2014) and in the scenarios using for gas sparging for the membrane fouling is higher energy demand than the scenarios using other membrane fouling methods in Harclerode's study (2020).

Meanwhile, operating temperature is another key issue for the energy demand in anaerobic treatment systems. Higher operating temperatures in anaerobic systems lead to improved energy efficiency as a result of enhanced hydrolysis and net methane

production. However, in cold areas, heating the anaerobic reactor may lead to increased energy consumption. The primary contributor to Cumulative Energy Demand (CED) in the mesophilic AnMBR was the heating of the influent using natural gas. Notably, conducting the reactor at room temperature rather than a higher temperature (35 °C) of led to substantial savings in both CED and GWP (Cashman et al., 2018). This highlights the significance of taking into account both climate conditions and operating temperatures as crucial factors for evaluating the life cycle effects of CED in anaerobic WWT systems. In another study, the prospect of raising the operating temperature from 27°C to 35°C was deemed unsustainable due to the significant heat energy requirement (9.3 kW/m<sup>3</sup>) (Pretel et al., 2016). Because of this uncertainty, each study should be evaluated individually.

Regarding temperature considerations, energy recovery from both methane gases in biogas and dissolved methane in the effluent emerges as a critical concern for energy demand. Lower temperatures may result in reduced methane solubility, leading to a decline in the efficiency of biogas recovery. This decrease in biogas production necessitates more energy input to capture it and less energy production for the entire system. As an illustration, in Sills's study (2016), the positive effects on all environmental impact categories resulting from bioelectricity production would rise by 30% for the ABR-CW and ABR, and by 20% for the ABR-TF gathering, considering that approximately one-third of the methane produced is dissolved methane. In addition, the most favorable outcome identified from a comprehensive environmental assessment was the operation of a psychrophilic AnMBR in a warm climate. This system would allow for the recovery of methane through combined heat and power (CHP) generation, as well as the capture of both headspace and dissolved methane (Cashman et al., 2018). Furthermore, it was discovered that achieving dissolved methane recovery exceeding 83% would ensure negative net greenhouse gas (GHG) emissions (Jiménez-Benítez et al., 2023).

## **2.6 Economic Evaluation**

In addition to LCA, evaluating the economic consequences is also essential for sustainable wastewater management. 64% of studies within this review gave information about their studies' cost analysis and economic consequences. The cost results showed that in the evaluated LCA studies that used AnMBRs, membrane

cleaning costs constitute approximately 5-7% of the operating cost. Additionally, primary sedimentation application before AnMBR could be preferable due to having higher cost values of the membrane cleaning (Harclerode et al., 2020). Pretel et al. (2016) found that the AnMBR scenarios employing high SRT (70 days) had the lowest operating costs due to the high biogas production. In that study, the operating cost of the scenarios using organic waste with wastewater was higher than those using only wastewater because of the increase in membrane cleaning cost. Additionally, in the study of Cashman et al. (2018), it was realized that AnMBR's overall cost was significantly impacted by the operating temperature. When the system was operated at 20°C instead of 35°C, all cost components, such as capital cost, operation, and energy cost, were reduced. Also, it was concluded that the cost of AnMBRs was higher than AeMBRs. In the same way, Xu et al. (2020) found that the operating cost of AnMBRs was higher than AeMBRs in case of direct discharge; however, the reuse of nutrient-rich anaerobic effluents as fertilizer makes AnMBR economically competitive with all AeMBR options in the study.

In the study of Pfluger et al. (2018), ABRs were compared with CAS, and the anaerobic primary treatment scenarios had lower cost values than CAS. Moreover, this study showed that the LCC of systems that used primary anaerobic treatment coupled with the aerobic system had lower values in most examined impact categories than CAS due to lower sludge and more biogas production. Similarly, it was observed that the application of municipal WWT with ABR systems or ABR coupled with TF systems has lower operating and capital cost components in the study by Sills et al. (2016). Also, one of the essential remarks about capital and operating costs is sludge disposal, which is less costly in anaerobic options than aerobic ones because of lower sludge production.

In addition to these results, in the study of Foglia et al. (2021), it was seen that using the UASB reactor coupled with AnMBR and reusing the effluent has the lowest energy cost compared to other scenarios (aerobic treatment with different disinfection and reuse options) thanks to the energy recovery. Nevertheless, this scenario's overall cost is the highest of all because of the need for membrane investment and replacement. Also, the energy cost of the UASB-FAL option in the study of Kalbar et al. (2013) has one of the lowest costs compared with aerobic options due to zero aeration demand, with the cost potentially being further reduced if biogas from the UASB reactor is

utilized. Moreover, in the study of Tian et al. (2020), the usage of the UASB reactor instead of the primary sedimentation tank decreases the total equipment cost by minimizing the aerated bioreactor volume. Additionally, it was realized that the maintenance cost has the largest share in the total cost of all alternatives, and retrofitting with pyrolysis had the lowest maintenance cost.

Furthermore, the UASB-IFAS treatment scheme had the lowest environmental prices for different impact categories compared to other treatment schemes (HRAS-IFAS, RBF (rotating belt filter) -CEPT (chemically enhanced primary treatment) -IFAS, and CAS) in the study of Arias et al. (2020). When examining operational and construction costs, in concerning operational costs, UASB-IFAS and HRAS-IFAS options were the most advisable compared to the other options due to electricity production. Besides, enhancements in energy production via biogas demonstrate a potential 50% reduction in operating costs. This is observed in scenarios UASB-IFAS and HRAS-IFAS, showcasing the advantages linked to this form of production. However, in the RBF-CEPT-IFAS scenario, despite higher energy production compared to the conventional system, operational costs increase due to additional chemical consumption. Furthermore, it was observed that the inclusion of the IFAS unit led to a 13% reduction in electricity consumption related to aeration, consequently lowering the associated costs.

In addition to the comprehensive cost assessments in the analyzed studies, the study conducted by Jimenez et al. (2023a) the LCC analysis of AnMBR technology revealed variations in the net energy demand (NED), ranging from -0.210 to -0.645 kWh/kgCODrem. The highest energy consumption was assigned to reactor mixing (0.056–0.124 kWh/kgCODrem) and membrane scouring (0.048–0.120 kWh/kgCODrem). The outcomes derived from the LCC assessment demonstrate that AnMBR stands as a potential alternative to conventional aerobic treatments. Its definitive advancement hinges, among other factors, on reinforcing its economic sustainability (Jiménez-Benítez, Ruiz-Martínez, et al., 2023).

When we look at the cost-related results within the evaluated anaerobic LCA studies, the following conclusion can be drawn; additional measures that contribute to enhancing its economic performance involve addressing nutrient recovery from the effluent and establishing favorable pricing for the sale of electricity generated from the produced methane.

## 2.7 Future Perspective

As mentioned before, data on construction, wastewater collection and transportation, and demolition are out of scope in most studies analyzed in this review and other LCA studies about WWT systems. Whether the inclusion of the construction phase in the system boundary is necessary or not has been a debate among researchers for years. Although the adverse effects of the construction phase are negligible, the environmental and cost evaluations should be researched, and more data should be obtained. Furthermore, it was discovered that the construction phase significantly affected a number of impact categories, including a 51-71% impact on the scarcity of mineral resources, an 18-27% impact on the scarcity of fossil resources, and a significant 21-28% impact on water use. The weight of the construction phase accounted for 8-13% of the total direct GWP impact (Jiménez-Benítez et al., 2023b). For a complete assessment of a treatment system, the excluded components of the system boundary must be carefully chosen.

Other significant points about LCAs concerning anaerobic WWT are sensitivity and uncertainty analyses. Sensitivity analysis often gives information about changing input parameters to examine how sensitive the LCA results are to each change. Using analytical approaches, LCA practitioners have discussed some sources of uncertainty in their LCA results, such as inaccurate measurements, methodological choices throughout the LCA, mathematical correlates, etc. (2018). In our study, 35% of the reviewed studies did not conduct any sensitivity or uncertainty analysis. Recent studies have used analytical or numerical approaches to examine uncertainty (Lam et al., 2020). The application of sensitivity analysis in LCA studies should be extended to assess the validity of the results.

Combining LCA with other system approaches like social and economic assessments can be considered for future research on LCAs about anaerobic treatment. As observed in the evaluated studies, economic assessments are commonly incorporated into LCA studies, while the inclusion of social assessments is less prevalent. Specifically, among the 20 studies reviewed, none included a social LCA study. The proper integration of such approaches with LCA has been limited (Byrne et al., 2017). The multifunctionality of economic and social approaches may provide LCAs with more effective implementations for sustainable WWT.

This study analyzed the environmental and economic effects of LCA studies using anaerobic WWT methods. As mentioned previously, ABRs, AFBRs, AnMBRs, and UASB reactors were used in LCA studies. Recent anaerobic treatment technologies should also be considered like EGSB, other ANMBR configurations, etc in future research. In anaerobic treatment, two essential criteria should be investigated: Water quality of effluent and dissolved methane in the effluent. According to the LCA studies examined some provided information about how the environmental and economic impacts change if dissolved methane is captured and recovered (Cashman et al., 2018; Sills et al., 2016), while some ignore them. In the The ABR's detrimental effects on CC were dominated by dissolved methane emitted from discharged wastewater, which accounted for 95% of the impact. This finding is consistent with prior research by (Smith et al., 2014) indicating that dissolved methane in anaerobic effluents is responsible for 75-95% of the environmental impact of CC. To make a better examination of the effect of dissolved methane on the environment and natural resources, these factors should also be considered.

When examining the analyzed studies, it was seen that the comparison of anaerobic municipal WWT systems with aerobic systems or CAS had been conducted, in general. The comparisons between different anaerobic systems should be prioritized in future studies to provide a better insight into which anaerobic treatment technology or pathway is more environmentally and economically friendly to avoid studying energy-consuming technologies. For instance, depicting the results of biogas production or the recovery ratio of dissolved methane coming from the effluent of different anaerobic treatment technologies would be helpful for anaerobic LCA studies. In this regard, the number of LCA studies related to anaerobic treatment technologies should increase to make more widespread anaerobic treatment applications in favor of their capacities for energy saving on national and global levels.

Another vital future improvement in anaerobic treatment LCA studies is integrated resource recovery. Economic and environmental experts make a remarkable effort to recover and reuse wastewater because it constitutes many valuable resources (Puyol et al., 2017). The next generation of municipal WWTPs aims to achieve energy neutrality, or even positivity, through complete nutrients (nitrogen and phosphorus) and energy recovery using anaerobic technology. Four studies of the 20 papers analyzed in this review evaluated energy recovery and nutrient recovery. The current

knowledge of the role of nutrient recovery and its environmental impact is scarce in the literature.

## **2.8 Conclusion**

LCA and environmental footprints have been widely discussed in the last decades to evaluate the environmental sustainability of systems or processes in terms of different environmental items like WWT technologies. Anaerobic WWT systems are preferable due to several benefits, such as their energy recovery capability and low energy consumption, compared to aerobic systems. This paper presents LCA studies dealing with anaerobic WWT technologies for municipal wastewater. At the same time, most reviews in the literature reviews discuss the development and management of conventional WWT systems or plants. This systematic review discusses sketching system boundaries, selecting the impact categories in the life cycle inventory and the impact assessment methods, interpretation of the results, and cost analysis in anaerobic treatment systems. When looking at LCA studies using anaerobic WWT technologies, some environmental impact categories show how these systems have contributed to the adverse effects on the earth, human health, and resources. The reviewed studies revealed that anaerobic WWT systems have lower environmental effects in terms of the most impact categories compared to conventional systems. Through energy recovery, anaerobic treatment systems have lower overall energy demand than aerobic treatment systems; therefore, they can potentially be energy neutral or energy positive under optimum operation conditions. However, if dissolved methane from anaerobic effluents is not captured and recovered, it causes an extra GWP effect and may also increase toxicity. In addition to dissolved methane, the EP increase may also occur if nutrient recovery is not carried out following the anaerobic unit by adding an aeration system or other alternatives. Another reason for the increased EP is the direct effluent discharge to the water body after anaerobic treatment without any reuse. LCA studies generally compare a chosen anaerobic process and CAS in the literature. However, the life cycle studies comparing anaerobic technologies with each other are limited, and LCA and wastewater practitioners should further investigate this subject. In addition to the definitions of methodologies suggested by ISO standards, extending LCAs with other technical tools like cost analysis TEA, social assessments, etc., has been vital in making integrated LCA studies.

### **3. LIFE CYCLE ANALYSIS OF ANAEROBIC FORWARD OSMOSIS MEMBRANE BIOREACTORS (ANFOMBRs) FOR MUNICIPAL WASTEWATER TREATMENT: USE OF DIFFERENT DRAW SOLUTIONS<sup>2</sup>**

#### **3.1 Introduction**

The urban water systems must expand their objectives beyond human health and water quality protection to achieve long-term ecological sustainability. In pursuit of greater sustainability, two primary approaches have emerged for improving wastewater treatment plants (WWTPs); energy efficiency improvement and resource recovery. Besides, reuse of treated wastewater offers multiple ecological benefits, including reducing the demand for freshwater and augmenting water supplies for various purposes. By maximizing energy capture from wastewater and minimizing energy use in treatment processes, wastewater treatment could transition from an energy consumer to a net energy producer (Lundin et al., 2000; McCarty et al., 2011; Mo & Zhang, 2013).

Membrane bioreactors (MBRs) stand as a notable wastewater treatment innovation, integrating biological treatment with membrane separation to achieve heightened efficiency in the treatment of municipal and industrial wastewater (Wang et al., 2016). MBRs, in contrast to conventional activated sludge (CAS) systems, deliver numerous advantages including a reduced spatial footprint, diminished sludge generation, and enhanced quality of effluent (Stazi & Tomei, 2018). Conversely, as an emerging technology, forward osmosis (FO) has garnered increasing interest due to its associated benefits, including high-quality product water, low energy consumption, and minimal fouling propensity. A new concept has recently evolved that incorporates the FO process within an MBR configuration, referred to as an osmotic membrane bioreactor

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<sup>2</sup> This chapter is submitted to “Environmental Monitoring and Assessment” as Yilmaz, M., Guven, H., Ozgun, H., Ersahin, M. E., & Koyuncu, I. “Life Cycle Analysis Of Anaerobic Forward Osmosis Membrane Bioreactors (AnFOMBRs) For Municipal Wastewater Treatment: Use Of Different Draw Solutions”.

(OMBR). Compared with conventional MBRs utilizing hydraulically driven processes like as microfiltration (MF) and ultrafiltration (UF), OMBRs have three notable advantages: better pollutant removal, lower membrane fouling and higher membrane fouling reversibility. (Liu et al., 2020) By integrating a FO membrane into an anaerobic bioreactor to retain and concentrate soluble organics, the innovative Anaerobic Osmotic Membrane Bioreactor (AnOMBR) is designed to achieve multiple objectives within a single, unified system. This includes high treatment efficiency for domestic wastewater, superior effluent quality, reduced energy demand, and enhanced methane yield. (Ansari et al., 2017; Gu et al., 2015).

Life cycle analysis (LCA) is a systematic tool that analyzes the environmental burdens caused by a product, service, or process throughout its 'life' and the potential effects of these burdens on the environment. LCA encompasses all energy, water, and material inputs, as well as waste and emissions generated throughout the life cycle of a product or process, and calculates the potential environmental impacts (Rebitzer et al., 2004; Mammodova et al., 2017; ISO, 2006). Besides industrial products, LCA studies regarding wastewater treatment systems have been increasing paralleling rapid urbanization and population increase since the 1990s. According to Razman et al. (2022), the MBR dominates the LCA studies dealing with membrane technology as there are many configurations and they are commonly used processes in past years. For example; the energy and life cycle and cost profiles of aerobic membrane bioreactors (AeMBRs) and anaerobic membrane bioreactors (AnMBRs) were determined in Cashman et al. (2018)'s work. The GWP and cumulative energy demand (CED) were found to be highly sensitive to reactor temperature in AnMBRs. When operating in warm areas and recovering the dissolved methane ( $\text{d-CH}_4$ ) in the permeate, the psychrophilic AnMBR's potential CED and GWP advantages improved. While operating the AnMBR at room temperature resulted in significant energy and GHG savings, the AnMBR costs remained higher than the AeMBR in all scenarios. On the other hand, Medeiros et al. (2023) investigated quantifying the energy demand and carbon footprint over the life cycle and the financial cost of sewage treatment with the recovery of  $\text{d-CH}_4$ . The energy demand, carbon footprint, and financial cost in the scenario with the  $\text{d-CH}_4$  recovery varied by +12%, -16%, and +2.3% compared to the scenario without the  $\text{d-CH}_4$  recovery. In addition, Resource recovery from sewage treatment with higher chemical oxygen demand (COD) influent, improved removal efficiency, cleaner electricity sources, and enhanced  $\text{d-CH}_4$  removal efficiency can

significantly improve biorefinery sustainability. These measures are crucial for promoting water, energy, and food security in the watershed, demonstrating their essential role in environmental engineering practices. Conversely, Harclerode et al. (2020) conducted a comprehensive LCA to compare domestic wastewater treatment systems like AnMBRs and CAS treatment. It was found that the removal of sulfide from AnMBR effluent using chemical coagulation was found to have a greater environmental impact compared to d-CH<sub>4</sub> removal and AnMBR energy efficiency methods.

Among the wastewater treatment technologies, FO and anaerobic digestion (AD) have emerged as promising methods for wastewater treatment (Ferrari et al., 2019; Y. Gao et al., 2020a). FO offers the advantages of moderate fouling propensity and easier fouling removal compared to pressure-driven membranes among other membrane technologies. The FO and AD technologies represent a shift in wastewater treatment towards removing pollution and focusing on resource recovery, energy generation, and sustainable water reuse. The selection of draw solution (DS) in forward osmosis (FO) systems both aerobic and anaerobic ones, is critical for the overall performance and efficiency of the process. The DS generates the osmotic pressure required to drive water flux across the membrane during the FO process. An ideal draw solution (DS) is expected to exhibit high osmotic pressure while causing no damage to the membrane or biogas production. Additionally, it should have minimal environmental and human health impacts, ensuring sustainability and safety in forward osmosis (FO) applications. An appropriate DS not only ensures high water flux but also minimizes energy consumption and reduces membrane fouling, thereby enhancing the system's operational sustainability and performance (Achilli et al., 2010; Bacaksız, 2019).

Due to the limited number of full-scale plants utilizing AnFOMBR technology, few LCA studies have been conducted on this topic. In the literature, Ferrari et al. (2019)'s pilot-scale study, the feasibility of concentrating real raw municipal wastewater using a submerged plate and frame FO module (0.34 m<sup>2</sup>) to achieve 70% water recovery is investigated for the first time. The study assesses membrane performance, fouling behavior, and the effective concentration of wastewater compounds by testing various draw solutions. In this study, sodium chloride (NaCl) proved to be a more suitable draw solute than magnesium dichloride (MgCl<sub>2</sub>) due to its higher water flux, lower cost, and lower final salinity in the concentrated feed solution, which is important for minimizing potential inhibitory effects on downstream biological processes.

Furthermore, some studies investigate draw solution performance,  $d\text{-CH}_4$  rejection performance, and differences in dissolved gas transfer in anaerobic FO membrane systems (Song et al., 2018; Gao et al., 2020; Zhang et al., 2019). However, existing studies have primarily been comparative and have not specifically focused on analyzing the environmental sustainability of AnFOMBR technology itself.

Two parallel LCA analysis were carried out to assess the environmental sustainability of possible full-scale AnFOMBR systems to address the gap for these systems. This study aimed to assess the effectiveness of mainstream treatment of domestic wastewater with the AnFOMBR system, which involves pre-treatment units, MBR unit (AnFOMBR unit, DS tank and reconcentrated tank), sludge treatment, and combined heat and power using the LCA approach. It was investigated the impact on LCA results of two commonly utilized draw solutions ( $\text{NaCl}$  and  $\text{MgCl}_2$ ) and their varying concentrations (0.5 M and 1 M) on the overall environmental performance. A separate LCA analysis was also used to assess the environmental effects of four distinct draw solutions (DS). Since an additional RO system is not needed in the fertilizer scenario to re-concentrate the DS used in this technology, the results of the study were considered with the expectation that this situation would affect the results.

## **3.2 Material and Methods**

### **3.2.1 Goal and scope**

To properly define the goals and aims of conducting the study, it is essential to explain the application areas of the Life Cycle Assessment (LCA) results (ISO, 2006). To determine the best operating conditions that minimize environmental burdens while maximizing treatment efficiency across a range of draw solutions and concentrations, the main objective of this LCA study is to methodically evaluate and quantify the environmental impacts of AnFOMBRs for the treatment of domestic wastewater. A critical component of the analysis is to investigate how different draw solutions and their varying concentrations influence the overall environmental performance of the system. There are two primary assessments in this LCA research. The first evaluation compares the effects on the environment of using two different DS solutions at varying concentrations in the AnFOMBR system. The second evaluation looks at how utilizing four different DS solutions—fertilizer (monoammonium phosphate, (MAP)- $\text{NH}_4\text{H}_2\text{PO}_4$ ),  $\text{NaCl}$ ,  $\text{MgCl}_2$ , and sodium sulfate ( $\text{Na}_2\text{SO}_4$ )—in the system affects the

environment. Environmental impact categories are considered, including toxicity, resource depletion, eutrophication, and the potential for global warming. Ultimately, the insights gained from this LCA will improve the sustainability of FO-based wastewater treatment processes, guiding future design and operational strategies in this field.

### 3.2.2 Functional unit and system boundary

Selecting the appropriate Functional Unit (FU) is crucial for conducting LCA studies effectively. The FU should represent all functional outputs, including flows and emissions, in a meaningful and representative manner. In wastewater treatment LCAs, commonly employed functional units (FUs) include the volume of treated wastewater, person equivalent (p.e.), and the removal of pollutant loads in the effluent (such as kg  $\text{PO}_4^{3-}$  eq. removed, kg N removed, etc.) (Yilmaz et al., 2024). Therefore, a volume-based functional unit has been selected; 1 m<sup>3</sup> of permeate produced, which better reflects the system's function when considering the quality of the final effluent.

This study includes several operational stages in the impact assessment, specifically focusing on wastewater treatment, sludge treatment, reconcentration of the draw solution, and biogas production processes. The construction and demolition phases were not considered due to their limited impact relative to the overall assessment. Fig 3.1. illustrated the system boundary used in this study, delineating the scope of analysis and the interactions considered within the evaluated processes.

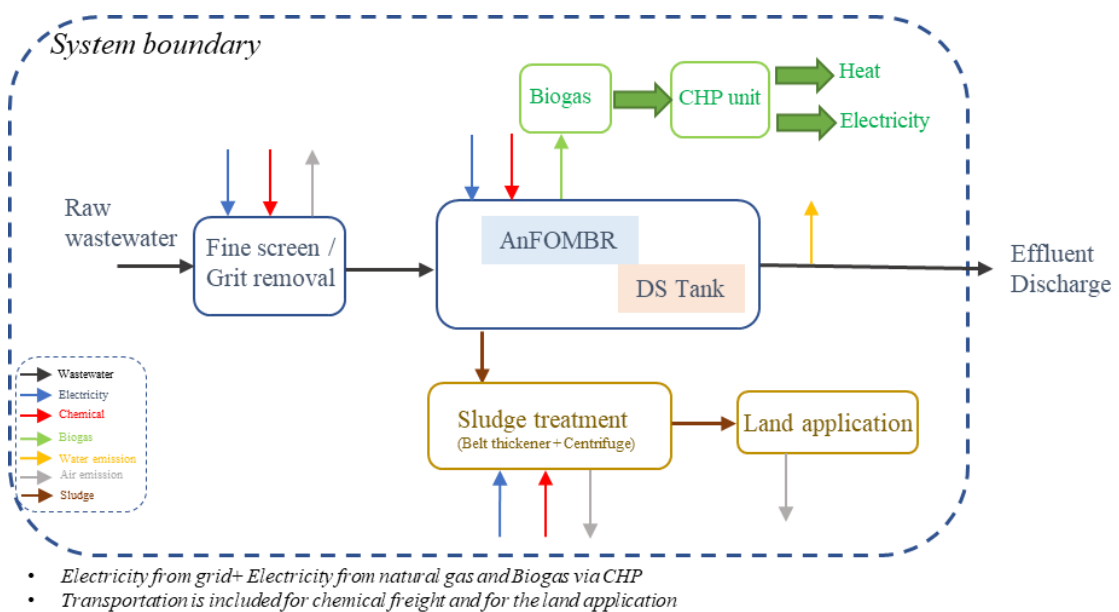


**Figure 3.1 :** The system boundary of this LCA study.

### 3.2.3 Life cycle inventory

This study's life cycle inventory data were sourced from research papers on anaerobic treatment systems. Additionally, data for the LCA of materials used in various system components were obtained from the Ecoinvent 3.9.1 database. Draw solutions with different types or concentrations generate varying levels of osmotic pressure. Since DSs possess distinct chemical and physical characteristics, so they directly influence FO processes' performance (Achilli et al., 2010; Bacaksız et al., 2019).

The wastewater treatment system, used in this LCA study, design was based on literature and previous studies conducted on experimental forward osmosis membrane bioreactor (FOMBR) and anaerobic forward osmosis membrane bioreactor (AnFOMBR) systems. This system consists of two main stages the first involves water recovery from the feed solution (wastewater) and the dilution of the draw solution, while the second focuses on regenerating the diluted draw solution and producing high-quality product water.

- The treatment performance data for various DS and its different concentrations were evaluated based on the research conducted by Hasanoglu et al. (2024), Gao et al. (2020), Adnan et al. (2019), and Bacaksız (2019). These treatment efficiencies were taken as a basis during the data calculations.
- According to the results of Gao et al. (2021), d-CH<sub>4</sub> was almost completely rejected by FO membranes. So, d-CH<sub>4</sub> in the effluent was ignored.
- The systems were assumed to have a lifespan of 15 years, considering the adverse effects resulting from the continuous circulation of a significant concentration of contaminants within the system, as indicated in prior studies (Ansari et al., 2017; Valladares Linares et al., 2016))
- For sludge dewatering, energy requirements were sourced from Hospido et al. (2012). Transport of chemicals was assumed to be carried out by van (under 3.5 tons), while trucks (7.5–16 tons) were selected for sludge disposal.
- The corresponding energy generation processes from natural gas were selected. Associated air emissions from biogas combustion were included using the emission factors reported by Doka (2007).

- The typical cleaning procedure for FO membranes involves an initial acid cleaning to remove scaling, followed by basic cleaning with surfactants to remove organic matter and other colloids (Giagnorio et al., 2021).
- It was assumed that the sludge thickener has one output: thickened sludge. Consequently, the study does not include side wastewater streams (thickener supernatants).
- The fertilizer usage as DS in FO systems offer the advantage of eliminating the need to separate and recover draw solutes, resulting in significantly lower energy consumption compared to desalination for using the RO process (Phuntsho et al., 2012).

**Table 3.1 :** Wastewater characterization of municipal real wastewater as the influent of AnOMBR in this study (Gao et al. 2020a).

| Water quality parameters | Concentration (mg/L) |
|--------------------------|----------------------|
| COD                      | 522.3                |
| TN                       | 55.4                 |
| TP                       | 8.5                  |

Wastewater characterization of municipal real wastewater as the influent of AnOMBR in this study is given in Table 3.1.

The summary of the data inventory taken from the related LCA studies is shown in Table 3.2.

**Table 3.2 :** Inventory data of this LCA study (per functional unit).

|                                      | Item/material                                  | Value     | Unit | Source                      |
|--------------------------------------|------------------------------------------------|-----------|------|-----------------------------|
| <b>Pre-treatment</b>                 | Screening waste                                | 3.4E-03   | kg   | ISKI (2023)                 |
|                                      | Grit                                           | 15.3E-03  | kg   | ISKI (2023)                 |
| <b>Membrane materials</b>            | Cellulose triacetate (Active layer)            | 3.68E-05  | kg   | Salinas et al. (2022)       |
|                                      | Polysulfone (PSF) (Support layer)              | 3.80E-04  | kg   | Pazouki et al. (2021)       |
| <b>Membrane cleaning</b>             | EDTA, (ethylene diamine tetraacetic acid)      | 2.80E-02  | kg   | Pazouki et al. (2021)       |
|                                      | Sodium hydroxide                               | 2.00E-32  | kg   | Pazouki et al. (2021)       |
| <b>Energy</b>                        | Sludge pumping                                 | 8.00E-04  | kWh  | Tchobanoglous et al. (2014) |
|                                      | Screening                                      | 4.00E-04  | kWh  | Tchobanoglous et al. (2014) |
|                                      | Sludge dewatering (screw press)                | 9.00E-04  | kWh  | Tchobanoglous et al. (2014) |
|                                      | AnOMBR unit                                    | 3.88E-01  | kWh  | Awad et al., (2019)         |
| <b>Sludge treatment and disposal</b> | DS Reconcentrated unit                         | 2.60E+00  | kWh  | Vinardell et al. (2023)     |
|                                      | Acetonitrile (thickening chemical)             | 3.72E-01  | g    | Postacchini et al. (2016)   |
|                                      | Transport (t.km)                               | 20        | t.km | Cashman et al. (2015)       |
| <b>Draw solution</b>                 | NaCl, 0.5 M                                    | 5,85E-02  | kg   | CD*                         |
|                                      | NaCl, 1 M                                      | 2,93 E-02 | kg   | CD*                         |
|                                      | MgCl <sub>2</sub> , 0.5 M                      | 4,7 E-02  | kg   | CD*                         |
|                                      | MgCl <sub>2</sub> , 1 M                        | 9,5E-02   | kg   | CD*                         |
|                                      | Na <sub>2</sub> SO <sub>4</sub>                | 11,5E-02  | kg   | CD*                         |
|                                      | NH <sub>4</sub> H <sub>2</sub> PO <sub>4</sub> | 14,2E-02  | kg   | CD*                         |
| <b>Avoided products</b>              | Biogas production                              | 4.34      | kWh  | CD*                         |
|                                      | Land application N fertilizer                  | 2.14      | g    | Hospido et al., (2005)      |
|                                      | Land application P fertilizer                  | 1.71      | g    | Hospido et al., (2005)      |

CD\*, Calculated Data

In addition, the efficiency data for wastewater pollutant removal ratios and biogas production, taken from the research of Hasanoglu et al. (2024), Gao et al. (2020), Adnan et al. (2019), and Bacaksız (2019), are shown in Tables 3.3 and 3.4. With these data for various scenarios were evaluated based on this information.

**Table 3.3 :** Information for the LCA study analyzing the effects of the DS concentration.

|                             | <b>COD<br/>Removal rate<br/>(%)</b> | <b>TP<br/>Removal rate<br/>(%)</b> | <b>TN<br/>Removal rate<br/>(%)</b> |
|-----------------------------|-------------------------------------|------------------------------------|------------------------------------|
| DS-NaCl (0.5M)              | 98                                  | 81                                 | 95                                 |
| DS-NaCl (1M)                | 96                                  | 64                                 | 92                                 |
| DS-MgCl <sub>2</sub> (0.5M) | 94                                  | 97                                 | 87                                 |
| DS-MgCl <sub>2</sub> (1M)   | 93                                  | 91                                 | 85                                 |

**Table 3.4 :** Information for the LCA study analyzing the effects of the DS type.

|                                                    | <b>COD<br/>Removal<br/>rate (%)</b> | <b>TP<br/>Removal<br/>rate (%)</b> | <b>TN<br/>Removal<br/>rate (%)</b> | <b>Methane yield<br/>(L CH<sub>4</sub>/gCOD)</b> |
|----------------------------------------------------|-------------------------------------|------------------------------------|------------------------------------|--------------------------------------------------|
| DS-NaCl                                            | 98                                  | 81                                 | 95                                 | 0.25                                             |
| DS-MgCl <sub>2</sub>                               | 96                                  | 64                                 | 92                                 | 0.18                                             |
| DS- Na <sub>2</sub> SO <sub>4</sub>                | 94                                  | 97                                 | 87                                 | 0.19                                             |
| DS- NH <sub>4</sub> H <sub>2</sub> PO <sub>4</sub> | 93                                  | 91                                 | 85                                 | 0.17                                             |

### 3.2.4 Life cycle impact assessment

This study utilizes the Recipe Midpoint (H) 2016 approach with SimaPro software v 9.4.0.1 and the Ecoinvent 3.9.1 database to conduct a LCA of an AnFOMBR system treating municipal wastewater. The goal is to assess their environmental impact across various categories including aquatic and terrestrial ecosystem effects, climate change, impacts on human health, and resource depletion. The methodology incorporates several midpoint impact categories, including human toxicity, respiratory effects, ionizing radiations, ozone depletion, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic eutrophication, terrestrial eutrophication, acidification, global warming, non-renewable energy use, and mineral extraction. The findings will inform decisions on

anaerobic wastewater treatment methods prioritizing environmental concerns and sustainability. Some information on these impact categories is given in Table 3.5.

**Table 3.5 :** The LCIA Method Recipe 2016 Midpoint (H) method as and list of impact categories.

| Impact Category                              | Unit                                    | Damage Category   |
|----------------------------------------------|-----------------------------------------|-------------------|
| Global warming potential (GWP)               | kg CO <sub>2</sub> to air eq.           |                   |
| Stratospheric ozone depletion (ODP)          | kg CFC-11 eq.                           |                   |
| Ionizing radiation (IRP)                     | kBq Cobalt-60 to air eq.                |                   |
| Ozone formation, human health (HH)           | kg NO <sub>x</sub> eq.                  |                   |
| Fine particulate matter formation (PMFP)     | kg PM <sub>2.5</sub> to air eq.         |                   |
| Ozone formation, terrestrial ecosystems (TE) | kg NO <sub>x</sub> eq.                  |                   |
| Terrestrial acidification (TA)               | kg SO <sub>2</sub> to air eq.           | Human Health      |
| Freshwater eutrophication (FE)               | kg P to freshwater eq.                  |                   |
| Marine eutrophication (ME)                   | kg N to marine eq.                      | Ecosystem Quality |
| Terrestrial ecotoxicity (TET)                | kg 1,4-DCB to industrial soil eq.       |                   |
| Freshwater ecotoxicity (FET)                 | kg 1,4-DCB to freshwater eq.            | Resource scarcity |
| Marine ecotoxicity (MET)                     | kg 1,4-DCB to marine water eq.          |                   |
| Human carcinogenic toxicity (HCT)            | kg 1,4-DCB eq.                          |                   |
| Human non-carcinogenic toxicity (HNCT)       | kg 1,4-DCB eq.                          |                   |
| Land use (LU)                                | m <sup>2</sup> × yr annual cropland eq. |                   |
| Mineral resource scarcity (MRS)              | kg Cu eq.                               |                   |
| Fossil resource scarcity (FRS)               | kg oil-eq.                              |                   |
| Water consumption (WC)                       | m <sup>3</sup> water-eq. consumed       |                   |

Commonly used impact categories in the LCA studies dealing with anaerobic WWT systems are GWP, AP, eutrophication potentials (ME, FE); ODP; toxicity impact categories; fossil depletion (FRS) (Yilmaz, M. et al., 2024). Consequently, this study has looked into the midpoint impact categories listed below:

Global warming (GWP): The contribution of greenhouse gases to the worldwide warming effect was assessed, considering key substances including CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and halogenated hydrocarbons associated with CC.

Stratospheric ozone depletion potential (ODP): Emissions of specific substances, including chlorinated and bromated halocarbons that deplete the stratospheric ozone layer, were expressed in the mass of trichlorofluoromethane (CFC-11), also known as Freon-11.

Human toxicity potential (HTP): The emission of toxic substances affecting human health in various environments was expressed in mass of 1,4-Dichlorobenzene equivalent. In this category, volatile organic substances, heavy metals, and persistent organic contaminants are the most important substances.

Freshwater ecotoxicity (FETP): The emission of toxic substances impacting freshwater ecosystems in different environments was also expressed in mass of 1,4-Dichlorobenzene equivalent. The substances that have the most importance contain organic volatile substances, heavy metals, and organic pollutants that remain persistent.

Terrestrial ecotoxicity potential (TETP): The emission of toxic substances affecting terrestrial (sediment) ecosystems was expressed in mass of 1,4-Dichlorobenzene equivalent.

Acidification potential (AP): Acids that are released into the atmosphere and cause acid rain. The deterioration of both terrestrial and aquatic species was measured in mass of equivalent SO<sub>2</sub>.

Eutrophication potential (EP): Emissions of macronutrients that lead to the eutrophication of aquatic ecosystems, resulting in increased plant growth and oxygen depletion, were expressed in mass of equivalent PO<sup>4-</sup>.

### 3.3 Results and Discussion

#### 3.3.1 Characterization results of the NaCl and MgCl<sub>2</sub> as draw solution

A comparative LCA was performed considering four different scenarios. The assessed results are represented using data analysis tools. In this LCA study, where the draw solutions used in the system were compared, the Ecoinvent (v9.4.1) database and data from studies on FOMBRs in the literature were used as inventory data. The results were obtained and interpreted using the Recipe Midpoint (H) method. The LCA results of the AnFOMBR system reveal nuanced environmental impacts associated with AnFOMBR systems, particularly highlighting the influence of draw solution type (NaCl vs. MgCl<sub>2</sub>) and concentration (0.5 M vs. 1 M). MgCl<sub>2</sub>-based draw solutions, especially at higher concentrations, exhibit elevated global warming potential, ionizing radiation, and terrestrial acidification impacts due to the energy-intensive production of MgCl<sub>2</sub> and its nutrient release characteristics. Additionally, these solutions contribute significantly to ODP and PMF, likely from energy demands in membrane manufacturing and chemical processes. The data also indicates that higher draw solution concentrations correlate with the increased TET and MET, underscoring the release of potentially harmful compounds into ecosystems. Both NaCl and MgCl<sub>2</sub> solutions at higher concentrations are associated with greater eutrophication impacts, with NaCl showing a more pronounced effect on FE and MgCl<sub>2</sub> on ME, driven by nutrient discharge. Resource scarcity metrics, including fossil fuel and mineral use, as well as water consumption, are similarly higher with more concentrated draw solutions, reflecting the additional material and energy requirements. Fig. 3.2 presents the characterization results of this LCA study, which examined the AnFOMBR system using NaCl and MgCl<sub>2</sub> as draw solutions at different concentrations.

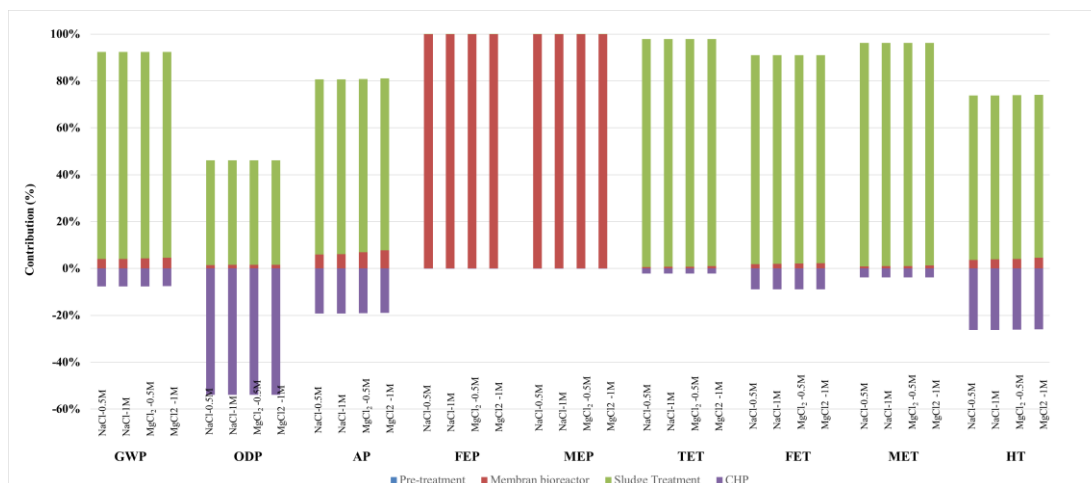


**Figure 3.2 :** Characterization results of the system (DS; NaCl (0,5 M-1M) and MgCl<sub>2</sub> (0,5 M-1M)).

### 3.3.2 Overall results of the NaCl and MgCl<sub>2</sub> as draw solution

Significant differences in the environmental impacts across various categories are revealed by the LCA of the AnFOMBR system using different draw solutions, namely NaCl and MgCl<sub>2</sub> at different concentrations. Global warming potential (0.527 kg CO<sub>2</sub> eq), terrestrial acidification (2.41E-03 kg SO<sub>2</sub> eq), ecotoxicity (e.g., terrestrial ecotoxicity at 1.32 kg 1,4-DCB), and resource scarcity (e.g., fossil resource scarcity at 0.141 kg oil eq) are among the major environmental burdens that MgCl<sub>2</sub>-based solutions, particularly at 1M concentration, exhibit. Higher concentrations enhance these effects, which may be caused by the energy-intensive production and chemical inputs needed for MgCl<sub>2</sub>. NaCl-based solutions, on the other hand, often have smaller effects in these categories but make a disproportionate contribution to FE, particularly at concentrations of 1M (6.42 kg P eq). ME is caused by both MgCl<sub>2</sub> and NaCl solutions, however the nitrogen-related effect of NaCl 1M is marginally greater (1.34 kg N eq). MgCl<sub>2</sub> based solution also has higher effects on human health, including carcinogenic and non-carcinogenic toxicity. The greatest values of non-carcinogenic toxicity (1.25E-01 kg 1,4-DCB) are found at 1M concentration, which may be caused by upstream production. All numeric results of this LCA study are given as Table 3.6.

**Table 3.6** : Life cycle impact assessment results of the first step of the study.

| <b>Impact category</b> | <b>Unit</b>           | <b>DS-NaCl<br/>0.5 M</b> | <b>DS-NaCl<br/>1 M</b> | <b>DS-MgCl<sub>2</sub><br/>0.5M</b> | <b>DS-MgCl<sub>2</sub><br/>1M</b> |
|------------------------|-----------------------|--------------------------|------------------------|-------------------------------------|-----------------------------------|
| <b>GWP</b>             | kg CO <sub>2</sub> eq | 4.60E-01                 | 4.65E-01               | 4.92E-01                            | 5.27E-01                          |
| <b>ODP</b>             | kg CFC11 eq           | 2.24E-07                 | 2.26E-07               | 2.33E-07                            | 2.44E-07                          |
| <b>TE</b>              | kg NO <sub>x</sub> eq | 1.47E-03                 | 1.48E-03               | 1.57E-03                            | 1.68E-03                          |
| <b>TA</b>              | kg SO <sub>2</sub> eq | 1.82E-03                 | 1.85E-03               | 2.11E-03                            | 2.41E-03                          |
| <b>FE</b>              | kg P eq               | 1.80E+00                 | 6.42E+00               | 5.34E+00                            | 5.23E+00                          |
| <b>ME</b>              | kg N eq               | 8.02E-01                 | 1.34E+00               | 9.51E-01                            | 1.19E+00                          |
| <b>TET</b>             | kg 1,4-DCB            | 7.80E-01                 | 8.70E-01               | 1.02E+00                            | 1.32E+00                          |
| <b>FET</b>             | kg 1,4-DCB            | 4.51E-04                 | 4.60E-04               | 4.97E-04                            | 5.50E-04                          |
| <b>MET</b>             | kg 1,4-DCB            | 9.03E-04                 | 9.63E-04               | 1.09E-03                            | 1.32E-03                          |
| <b>HCT</b>             | kg 1,4-DCB            | 5.73E-03                 | 5.98E-03               | 6.41E-03                            | 7.29E-03                          |
| <b>HCNT</b>            | kg 1,4-DCB            | 9.06E-02                 | 9.62E-02               | 1.06E-01                            | 1.25E-01                          |

According to the global warming impact category results of this study, MgCl<sub>2</sub> consistently shows a marginally higher GWP compared to NaCl at each concentration level (0.5 M and 1 M). This difference, while small (ranging from 0.05 to 0.06 kg CO<sub>2</sub>-equivalent), could indicate that the extraction, production, or transport of MgCl<sub>2</sub> is more energy-intensive or emits more CO<sub>2</sub> than NaCl. The GWP slightly declines from 4.60E-01 kg CO<sub>2</sub>-eq at 0.5 M to 4.50E-01 kg CO<sub>2</sub>-eq at 1 M, indicating a negligible change in environmental performance with the increase in concentration (2.7%). Besides, the GWP value increased from 4.92E-01 to 5.27E-01 0.492 to 0.527 (6.5%) kg CO<sub>2</sub>-eq. for the MgCl<sub>2</sub>. It suggested that ignoring change in environmental performance with the concentration increase for the both choices. Therefore, there is a slight increase in GWP with concentration and between the different draw solutions, the overall differences are quite small. This shows that the choice of draw solution (NaCl vs MgCl<sub>2</sub>) and concentration (0.5 M vs 1 M) may not significantly effect the global warming potential in this system. These findings imply that sludge

management, membrane materials, system energy demand, and other variables may have a greater impact on the overall environmental footprint than draw solution selection, which has a negligible effect on GWP (Fig. 3.3a).

Ozone layer depletion refers to the reduction of ozone in the stratosphere, which permits increased levels of ultraviolet (UV) radiation to penetrate the Earth's atmosphere. Emissions of specific substances, including chlorinated and brominated halocarbons deplete the stratospheric ozone layer. The AnFOMBR system possesses a minimal capacity to deplete the ozone layer, and the minor differences between NaCl and  $\text{MgCl}_2$  are likely to affect the environment adversely. Regarding ozone depletion, both draw solutions function similarly, with  $\text{MgCl}_2$  displaying slightly higher value. For this system, the numbers imply that the AnFOMBR system's chemical usage does not considerably worsen the stratosphere's ozone layer. Consequently, in comparison to other impact categories such as TET or EP, ODP does not constitute a severe environmental issue (Fig. 3.3b).

Terrestrial acidification is the emissions of acidifying substances that contribute to acid rain and the degradation of terrestrial species. The burning of fossil fuels for energy consumption in the AnOMBR unit and related processes contributes to sulfur dioxide ( $\text{SO}_2$ ) emissions, which in turn lead to acidification. Besides, the production and disposal of membrane materials, particularly PSF and CTA, require energy, which could contribute to acidification through the emissions from industrial processes. On the other side, both NaCl and  $\text{MgCl}_2$  solutions contribute to acidification through their production processes, particularly if these salts are produced using energy from fossil fuels.  $\text{MgCl}_2$  tends to slightly increase terrestrial acidification compared to NaCl, which could be attributed to the higher energy required for  $\text{MgCl}_2$  production (Fig 3.3c). In addition, the transport requirement of the treated sludge (20 t.km) further contributes to acidification through fuel combustion during transportation.

One of the main causes of FE is the release of phosphorus during the treatment and disposal of waste. While sludge treatment itself may release P, the application of fertilizers helps to lessen the burden of eutrophication. Besides, the energy required to create the draw solutions can contribute to eutrophication through emissions from the energy generation process, even if the draw solutions themselves might not directly release nutrients. When FE is evaluated, the concentration of NaCl at 1M has the greatest influence (6.42 kg P eq.), followed by  $\text{MgCl}_2$  at 0.5M (5.34 kg P eq.) and 1M

(5.23 kg P eq.), while the concentration of NaCl at 0.5M has the lowest (1.80 kg P equivalent). This implies that more phosphorus or phosphorus-equivalent substances are released into freshwater systems with greater NaCl concentrations. On the other hand, ME is caused by nitrogen emissions from sludge treatment procedures and the possibility of nutrient runoff, just like FE. The impact is lessened by avoiding the application of N fertilizers (2.14 g). Since biogas replaces traditional energy and fertilizers, its production and usage as an energy source help reduce nutrient discharges. NaCl at 1 M similarly has the biggest influence (1.34 kg N eq) on the side of ME, followed by MgCl<sub>2</sub> at 1M (1.19 kg N eq) and MgCl<sub>2</sub> at 0.5M (0.951 kg N eq). NaCl at 0.5M again has the least impact (0.802 kg N eq). This suggests that both NaCl and MgCl<sub>2</sub>, especially at higher concentrations, add nitrogen-based chemicals to marine ecosystems that can deplete oxygen and cause algal blooms, both of which are detrimental to marine life. The findings emphasize the possible trade-offs of employing larger concentrations of draw solutions, particularly NaCl, as they exacerbate the effects of eutrophication in freshwater and marine environments (Fig 3.3d).

The AnFOMBR system's draw solutions, operating NaCl and MgCl<sub>2</sub> at different concentrations, varies slightly, according to the HT data. MgCl<sub>2</sub> solutions greater effects than NaCl solutions in the human carcinogenic toxicity category. In particular, the greatest impact is caused by MgCl<sub>2</sub> at 1 M (7.3E-03 kg 1,4-DCB), which is followed by MgCl<sub>2</sub> at 0.5 M. NaCl solutions, on the other hand, have somewhat lower levels. Similar trends were seen in non-carcinogenic toxicity in humans. NaCl at 0.5 M has the lowest impact, whereas MgCl<sub>2</sub> at 1 M once more exhibits the maximum impact (1.2E-01 kg 1,4-DCB), followed by MgCl<sub>2</sub> at 0.5 M (1.1E-01 kg 1,4-DCB). The increased rates of pollutant emissions and resource-intensive production methods linked to MgCl<sub>2</sub> are the causes of the increase in non-carcinogenic toxicity in humans (Fig 3.3e).

The ecotoxicity impact category addresses the emission of toxic substances, including heavy metals and persistent organic pollutants, adversely affecting freshwater, marine, and terrestrial ecosystems. The production of cellulose triacetate (CTA) and polysulfone (PSF) may contribute the environmental toxicity.. Hazardous compounds may seep into the soil during membrane disposal, adding to this burden. Also, when employed the chemical usage in membrane cleaning with EDTA and sludge treatment

with acetonitrile have a significant potential for ecotoxicity and, if not handled properly, can contribute to terrestrial ecotoxicity. Moreover, the emissions of COD and TN, particularly 0.25 kg methane from the DS-NaCl (0.5 M) scenario, could have secondary effects on ecotoxicity, particularly in aquatic environments due to oxygen depletion.  $\text{MgCl}_2$  contributes slightly more to terrestrial toxicity than NaCl, and this impact category varies the most different draw solutions and concentrations. There are very little variations between NaCl and  $\text{MgCl}_2$  in terms of ecotoxicity, and both freshwater and marine ecotoxicity values are far lower than terrestrial impacts. Although the absolute results are extremely tiny, the slightly greater ecotoxicity for  $\text{MgCl}_2$  probably reflects the production-related consequences observed in terrestrial toxicity. There is a marginal rise in ecotoxicity in all three ecotoxicity categories when the draw solutions' concentration is raised from 0.5 M to 1 M. This implies that increased chemical use somewhat worsens environmental effects, but the overall impact is still negligible (Fig. 3.3f).

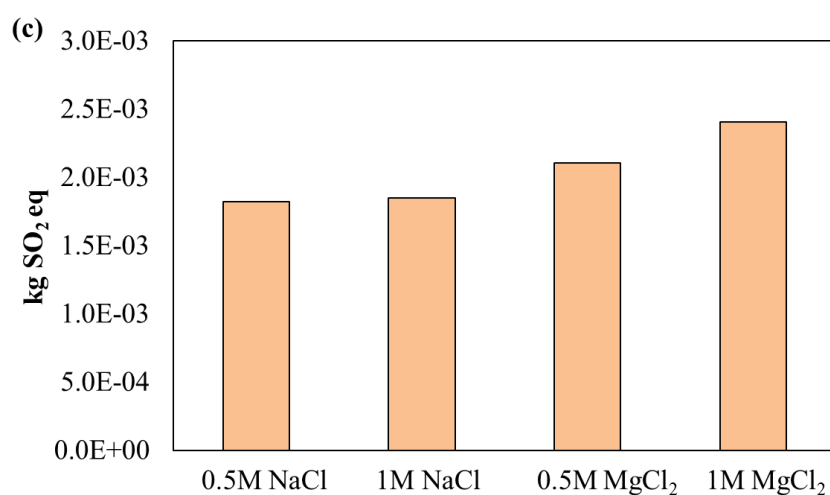
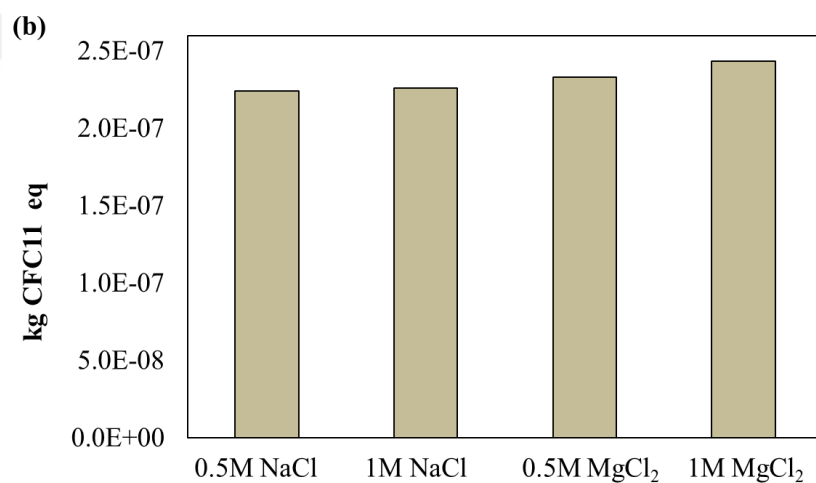
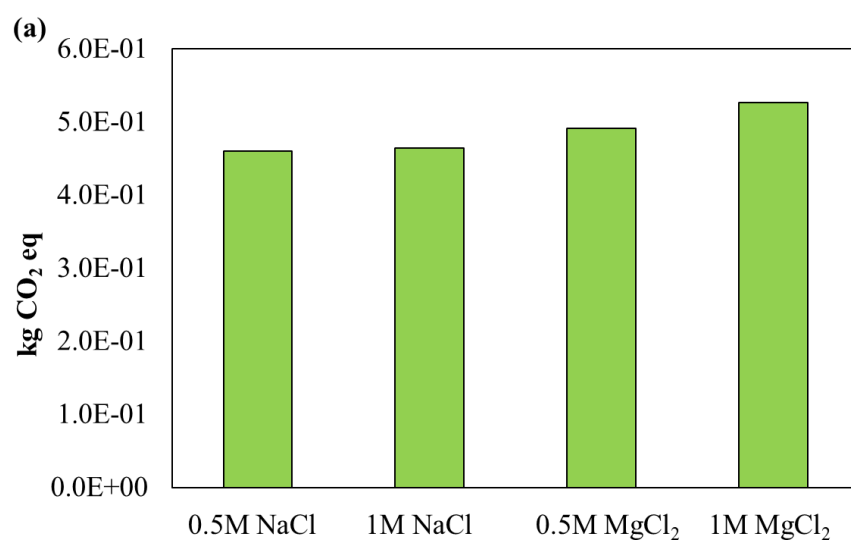


**Figure 3.3 :** (a) GWP results, (b) ODP results, (c) TA results, (d) ME, TE results, (e) HNT, HCNT results, (f) FET, MET, TET results (DS: NaCl and MgCl<sub>2</sub> scenarios).

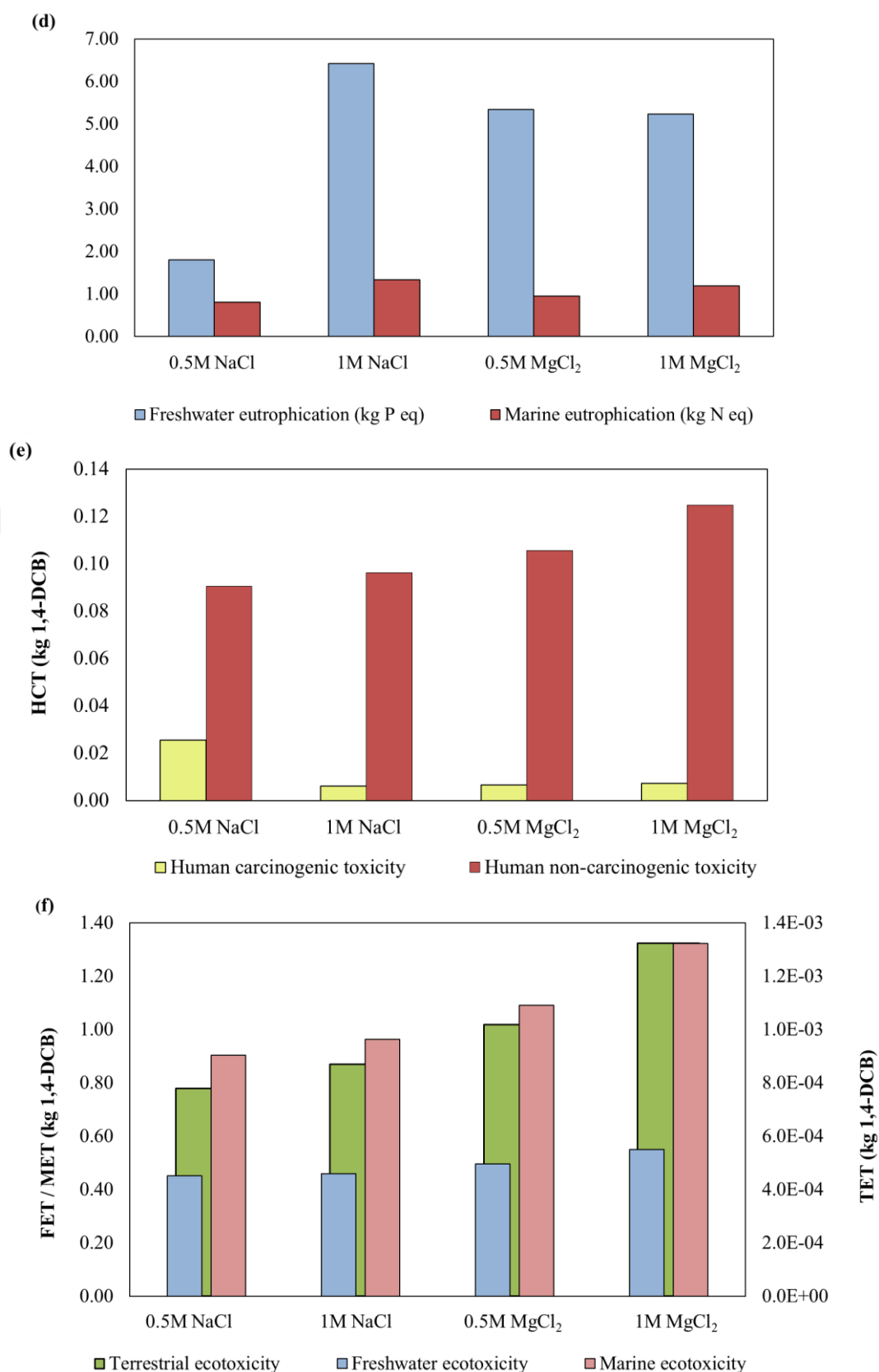


**Figure 3.3 (continued)** : (a) GWP results, (b) ODP results, (c) TA results, (d) ME, TE results, (e) HNT, HCNT results, (f) FET, MET, TET results (DS: NaCl and MgCl<sub>2</sub> scenarios).

### 3.3.3 Characterization results of the NaCl and MgCl<sub>2</sub>, Na<sub>2</sub>SO<sub>4</sub> and MAP as draw solutions

Each of the four draw solutions (DS) for the AnFOMBR system exhibits unique trade-offs between operational performance and the environment. Its global warming potential (GWP), acidification potential (AP), and resource depletion impacts are greatly reduced by the lack of a regeneration unit, making MAP the most efficient in terms of energy and nutrient recovery, requiring only 0.4 kWh/m<sup>3</sup>. With a 99% TP removal rate, it also achieves the most efficient nutrient removal and the highest methane output (0.26 LCH<sub>4</sub>/gCOD), which makes it ideal for nutrient recycling. With high rates of COD and TN removal (98% and 95%, respectively) and a moderate environmental profile, DS-NaCl performs well after MAP fertilizer. On the other hand, its 2.43 kWh/m<sup>3</sup> energy requirement increases its GWP and resource depletion in comparison to MAP. In addition to having a lower TP removal rate (64%) and COD removal and methane yield (0.20 LCH<sub>4</sub>/gCOD), DS-MgCl<sub>2</sub> also has greater energy requirements, which increase greenhouse gas emissions and resource depletion. Lastly, with a removal rate of 88% for COD and TN and a comparatively low methane production of 0.19 LCH<sub>4</sub>/gCOD, Na<sub>2</sub>SO<sub>4</sub> exhibits inferior treatment efficiency overall. Its high energy consumption also makes it the least advantageous scenario in terms of environmental impact across GWP, AP, and resource use. All numeric results of this LCA study are given as Table 3.7.

**Table 3.7** : Life cycle impact assessment results of the second step of the study.

| Impact category | Unit                  | Fertilizer (MAP) | Na <sub>2</sub> SO <sub>4</sub> | MgCl <sub>2</sub> | NaCl     |
|-----------------|-----------------------|------------------|---------------------------------|-------------------|----------|
| <b>GWP</b>      | kg CO <sub>2</sub> eq | 1.06E+01         | 1.20E+01                        | 1.19E+01          | 1.18E+01 |
| <b>TA</b>       | kg SO <sub>2</sub> eq | 2.44E-02         | 3.43E-02                        | 3.08E-02          | 3.02E-02 |
| <b>FE</b>       | kg P eq               | 1.98E-03         | 4.98E-03                        | 5.22E-03          | 7.70E-03 |
| <b>ME</b>       | kg N eq               | 3.31E-04         | 1.32E-03                        | 1.32E-03          | 1.47E-03 |
| <b>FET</b>      | kg 1,4-DCB            | 2.15E-02         | 2.25E-02                        | 2.23E-02          | 2.22E-02 |
| <b>MET</b>      | kg 1,4-DCB            | 9.75E-02         | 9.95E-02                        | 9.90E-02          | 9.86E-02 |
| <b>HCT</b>      | kg 1,4-DCB            | 1.12E-01         | 1.27E-01                        | 1.25E-01          | 1.23E-01 |
| <b>HNCT</b>     | kg 1,4-DCB            | 2.51E+00         | 2.83E+00                        | 2.79E+00          | 2.76E+00 |

### 3.3.4 Overall results of the fertilizer (MAP), NaCl, Na<sub>2</sub>SO<sub>4</sub> and MgCl<sub>2</sub> as draw solution

The energy-intensive procedures needed for their reconcentration and nutrient treatment are probably the reason why the MgCl<sub>2</sub> and Na<sub>2</sub>SO<sub>4</sub> scenarios have the largest GWP contributions in this phase. For all draw solutions except MAP, the system's energy consumption is 2.43 kWh/m<sup>3</sup> due to the AnFOMBR system's regeneration unit, while MAP requires only 0.4 kWh/m<sup>3</sup> without regeneration, reducing its GWP since energy drives carbon emissions. Membrane materials and cleaning chemicals, including cellulose triacetate, polysulfone, and EDTA, also contribute to GWP, with additional impacts from disposed membranes (Fig 3.4a).

Also, the pre-treatment units and reconcentration process of the DS have the greatest influence, according to ODP values across scenarios, which show minimal impact directly. Chemicals like EDTA employed in cleaning and nutrient recovery processes are responsible for the greater ODP during reconcentration in the MAP and Na<sub>2</sub>SO<sub>4</sub> scenarios. Significantly, under specific operating conditions, the MgCl<sub>2</sub> and NaCl scenarios have negative values in the bioreactor phase, which may indicate mitigating

effects on ozone depletion, possibly as a result of decreased chlorofluorocarbons (CFC) emissions during this period (Fig 3.4b).

When examining the impact category of AP; since sulfur and nitrogen molecules play a major role, AP is noticeably affected in the ANFOMBR in all DS conditions. The highest AP in the ANFOMBR is displayed by  $\text{Na}_2\text{SO}_4$  and  $\text{MgCl}_2$ , which may be related to sulfur releases and how they interact with other emissions. Since MAP has the lowest AP, it might be a more environmentally friendly choice regarding acidification. AP is increased by higher energy consumption for  $\text{NaCl}$ ,  $\text{MgCl}_2$ , and  $\text{Na}_2\text{SO}_4$  because of emissions from fossil fuels used to generate power. Furthermore, if EDTA is used for membrane cleaning without enough oversight, chemical loss increases AP (Fig 3.4c).

Moreover, due to the exposure to concentrated waste streams and cleaning chemicals throughout the Sludge treatment and Membrane cleaning processes of the system, FET is increased in all cases. In the bioreactor, MAP and  $\text{MgCl}_2$  show greater FET due to nutrient back-transport and possible phosphorus and magnesium compound releases. Even though  $\text{Na}_2\text{SO}_4$  contributes less to FET, it still poses a moderate risk, underscoring the necessity of improved sludge management and optimized chemical use during cleaning. Like FET, MET has higher effects in the MAP and  $\text{MgCl}_2$  situations, with the bioreactor and sludge treatment phases contributing significantly. The high phosphorus content of MAP causes marine toxicity, which may be harmful to aquatic life (Fig 3.4d).

In addition, in the ANFOMR unit, FEP is considerably higher in all cases, with MAP having the highest FEP because of its phosphorus-rich effluents. This result emphasizes how crucial it is to manage nutrient back-transport in DS systems that rely on fertilizer. In the DS Tank and Bioreactor unit,  $\text{Na}_2\text{SO}_4$  and  $\text{MgCl}_2$  also show significant FEP, indicating that sulfate and magnesium draw solutions may raise the phosphorus burden in effluents, but less so than MAP. On the other side, the effects of MEP are similar to those observed with FEP, with the highest loads in the ANFOMBR unit coming from MAP and  $\text{MgCl}_2$  situations. Because of its comparatively inert  $\text{NaCl}$  composition,  $\text{NaCl}$  has the lowest MEP. Ammonia nitrogen in the MAP draw solution increases the risk to marine ecosystems because nitrogen releases are a major cause of ME. The use of MAP as a draw solution may increase nitrogen emission risk but also provides nutrient benefits when applied as fertilizer, potentially offsetting EP in

agricultural applications. Avoiding additional nitrogen and phosphorus fertilizers further helps reduce overall EP (Fig 3.4e).

In addition to these results, there is a considerable risk of exposure to concentrated pollutants in treated sludge, as evidenced by the particularly high HT in all scenarios, but particularly during sludge treatment. Because of ammonia and sulfur compounds, MAP exhibits the highest HT in the bioreactor, being roughly 15% higher than  $\text{Na}_2\text{SO}_4$  and 50% higher than NaCl. NaCl has around 20% less HT than  $\text{MgCl}_2$ , indicating that lowering cleaning frequency or using different chemicals could lessen these effects. Membrane cleaning chemicals can contribute to HT. The results highlight the significance it is to use safer cleaning methods and sludge processes in order to reduce the dangers to human health in all DS options (Fig 3.4f).

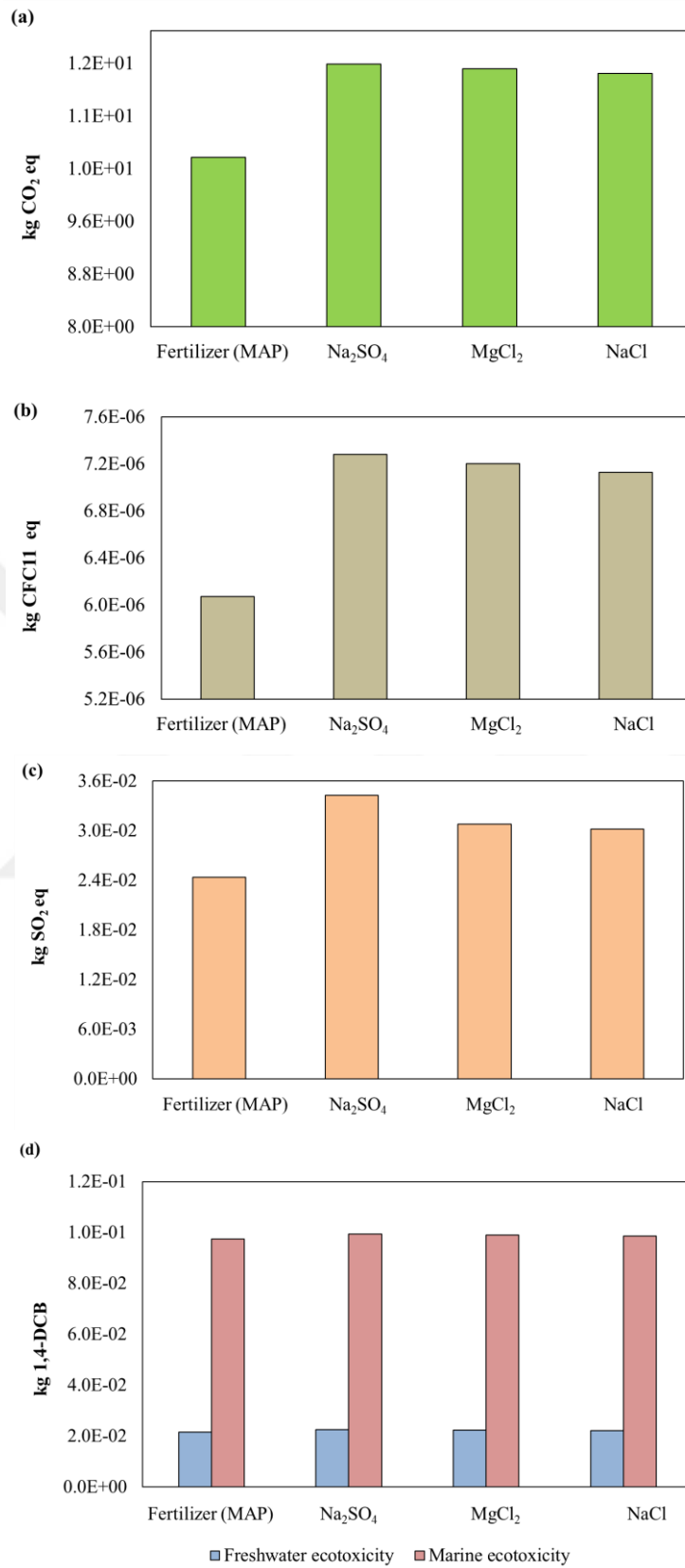


**Figure 3.4 :** (a) GWP results, (b) ODP results, (c) TA results, (d) FET, MET results, (e) FE, ME results, (f) HCT, HCNT results (DS: Fertilizer (MAP),  $\text{Na}_2\text{SO}_4$ ,  $\text{MgCl}_2$  and  $\text{NaCl}$  scenarios).

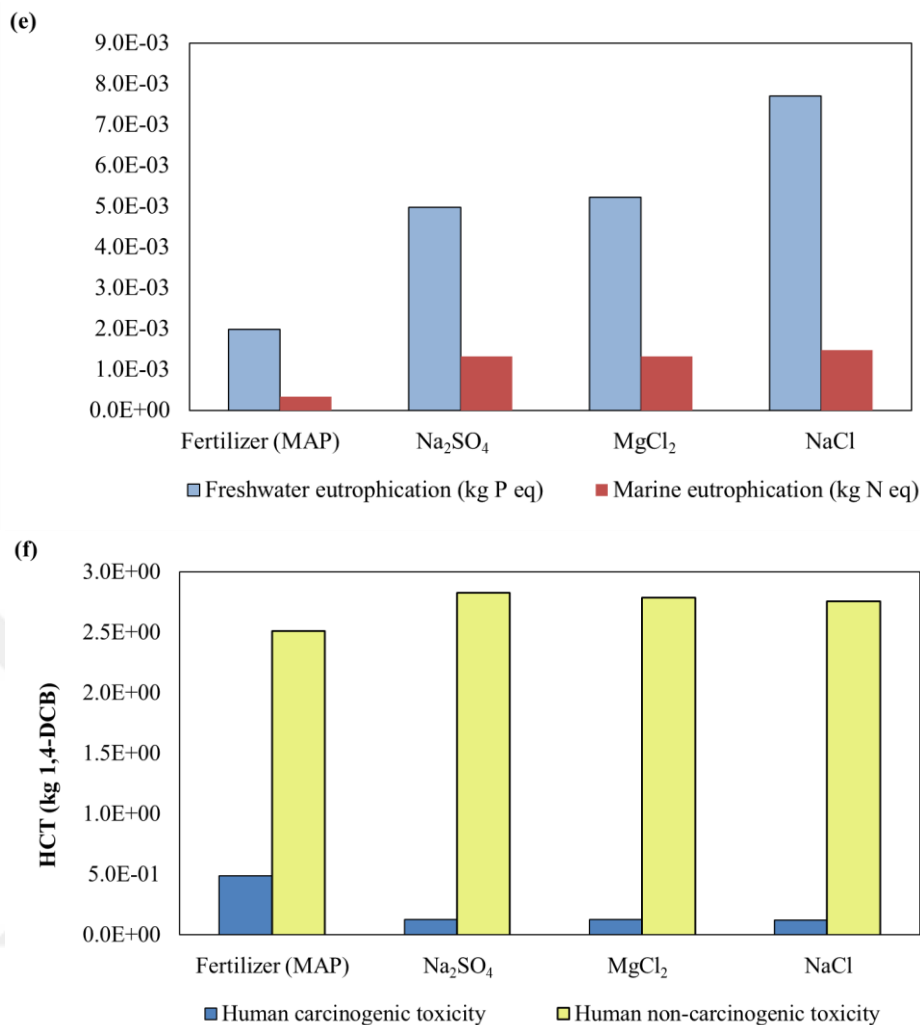


**Figure 3.4 (continued) :** (a) GWP results, (b) ODP results, (c) TA results, (d) FET, MET results, (e) FE, ME results, (f) HCT, HCNT results (DS: Fertilizer (MAP), Na<sub>2</sub>SO<sub>4</sub>, MgCl<sub>2</sub> and NaCl scenarios).

The LCA findings indicate that sludge treatment is the predominant source of environmental impacts in all scenarios, particularly in categories such as GWP, AP, and FE, with GWP approximately 10 kg CO<sub>2</sub>-eq. NaCl and MgCl<sub>2</sub> demonstrate comparable environmental profiles, however, Na<sub>2</sub>SO<sub>4</sub> is notable for its higher GWP contribution (0.1456 kg CO<sub>2</sub>-eq) in the draw solution part. The MBR unit notably impacts GWP, especially for NaCl and MgCl<sub>2</sub>, at around 1.5 kg CO<sub>2</sub>-eq. The pre-treatment and membrane cleaning processes generate minor effects across all categories. Despite the similar impact distributions observed in NaCl, MgCl<sub>2</sub>, and Na<sub>2</sub>SO<sub>4</sub> processes, the absence of a reconcentration unit results in a distinct distribution of MAP.(Fig. 3.5).

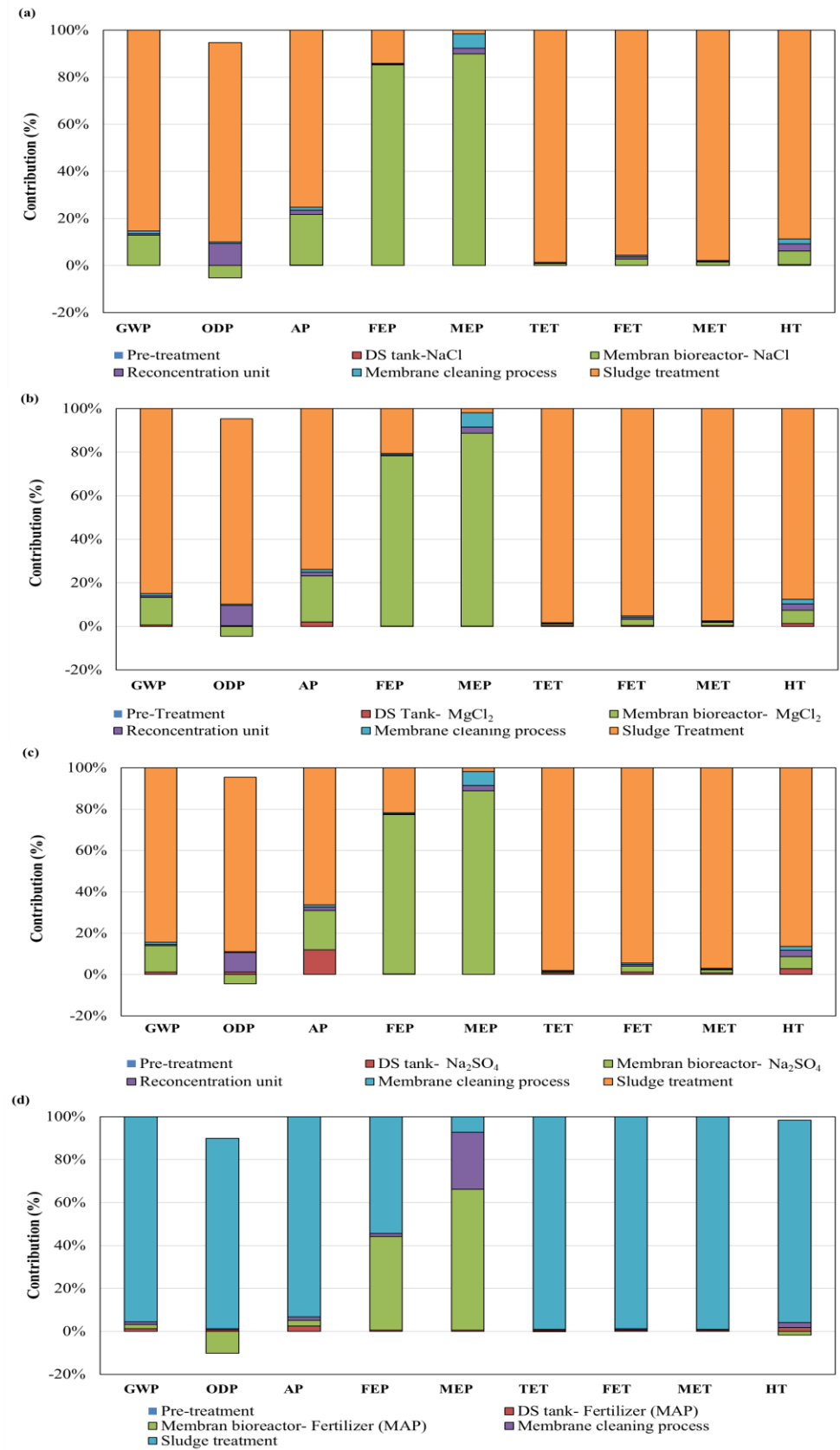


**Figure 3.5 :** Environmental impact contribution of four main DS options: (a) DS-NaCl, (b) DS-MgCl<sub>2</sub>, (c) DS-Na<sub>2</sub>SO<sub>4</sub>, (d) DS-MAP.

### 3.4 Conclusion

In this study, basically two LCA studies were carried out. At the first part of the study assessed how the environmental impact categories changed when two different DS solutions were used at different concentrations. The second part of the study analysed in detail how the environmental impact categories changed with the changes in the system when 4 different DS solutions were used. Using Simapro 9.4.0.1 as the software and Recipe 2016 Midpoint (H) as the LCIA method, the impact categories for GWP, ODP, HT, FEP, TEP, AP, and EP were investigated in detail. The findings of the first part of this study show that choosing a draw solution, especially between NaCl and MgCl<sub>2</sub>, has a major impact on sustainability indicators. The production of MgCl<sub>2</sub> requires more energy and releases more nutrients, which generally leads to increased impacts on GWP, AP, and ecotoxicity. Furthermore, there was a correlation between higher concentrations of draw solution and increased environmental consequences, highlighting the necessity for optimization. Energy use became clear as a significant factor affecting these categories, although the production of biogas showed positive effects by lowering reliance on fossil fuels and promoting nutrient recovery.

Besides, when examined the second part of the LCA analysis of an AnFOMBR system using different DS options (MAP (fertilizer), NaCl, MgCl<sub>2</sub>, and Na<sub>2</sub>SO<sub>4</sub>), it showed that although MAP promotes nutrient recovery, it has a significant negative influence on eutrophication, particularly in freshwater and marine environments whereas, it is the most energy-efficient choice since it doesn't require a regeneration (RO) unit, MgCl<sub>2</sub> provides a balanced impact profile, making it appropriate for applications requiring mild environmental consequences, while NaCl reduces toxicity, making it the safest choice environmentally. Although Na<sub>2</sub>SO<sub>4</sub> has a severe toxicity impact, it is practical in terms of greenhouse gas emissions. In every case, sludge treatment has a major impact on toxicity and global warming, underscoring the necessity of effective sludge management. Typically, selecting a draw solution requires balancing the benefits of nutrient recovery against the consequences on the environment; more sustainable options are usually NaCl and MAP. Moreover, this LCA study also recommends that future research concentrate on operational optimizations and alternative draw solutions for better sustainability in wastewater treatment. In addition, Since LCA studies on these systems are limited in the literature, the comparison of

ANFOMBRs with other anaerobic wastewater treatment systems and their evaluation in terms of environmental impact may be among the future studies. Furthermore, a comprehensive cost analysis of these innovative anaerobic wastewater treatment systems plays an important role in evaluating the issue holistically regarding sustainability.



## **4. LIFE CYCLE ANALYSIS OF ANAEROBIC FORWARD OSMOSIS MEMBRANE BIOREACTORS WITH ANMBRs AND UASB REACTORS<sup>3</sup>**

### **4.1 Introduction**

depending on the characteristics of the wastewater. Among these, biological wastewater treatment is an effective and widely adopted method in many industrial and municipal wastewater treatment facilities worldwide. While aerobic treatment processes are widely recognized for producing high-quality effluents, they entail significant energy consumption due to intensive aeration and sludge management requirements (Gomec, 2010; Stazi and Tomei, 2018). To address these limitations, anaerobic treatment technologies present an energy-efficient alternative, offering benefits such as biogas recovery, reduced sludge production, and lower overall operational costs for domestic wastewater treatment. Various anaerobic treatment configurations have been developed over the past four to five decades, improving process efficiency and system resilience.

Anaerobic membrane bioreactors (AnMBRs) and anaerobic osmotic membrane bioreactors (AnFOMBRs) are emerging technologies that are gaining increasing attention in the field of wastewater treatment. AnMBR systems demonstrate high performance in the removal of organic matter from both domestic and industrial wastewaters, while membrane filtration ensures the production of high-quality effluent (Pretel et al., 2016; Bacaksız et al., 2019). Key advantages of AnMBRs include biogas production, which offers energy recovery potential, and low sludge generation. AnFOMBRs, on the other hand, are formed by integrating the forward osmosis (FO) process into AnMBR systems, enabling higher contaminant removal efficiencies and reduced membrane fouling tendencies (Hu et al., 2020). A recent study investigated

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<sup>3</sup> This chapter is submitted to “Journal of Cleaner Production” as Yilmaz, M., Guven, H., Ozgun, H., Ersahin, M. E., & Koyuncu, I. “Life Cycle Analysis Of Anaerobic Forward Osmosis Membrane Bioreactors With AnmbRs And Uasb Reactors”.

the treatability of brewery wastewater using an AnOMBR system and evaluated the performance of various draw solutions (DS). The Analytic Hierarchy Process (AHP) was employed to determine the most suitable DS types, and both treatment efficiency and membrane fouling were examined in detail. Operated by osmotic driving force, the FO process requires low hydraulic pressure and offers energy savings. AnFOMBR systems, with their potential for both energy and water recovery, represent promising technologies for sustainable wastewater management.

Anaerobic upflow sludge blanket (UASB) reactors are widely used technologies in wastewater treatment, operating on the principle of organic matter degradation under anaerobic conditions within a bed of granular sludge. These reactors promote sludge mixing through an upward wastewater flow, while a gas-solid separator located at the top prevents the washout of granular biomass. UASB reactors are applicable for various wastewater types, including those from the brewing industry, and have been utilized for the isolation of hydrogen-producing bacterial strains. Integrated systems such as UASB-sequencing batch reactors (UASB-SBR) have been developed for the co-treatment of domestic wastewater and organic waste. The integration of UASB reactors with ultrafiltration membranes has also shown potential to influence treatment performance and sludge characteristics in domestic wastewater applications.

This study aimed to assess three anaerobic wastewater treatment technologies (AnMBR, UASB Reactor and AnFOMBR). With this study will be valuable data since the comparison of anaerobic WWT systems with each other is very limited in the literature. In particular, there is no comparison in the literature of AnFOMBR WWT systems, which is an innovative approach and whose areas of use are increasing day by day, with any other WWT systems. This study has an important place in filling this gap. Data such as nutrient and dissolved methane removal efficiencies, produced and consumed energy amount, which have an important place in anaerobic systems, have been decisive in the comparison of these systems with the LCA approach.

## **4.2 Material and Methods**

### **4.2.1 Goal and scope definition**

The primary aim of this LCA is to systematically evaluate and compare the environmental impacts associated with anaerobic forward osmosis membrane

bioreactor (AnFOMBR) systems with AnMBRs and UASB reactors, used for domestic wastewater treatment. A central focus of the study is to examine how different anaerobic treatment systems influence the environmental performance.

#### **4.2.2 System boundary**

This study includes several operational stages in the impact assessment, specifically focusing on wastewater treatment, sludge treatment, and biogas production processes. The construction and demolition phases were not considered due to their limited impact relative to the overall assessment. Fig. 4.1 presents the three scenarios considered in this study, which were defined based on available literature on anaerobic wastewater treatment technologies.

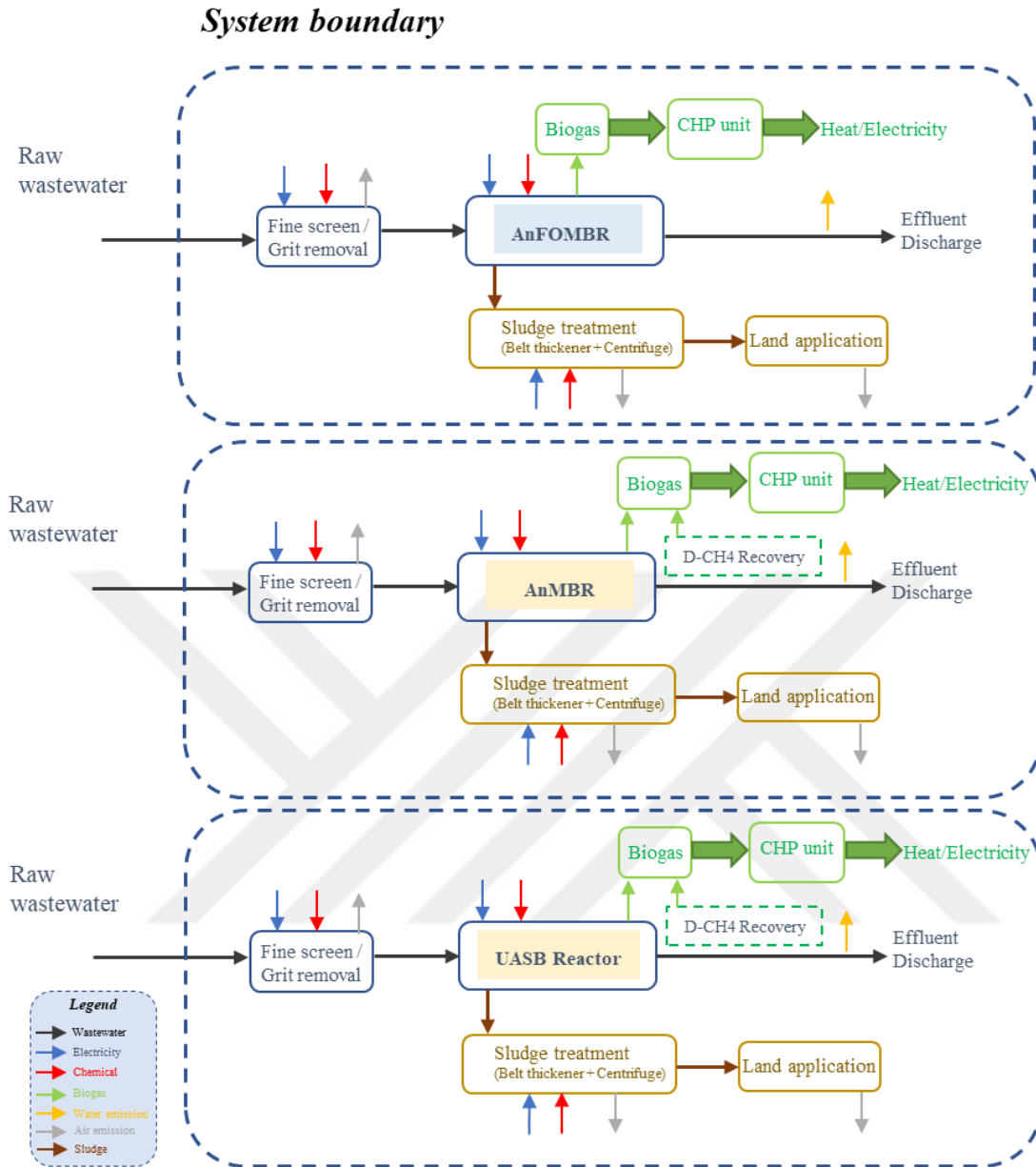


**Figure 4.1 :** The system boundary of the study.

In Life Cycle Assessment (LCA) studies of wastewater treatment systems, commonly adopted functional units (FUs) include the volume of treated effluent, person equivalent (p.e.), and the removal of specific pollutant loads (e.g., kilograms of  $\text{PO}_4^{3-}$  equivalents or nitrogen removed) (Yilmaz et al., 2024). For this study, a volume-based functional unit was selected—specifically, 1 m<sup>3</sup> of permeate produced—as it more accurately represents the system’s primary function in relation to the quantity and quality of the treated effluent. This choice ensures a consistent basis for comparing environmental impacts across different treatment configurations and operational conditions. Detailed information on the different scenarios is described as follows:

*AnFOMBR scenario:* The system boundaries considered in this study include several stages. Beginning with the pre-treatment units, the process continues with wastewater treatment via AnFOMBR, which integrates an MBR unit and a draw solution (DS) regeneration unit. In this scenario, NaCl was applied as the DS instead of MAP due to limited data availability. A combined heat and power (CHP) unit utilizing biogas from anaerobic treatment was incorporated into the analysis. Sludge management, including thickening, dewatering, and subsequent land application, was also considered. According to Gao et al. (2021), dissolved methane ( $d\text{-CH}_4$ ) is almost completely rejected by FO membranes; therefore,  $d\text{-CH}_4$  in the effluent was excluded from the AnFOMBR scenario. Energy consumption data were obtained from Awad et al. (2019), while emissions to water were calculated using treatment efficiencies reported by Ansari et al. (2017) (Table 4.1).

*AnMBR Scenario :* The system boundaries considered in this study include several stages. The process begins with pre-treatment units and proceeds with wastewater treatment through AnMBR. A CHP unit, utilized by biogas generated from anaerobic treatment, was included in the analysis. Sludge management processes, including thickening, dewatering, and subsequent land application, were also considered. In this scenario, the recovery ratio of dissolved methane ( $d\text{-CH}_4$ ) was assumed to be 70%. Energy consumption data were adopted from Lijo et al. (2017), while emissions to water were estimated based on treatment efficiencies reported by Xu et al. (2020) (Table 4.1).

*UASB reactor Scenario :* The UASB scenario is similar to the AnMBR scenario in terms of the  $d\text{-CH}_4$  recovery ratio and overall system configuration. The data on  $\text{CH}_4$  production, energy consumption, and emissions for this scenario were derived from Amaral et al. (2020).

#### **4.2.3 Life cycle inventory and data collection**

The life cycle inventory (LCI) data for this study were primarily derived from peer-reviewed literature on anaerobic treatment systems. Supplementary data related to the life cycle impacts of materials used in various system components were extracted from the Ecoinvent v3.9.1 database to ensure comprehensive and standardized environmental modeling.

Since the data of the study are based on literature data, some assumptions were made while deciding on the system definition and boundary. The following system boundaries were considered:

- The construction and demolition phases were not considered in this research. Additionally, the transportation of sludge was considered, with assumed transport distances of 20 km.
- It was assumed that the sludge thickener has one output: thickened sludge. Consequently, the study does not include side wastewater streams (thickener supernatants).
- According to the results of Gao et al. (2021), d-CH<sub>4</sub> was almost completely rejected by FO membranes. So, d-CH<sub>4</sub> in the effluent was ignored in AnFOMBR.
- The characterization of influent wastewater was determined according to urban wastewater values as follow: COD: 522 mg/L, TN: 55 mg/L, TP: 8,5 mg/L (based on ; Gao et al. 2020a).
- Potential biogas upgrading processes—such as the removal of hydrogen sulfide and siloxanes to meet the quality requirements for combined heat and power (CHP) applications—were excluded from the scope of this analysis due to insufficient data on the concentrations of these trace compounds.
- CO<sub>2</sub> emission data were not included due to lack of information for these three anaerobic wastewater treatment systems.
- The waste data produced by the pre-treatment unit were taken from the ISKI Annual Report (2023). Also, the land application fertilizer data was taken from Hospido et al., (2005)

The summary of the data inventory taken from the related LCA studies is shown in Table 4.1.

**Table 4.1** : Life cycle inventory data for this study (FU:1 m<sup>3</sup> treated wastewater).

|         |                   |                                             | Unit | AnMBR     | AnFOMBR   | UASB Reactor |
|---------|-------------------|---------------------------------------------|------|-----------|-----------|--------------|
| Inputs  | Electricity       | Sludge pumping                              | kWh  | 8.00E-04  | 8.00E-04  | 8.00E-04     |
|         |                   | Screening                                   | kWh  | 4.00E-04  | 4.00E-04  | 4.00E-04     |
|         |                   | Sludge dewatering (screw press)             | kWh  | 9.00E-04  | 9.00E-04  | 9.00E-04     |
|         |                   | Treatment units                             | kWh  | 8.65E-01  | 3.4E-01   | 3.88E-01     |
|         | Chemicals         | Polyacrylamide                              | g    | 3.72E-01  | 3.72E-01  | 3.72E-01     |
|         |                   | Draw solution (NaCl)                        | kg   | -         | 2,93 E-02 | -            |
|         | Transport         |                                             | t.km | 20        |           |              |
| Outputs | Emission to air   | CH <sub>4</sub>                             | g    | 18.6      | 25        | 29.9         |
|         |                   |                                             |      |           |           |              |
|         | Emission to water | COD                                         | g    | 4.10E-02  | 3.13E-02  | 1.05E-01     |
|         |                   | Nitrogen, total                             | g    | 4.25E-03  | 0.95E-03  | 7.65E-03     |
|         |                   | Phosphorus, total                           | g    | 3.60E-02  | 1.16E-02  | 4.71E-02     |
|         |                   | D-CH <sub>4</sub> in the anaerobic effluent | g    | 4.00 E-02 | -         | 6.00 E-02    |
|         | Waste             | Screening waste                             | kg   | 3.4E-03   | 3.4E-03   | 3.4E-03      |
|         |                   | Grit                                        | kg   | 15.3E-03  | 15.3E-03  | 15.3E-03     |

**Table 4.1 (Continued)** : Life cycle inventory data for this study (FU:1 m<sup>3</sup> treated wastewater).

|                  |            |                                                         | Unit | AnMBR   | AnFOMBR | UASB Reactor |
|------------------|------------|---------------------------------------------------------|------|---------|---------|--------------|
| Avoided products | Energy     | Energy production                                       | kWh  | 6.0E-01 | 5.6E-01 | 5.0E-01      |
|                  |            | D-CH <sub>4</sub> recovery ratio (to biogas)            | %    | 70      | -       | 70           |
|                  | Fertilizer | N (as ammonium sulfate)                                 | kg   | 2.14    | 2.14    | 2.14         |
|                  |            | P <sub>2</sub> O <sub>5</sub> (as diammonium phosphate) | kg   | 1.71    | 1.71    | 1.71         |

In addition, the efficiency data for wastewater pollutant removal ratios taken from the related studies are shown in Table 4.2.

**Table 4.2 :** Assumptions for the three system.

|              | <b>COD<br/>Removal<br/>rate (%)</b> | <b>TP<br/>Removal<br/>rate (%)</b> | <b>TN<br/>Removal<br/>rate (%)</b> |
|--------------|-------------------------------------|------------------------------------|------------------------------------|
| AnMBR        | 90                                  | 30                                 | 25                                 |
| UASB reactor | 80                                  | 10                                 | 15                                 |
| AnFOMBR      | 98                                  | 85                                 | 35                                 |

### 4.3 Results and Discussion

#### 4.3.1 The midpoint results of the three systems

The life cycle assessment (LCA) results provide a comprehensive comparison of the environmental performance of three prominent anaerobic wastewater treatment technologies: AnMBR, AnFOMBR, and UASB. Across a broad range of midpoint impact categories, the findings reveal significant differences in their environmental burdens. Among these, the AnFOMBR system stands out by consistently demonstrating the lowest environmental impacts, which highlights its superior sustainability profile. This reduced environmental footprint is evident in categories such as global warming potential, eutrophication, acidification, and human toxicity, where AnFOMBR outperforms both the AnMBR and UASB reactors. The results emphasize the potential of AnFOMBR technology to serve as a more eco-efficient alternative, offering enhanced environmental benefits while maintaining effective wastewater treatment performance. All numeric results given by Table 4.3.

**Table 4.3 :** Life cycle impact assessment results of the study.

| <b>Impact category</b>                   | <b>Unit</b>             | <b>AnMBR</b> | <b>UASB Reactor</b> | <b>AnFOMBR</b> |
|------------------------------------------|-------------------------|--------------|---------------------|----------------|
| Global warming potential (GWP)           | kg CO <sub>2</sub> eq   | 1.28E+01     | 9.49E+00            | 8.49E+00       |
| Stratospheric ozone depletion (ODP)      | kg CFC11 eq             | 5.15E-06     | 4.27E-06            | 4.19E-06       |
| Ozone formation, Human health (HH)       | kg NO <sub>x</sub> eq   | 2.84E-02     | 2.15E-02            | 2.09E-02       |
| Fine particulate matter formation (FPMF) | kg PM <sub>2.5</sub> eq | 5.63E-02     | 3.29E-02            | 3.10E-02       |
| Terrestrial acidification (AP)           | kg SO <sub>2</sub> eq   | 4.03E-02     | 2.68E-02            | 2.56E-02       |
| Freshwater eutrophication (FE)           | kg P eq                 | 5.04E+00     | 7.02E+00            | 1.63E+00       |
| Marine eutrophication (ME)               | kg N eq                 | 1.22E+01     | 2.27E+00            | 1.24E+00       |
| Terrestrial ecotoxicity (TET)            | kg 1,4-DCB              | 6.62E+01     | 6.47E+01            | 6.46E+01       |
| Freshwater ecotoxicity (FET)             | kg 1,4-DCB              | 1.33E-02     | 1.20E-02            | 1.19E-02       |
| Marine ecotoxicity (MET)                 | kg 1,4-DCB              | 5.38E-02     | 5.12E-02            | 5.10E-02       |
| Human carcinogenic toxicity (HCT)        | kg 1,4-DCB              | 9.04E-02     | 7.28E-02            | 7.13E-02       |

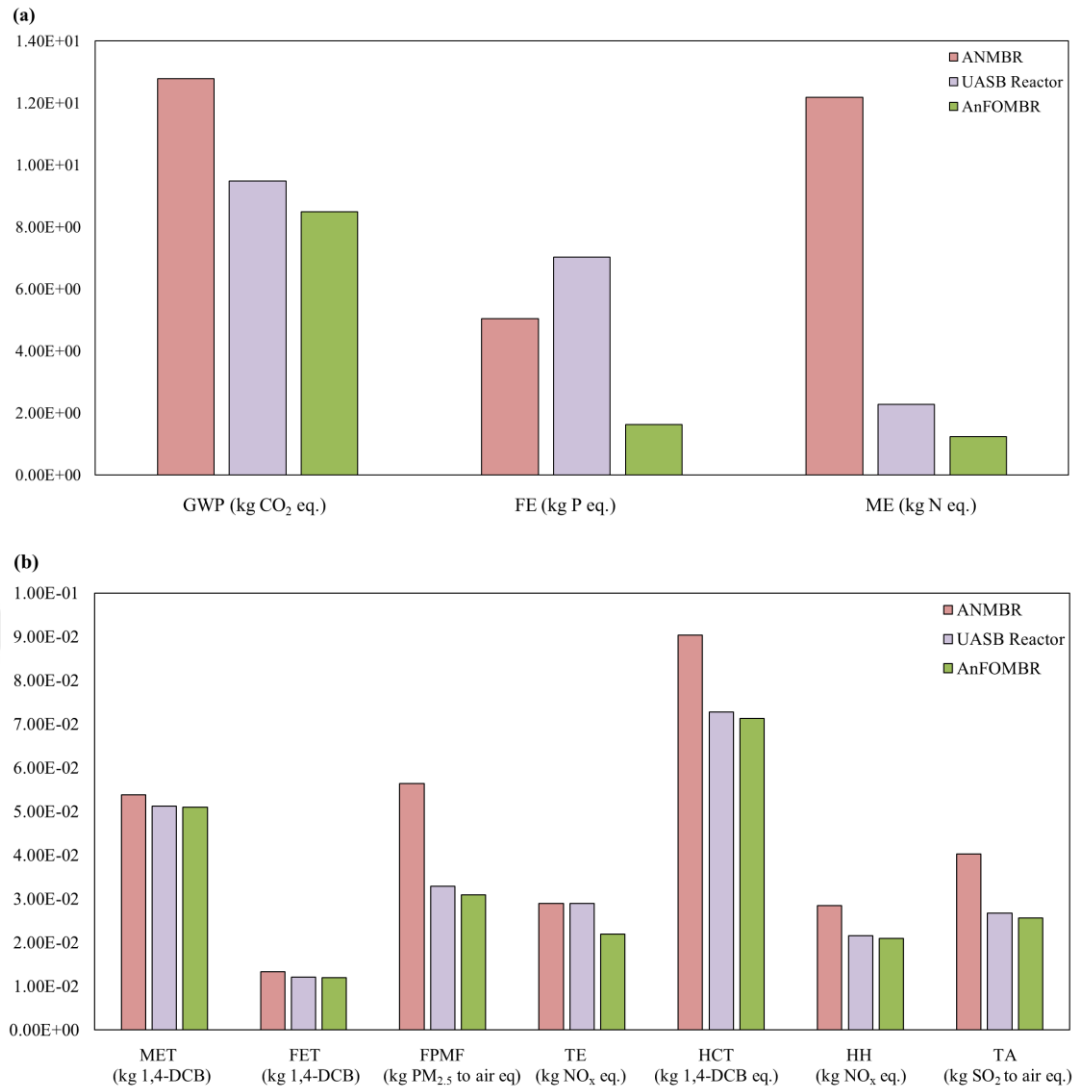


**Figure 4.2 :** Midpoint results (a) GWP, ME, TE results (b) FPMF, TE, HCT, HH, TA and ODP results.

This LCA study conducted a detailed life cycle assessment (LCA) of three anaerobic wastewater treatment technologies—Anaerobic Membrane Bioreactor (AnMBR), Anaerobic Forward Osmosis Membrane Bioreactor (AnFOMBR), and Upflow Anaerobic Sludge Blanket (UASB)—to compare their environmental performances across a wide range of midpoint impact categories. The evaluation incorporated operational inputs, emissions to air and water, waste generation, and credits from energy and nutrient recovery, using the ReCiPe midpoint method. The results indicate that the AnFOMBR system demonstrates the best overall environmental performance, achieving the lowest impact scores in 9 out of 11 evaluated categories. Notably, AnFOMBR had the lowest Global Warming Potential (GWP) at 8.49 kg CO<sub>2</sub> eq, which is approximately 33.7% lower than AnMBR (12.8 kg CO<sub>2</sub> eq) and 10.5% lower than

UASB (9.49 kg CO<sub>2</sub> eq). This significant reduction can be attributed to its low electricity consumption (0.34 kWh per unit, compared to 0.865 kWh in AnMBR), and its high nutrient removal efficiencies which reduce downstream environmental impacts associated with nitrogen and phosphorus pollution. AnFOMBR had the lowest freshwater eutrophication impact, at 1.63 kg P eq, which is 67.7% lower than AnMBR and 76.8% lower than UASB. This correlates with its phosphorus removal efficiency of 85%, compared to only 30% for AnMBR and 10% for UASB. Similarly, in marine eutrophication, AnFOMBR emitted 1.24 kg N eq, representing a 90% reduction compared to AnMBR, which had 12.2 kg N eq. The UASB reactor also performed relatively better in marine eutrophication than AnMBR, but still emitted 83% more nitrogen than AnFOMBR. These differences underscore the crucial importance of nutrient removal efficiency in mitigating the impacts on aquatic ecosystems. (Fig. 4.2 a). In terms of stratospheric ozone depletion (ODP), AnFOMBR again had the lowest value ( $4.19 \times 10^{-6}$  kg CFC11 eq), representing a 19% improvement over AnMBR. Similarly, for ozone formation impacting human health, AnFOMBR produced the lowest emissions ( $2.09 \times 10^{-2}$  kg NO<sub>x</sub> eq), which is 26% lower than AnMBR and 2.8% better than UASB. These reductions stem from minimized fossil fuel-based energy use and reduced chemical requirements. When comparing fine particulate matter formation, which is closely related to human respiratory health, AnFOMBR emitted only  $3.10 \times 10^{-2}$  kg PM<sub>2.5</sub> eq, a 45% reduction compared to AnMBR. For terrestrial acidification, the impact was  $2.56 \times 10^{-2}$  kg SO<sub>2</sub> eq, which is 36.5% lower than AnMBR, again showing the benefit of energy-efficient operation (Fig. 4.2b). A particularly notable result was found in eutrophication-related categories. Although differences in ecotoxicity and human toxicity categories were smaller, AnFOMBR still had the lowest scores across all toxicity-related impacts, including terrestrial, freshwater, and marine ecotoxicity, as well as human carcinogenic toxicity. For instance, AnFOMBR had a human carcinogenic toxicity of  $7.13 \times 10^{-2}$  kg 1,4-DCB eq, which is 21.1% lower than AnMBR. The AnMBR system, while technically advanced, exhibited the highest environmental burden in almost all categories. Its electricity demand is more than 2.5 times higher than that of AnFOMBR, driving up its climate and toxicity impacts. Although AnMBR achieved high COD removal (90%) and moderate nutrient removal (TP: 30%, TN: 25%), these benefits were insufficient to offset the impacts associated with its high operational energy use. The UASB reactor, with the lowest energy input among the three systems and moderate

biogas recovery, showed reasonable performance in energy-related categories, but it was inferior in nutrient removal, particularly phosphorus and nitrogen. As a result, it had the highest freshwater eutrophication impact (7.02 kg P eq) and moderately high marine eutrophication (2.27 kg N eq). These values are, respectively, 3.3 times and 1.8 times higher than those of AnFOMBR, showing that poor nutrient removal significantly increases environmental burdens even in energy-efficient systems. All three systems benefited from avoided burdens due to biogas production (0.5–0.6 kWh recovered per unit) and nutrient recovery (2.14 kg N and 1.71 kg P<sub>2</sub>O<sub>5</sub> as fertilizers). However, these credits were not enough to outweigh the disadvantages of poor nutrient retention (UASB) or excessive energy use (AnMBR). AnFOMBR, despite the absence of methane recovery in this configuration, still outperformed the others due to net savings in nutrient emissions and reduced upstream emissions from lower electricity use."

In conclusion, the results clearly demonstrate that AnFOMBR is the most environmentally sustainable option among the technologies studied. It delivers excellent treatment performance and lower life cycle impacts, especially in categories related to climate change, eutrophication, and air pollution. Further optimization of methane recovery and draw solution management could further enhance its sustainability. These findings strongly support the potential of AnFOMBR as a next-generation solution for low-impact, resource-efficient wastewater treatment, particularly in settings where nutrient recovery and effluent quality are prioritized. This study emphasizes the value of integrating life cycle thinking into process design and selection and shows that energy demand alone does not determine environmental performance; nutrient removal efficiency and recovery play an equally critical role. Therefore, decision-makers and engineers should balance energy savings with effluent quality goals to ensure the overall sustainability of wastewater treatment systems.

#### **4.3.2 The endpoint results of the three systems**

The endpoint results of the life cycle assessment (LCA) provide a high-level overview of the overall damage caused by each anaerobic wastewater treatment system in terms of human health, ecosystems, and resource depletion. These indicators summarize the cumulative environmental burdens into tangible damage units, allowing for clearer interpretation of sustainability trade-offs.

In the human health category, measured in Disability-Adjusted Life Years (DALYs), the AnFOMBR system shows the lowest impact, followed closely by the UASB reactor, while the AnMBR has the highest burden. This means the AnFOMBR system contributes to approximately 42% less damage to human health compared to the AnMBR, demonstrating its potential to reduce public health risks related to environmental emissions. In terms of ecosystem quality, evaluated in species loss per year (species.yr), the AnFOMBR again performs best with a minimal impact of  $1.13 \times 10^{-6}$  species.yr, which is about 67% lower than the UASB and 67% lower than the AnMBR. This indicates a significantly reduced threat to biodiversity and ecosystem function, likely due to lower emissions contributing to acidification, eutrophication, or ecotoxicity. Finally, in the resource depletion category, expressed in USD 2013 as the additional economic cost due to future resource scarcity, the AnFOMBR system incurs the lowest cost at 0.76 USD, slightly outperforming the UASB (0.77 USD) and more notably the AnMBR (0.89 USD (Fig. 4.3). This reflects a lower long-term burden on material and energy resources, emphasizing the economic efficiency and environmental compatibility of the AnFOMBR design.

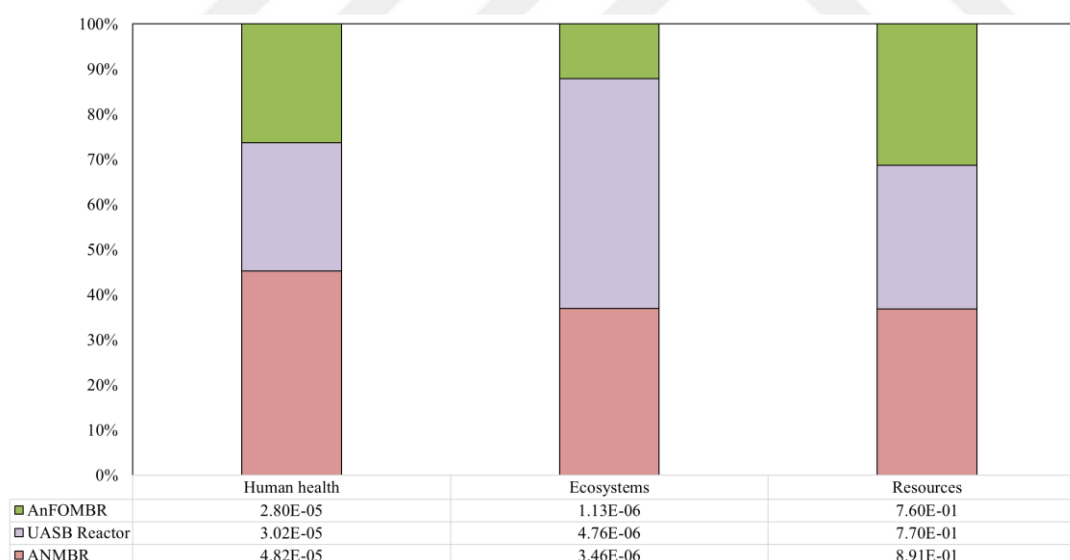


**Figure 4.3 :** The endpoint results.

### 4.3.3 Conclusion

This study conducted a comprehensive Life Cycle Assessment (LCA) of three anaerobic wastewater treatment systems—AnMBR, AnFOMBR, and UASB—to evaluate their environmental impacts through midpoint and endpoint indicators. The

results demonstrate that the AnFOMBR system offers the best overall environmental performance, driven by its high nutrient removal efficiencies and low electricity demand. At the midpoint level, AnFOMBR showed the lowest impacts in 9 of 11 categories, including global warming (33.7% lower than AnMBR), freshwater eutrophication (up to 77% lower than UASB), and marine eutrophication (over 90% lower than AnMBR). Air pollution and toxicity impacts were also consistently lower, due to reduced operational energy and minimal chemical use. Despite lacking methane recovery in this configuration, AnFOMBR's advantages in nutrient removal and energy efficiency resulted in a net environmental benefit. At the endpoint level, AnFOMBR caused 42% less damage to human health (DALYs) and 67% less ecosystem damage (species.yr) compared to AnMBR and UASB. It also had the lowest resource depletion cost (0.76 USD), indicating long-term economic and environmental compatibility. While AnMBR offered high COD removal, its high energy consumption led to significantly greater emissions and human health risks. UASB, although energy-efficient, was limited by poor nutrient removal, resulting in higher eutrophication impacts. In conclusion, the AnFOMBR system stands out as the most sustainable option, offering a favorable balance of treatment performance, environmental impact, and resource efficiency. These results support its potential as a next-generation solution for sustainable and circular wastewater management.

Future studies should aim to expand the scope and resolution of LCAs on anaerobic wastewater treatment systems by integrating site-specific operational data, long-term performance monitoring, and emerging treatment configurations such as AnFOMBRs with nutrient recovery, hybrid membranes. Also, Further attention is needed to assess the variability in feedwater characteristics, yet are often oversimplified in LCA models. Considering social and economic co-benefits alongside environmental performance will also help contextualize LCA outcomes for policy and decision-makers.



## 5. CONCLUSION AND FUTURE REMARKS

This thesis advances the understanding of the environmental sustainability of innovative anaerobic wastewater treatment technologies by conducting two complementary and detailed Life Cycle Assessment (LCA) studies. The first focused on the Anaerobic Forward Osmosis Membrane Bioreactor (AnFOMBR) system, assessing the influence of draw solution (DS) type and concentration on environmental performance. The second compared the life cycle impacts of three anaerobic treatment technologies—Anaerobic Membrane Bioreactor (AnMBR), AnFOMBR, and Upflow Anaerobic Sludge Blanket (UASB)—using both midpoint and endpoint indicators. The results, assessed using Simapro LCA software and the ReCiPe 2016 Midpoint (H) methodology, and by examining environmental impact categories, including global warming potential (GWP), ozone depletion potential (ODP), human toxicity (HT), freshwater and terrestrial ecotoxicity (FEP, TEP), acidification potential (AP), and eutrophication potential (EP).

In the DS-focused study, two parallel analyses were conducted: (i) evaluating NaCl and MgCl<sub>2</sub> at concentrations of 0.5 M and 1 M, and (ii) comparing four distinct DSs (MAP, NaCl, MgCl<sub>2</sub>, and Na<sub>2</sub>SO<sub>4</sub>) under full-scale operational scenarios. Results, assessed using the ReCiPe 2016 Midpoint (H) method, showed that DS choice and concentration are critical determinants of environmental performance. NaCl exhibited lower toxicity impacts, while MgCl<sub>2</sub> demonstrated balanced results but higher GWP and eutrophication impacts due to energy-intensive production. Increasing DS concentration from 0.5 M to 1 M consistently increased environmental burdens. MAP offered energy efficiency advantages, particularly because it does not require regeneration (RO) units and can be reused as fertilizer; however, its nutrient-rich nature significantly increased freshwater and marine eutrophication. Na<sub>2</sub>SO<sub>4</sub>, while relatively favorable in greenhouse gas terms, showed severe toxicity impacts, limiting its suitability without additional mitigation measures. These findings highlight the trade-offs between energy efficiency, nutrient reuse, and potential ecological harm.

In the system-comparison study, the AnFOMBR system outperformed AnMBR and UASB across 9 of 11 midpoint impact categories. Notably, its Global Warming Potential (8.49 kg CO<sub>2</sub> eq) was 33.7% lower than AnMBR and 10.5% lower than UASB, primarily due to its low electricity consumption (0.34 kWh per unit, versus 0.865 kWh in AnMBR) and high nutrient removal efficiencies, which reduce downstream eutrophication impacts. Freshwater eutrophication was reduced by 67.7% compared to AnMBR and 76.8% compared to UASB, while marine eutrophication impacts were over 90% lower than AnMBR. Air pollution-related categories, including ozone formation, fine particulate matter, and acidification, were also consistently lower due to reduced operational energy and chemical use. AnMBR, despite high COD removal (90%), exhibited the highest impacts in almost all categories due to excessive energy demand. UASB achieved the lowest energy use but performed poorly in nutrient removal, leading to high eutrophication burdens.

Endpoint results confirmed AnFOMBR's superiority, with 42% less damage to human health (DALYs) than AnMBR, and 67% lower ecosystem damage (species.yr) than both AnMBR and UASB. Resource depletion costs were also lowest for AnFOMBR (0.76 USD), slightly ahead of UASB (0.77 USD) and significantly better than AnMBR (0.89 USD), indicating both environmental and economic compatibility. These outcomes demonstrate that nutrient removal efficiency, alongside low energy demand, is a decisive factor in determining the sustainability of anaerobic systems.

Overall, this thesis demonstrates that the AnFOMBR system is a promising next-generation technology for sustainable wastewater management, offering favorable trade-offs between treatment performance, environmental impact, and resource efficiency. However, optimization of methane recovery, DS selection and concentration, and nutrient discharge control will be essential to further improve its sustainability profile.

Future research priorities identified by this work include:

- Conducting studies with different dissolved methane recovery and nutrient recovery ratios in AnMBRs and UASB reactors scenarios will enrich the subject area.
- Optimization of DS properties and regeneration strategies for site-specific applications; future research should explore alternative, lower-impact draw solutions, such as bio-based.

- Reuse alternatives of treated wastewater may be included in LCA studies about these systems.
- Integration of Social LCA (S-LCA) and Techno-Economic Analysis (TEA) for holistic assessment;
- Future studies should collect primary data from pilot or full-scale AnFOMBRs with site-specific operational parameters and long-term performance.
- Also, sensitivity analysis may be run by changing influent wastewater characterization for a better understanding of the effects on the systems.

By integrating draw solution optimization with system-level comparisons and endpoint assessments, this thesis bridges the gap between environmental sustainability goals and practical implementation of anaerobic wastewater treatment technologies. The findings provide a robust evidence base for guiding both policy and engineering decisions towards low-impact, circular wastewater management solutions.



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## PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Yilmaz, M., Guven, H., Ozgun, H., Ersahin, M. E., & Koyuncu, I.** 2023. The application of Life Cycle Assessment (LCA) to anaerobic technologies for the treatment of municipal wastewater: A review, *Process Safety and Environmental Protection*,182, 357-370.
- **Yilmaz, M., Guven, H., Ozgun, H., Ersahin, M. E., & Koyuncu, I.** Life Cycle Assessment of Anaerobic Forward Osmosis Membrane Bioreactors 2 (AnFOMBRs) for Municipal Wastewater Treatment: Use of Different Draw Solutions (submitted to *Environmental Monitoring and Assessment*).

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- **Yilmaz M., Koyuncu I.,** 2022: Life cycle environmental and economic assessment of AnFOMBRs and AnMBRs. Network Young Membranes Meeting 2022 - Membrane Technologies and Applications, November 17-19, Napoli, Italy.
- **Yilmaz M., Koyuncu I.,** 2024 .IWA-AD18 Conference, June 2-6, 2024, Istanbul, "Evaluating the environmental performance of Anaerobic Membrane Bioreactors and other anaerobic systems by using LCA approach".

#### OTHER PUBLICATIONS, PRESENTATIONS

- **Yilmaz Merve.** *Vibration applications for fouling control of membrane bioreactors (MBR).* Master's Thesis, Istanbul Technical University, 2016.
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- **Korkusuz S., Ardiç R., Yılmaz M., Köse Mutlu B., Koyuncu İ., (2023).** Investigation of the Effect of Traditional and Innovative Immobilization Media Materials in Quorum Quenching Membrane Bioreactors and Quorum Quenching Activity Test. 7th MEMTEK International Symposium on Membrane Technologies and Applications, 202. (Abstract/Oral Presentation) (No:0251).

