ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

LIFE CYCLE ASSESSMENT OF PACKAGE AND ULTRAFILTRATION SYSTEMS AND FOUR DISINFECTION TECHNOLOGIES FOR A FULL-SCALE WATER TREATMENT PLANT

Ph.D. THESIS

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Department of Environmental Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

TAM ÖLÇEKLİ BİR SU ARITMA TESİSİ İÇİN PAKET VE ULTRAFİLTRASYON SİSTEMLERİ İLE DÖRT DEZENFEKSİYON TEKNOLOJİSİNİN YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ

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Mehmet Zahid DEMİR, a Ph.D. student of ITU Graduate School student ID 501152714, successfully defended the dissertation entitled "LIFE CYCLE ASSESSMENT OF PACKAGE AND ULTRAFILTRATION SYSTEMS AND FOUR DISINFECTION TECHNOLOGIES FOR A FULL-SCALE WATER TREATMENT PLANT", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my beloved father, son and family..

FOREWORD

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ABBREVIATIONS

AOP : Advance Oxidation Process
DBP : Disinfection by Products
DEC : Department of Environment and Conservation Water Resources Management Division
ELCC : Environmental Life Cycle Cost
EOFP : Ozone Formation - Terrestrial Ecosystems
EPA : Environmental Protection Agency
EPLCA : European Platform on LCA
EU : European Union
FEP : Freshwater Eutrophication
FETP : Freshwater Ecotoxicity
FFP : Fossil Resource Scarcity
FU : Functional Unit
FWT : Freshwater Transfer
GAC : Granular Activated Carbon
GFRP : Glass Fiber Reinforced Plastic
GWP : Global Warming Potential
HOFP : Ozone Formation - Human Health
HTPc : Human Carcinogenic Toxicity
HTPnc : Human Non-Carcinogenic Toxicity
ILCD : The International Reference Life Cycle Data System
IRP : Ionizing Radiation
ISO : International Organization for Standardization
IWA : The International Water Association
LCA : Life Cycle Assessment
LCI : Life Cycle Inventory Analysis
LCIA : Life Cycle Impact Assessment
LED : Light Emitting Diode
LOP : Land Use
LP : Low pressure
LPHO : Low Pressure High Output
LPRO : Low Pressure Reverse Osmosis
LWA : Local Water Administration
MDH : Minnesota Department of Health
MEP : Marine Eutrophication
METP : Marine Ecotoxicity
NF : Nanofiltration
ODP : Stratospheric Ozone Depletion
OM : Organic Matter
PMFP : Fine Particulate Matter Formation
PU : Polyurethane
PVC : Polyvinyl Chloride
PVDF : Polyvinylidenefluoride

PWTS : Package Water Treatment System
RO : Reverse Osmosis
SDGs : Sustainable Development Goals
SOP : Mineral Resource Scarcity
SS : Suspended Solids
TAP : Terrestrial Acidification
TETP : Terrestrial Ecotoxicity
UF : Ultrafiltration
UFWTS : Ultrafiltration Water Treatment System
UN : United Nations
UNICEF : The United Nations Children's Fund
UV : Ultraviolet
WCP : Water Consumption
WHO : World Health Organization
WTP : Water Treatment Plant

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LIFE CYCLE ASSESSMENT OF PACKAGE AND ULTRAFILTRATION SYSTEMS AND FOUR DISINFECTION TECHNOLOGIES FOR A FULL-SCALE WATER TREATMENT PLANT

SUMMARY

A growing global population underscores the urgent need for access to adequate drinking water, a basic human need. As recognized by the United Nations, access to safe and clean drinking water is a basic human right and obliges governments to ensure this right. To meet this need, various treatment and disinfection methods are used depending on the water source. The materials and equipment used in these processes are sourced from different sectors and discarded after use, potentially leading to significant environmental consequences such as depletion of natural resources, emissions and waste generation. To comprehensively assess these environmental impacts, Life Cycle Assessment is one of the most comprehensive and accuratemethodologies available.

Today's approaches to improving drinking water quality are mainly based on physical and chemical processes as well as combination of those. Package treatment systems offer several advantages over conventional plants by treating water through pre-built treatment tanks using both physical and chemical processes. These systems are characterized by relatively low initial investment cost, minimal spatial footprint, quick installation and ease of operation. Furthermore, the materials used in these systems are recyclable, reducing their environmental impact. In contrast, ultrafiltration systems rely on physical processes which provide advantages such as reduced chemical use, minimal space requirements, operational simplicity and potential for capacity expansion. Regardless of the treatment method, disinfection of water is essential to ensure safety for consumption.

Drinking water must be free of pathogenic microorganisms to be considered safe for human consumption. Common water disinfection techniques include chemical methods such as chlorination and ozonation, physical methods such as ultraviolet (UV) irradiation, advanced oxidation processes and electrochemical methods. UV irradiation is increasingly preferred because it is effective against a wide range of microorganisms and easy to use. From an economic point of view, chemical disinfection methods are generally more cost-effective, with the exception of ozone due to its high investment and operational costs. Although the adoption of UV systems has been increasing, it is supported by installations that utilize a variety of UV sources despite its relatively high investment cost.

The aim of this thesis is to present a comparative analysis of the environmental impacts of the most widely used disinfection systems, including gas chlorine, ultraviolet and ozone, as well as package treatment and ultrafiltration water treatment systems, using the Life Cycle Assessment methodology. This study aims to achieve a thorough comprehension of the ecological consequences associated with both water treatment and water disinfection systems, with the objective of facilitating knowledgeable

decision-making in the pursuit of environmentally sustainable water treatment and disinfection alternatives.

The comparisons were made by following the steps of ISO 14040 "Environmental management - Life cycle assessment - Principles and framework" standard. ISO 14040 specifies the steps to be applied in LCA studies and how they should be, and ISO 14044 "Environmental management - Life cycle assessment - Requirements and guidance" explains these steps in detail. The treatment and disinfection systems examined in this thesis include phases i) Goal and scope definition ii) Life cycle inventory analysis (LCI) iii) Life cycle impact assessment (LCIA) and iv) Life cycle interpretation. The data used for the environmental impact calculations were collected through site visits, literature and market researchThe data collected were arranged in accordance with the functional unit and utilized in the computational process.. For the calculation of environmental impact values, SimaPro, an LCA software, was used to evaluate 18 impact categories together with the ReCiPe LCA methodology. The results of the water treatment and disinfection systems examined within the scope of the thesis were analyzed and the results were compared with the existing studies in the literature in line with the thesis subject.

The water treatment systems were compared in terms of their environmental impacts from both operation and construction. Although more material is used to produce package water treatment system than ultrafiltration water treatment system, it is seen that the environmental impact of package treatment systems is less in all impact categories. The main reason for this is the high environmental impact of the production of materials used in the production of ultrafiltration systems and the high energy consumption required for operation. Another important aspect is that the materials used in the production of the treatment tanks used in package treatment systems (e.g. stainless steel, galvanized sheet) can be reused instead of being disposed of at the end of their useful life.

The comparison of water disinfection systems considers only the impacts caused by the operational phase. Environmental impacts caused by the production of the water disinfection equipment are not included in the calculations. The reason for this is that there is no literature information about the production of the disinfection equipment examined and the manufacturers do not share this information. Among the water disinfection equipment compared, the systems with the lowest environmental impact were the UV system using low pressure amalgam ultraviolet lamps and the gas chlorine system. The ozone system and the UV system using LED ultraviolet lamps had the highest environmental impact. The main reason for this result is the amount of energy required for operation.

The results show that the environmental impacts of the water treatment and disinfection processes are important for the source of the energy and material production steps used in the plant. When utilizing two separate sets of electricity generation data - one encompassing global electricity generation and the other focusing on local electricity generation - no alteration was observed in the ecological impact rating of water disinfection systems. However, variations were evident in each impact category, both showing increases and declines. The use of renewable energy sources will reduce the environmental impacts of drinking water treatment and disinfection systems.

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ÖZET

Artan küresel nüfus, temel bir insan ihtiyacı olan yeterli içme suyuna acil erişim ihtiyacının altını çizmektedir. Birleşmiş Milletler tarafından da kabul edildiği üzere, güvenli ve temiz içme suyuna erişim temel bir insan hakkıdır ve hükümetleri bu hakkı sağlamakla yükümlü kılar. Bu ihtiyacı karşılamak için su kaynağına bağlı olarak çeşitli arıtma ve dezenfeksiyon yöntemleri kullanılmaktadır. Bu süreçlerde kullanılan malzeme ve ekipmanlar farklı sektörlerden temin edilmekte ve kullanım sonrasında atılmakta, bu da potansiyel olarak doğal kaynakların tükenmesi, emisyonlara ve atık oluşumu gibi önemli çevresel sonuçlara yol açmaktadır. Bu çevresel etkileri kapsamlı bir şekilde değerlendirmek için Yaşam Döngüsü Değerlendirmesi mevcut en kapsamlı ve hassas metodolojilerden biridir.

Günümüzde içme suyu kalitesinin iyileştirilmesine yönelik yaklaşımlar temel olarak fiziksel ve kimyasal süreçlerin yanı sıra bunların birlikte kullanılmasına dayanmaktadır. Paket arıtma sistemleri, suyu hem fiziksel hem de kimyasal süreçler kullanarak önceden inşa edilmiş arıtma tankları aracılığıyla arıtarak geleneksel tesislere göre çeşitli avantajlar sunmaktadır. Bu sistemler nispeten düşük ilk yatırım maliyeti, minimum alan ihtiyacı, hızlı kurulum ve işletme kolaylığı ile karakterize edilir. Ayrıca, bu sistemlerde kullanılan malzemeler geri dönüştürülebilir ve çevresel etkilerini azaltır. Buna karşılık, ultrafiltrasyon sistemleri daha az kimyasal kullanımı, minimum alan gereksinimi, operasyonel basitlik ve kapasite genişletme potansiyeli gibi avantajlar sağlayan fiziksel süreçlere dayanır. Arıtma yöntemi ne olursa olsun, tüketiciye sağlıklı ve güvenli içme suyu sağlamak için suyun dezenfeksiyonu esastır.

İçme suyunun insan tüketimi açısından güvenli kabul edilebilmesi için patojen mikroorganizmalardan arındırılmış olması gereklidir. Yaygın su dezenfeksiyon teknikleri arasında klorlama ve ozonlama gibi kimyasal yöntemler, ultraviyole (UV) gibi fiziksel yöntemler, gelişmiş oksidasyon işlemleri ve elektrokimyasal yöntemler yer almaktadır. UV çok çeşitli mikroorganizmalara karşı etkili olması ve kullanımının kolay olması nedeniyle giderek daha fazla tercih edilmektedir. Ekonomik açıdan bakıldığında, yüksek yatırım ve işletme maliyetleri nedeniyle ozon hariç, kimyasal dezenfeksiyon yöntemleri genellikle daha uygun maliyetlidir. UV sistemlerinin kullanımı artmakla birlikte, nispeten yüksek yatırım maliyetine rağmen çeşitli UV kaynaklarını kullanan tesislerin sayısı her geçen gün artmaktadır.

Bu tezin amacı, Yaşam Döngüsü Değerlendirmesi metodolojisini kullanarak gaz klor, ultraviyole ve ozonun yanı sıra paket arıtma ve ultrafiltrasyon su arıtma sistemleri de dahil olmak üzere en yaygın kullanılan dezenfeksiyon sistemlerinin çevresel etkilerinin karşılaştırmalı bir analizini sunmaktır. Bu çalışma, çevresel açıdan sürdürülebilir su arıtma ve dezenfeksiyon alternatifleri arayışında karar vermeyi kolaylaştırmak amacıyla, hem su arıtma hem de su dezenfeksiyon sistemleriyle ilişkili ekolojik sonuçların kapsamlı bir şekilde anlaşılmasını sağlamayı amaçlamaktadır.

Karşılaştırmalar ISO 14040 “Çevre yönetimi - Yaşam döngüsü değerlendirmesi - İlkeler ve çerçeve” standardının adımları takip edilerek yapılmıştır. ISO 14040, LCA çalışmalarında uygulanacak adımları ve bunların nasıl olması gerektiğini belirtirken, ISO 14044 “Çevre yönetimi - Yaşam döngüsü değerlendirmesi - Gereklilikler ve kılavuz” bu adımları detaylı olarak açıklamaktadır. Bu tezde incelenen arıtma ve dezenfeksiyon sistemleri i) Hedef ve kapsam tanımı ii) Yaşam döngüsü envanter analizi (LCI) iii) Yaşam döngüsü etki değerlendirmesi (LCIA) ve iv) Yaşam döngüsü yorumlama aşamalarını içermektedir. Çevresel etki hesaplamaları için kullanılan veriler saha ziyaretleri, literatür ve piyasa araştırması yoluyla toplanmıştır. Toplanan veriler fonksiyonel birime (functional unit) göre düzenlenmiş ve hesaplama sürecinde kullanılmıştır. Çevresel etki değerlerinin hesaplanmasında, ReCiPe LCA metodolojisi ile birlikte 18 etki kategorisini değerlendirmek için bir LCA yazılımı olan SimaPro kullanılmıştır. Tez kapsamında incelenen su arıtma ve dezenfeksiyon sistemlerinin sonuçları analiz edilmiş ve sonuçlar tez konusu doğrultusunda literatürdeki mevcut çalışmalarla karşılaştırılmıştır.

Modellemede kullanılan veriler iki grup altında toplanmıştır. Birinci grubu ön plan verileri (foreground data) ve ikinci grubu ise arka plan verileri (background data) oluşturmaktadır. Ön plan verileri, bir ürünün yaşam döngüsünün sistem sınırı içindeki süreçlerden doğrudan toplanan spesifik, birincil verileri ifade eder. Bu veriler genellikle doğrudan ölçümlerden veya ayrıntılı şirket kayıtlarından toplanır ve değerlendirilen belirli ürün veya sürece özgüdür. Ön plan verileri saha ziyaretleri, üretici firmalar ve işletmeciler ile direkt görüşmeler gibi çalışmalar ile toplanabilmektedir. Arka plan verileri, incelenen sistemin doğrudan kontrolü dışındaki ortalama koşulları veya süreçleri temsil eden genel verileri kapsar. Bu veriler genellikle veri tabanlarından, literatürden veya diğer ikincil kaynaklardan elde edilir ve enerji üretimi, malzeme üretimi ve atık yönetimi gibi süreçler için daha geniş bir bağlam sağlar. Arka plan verileri belirli süreç detaylarının mevcut olmadığı genel durumlarda kullanılmaktadır. Bu tez kapsamında ön plan verileri pilot içme suyu arıtma tesisine yapılan saha ziyaretleri, ekipman üreticileri ile görüşmeler, arıtma tesisi işletmecileri ile yapılan görüşmeler ve ilgili kurumun işletme kayıtları incenelerek oluşturulmuştur. Arka plan verileri ise Ecoinvent veritabanı, litereatür araştırmaları ve Amerika Çevre Ajansı (US EPA) gibi kurumların hazırlamış olduğu raporlar kullanılarak oluşturulmuştur.

Su arıtma sistemleri hem işletme hem de inşaat kaynaklı çevresel etkileri açısından karşılaştırılmıştır. Paket su arıtma sistemi üretmek için ultrafiltrasyon su arıtma sistemine göre daha fazla malzeme kullanılmasına rağmen, paket arıtma sistemlerinin çevresel etkisinin tüm etki kategorilerinde daha az olduğu görülmektedir. Bunun temel nedeni, ultrafiltrasyon sistemlerinin üretiminde kullanılan malzemelerin üretiminin yüksek çevresel etkisi ve işletme için gereken yüksek enerji tüketimidir. Bir diğer önemli husus ise paket arıtma sistemlerinde kullanılan arıtma tanklarının üretiminde kullanılan malzemelerin (örn. paslanmaz çelik, galvanizli sac) kullanım ömürlerinin sonunda bertaraf edilmek yerine yeniden kullanılabilmesidir. Su arıtma sistemlerinin ön plan verileri incelen ekipmanlarında kullanılan malzemeler, içme suyu arıtma tesisinin belirlenen faydalı ömrü boyunce işletme esnasında kullanılan sarf malzemeleri, kimyasallar enerji ve arıtılan içme suyu miktarı üzerinden oluşturulmuştur.

Su dezenfeksiyon sistemlerinin karşılaştırılmasında sadece işletme aşamasından kaynaklanan etkiler dikkate alınmaktadır. Su dezenfeksiyon ekipmanının üretiminden kaynaklanan çevresel etkiler hesaplamalara dahil edilmemiştir. Bunun nedeni, incelenen dezenfeksiyon ekipmanlarının üretimine ilişkin literatür bilgisi bulunmaması ve üreticilerin bu bilgileri paylaşmamasıdır. Karşılaştırılan su dezenfeksiyon ekipmanları arasında çevresel etkisi en düşük olan sistemler düşük basınçlı amalgam ultraviyole lambaların kullanıldığı UV sistemi ve gaz klor sistemi olmuştur. Ozon sistemi ve LED ultraviyole lambaları kullanan UV sistemi en yüksek çevresel etkiye sahip sistemlerdir. Bu sonucun ana nedeni işletme için gereken enerji miktarıdır. Su dezenfeksiyon sistemlerinin ön plan verileri menşe ülke, nakliye rotası ve türü, işletme için gerekli olan kimyasallar, enerji ve dezenfekte edilen içme suyu miktarı üzerinden oluşturulmuştur.

Sonuçlar, su arıtma ve dezenfeksiyon proseslerinin çevresel etkilerinin, tesiste kullanılan enerji ve malzeme üretim adımlarının kaynağı açısından önemli olduğunu göstermektedir. Biri küresel elektrik üretimini kapsayan, diğeri ise yerel elektrik üretimine odaklanan iki ayrı elektrik üretim verisi seti kullanıldığında, su dezenfeksiyon sistemlerinin ekolojik etki derecelendirmesinde herhangi bir değişiklik gözlenmemiştir. Ancak, her bir etki kategorisinde hem artış hem de düşüş gösteren farklılıklar görülmüştür. Yenilenebilir enerji kaynaklarının kullanımı, içme suyu arıtma ve dezenfeksiyon sistemlerinin çevresel etkilerini azaltacaktır.

1. INTRODUCTION

Delivering safe and healthy drinking water to consumers requires a comprehensive strategy influenced by a combination of processes and expertise combining various industries. It can be accepted that the extraction of natural sources is the beginning of the water treatment operation because the equipment and the chemicals used in the production of drinking water are made with the various process that converts raw materials to a product. Even though different chemicals and equipment are used depending on the chosen water treatment process, all of them are energy and chemical dependent.

Every step involved in producing drinking water has environmental implications, impacting soil, water, air, and the surrounding ecosystem. These impacts can be assessed and managed using different methods, such as carbon footprint, water footprint, or life cycle assessment (LCA). While methods like carbon and water footprint focus on specific aspects, LCA provides a holistic view, covering multiple areas that require protection.

In conducting life cycle assessments, various categories are surveyed to evaluate impacts. Common categories include acidification, climate change, depletion of resources, eutrophication, ionizing radiation, and human and ecological toxicity. As global awareness of the urgent need for environmental conservation and the fight against global warming continues to rise, the importance of Life Cycle Assessment (LCA) is poised to increase significantly in the years ahead.

This thesis compared an existing municipal water treatment plant (conventional package water treatment system) with a virtually designed ultrafiltration water treatment system. Together with the whole water treatment process, four different water disinfection systems; chlorination, ultraviolet (UV) system using low pressure high output (LPHO) amalgam lamps, ultraviolet (UV) system using light emitting diodes (LED) lamps and ozonation.

1.1. Purpose of Thesis

In this thesis, the goal is to conduct a thorough examination of the environmental consequences associated with the production of drinking water and its disinfection at a municipal level, utilizing the framework of Life Cycle Assessment (LCA). Water treatment involves a complex blend of industrial processes, each exerting a direct influence on natural resources and ecosystems. To quantify these impacts, the ReCiPe midpoint impact category methodology is employed. Through the analysis, we analyze different water treatment and disinfection systems to understand their environmental impacts, including those from production, operations, energy use, and transportation.

1.2. Unique Aspect

A notable aspect of this research lies in its response to a gap identified in the existing literature. Previous studies on LCA within the field of water treatment and disinfection have predominantly focused on small-scale facilities. By contrast, this thesis addresses this deficiency by examining into the LCA of a full-scale water treatment plant, with a capacity of 9072 m^3/h. Moreover, the study extends its scope beyond conventional boundaries by evaluating novel disinfection systems such as the LPHO UV, UV LED, and ozone disinfection technologies. The inception of these systems was influenced by a pilot water treatment facility that is currently operational. This departure from traditional practices lends a unique perspective to the LCA analysis, offering insights into technologies and flow rates that are up to the present remained uninvestigated.

1.3. Organization of the Thesis

The structure of this thesis comprises five main sections, each subdivided into subsections to facilitate a comprehensive analysis of the research. The first section starts with the introduction where the insights of thesis is explained. Following this, the thesis includes literature riveiw section, providing a thorough examination of relevant literature. Chapters three and four present the main research chapters describing the methodology of the compared water treatment and water disinfection systems, findings and discussions in the sub-chapters. These investigations were carefully constructed using collected data and then modeled using LCIA software. Finally, the thesis concludes with a comprehensive conclucions and recommendations section, wherein the outcomes of the study are deliberated upon, accompanied by reflections on future research directions.

2. LITERATURE REVIEW

United Nations recognizes that access to safe drinking water is accepted as a human right and indicates this right, as well as other human rights, must be provided and protected by States that infers giving the duty to governmental institutions to provide safe water to the public (UN, 2010). Assessing the potential environmental impacts of water treatment is essential to ensuring that these projects are implemented in a sustainable manner. The production of quality and safe drinking water for the public can have environmental and human health impacts, which need to be carefully considered. An evaluation method named Life Cycle Assessment (LCA) started to be used in the late 20th century to evaluate the enviromental impacts of products or services. Even though LCA is mainly used to compare the environmental impacts of different alternatives to a product/service, it can also be used to assess the environmental impacts of a particular product/service (Collado-Ruiz & Ostad-Ahmad-Ghorabi, 2010). International Organization for Standardization (ISO) internationally standardizes the method with ISO 14040 and ISO 14044. The LCA evaluation method is also being used to address the environmental impacts of water production and water disinfection.

Water treatment and disinfection technologies have been continuously developing since the 18th century (Symons, 2006). Water production in the 21st century mainly uses groundwater, surface water, and seawater as raw water sources. Surface water and groundwater are the most common water sources used to provide fresh water to people. Depending on the water quality, some groundwaters are eligible for direct use with filtration and disinfection, but others need treatment before consumption. With the improvements in membrane technology, water from the sea or brackish waters started to be used for human consumption after treatment methods such as advanced membrane treatment or thermal processes (Younos & Tulou, 2009). Conventional water treatment plants usually consist of steps for coagulation, flocculation, settling, filtration and disinfection (Weiner & Matthews, 2003). Process modifications can be implemented in conventional water treatment plants depending on the raw water quality and the targeted quality determined by regulations (Jiménez et al., 2018). Nowadays, package water treatment systems are starting to be used in water treatment. Package treatment systems combine coagulation, flocculation, settling, and filtration in a one single tank taking less space than conventional methods. In case of high expropriated pricing, it is a good solution for using less space (Kulkarni et al., 2022).

Raw water that enters the water treatment plant (WTP) may have turbidity, and to reduce the turbidity, coagulants are used to neutralize the particles and bring them together to make flocs. Once the flocs are formed, they need to be removed from the water by a settling process. Suspended particles in the water settle in the settling tank, and sludge is removed from the settling tank. After the settling tanks, water is filtered to retain suspended solids from the flocculation and settling process. The next step is water disinfection, which is crucial in preventing waterborne diseases caused by pathogenic microorganisms. Chlorination is the maturest and the most commonly used disinfection method in water treatment (Monaghan et al., 2011). Different types of chlorine-based disinfectants are used in water treatment plants for water disinfection such as gaseous chlorine (HOCl) and liquid chlorine (NaOCl) (Kumar & Pandit, 2012). Chlorine has a distinct advantage as being a residual disinfectant, but at the same time, it has a disadvantage due to the formation of disinfection by-products (DBPs) which is caused by the organic matter in the treated water. Optimization of the chlorine is essential to control DBPs, which are cancerogenic for humans. Even though chlorine is well known and highly used for water disinfection, it affects the aesthetics of water in the means of taste and odor. When chlorine is used as a disinfectant, and if there are chlorine-resistant microorganisms in the water source, a second or different disinfection alternative is needed. For this issue and to reduce the usage of chlorine, other alternative water disinfection technologies, such as ozone and ultraviolet, are increasing around the globe. The Multi-Barrier Approach, which combines two different water disinfection alternatives, helps to minimize DBP formation, increase the disinfection effect, improve water aesthetics and meet the required limits.

Another water treatment method that is started to be used widely is desalination, Jones et al. (2019). Desalination uses advanced membrane technologies or thermal processes to produce drinking water from seawater. The desalination process can be divided into three steps; pre-treatment, main treatment and post-treatment. For the main treatment, membrane and thermal processes are mainly used. The cost of desalination is higher than conventional treatment in terms of capital investment, operation and cost of producing a cubic meter of water, but the forecast shows that in 20 years, the construction costs, water production costs, and electricity consumption will be reduced by almost 50% and the efficiency of membranes for producing one cubic meter of water will increase 3 times (IWA, 2016).

When the environmental impacts of a product or service are evaluated, carbon footprint (Hofs et al., 2022b) and water footprint (Leão et al., 2022) are also considered as an individual category for impact assessment method. Although these two factors are essential, a more comprehensive approach is needed to evaluate the broader impacts of environment. At this point, Life Cycle Assessment (LCA) is used, which covers a wide range of environmental impacts with midpoint and endpoint indicators (Finnveden & Potting, 2014). Depending on the region, different approaches to LCA are made with the chosen Life Cycle Impact Assessment methodologies and databases which screen different impact categories (Su, 2021). Regarding LCA of water production, studies on conventional and membrane process water production have been carried out.

Scopus, a peer-reviewed literature database that can be used for article searches, is used for literature search on LCA of water treatment and water disinfection techniques. 4 different research topics are used to find the related articles on this paper's topic; i) LCA Water Treatment ii) LCA Potable Water Production iii) LCA Water Disinfection iv) Life Cycle Water Disinfection. Article research is carried out in the article title, abstract and keywords section of articles with using keywords together with conjunction "AND" between them. A large number of research articles are seen at first glance but these results contained many articles which are not related LCA of drinking water treatment or drinking water disinfection. When the detailed search is made using the advanced search section of Scopus, different results are received. To be able to narrow down the search for the exact articles that are related, connective "AND NOT" is used to exclude words that are not related to this review paper. Even after using this method some unrelated articles were shown on the search page. Each article had to be checked and narrow it down to the ones that are related with the area of this paper. Table1 shows the search results of the articles from Scopus with different search options and their results. In addition to Scopus, ScienceDirect and Google Scholar was used to access to research articles on the topic of this review article. Table 2.1 shows the number of articles on drinking water treatment and drinking water disinfection published in the Scopus database between 1997 and 2022.

This chapter of the thesis thesis conducted a comprehensive review of studied articles that investigated the life cycle assessment (LCA) of water treatment and disinfection, encompassing those that analyzed water treatment and disinfection within the water supply system, as well as a restricted number of articles that integrated economic factors in conjunction with the life cycle of water treatment. In light of the fact that capital and operational costs are crucial considerations for decision-makers, it would be advantageous to assess LCA models that consider the financial implications for the public interest. LCA studies in the field of water disinfection technology are limited, with a narrow focus on the disinfection of water itself rather than on related areas such as the disinfection of wastewater, reuse water disinfection or disinfection by-products. The present review paper aims to examine the existing life cycle assessment (LCA) studies on water treatment and disinfection, while also identifying the research gaps and providing recommendations for future LCA investigations in this area.

2.1. Historical Development of Water Teratment, Water Disinfection and LCA

The history of water treatment started with the filtration process. The first illustrated filtration system dated back to 1685: Sand filtration following straining (coarse filtration) and sedimentation. Around the 1750s, the first patent of filtration was issued, which used a sponge, sand, and wool filtration, and in 1791 a British inventor, James Peacock, patented his slow sand filter with backwashing. At the beginning of the 18th century, Dr. Pluche stated that river water quality could be increased by sedimentation. The industry used these filters, and the first municipal installation of a filtration system was made in Scotland in 1804, but there was no distribution system. In 1807, Glasgow became the first city in the world to have a water treatment system with a distribution network. At these times, the treatment was used to improve water quality parameters such as odor, color, and taste. Parallel to studies on filtration, softening of water started to be tested by researchers. In 1882, Doctor Robert Koch discovered tuberculosis bacillus, and the studies on bacteriology started to receive more attention (Symons, 2006). The mid-1880s was a turning point for water treatment when cholera bacteria were discovered, and water was the carrier (Lippi & Gotuzzo, 2014). These discoveries' outcome was the understating and need for water disinfection. Different methods for water disinfection were carried out in the world around at the same time. Belgium was the first country in the world to use chlorination for water disinfection in 1902 followed by the USA with first experimental ozone water disinfection in 1906 (Miller et al., 1978) and France with the first UV water disinfection system installation in 1910 (Chen et al., 2006). Another historical moment for water treatment was the desalination process. Around 1965, the first desalination plant was built in San Diego (Swyngedouw & Williams, 2016).

Table 2.1 : Scopus Search Results.

Search Topic	Search Within	Keywords Included	Keywords Excluded	Number of Papers
LCA Water Treatment				
	TITLE-ABS-KEY	LCA, water, treatment	None	1,165
	TITLE-ABS-KEY	LCA, water, treatment, plant	none	529
	TITLE-ABS-KEY	LCA, water, treatment, plant	Wastewater, recovery, effluent, sewage, recycle, waste, industry, sludge, soil, fire, harvesting, rainwater, biomass, power-plant, wash, chemicals, reuse, purification	27
LCA Potable Water Production				
	TITLE-ABS-KEY	LCA, potable, water, production	none	68
	TITLE-ABS-KEY	LCA, potable, water, production	Wastewater, food, solvent, chemical, bone	33
LCA Water Disinfection				
	TITLE-ABS-KEY	LCA, water, disinfection	none	45

Table 2.2 (continued): Scopus Search Results.

	TITLE-ABS-KEY	LCA, water, disinfection	wastewater	24
	TITLE	LCA, water, disinfection	none	1
Life Cycle Water Disinfection				
	TITLE-ABS-KEY	Life, cycle, water, disinfection	Wastewater, covid, hospital, bacteria, textile, health, clean, rain, solar	10
	TITLE	Life, cycle, water, disinfection		5

The first LCA study was made by the Midwest Research Institute in 1969 for a private beverage company to assess the environmental impacts attributed to energy and material consumption of different packaging material production processes from the extraction of raw materials to the removal of the packaging materials (Hunt et al., 1992). The target of the beverage company was to determine the packaging material with the least impact on natural sources and the environment. Depending on the region, LCA studies were conducted under the names such as Resource and Environmental Profile Analysis and Ecobalances. During the late 1980s and early 1990s, the foundations of LCA were laid out as two LCA Software programs were launched, followed by the Society of Environmental Toxicology and Chemistry's introduction of the Life Cycle Assessment (LCA) concept in 1996, which further solidified its structure (Hunt & Franklin, 1996). One of the turning points for LCA was the introduction of ISO 14040 (LCA principles and framework) in 1997. Following years ISO 14041/14042/14043 was released. In 2006, ISO 14044 and ISO 14040:2006 was published, and ISO 14040:1997, ISO 14041:1988, ISO 14042:2000, and ISO 14043:2000 were repealed. Figure 2.1 shows the critical milestones of LCA history, starting from the study accepted as the first LCA work. In following years, the field of

LCA underwent significant development. The introduction of various LCA methodologies and software, alongside the standardization of LCA by ISO, facilitated a more intense approach. However, it was not until 1997 that global concern for environmental impacts gained international recognition. With the adaptation of Kyoto protocol, targets were set for the UN member states to reduce the emissions. The global efforts to reduce the emissions of the gases which were responsible for global warming and climate change continued. UN's Sustainable Development Goals (SDGs) targets various objectives. 17 goals are described and for each goal various targets are set. Goals number 6 (clean water and sanitation), number 7 (affordable and clean energy), number 9 (industry, innovation and infrastructure), number 12 (responsible consumption and production) and number 13 (climate action) are directly related with LCA by the means of protecting natural resources, shifting towards renewable energy sources, using cleaner industrial processes, waste management, sustainable use of natural resources and reducing Greenhouse Gases.

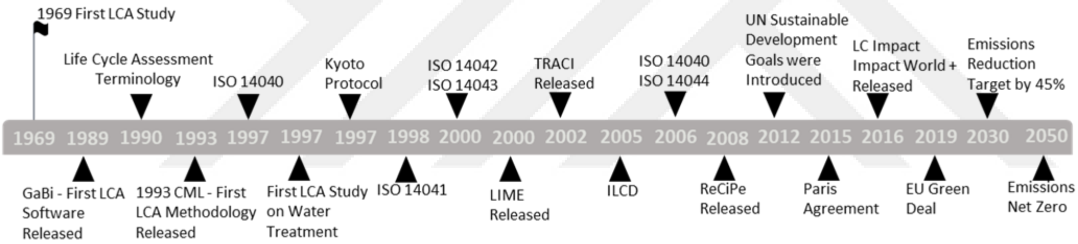

Figure 2.1 : Milestones of LCA history.

The earliest study on LCA of water treatment was made by Sombeke et al.(1997), where an environmental impact assessment of groundwater treatment with nanofiltration was made. Since then, some LCA studies of water treatment, potable water production, water systems, and desalination have been made. When the literature was investigated, it was seen that there are more desalination and membrane process water treatment LCA articles than conventional water treatment articles.

2.2. Life Cycle Assessment of Water Treatment and Disinfection

2.2.1. Goal and Scope

Defining the goal of the LCA is very important due to its effect on interpreting the outcomes. Other phases of LCA should comply with the goal definition to prevent misleading. Based on the ISO standard 14040 (ISO-14040), defining the Goal and Scope is the first step of an LCA study. On the International Life Cycle Data system (ILCD, 2010) LCA Guidance, it is stated that, based on ISO 14044, the goal of an LCA study should cover/answer six aspects; i) Type of application(s) that the deliverables and results will be used ii) Limitations for the study due to the chosen method, impact coverage and assumptions iii) Why this study and decision is carried out iv) Who are the targeted audience for results? v) Will the comparative study be shared with the public? vi) Who is commissioning the study, and are there influential decision-makers.

Most of the reviewed articles about LCA water treatment/disinfection clearly described their goal. The LCA study by Walsh and Mellor (2020) compared four methods (boiling, bio sand filtration, ceramic water filters, chlorination) for drinkable water production and described their goals as a comparative analysis of these four methods. An evaluation of water services in the city of Iasi, Romania, was conducted by Barjoveanu et al. (2013) to analyze the water system of the city through LCA. The LCA study made by Jachimowski & Nitkiewicz (2019) compared only the disinfection process, and the goal was to check the environmental impacts of UV disinfection and chlorine disinfection. Igos et al. (2014) compared two water treatment plants (WTP) from the point of view of LCA, and the goal was to investigate each process by focusing on their infrastructure and waste generated by the plants. LCA studies are not always carried out to compare outputs. Meron et al. (2020) applied LCA to the water system of Israel, and the goal was to evaluate the life cycle environmental impacts of the centralized water system of Israel. Together with the described goal, there were some other objectives of the study, such as acting as a guideline for future LCA studies for Israel's water system, contributing to regional LCA methodology, and observing the environmental impacts of water production while identifying the critical elements of water distribution system to reduce the energy needs together with the environmental impacts.

The scope definition of an LCA study also works as a guideline for the goal definition. This part of an LCA study defines essential aspects such as functional unit, system boundary, limitations, assumptions (if made), the system that will be studied, data needed, and the interpretations used. One thing that needs to be described in the scope of the an LCA study is the Life Cycle Impact Assessment (LCIA) methodology and type of impact. The parameter for the LCA study to work on is the Functional Unit (FU) which works as an anchor point for the carried-out LCA study. FU should contain quantitative and qualitative aspects of the studied system and it should correlate with the definitions of goal and scope defined in the study (Joint Research Center, 2010). A valid and fair comparison of studied systems/products without FU is impossible. ISO 14044 defines FU as the "quantified performance of a product system for use as a reference unit." The ILCD LCA guidelines stated that FU should answer the questions what, how much, how, well, and how long? The LCA studies on water treatment mostly use 1 m^3 treated water at the plant. Unlike most articles, Bonton et al. (2012) chose the FU of 1 m^3 nano-filtered quality water based on four water parameters and compared two WTPs with the same function. Barjoveanu et al. (2019) brought a different approach by choosing two FU for their LCA study. The author's first FU was 1 m^3 of treated water, and his second FU was 1 kg of organic matter and suspended solids removed from the water. Amores et al. (2013) detailed her FU, 1 m^3 of water received by consumers in the Spanish Mediterranean region, as defining the exact location for water usage.

The System boundary is the investigation of processes covered in the LCA for production or service. Choosing a system boundary that is compatible with the study's goal and scope is essential. In case of neglecting a process or a stage used in the production, it should be specified with the reasons. In the reviewed articles, system boundaries were defined, but only a few explained the reasons for excluding the processes which were not used for the LCA study. Capitanescu et al. (2016) conducted an LCA study that compared WTP from a cost and LCA perspective. The study system boundary was explained as the operation stage of WTP's life cycle without the construction and decommissioning stages. Goga et al. (2019) studied the LCA of two potable water production systems and included construction and operation phases to the system boundary while neglecting the decommissioning stage. The author neglected the decommissioning stage considering the findings of Friedrich (2002) & Raluy et al. (2005), which showed the impact of the decommissioning stage had a low overall impact compared with other processes. Similar to Goga et al. (2019), Tarnacki et al. (2012) neglected the construction and dismantling phases of the LCA study, which compared two desalination processes due to their minor impact on the results. Godskesen et al. (2013) selected a comprehensive system boundary, which included water intake from three different water sources, a water treatment facility including all the processes, a water distribution network and the transportation/treatment of wastewater. Figure 2.2 shows the general demonstration of the stages included in the system boundary of a water treatment plant LCA study. The figure shows the input and output parameters of the three main stages of the WTP LCA study. Materials are transported to the site in construction, and energy is used to build the facility. The water treatment phase uses materials (transportation), energy and raw water to produce treated water. Once the economic life of the WTP is completed, decommissioning stage starts and materials that could be reused are recycled, and the rest is sent to landfills.

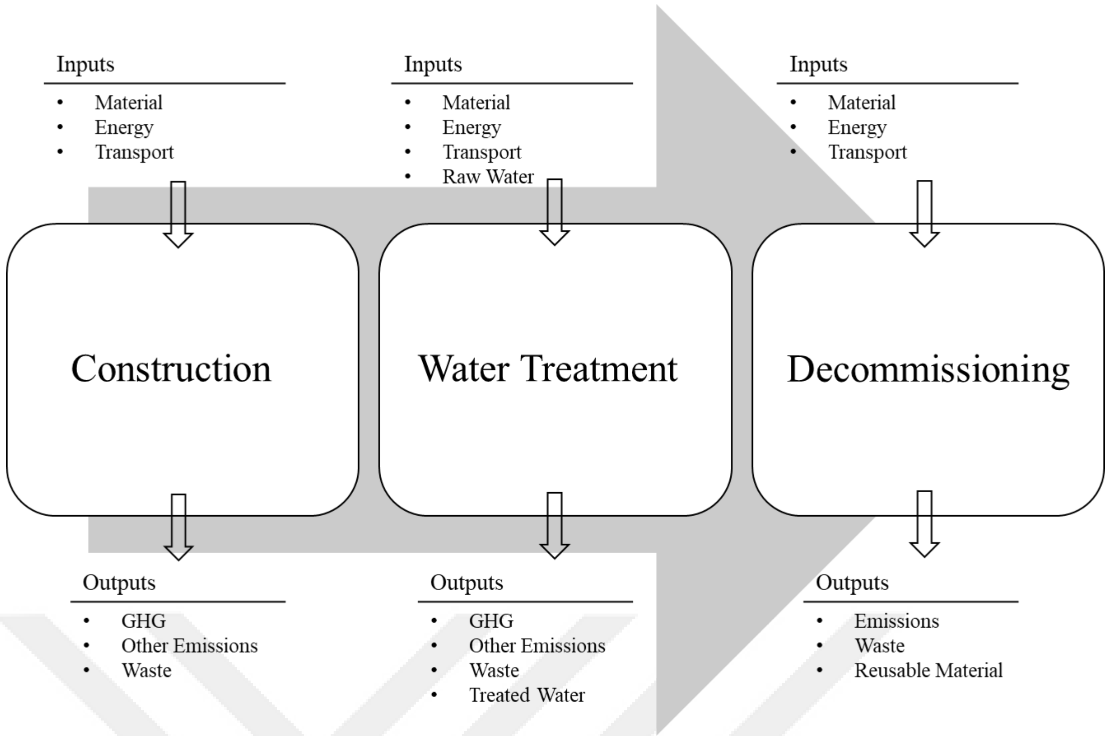

Figure 2.2 : Stages typically used for the system boundary for water treatment plant LCA studies.

2.2.2. Life cycle inventory analysis (LCI)

Life cycle inventory analysis (LCI) is the second phase of an LCA study and is the part where the data for LCA is collected. These data include the inputs and the outputs of the studied system. The goal and scope stage guide this phase and directs data collection and analysis. The input data can include construction, operation, and decommissioning data depending on the system boundary. The LCI process is the most time-consuming step of an LCA study. During the data collection, more insights about the system can be gained, and this can cause new data collection and limitations. In some cases, the LCI phase can cause an update in the goal and scope of the LCA study.

In the reviewed articles, there were different approaches for the LCI phase. Some of them used existing data from the operators, some used data from the databases, and some used literature data for the LCI phase. The reviewed 60 articles were focused on the LCA of the water supply process and water disinfection. The LCI phase generally consists of data from i) construction, ii) operation & maintenance iii) decommissioning. Depending on the LCA study's goal, the data collection and selection can vary (Corominas et al., 2020).

In the study by Bonton et al. (2012), the authors compared one existing WTP plant with a virtual WTP which is designed with the same water outlet parameters as the existing WTP. For this LCA study, the existing data was used together with the design data of the non-existing plant. The input and output data for the construction and decommissioning phases included in the LCA study were drawn for the Ecoinvent database. A similar study and inventory data collection were made by Goga et al. (2019), where the LCA of a desalination plant was made for potable water production. The data was drawn from the plant by a spreadsheet that included input and output data for all unit operations. In situations where the data could not be received, such as the weights of the tanks, it was calculated based on the available data. In their article, Vince et al. (2008) stated that the studied system's environmental impacts depend on the LCI, where all the inputs and outputs are generated as the system boundary explains. The LCI phase of this study was mostly built by the literature, modeling, and assumptions. Similar to Vince et al. (2008), Tarnacki et al. (2012) used data from the pilot and laboratory plants, data, and assumptions based on the literature. Barrios et al. (2008) interviewed WTP personnel, collected internal reports, and withdrew data from databases to generate LCI for the study.

2.2.3. Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is the third step of an LCA study. In this step, the LCI results are evaluated regarding potential environmental impacts through the chosen LCIA methodology. It is essential to plan the LCIA phase for the success of the goal and scope of the LCA study. There are mandatory and optional elements for the LCIA based on ISO 14040/14044. Mandatory elements consisted of

1. characterization models, indicators for the category, and determining impact categories;
2. grouping the LCI results based on impact categories;
3. calculating category impact results (ISO, 2006).

Choosing an LCIA method depends on different factors such as data availability, requirements, need for midpoint/endpoint assessment, etc. The most crucial point is that the chosen method must meet the requirements of ISO 14040. ISO 14040/14044 does not address using a specific LCIA methodology, but in some cases, national governmental institutions can advise using a specific LCIA methodology (Hauschild et al., 2018). One crucial point is that LCIA is that each impact category has its approach in the means of values, assumptions, and reference data used for the weighting and normalization (Roth et al., 2022). There are different LCIA methods; on a global scale, IMPACT World+, LC-IMPACT, and ReCiPe 2016 are widely used. In North America, BEES and TRACI are prevalent methods for LCIA. European methods have more variety from CML-IA, Environmental Prices, Ecological Scarcity 2013, EF 3.0, EN 15804 + A2, WPD 2018, and EPS 2015d and EPS 2015dx (SimaPro, 2022).

In the reviewed articles, most used methodologies were ReCiPe, CML, and Eco indicator. Figure 2.3 shows the distribution of the LCIA methodologies among the reviewed articles. In accordance with Figure 2.4, the LCA software employed and its corresponding percentage are illustrated. SimaPro and Gabi are the most widely used ones compared to other software. This two software are European-based and contain different datasets and LCIA methodologies. Around 30% of the reviewed articles did not specify the software they used.

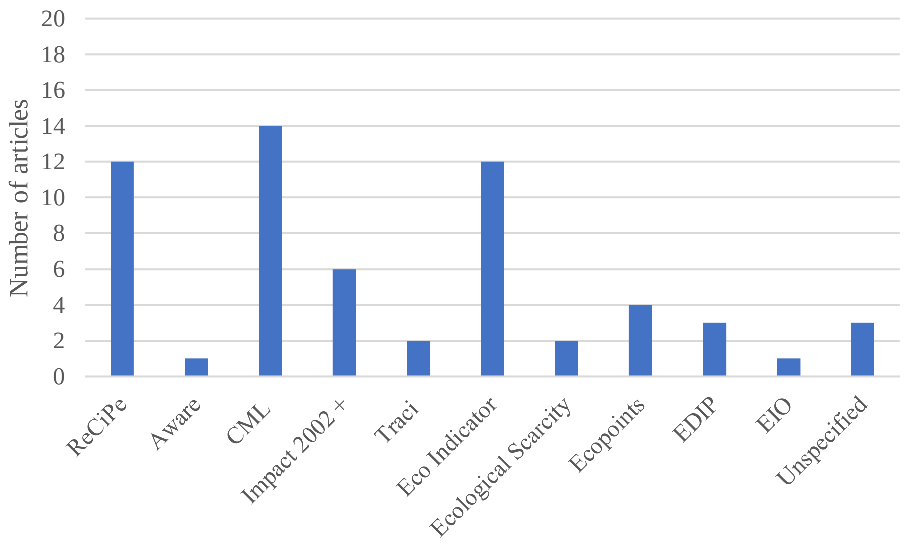

Figure 2.3 : LCIA methodologies distribution among the reviewed articles.

The study of Bonton et al. (2012) Impact 2002+ methodology was used. Three scenarios were developed for nanofiltration WTP by controlling corrosion and the energy source. Renzoni & Germain (2007) studied the LCA of water from the pumping station to the wastewater treatment plant and used Eco Indicator as an impact assessment method. However, instead of working on all categories, he only worked with eight categories chosen by the author.

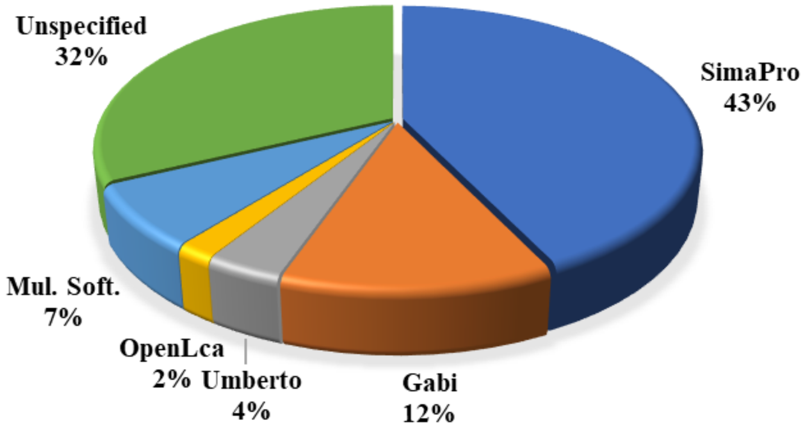

Figure 2.4 : LCA software percental distribution among the reviewed articles.

In the reviewed articles, it was seen that different methods for LCIA were used. It was observed that depending on the goal and scope definition of the study, region and targeted environmental issues have an essential role in choosing the LCIA methodology. After the methodology is chosen, targeted impact categories (midpoint) and damage categories are studied with the LCA modeling software.

2.2.4. Interpretation

Interpretation is the last phase of an LCA study where the outcomes of the study, based on the results of the LCI/LCIA, are evaluated together to address the issues described in the goal definition with recommendations (European Commission, 2010). Depending on the goal and scope of the study, interpretation could contain opinions for decision-makers and recommendations. While the LCI and LCIA stages offer valuable insights into the production system or service being analyzed, the definition of the study's goals and scope, as well as the interpretation of the results, form the backbone of the LCA study. The LCI and LCIA findings should be interpreted based on the goal and scope definition. Based on ISO 14040/14044 (ISO, 2006) the interpretation phase should proceed by i) identifying the significant issue, ii) assessment of the study by conducting a completeness check, sensitivity check, and consistency check iii) determining the limitations, building the conclusion and recommendations for the targeted audience. Most of the reviewed articles had a section explicitly titled "interpretation." Instead, the authors presented their analysis and conclusions on the findings and outcomes of the LCA study under sections labeled as "results & discussion" or "conclusion."

Testing different input parameters and developing further scenarios could be used to perform sensitivity analysis and can be made by changing the operating conditions and the energy source or chemicals used in the process. In the study of Mohapatra et al. (2002), they increased and decreased the values of selected parameters by 50% using Monte Carlo simulation and found that conducting the granular activated carbon filtration (GAC), softening, and pumping under different conditions can reduce the environmental impacts. Amini et al. (2015) did the sensitivity analysis by changing the input values by 10%, and the results indicated that impact categories are sensitive to different aspects of the LCA study. Saad et al. (2019) only performed a sensitivity analysis on energy sources and pumping efficiency in their study. Mo et al. (2018) studied the environmental impacts (embodied energy, life cycle cost, and carbon footprint) of upgrades', on small water systems that served less than 3,300 people, to reduce disinfection by-products. They analyzed four different disinfection scenarios. The study showed that, for the GAC, reduction in the regeneration (a process to remove the contaminations from the activated carbon granules) weight loss and changes in the carbon type reduce energy consumption. Another study on LCA of drinking water production also indicated that the energy sources have drastic effects on environmental impact categories. Roth et al. (2022) presented the effects of energy sources on impact categories while conducting sensitivity analyses on electrical energy sources caused by the usage of UV/H_2O_2 (hydrogen peroxide) with GAC, and Ultra Filtration (UF) - Low Pressure Reverse Osmosis (LPRO) - O_3/H_2O_2 with GAC. This LCA study observed the effect of energy sources on environmental impact categories. Prezelus et al. (2021) first conducted a sensitivity analysis to the baseline scenario with the 4 other scenarios in the means of electricity mix where nuclear energy was the reference (baseline scenario) and this energy source compared to the French renewable electricity sources. In this study, another sensitivity analysis was performed by changing the operating conditions, e.g., backwash efficiency and cleaning in place. In 3 out of 4 scenarios, by changing the operating conditions, a slight improvement for the environmental impacts were gained. However, in the other scenario, high environmental scores were observed when filtration flux and cycle duration were changed. Manda et al. (2014) studied membrane filtration and its LCA. Sensitivity analysis was made for electricity source and membrane coating frequency by assumptions with the electricity consumption per m^3 of water between 0.1 kWh/m^3-0.9 kWh/m^3 (reference 0.45 kWh/m^3) and coating (reference lifetime - covalent bond coating and adsorption coating) of the membrane for a lifetime, yearly, quarterly, monthly, weekly and daily.

The parameters were chosen for sensitivity analysis based on different causes. The causes could be the environmental impact score, the effect on the water quality, or operation conditions. All the parameters can be subjected to sensitivity analysis but are usually carried out to identify the parameters with the most effect on impact scores. These parameters are changed by ratio or assigned new values between the ranges of minimum and maximum values. Sensitivity and uncertainty analysis are essential for interpreting the environmental impact assessment results by showing the accuracy of the LCA study. Some of the reviewed articles conducted uncertainty analyses in their studies using simulations like Monte Carlo analysis. Uncertainty analysis shows the accuracy of the gathered data for the LCA study. It should be kept in mind that uncertainty analysis and sensitivity analysis should be made when the LCA study is made for comparison and shared with public (ISO, 2006). Bonton et al. (2012) conducted a Monte Carlo analysis for the processes contributing more than 2% to at least one damage category. 3000 iterations were made for each Monte Carlo analysis. Another LCA study carried out an uncertainty analyses by Godseken et al. (2013). The LCA of three water systems were studied, and the uncertainty analyses showed that their results were accurate. Accuracy of an LCA study is based on the collected data and the assumptions and their results compared to the real-world scenarios (EPLCA, 2021). Uncertainty analysis shows the accuracy of the gathered data and the assumptions for the LCA study. The article by Meron et al. (2020) shows that the impact scores on six categories are accurate up to 98% (range changes between 60%-98%) with the results of uncertainty analyses made using Monte Carlo simulation. Lee et al. (2012) compared the LCA of disinfection methods in their study and chose electricity consumption as the parameter for sensitivity analysis. It was stated that the study did not require uncertainty analysis. Hence electricity consumption can be measured precisely.

2.3. Current LCA Studies on Water Treatment and Water Disinfection

Different types of water such as groundwater, surface water and seawater are used as water sources in the viewed articles. Current LCA studies on water treatment plants and water disinfection technologies are addressed in this section depending on their water sources. The results of the studies have similar results for the processes that have major environmental impacts. Table 2.2 outlines a selection of several reviewed articles along with the year of publication and the subject area in which LCA was utilized to assess environmental impacts.

Table 2.3 : LCA articles on water supply systems, water treatment and disinfection.

LCA Topic	Reference
Drinking water production	Sombekke et al. 1997, E. Friedrich 2002, Barrios et al. 2008, Vince et al. 2008, Sharaai et al. 2010, Bonton et al. 2012, Mery et al. 2013, Zine et al. 2013, Igos et al. 2014, Ahmadi and Barna 2015, Garfi et al. 2016, Capitanescu et al. 2016, Barjoveanu et al. 2019, Saad et al. 2019, Walsh and Mellor 2020, Prezelus et al. 2021, Lakho et al. 2022
Drinking water production (desalination)	Raluy et al. 2006, Tarnacki et al. 2012, Goga et al. 2019
Water supply systems	Mohapatra et al. 2002, Lassaux et al. 2007, Lyons et al. 2009, Godskesen et al. 2011, Borghi et al. 2012, Amores et al. 2013, Uche et al. 2013, Godskesen et al. 2013, Barjoveanu et al. 2014, Mo et al. 2018, Meron et al. 2020, Tarpani et al. 2021
Drinking water disinfection	Jones et al. 2018, Jachimowski and Nitkiewicz 2019, Romanovski et al. 2020, Busse et al. 2022
Drinking water production with financial evaluation – Processes in drinking water production	Nessi et al. 2012, Igos et al. 2013, Amini et al. 2015, Holloway et al. 2016, Roth et al. 2022

When it is searched on Scopus earliest study for drinking water LCA goes back to 1997 to assess the environmental impacts of groundwater treatment with membrane process. This study could be accepted as a turning point for water treatment LCA studies. When the study is reviewed, it could be seen that it is not comprehensive as the current LCA studies due to the limited sources and lack of LCA methodology at that time. The study showed comparable results between conventional treatment with GAC (Granular Activated Carbon) and pellet softening, and nanofiltration water treatment had very little difference, Sombeke et al. (1997). Another LCA study for water production from groundwater by Zine et al., (2013), for a conventional water treatment plant, only focused on Global Warming Potential (GWP). The findings of this study showed that the production of chemicals for coagulation and remineralization contributed the most, followed by lime production and electricity consumption.

LCA studies on surface water treatment to produce water had similar results. The most comprehensive surface water treatment LCA study in the reviewed articles was made by Bonton et al. (2012) using IMPACT 2002+, where two WTP, nanofiltration (NF) and conventional WTP with GAC filtration, were compared for 13 midpoint impact categories and 4 endpoint damage categories. In both systems, the main burden is derived from the operational stage compared to the construction and decommissioning stages. Results of the study showed that the impacts of conventional treatment were higher than the NF system. The main contributor of impacts for the conventional system was GAC and wastewater treatment, while the impacts of NF treatment are almost equally distributed between the processes. Electricity consumption is the main parameter for the impacts caused by the NF system. The environmental impacts of ionizing radiation and ozone depletion were slightly higher with the NF system. Using different chemicals, GAC, and green energy sources can help to reduce the environmental impacts. Igos et al. (2014) compared two water treatment plants (WTP), WTP1 and WTP2, both using conventional water treatment processes to treat the same surface water source and the main difference between these two WTPs is WTP2 has an extra water line to use in irrigation. The purpose of the study was to investigate the environmental impacts of WTPs and examining the economic aspects at the same time. For this study, 3 LCIA methodologies, ReCiPe/Stepwise/Ecocosts (Stepwise and Ecocosts are environmental evaluation methods from the financial perspective) were used, and additionally, the cost performance of the plants was also surveyed. Regardless of the LCIA method, the findings showed that the main contributors to environmental impact for both WTPs were CO_2 emissions caused by electricity and active carbon production. The operational costs for WTP1 were lower than for WTP2, but the environmental impact was higher. Another study on LCA of WTP with cost analysis was made by Capitanescu et al. (2016), and the author only focused on the environmental impacts caused by climate change impact and GWP100 by using the ReCiPe method. The LCA study included scenarios based on minimum environmental impact, cost and considering both together. The scenario that minimizes the cost of operation results in the maximum CO_2 emissions, while the scenario to minimize the environmental impacts resulted in a reduction in cost and impact compared to the current situation. The study's findings suggest that modifications to the ozonation process, such as adjusting the ozone transfer efficiency by altering the gas-liquid ratio, bubble sizes, or ozone concentration, as well as regulating the frequency of activated carbon regeneration and the dosage of coagulant, can result in cost-effective improvements.

Other review studies for surface water treatment had similar results. Saad et al. (2019) and Friedrich (2002) stated that the main contribution comes from electricity consumption, followed by using chemicals in the treatment process. In his LCA study, Shaari et al. (2010) compared 3 technologies, which included conventional WTP with dissolved air flotation (DAF), conventional WTP with Pulsatube® (a technology that joins flocculation and clarification processes in one area) and UF, for surface water treatment to produce water and derived similar results as the previously mentioned studies stating that the electricity and the chemicals used during the treatment stages are the primary sources for selected environmental impacts and damage categories. An LCA study, by Roth et al. (2022), for surface water treatment focused on the removal of specific contaminants (micropollutants) with two different treatment methods with evaluation from 3 different LCA methods (Ecological Scarcity 2013, EDIP 2003, ILCD 2011). The compared treatment methods for this LCA study were advance oxidation process (AOP) (UV/H_2O_2 oxidation) followed by GAC filtration and LPRO with UF pretreatment (retentate treated with O_3/H_2O_2 and GAC before discharge to the river). The main environmental impact for AOP was caused by the operational stage, where GAC filtration had more impact on the oxidation process, while the impacts from construction were negligible. For the LPRO system, the main contribution came from the operational stage, with LPRO and liquid oxygen having a significant share, followed by construction. Between two systems, results showed that LPRO is more environmentally friendly compared to AOP in in the chosen 3 LCA methodologies.

Another water source to produce potable water is seawater, and advanced treatment systems such as membrane or thermal processes can be primarily used. Goga et al. (2019) compared potable water production from the sea and mine water (wastewater from mining activities). Reverse osmosis (RO) was used for the desalination process, and the mine water reclamation, NF + RO was used. Environmental impacts caused by construction and operational stages were included, and the decommissioning stage was neglected due to the findings of previous literature studies, which showed that the impacts were negligible. Electricity consumption was the main contributor to the environmental impacts of both water treatment options, followed by chemical usage. However, one interesting finding of this study was that chemical usage for the mine water reclamation had a positive environmental impact on agricultural land due to the use of ferric chloride and hydrochloric acid. Overall, the environmental impacts of desalination were higher except for water and metal depletion. The authors outline one crucial point to make an equal comparison between the two systems; the assumptions and the conditions (same raw water quality and same treatment efficiency) must be the same due to ISO 14040 (ISO, 2006). In this case, it was evident that the raw water quality was not the same as stated in the paper. Tarnacki et al. (2012) compared two membrane technologies, RO and Memstil® (a membrane desalination process), for water production from seawater. The study surveyed the electric mix of different countries with their effect on 8 impact categories. Since both membrane technologies were energy driven, the main cause for the environmental impacts was electricity and the heat needed for the Memstil® process. The production of energy results in different impacts depending on the technology to produce it. The minimum environmental impacts for RO were achieved with wind power and mixed with solar heating for Memstil® (except for Eutrophication potential and ionizing radiation). The countries with different electricity mixes (total electricity produced with different electricity generation technologies) were compared were France electricity mix, Germany, Netherlands, Portugal, and Spain. The comparison of the environmental impacts due to the electricity mix showed the most negligible impacts for GWP, achieved with

France electricity mix, with 78%. Environmental impacts caused by chemical usage had a minor effect compared to energy, and RO chemicals had more effect to impact categories over Memstil®. The study indicates that using renewable energy sources improves energy efficiency and employment of energy recovery systems. Raluy et al. (2005) made the LCA of 3 standard desalination technologies, Multi Stage Flash (MSF – thermal desalination process)/Multi Effect Distillation (MED - sea water distillation process based on evaporation)/RO, using EI 99, CML2 baseline 2000, and Ecopoints 97 LCA methodologies. The operation stage for these technologies has a significant impact on the environment. Based on the used 3 LCIA methods in the study, MSF had the highest environmental loads while RO had the least. Since these desalination technologies require massive energy, changes in the energy sources have a great potential to reduce environmental loads. When MSF and MED systems, which require thermal energy, use waste heat instead of fossil fuels, up to 84% of emissions can be reduced. Similar results are achieved with the use of renewable energy sources for RO. Another study by Raluy et al. (2005) compared RO desalination water production with a freshwater transfer (FWT) project from the LCA point of view. The study included the environmental impacts of materials for construction and energy for the operation stage. The results showed that both methods have similar environmental loads, and loads caused by the operational stage are higher than the construction stage.

Some of the LCA studies for water treatment used more than water sources. Barrios et al. (2008) surveyed a conventional water treatment plant's environmental and financial life cycle assessment in the Netherlands. The study showed that the processes that caused the main environmental impacts were softening, coagulation, and biological activated carbon filter. Alternatives to reduce environmental impacts are presented in the study. Replacing the existing coagulant (ferric chloride) with alum or ferrous sulphate and softening chemical (sodium hydroxide) with lime/soda ash or soda ash decreases the environmental impacts. Another way to reduce the environmental impacts due to chemicals used in water treatment is to use green energy to produce existing chemicals. The biological activated carbon filter changes in the run time and regeneration period could help reduce environmental impacts, but this is not feasible because it requires a change in the treatment scheme. The author stated in the article that the measures to decrease the environmental impacts are expected to cause an increase in financial impacts. Barjoveanu et al. (2019) evaluated a conventional WTP from the LCA perspective using groundwater and surface water as a source. The results showed that most of the environmental impacts are caused by electricity consumption and chemical usage. In this study, FU was chosen as $1m^3$ treated water, but the researcher also worked with another FU, which was the removal of 1 kg of suspended solids (SS) and organic matter (OM). In this situation, the main environmental impacts for SS removal result from electricity consumption and coagulant usage, and for OM removal, electricity consumption is followed by ferric chloride usage. A study by Vince et al. (2008) provides similar results to the other reviewed articles stating that electricity and chemical usage, together with remineralization, a process by adding minerals to protect the treated water against corrosion and reverse the against human health (Lesimple et al., 2020) in some treatment systems, are the main contributors to environmental impact and the damage categories. Reduction of these impacts and damages could be achieved by green energy and the use of alternative chemicals. One critical remark made by the author is that water transfer to a distant location will cause more impact than local treatments.

Researchers have conducted LCA studies for different water treatment methods. One was made by Walsh and Mellor (2020), where four endpoint (treatment at the point of use) water treatment technologies were used in a city in South Africa where the municipal water system lacks. The examined water treatment technologies were i) boiling, ii) ceramic water filters, iii) bio-sand filters iv) chlorination. The end users applied these treatment methods at the point of consumption. Boling of water outscored other methods in 4 out of 6 categories, and chlorination outscored others in 2 out of 6 categories. Garfi et al. (2016) compared 5 different alternatives for the consumption of drinking water from an LCA perspective, i) tap water from conventional WTP, ii) tap water from conventional WTP and RO, iii) tap water from conventional WTP and RO at the endpoint, iv) mineral water in PET bottles v) mineral water in glass bottles. Conventional WTP is the most environmentally friendly method within all 6 impact categories, and bottled waters are the minuscule environmentally friendly method. PET bottles had less environmental impact than bottled water except for global warming and photochemical oxidation. Significant contributors to the conventional WTP method were electricity consumption and coagulant use. For the RO scenario, the end point of use had lower impacts than conventional WTP with RO.

Only a few studies on the LCA of water disinfection are available compared to the LCA of wastewater disinfection. As part of the chemicals used in the water treatment process, chlorination process for disinfection contributes to environmental impacts. On the other hand, other water disinfection systems, such as UV and ozone, are energy-intensive processes. In the study of Jones et al. (2018), the environmental impacts of chlorine disinfection were compared with UV disinfection. The study made assumptions for 3 different scenarios, and in all scenarios, disinfection with chlorine was more environmentally friendly than UV disinfection. Environmental impacts due to construction was much lower than the operational stage in both technologies. Similar outcomes were reported in the study of Jachimowski & Nitkiewicz (2019), where chlorination (gaseous chlorine) was compared with UV disinfection. The study stated that additional sodium hypochlorite was used because UV disinfection does not have a residual effect. For the gaseous chlorine disinfection, the impacts are directly from the use of Cl_2, and for the UV disinfection, almost 25% is from NaCl, and the rest is electricity generation.

The findings in the reviewed articles showed that chlorine disinfection has lower environmental impacts than UV disinfection except for ozone layer depletion. In the study of Mo et al. (2018), different disinfection methods, including GAC, ozone, UV30 (30 mJ/cm^2), and UV186 (186 mJ/cm^2), were compared to assess the life cycle of these technologies. The study aimed to address the optimal disinfection upgrade in achieving the DBP reduction goal, energy consumption, GWP, and cost. Only in the UV scenarios, additional disinfectant was used to have a residual effect to protect against the contamination possibilities in the distribution system. The results showed that the UV30 scenario has the lowest energy consumption while GAC has the lowest impact on GWP. After the sensitivity analysis, results have altered by favoring other scenarios. When the outlet water quality changes from 1 mg TOC/L to 1.5 mg TOC/L, ozone disinfection requires the lowest energy for the operation. An LCA study on the disinfection process for the low income settings compared 4 alternatives for water disinfection with different lifespan and amount of water disinfected (Busse et al., 2022). The important point of this study was that it compared 2 non-technological solar disinfection techniques (methods that uses only the sun light for water disinfection), which rely on solar disinfection, with UV and chlorination. The solar disinfection techniques, which rely on the sunlight for disinfection, were continues flow compound parabolic collector and storage of water in clear plastic containers. Also, for the UV disinfection there were two alternatives one using LED UV lamps and the other using low pressure mercury UV lamps. Results showed that disinfection with chlorination show the lowest environmental impacts in all scenarios followed by solar methods, mercury UV lamps and LED UV lamps. Romanovski et al., (2020) studied the environmental impacts of ozone and hypochlorite disinfection together with their corrosion effect. The findings stated that ozone disinfection has less impact on the 17 midpoint impact categories, except ozone depletion and ionizing radiation, over sodium hypochlorite and calcium hypochlorite. The reason for this outcome was the environmental impacts generated for the production of hypochlorite disinfectants.

2.4. Economic Considerations

In the literature, some articles also included the costs of water treatment and water disinfection together with LCA. Combining the cost performance of treatment processes with the LCA requires more time and data. The cost analysis of a WTP usually starts with investment cost, which includes infrastructure (construction) and equipment (mechanical, electrical, and automation). The operational costs include chemical, personnel, energy, maintenance, repair, and disposal costs (waste). Economic parameters are vital to support new investment decisions and the environmental impacts.

The integration of life cycle assessment studies with economic assessments can provide decision-makers or stakeholders with a more comprehensive perspective. Capitanescu et al. (2016) made a study where the cost and LCA of WTP, which has conventional processes, was analyzed and compared based on operational costs and reducing the environmental impact. The results indicated that optimizing the plant to GWP100 also causes a reduction in costs compared to the base scenario. In practice, this can be achieved by ozone transfer efficiency, change in the activated carbon regeneration frequency, and adjustment with the coagulant dosing. Amini et al. (2015) showed that when the treatment plants' flow rate increases, the environmental impacts, and cost per FU decrease. Another important point mentioned in the article about the cost performance of WTP is directly affected by waste disposal and chemicals used in the plant. The study which monitored the environmental and financial life cycle impacts of water production in the Netherlands showed that the operational processes with the highest environmental impact also have the most financial impacts Barrios et al. (2008). The financial impacts were caused by softening, biologically activated carbon filters, and slow sand filtration. Garfi et al. (2016) showed the cost of producing one m^3 of water in 3 different treatment scenarios (conventional WTPs with/without reverse osmosis at different points of the water treatment process) and 2 different bottling methods. The lowest cost was achieved with conventional WTP at 0.95 €/m^3, conventional WTP with RO at 1.2 €/m^3, RO domestic use (end user) at 31 €/m^3, mineral water in PET bottles at 267 €/m^3, and mineral water in glass bottles with 600 €/m^3.

2.5. Future Perspectives

When the literature is reviewed, LCA studies focus on different water treatment technologies. Some of these article/research results need to be updated due to new technological improvements, energy-efficient treatment equipment, changes in the electricity mix, developments in package water treatment plants or higher efficiencies in green energy production. The efficiency rate of photovoltaic energy started its journey at 1%, but now it is possible to reach up to 47% efficiency with multijunction cells (NREL, 2020). A similar situation is with the electricity mixes of the countries. In year 2000, electricity production from renewable energy was 6.3% in Germany. However, as of 2022, the ratio of renewable energy is 46.2% which can cause a significant change to LCA results (UBA, 2023). Databases should be up to date for fair comparisons in the LCA studies. To carry out fair and comprehensive LCA studies LCI phase must be precise, and to accomplish this, data for the LCA study should be reachable. Companies producing water treatment equipment should carry out LCA studies for their products or share production data (i.e., raw materials used) with researchers making LCA studies.

The cost of reducing environmental impacts is often the critical investment parameter. Some studies in the literature have also considered the economic impacts of these interventions. As seen from the literature, some studies included the economic impacts. However, the life cycle cost (LCC) analysis is not as broad as having an Environmental Life Cycle Cost (ELCC) aligned with the LCA. Instead of having costs on specific processes, the whole treatment system could be surveyed and controlled with future economic perspectives together with environmental impacts (i.e., new regulations causing either improvements or penalties). There are some differences between LCC and ELCC. A crucial distinction lies in; LCC is made from the view of a single actor, such as a producer or consumer, to a product for the economic results whereas ELCC is carried out, with all the stakeholders involved, to support LCA parallel to ISO 14040/44 and involves environmental and economical results together (Hauschild et al., 2018). The outcome of an LCA study is sometimes shared with the public. In the case of water production, the results of the LCA study should be made public when the improvements for environmental impacts come with an extra cost. The financing of these improvements can be a burden to the local authorities and the public. The compensation for these improvements needs to be discussed publicly if it is going to be laid on the shoulders of the end users, which can financially impact society.

One crucial point is that water treatment should be considered as a whole system, from the raw water intake structure to the end user. There are researchs in the literature where the whole water systems is inspected from the LCA perspective, and these studies are the pioneers in this field. If the water treatment LCA studies are made together with ELCC of the whole water system, it could have a different impact as it covers all the aspects of the water supply system. This can result in choosing decentralized water solutions over centralized water treatment systems or encourage end users to have a solution at the endpoint to decrease the environmental impacts.

The protection of the public from waterborne diseases is an essential duty of water providers. Water disinfection is a critical step in the water treatment process to achieve this goal. Chlorine-based disinfectants are the most common and economical method. The most common and well-known method, which is also the most economical, is chlorine-based disinfection. One of the reasons chlorine-based disinfectants are popular is their effect on the water distribution system as a residual disinfectant. Chlorination has some adverse effects, such as forming disinfection by-products and impacting the end users because of taste and odor. Over the years, different disinfection technologies such as UV and ozone are started used in water treatment systems. The environmental impacts of these systems are higher than those of chlorination systems caused by electricity consumption. New-generation UV lamps with higher efficiency and lower electricity consumption (Schalk et al., 2006) should be studied with renewable energy sources. Another crucial area for the researchers should be the multi-barrier disinfection strategy for water disinfection. Combining different water disinfection technologies to have the optimal solution for disinfection and environmental impact. The use of a combination of chlorine with UV disinfection started to increase globally. A critical part of water disinfection is that the negative results of poorly disinfected water are immediately observed in society as sicknesses. The cost of multi-barrier disinfection can be high, but further LCA studies with ELCC can involve the cost of waterborne diseases to the public and their social impacts using SLCA (social life cycle assessment). This approach can bring a broader perspective to water disinfection LCA studies.

States regulate their drinking water regulations with the new developments in technology and scientific studies. For example; with the detection of micro/nano plastics in drinking water sources brought up concerns for removal of these micro pollutants from drinking water which caused updates to drinking water regulations (Directive 2020/2184). Similar to European Union, US EPA regulated drinking water policies starting from 1979 with latest update on 2019 (Humphreys & Tiemann 2021). When the evaluation and decision making for drinking water policies were examined for the United States of America, it states the important points for making new regulations which involves contamination’s negative health impacts, possibility of having contamination in the water system and its concentration and economical analyses based on cost and benefit but the environmental impacts do not play an important role as the others (US EPA, 2020). As the regulations gets tighter, the quality of treated water increases but at the same time it might cause more environmental impacts from WTP. The United Nations Sustainable Development Goals (SDGs), signed by 193 countries, includes topics for clean energy, sustainability and climate change (UN, 2021) which are directly related with LCA. SDGs also has a topic for safe water, that requires states to provide safe water for consumption and sanitation. In the light of SDGs and developing water regulations it can be clearly stated that more LCA studies on water treatment and disinfection must be made for having sustainability for water production.

2.6. Conclusions

To address the historical development and highlight the current situation on LCA of water treatment and disinfection, sixty articles were reviewed on the topics of LCA of water treatment, LCA of water systems, LCA of water disinfection methods and cost impacts. The findings of these papers revealed similar environmental impacts, and their results on the contributors to environmental impacts are consistent. Depending on the chosen LCIA methodologies, different midpoint and endpoint impacts were covered in these papers. The results indicated that the impacts from the construction and decommissioning stages, having the most negligible environmental impact, are minimal compared to the operational stage. Significant environmental impacts from the operational stages were caused by energy consumption, GAC filtration, and chemical usage in the different stages of the treatment process. The environmental impacts caused by energy consumption could be reduced by using green/renewable energy and technological improvements to the machinery used in the water treatment plant. In the GAC process, the generation of environmental impact is attributed to the production of GAC, as well as the processes of filtration and regeneration. Plant-based materials (such as coconut shelves) and changes in regeneration frequency were recommended to decrease the impacts due to GAC. The environmental impacts caused by the chemical's usage are primarily due to softening and coagulation processes. It was shown that changing the chemicals with alternative ones and using green energy in production will reduce environmental impacts.

LCA of water disinfection favors the usage of chlorination to disinfect water over UV and ozonation. The high energy consumption of UV and ozone disinfection for operation is the main cause of the environmental impacts. One crucial point is that the LCA water disinfection studies are not up to date. The technology for UV disinfection changed dramatically over the last ten years, where the efficiency of UV lamps went up to 40% from 12%, which caused a significant difference in the production and operation of these systems. A similar situation is with ozone disinfection systems; the new ozone technologies with lower energy consumption and higher ozone efficiency need to be surveyed. As a result, the environmental impacts and the cost need to be re-examined. New LCA studies must be conducted comparing the newly developed disinfection technologies for water.

Overall outcome of the reviewed article shows that the LCA of water treatment plants and water disinfection circles around energy and chemical consumption while putting pressure on water sources. The future of producing “environmentally friendly” safe water relies on using green energy, less chemicals and using other possible water sources such as wastewater and rainwater. There are studies that shows the unnecessity of residual disinfectants which can directly influence the environmental impacts of water treatment plants and water disinfection systems. Right decision, maintenance and optimization of the equipment used at the water treatment plants are also essential to reduce the impacts. For example, pumps which are a vital component of a water treatment plant, will keep their pumping efficiency and longer life span if maintenance and optimization is performed on regular bases. This will result in using less energy and not replacing the equipment helping to reduce the impacts caused to produce equipment. Another operational thing is to control the energy consumption at intervals of the equipment so modifications or adjustments can be made. When the water supply system is considered, decreasing run off waters will have a positive result in environmental impact. Last but not the least is that manufacturers must take on responsibility for their products by conducting LCA studies or making date available so these LCA studies can be made by researchers.

3. COMPARATIVE LIFE CYCLE ASSESSMENT OF FOUR MUNICIPAL WATER DISINFECTION METHODS[1]

3.1. Introduction

Historical recordings show that activities to improve the aesthetics of water go back to 4000 B.C. (USEPA 2000), when they made water treatments using physical methods. With the invention of the microscope and finding about animalcules (Symons 2006), the connection between drinking water and health started to be investigated. An important milestone for water and health was the introduction of Germ Theory by Pasteur, which indicated that organisms were responsible for the spread of infectious diseases (Smith 2012). Water is a pathway for viruses, bacteria and protozoa to transmit to humans, and different types of effects on human health are observed when unsafe drinking water is consumed. The health effects include diarrhea, gastroenteritis, acute gastroenteritis, vomiting and nosocomial infections (Griffith 2017). Annual causes of death related to unsafe water are around 829,000 worldwide (UNICEF 2024) and around 255,500 of these are children (UN 2022). These deaths have a major social impact on society, which also causes an economic impact. A person who is affected by a waterborne pathogen is treated, and while their treatment continues, there are direct costs, indirect costs and intangible costs that have an impact on public and personnel budgets (Scott II 2009). Waterborne diseases are not only a concern for developing countries, but they also affect developed countries (WHO, 2009). A study by Collier et al. (2021) showed that around 7.15 million illnesses are caused by drinking water, and the burden on the economy in the USA is USD 3.33 billion. The

[1] This chapter is based on "Mehmet Zahid Demir, Huseyin Guven, Mustafa Evren Ersahin, Hale Ozgun, Mehmet Emin Pasaoglu and Ismail Koyuncu. 2024. "Comparative Life Cycle Assessment of Four Municipal Water Disinfection Methods". Sustainability. Volume 16 Issue 13 July-1 2024

solution for safe drinking water comes from comprehensive and proper disinfection following water treatment.

The need for water disinfection was understood after it was discovered that water is a pathway for transmitting diseases. Chlorine usage for drinking water disinfection started to spread after it was introduced for municipal water disinfection in 1902 in the city of Middelkerke, Belgium (Bull 1999). Different water disinfection methods, such as ozone and UV, were tested and started to be used in a similar time phase. The first country to use ozone as a water disinfectant was the Netherlands, and they used ozone in the water treatment plant in the city of Oudshoorn in 1893 (Miller et al. 1978). Ozone disinfection remains widely used in major cities such as San Diego (City of San Diego 2022), Tokyo (Tokyo Water News 2020) and Zürich (Kaiser 2018). In 1910, the first ultraviolet (UV) water disinfection system was installed in Marseilles, France (Bolton 2008). Since then, UV water disinfection systems have been implemented in numerous cities, including New York (New York City Department of Environmental Protection 2019), Berlin (LIT UV 2020), St Petersburg (Svarog UV 2007), Las Vegas (AquiSense 2023) and Wien (LIT UV 2020), showcasing their widespread usage and effectiveness. The working principles of UV, ozonation and chlorination are different. Chemical methods such as ozonation and chlorination inactivate microorganisms by oxidatively degrading amino acids, damaging DNA and RNA, and altering cell membrane permeability (Zhang et al. 2023). Chlorination has advantages, such as lower investment and operation costs, is an easy-to-operate well-known technique, and has a residual effect. Still, it also has disadvantages, such as the taste and odor of the water, the formation of disinfection by-products (DBPs) (Mazhar et al. 2020), not being effective for certain microorganisms, such as cryptosporidium, requiring care and attention for operators and being corrosive (MDH 2023). The ozonation process uses the ozone for the disinfection process and can work in a wide range of pH and temperature. While having a positive impact on the taste and odor of water, it is highly corrosive and requires corrosion-resistant material (DEC 2005). Unlike chlorine and ozone, UV is a physical disinfection method (Wang and Lin 2021). The working principle of UV disinfection is based on the UVC light produced by various types of UV lamps, such as low-pressure (LP) amalgam UV lamps, low-pressure high-output (LPHO) amalgam UV lamps, medium-pressure mercury UV lamps and light-emitting diode (LED) UV lamps. UVC light damages nucleic acid, which is responsible for the reproduction of microorganisms (Pirnie et al. 2006). This process is called inactivation rather than destruction because the microorganisms are not killed. The implied UV dosage and contact time are very important for UV water disinfection systems because microorganisms can repair themselves if the suitable UV dosage and contact time are not applied (Fitzhenry et al. 2021) (Li et al. 2017). The main consumption of the chlorination system is chemical, while for UV and ozonation systems, it is energy. When choosing a water disinfection method, multiple criteria, such as targeted microorganisms, disinfection by-products (DBPs), the need for residual disinfectant, land use, regulations and operational conditions, play an important role. In a study by Gelete et al. (2020), UV disinfection was compared with ozonation, chlorination, chloramination and chlorine dioxide in terms of their operational aspects and efficiency. The results show that UV disinfection is significantly more convenient in terms of operational aspects and efficiency, although it is unsuitable for providing residual disinfection.

Life cycle assessment (LCA) is a tool that can be used to understand the environmental impacts of a product, process or service throughout its life cycle (Sabet et al. 2023). LCA was standardized by the International Organization for Standardization (ISO) in 1997 with the first publication of ISO 14040. The latest update was published in 2020 with the amendment of the 2006 version (ISO 14040:2006). Reviewing the literature reveals that the availability of studies on the LCA of the drinking water disinfection process is limited. The LCA of the water disinfection process was managed as a part of the whole water treatment process, and the impacts of water disinfection were compared with other processes at a water treatment plant as a contributor. There are only a limited number of papers that compared UV disinfection with chemical disinfection and only focused on the LCA of water treatment disinfection techniques. It was observed that there were more articles on the LCA of wastewater disinfection than the LCA of water disinfection. There were more studies on wastewater disinfection due to the importance of the disinfection process having a key role in the reclamation (Foglia et al. 2021) and reuse of treated wastewater (Maryam and Büyükgüngör 2019). In the case of residual disinfectant requirements, UV systems were combined with a chemical disinfectant. In a study by Jachimowski and Nitkiewicz (2019), the authors compared gas chlorine with a combination of UV and sodium hypochlorite. Another study on the LCA of water disinfection was made by

Mo et al. (2018) in order to analyze four alternative disinfection methods' environmental impacts in order to reduce DBPs. The comparison of water disinfection methods is sometimes combined with other research topics. Romanovski et al. (2020) combined their LCA water disinfection study with the corrosion effect of disinfectants. Some LCA studies on the topic of our paper use more than one scenario to make a comparison between the disinfection methods. Busse et al. (2022) compared solar radiation disinfection, UV LED disinfection, a low-pressure mercury UV lamp and chlorine-based disinfection on different amounts of water disinfected with different life spans. It can be clearly seen that LCA studies on water disinfection are studied individually or together with aspects that will provide information to the public, researchers and decision-makers.

Studies on the effects of residual disinfectants demonstrate that they have no significant influence on the protection of water distribution systems when used (Linden et al. 2019). Furthermore, they have a favorable influence on the growth of biofilms (Fish et al. 2020). Residual disinfectants are not utilized in water treatment and delivery systems in the Netherlands since they are thought to have more detrimental effects than advantages for end users. They strive to prevent contamination of the water supply system and create biologically stable water rather than utilize a residual disinfectant (Smeets et al. 2009). Another study on the subject found that utilizing a residual disinfectant is insufficient for protecting water supply systems against pathogens. The study evaluated the occurrence of *E. coli* in water supply systems and evaluated the situation in Germany, the Netherlands, and France (Hambsch et al. 2007).

The purpose of this study is to examine the function of four different full-scale (municipal-level) water disinfection technologies from an LCA standpoint. This research distinguishes itself through its unique dataset and innovative approach, concentrating exclusively on comprehensive water disinfection technologies. Utilizing onsite data from a large-scale, operational water treatment facility, this study encompasses established and emerging disinfection technologies. The findings identify critical environmental impact factors and delineate essential components of an effective water disinfection system, providing forward-looking insights.

3.2. Materials and Methods

3.2.1. Goal and Scope

The goal of this study is to compare the environmental impacts of different water disinfection methods for a municipal water treatment plant. The study compares the environmental impacts of four different water disinfection methods, including chlorination, ozonation, LP UV and LED UV, for the operational phase only. The reason for carrying out this study is to compare the alternative water disinfection methods to supply safe drinking water for public use with the lowest environmental impact. The findings of this study will serve as a valuable resource for future researchers, helping them fill the gap in the LCA for drinking water disinfection technologies. The Local Water Administration (LWA) wants to reduce the usage of gaseous chlorine and build an effective water disinfection system. The disinfection level is determined by meeting the limits regulated by the governmental authorities, which is in line with the EU drinking water regulations, requiring zero Escherichia coli and intestinal enterococci (EU Directive 2020/2184).

The functional unit (FU) chosen for this research was 1 m^3 of disinfected water ready to be distributed to the main water supply network of the city. The current disinfection method, which is the baseline scenario, uses gaseous chlorine for disinfection that is transported to the WTP in tanks. The baseline scenario was compared with closed-vessel UV systems with LP amalgam lamps, an ozonation system and a closed-vessel UV system with UV LED lamps. It was accepted that the water supply network was free of contamination, and no residual disinfectant was required. The amount of residual disinfectant used in the baseline scenario was excluded from the calculations. Water disinfection systems were located straight after the treatment process. The system boundary for all four water disinfection systems was limited to energy consumption, chemicals and the transportation of equipment (except spare parts). The structural construction and dismantling phases were not included in the system boundary due to their low impact, which was negligible. Earlier publications on the LCA of water treatment facilities show that the environmental impacts generated by the construction and dismantling phases are insignificant when compared to the operational phases (Tarnacki et al., 2012). ReCiPe (representing the institutions that contributed: RIVM, Radbound University, CML and Pre Consultants) 2016 methodology, an LCIA calculation methodology, was applied, which addresses 18 midpoint impact category indicators. The addressed impact categories are global warming (GWP), stratospheric ozone depletion (ODP), ionizing radiation (IRP), ozone formation–human health (HOFP), fine particulate matter formation (PMFP), ozone formation–terrestrial ecosystems (EOFP), terrestrial acidification (TAP), freshwater eutrophication (FEP), marine eutrophication (MEP), terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FETP), marine ecotoxicity (METP), human carcinogenic toxicity (HTPc), human non-carcinogenic toxicity (HTPnc), land use (LOP), mineral resource scarcity (SOP), fossil resource scarcity (FFP) and water consumption (WCP). Foreground data were gathered from the WTP operators and the literature, while for the background, the Ecoinvent database was used. Figure 3.1 shows the system boundary of this LCA study.

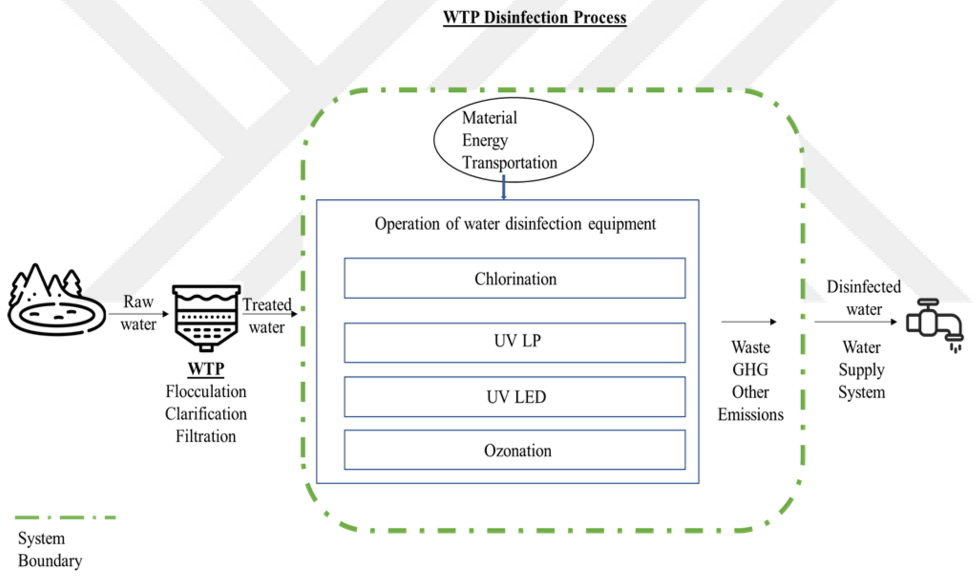

Figure 3.1 : The system boundary of four disinfection methods.

3.2.2. LCI

The second step of an LCA study is the Life Cycle Inventory (LCI), which is critical for the subsequent impact calculations. This phase includes key parts, such as data collection, calculation of the collected data and data validation. The water treatment plant used for this LCA analysis provides drinking water for a population of 607,502 and uses a lake as a water source. The treatment method comprises treatment tanks that utilize conventional water treatment processes (physical treatment, chemical treatment and disinfection). The WTP has a current capacity of 9072 m^3/h, with a maximum capacity of 12,960 m^3/h. Figure 3.2 illustrates the location of the Water Treatment Plant (WTP) in Turkey, situated at the coordinates 40°44′50.55″ N and 30°21′51.78″ E. The water network is monitored for DBP forms while being disinfected with gaseous chlorine. Despite the fact that the treated water is disinfected and extra disinfectants are used for residual disinfection, the LWA indicates that there are disease causes related to waterborne pathogens, particularly during the summer season.

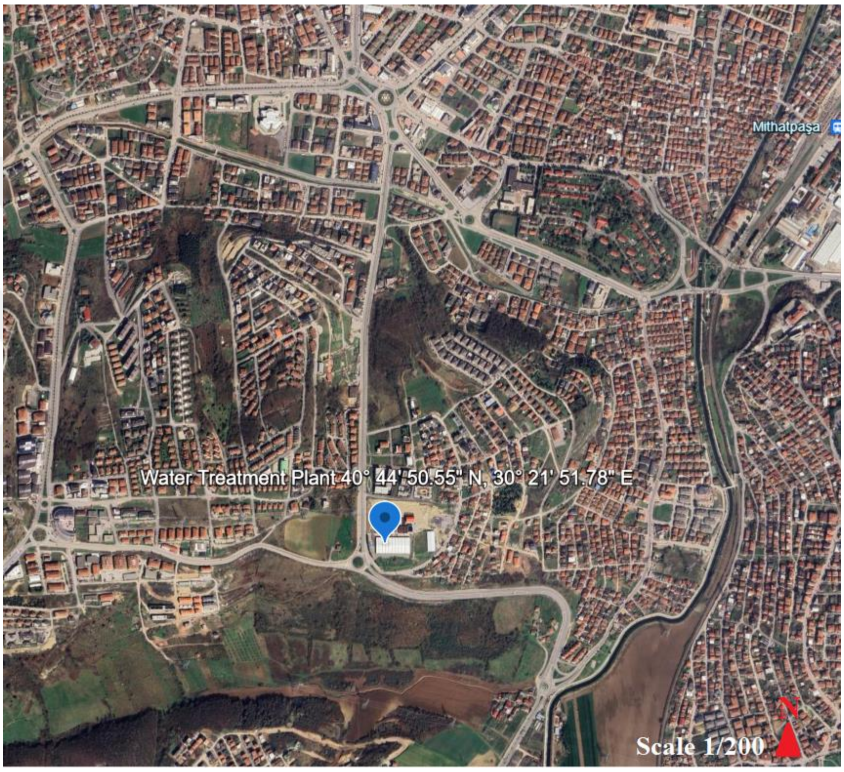

Figure 3.2 : Location of the Water Treatment Plant where LCI data are collected.

The operational data for the WTP's disinfection process were sourced from the LWA and served as a guideline for designing the other three disinfection systems. The operational on-site data for the baseline scenario were provided by the LWA for the year 2021. This includes the amount of chemicals used, their origin of production (needed to calculate the environmental impacts due to transportation of the material), and electricity consumption. Three companies provided data for the other water disinfection alternatives. The WTP's treated water characteristics and disinfection objectives were shared with manufacturers. Based on the information provided, manufacturers developed disinfection methods. The manufacturers' data regarding the operation of their water disinfection system were utilized to analyze the environmental impacts of the WTP disinfection process. The Ecoinvent database provides the material used for producing ozone and gaseous chlorine, but the material used for both UV systems is not provided except for the lamps. The materials used for UV systems were added manually to the software using the data from the report published by the United States Environmental Protection Agency (Cashman et al. 2014).

The process of chlorine disinfection consists of three primary stages: the generation of chlorine gas, its transportation and dosing. Among the various disinfection methods assessed, the baseline scenario displays the lowest energy consumption. Both UV disinfection systems are based on UVC production from a light source. Light sources are installed in steel closed vessel systems. In this paper, two light sources, low-pressure high-output UV lamps and LED UV lamps, were used. The energy to produce UVC is provided by electricity and chemicals such as oxalic acid, and isopropyl acetate is used to clean the closed vessel UV systems, which is part of the operational element along with electricity. The energy demand of the UV LP system is lower than the ozone system, while the UV LED system has a higher energy demand. The equipment used in the ozone process is more complex compared to other disinfection methods. The ozone disinfection system contains an ozone generator, cooling unit, air preparation unit and ozone destruction unit, which are energy-intensive. The energy consumption of the compared water disinfection systems per 1 m^3 of treated water is as follows: in the baseline scenario: 0.000314 kWh; UV LP: 0.007 kWh; UV LED: 0.054 kWh; and Ozone: 0.03744 kWh.

3.2.3. LCIA

Data from the LCI were used to calculate the environmental impacts of the disinfection methods for the chosen impact categories. The data were broken down to the FU at the LCI phase and loaded into the environmental impact assessment software for the impact calculations. SimaPro 9.4 was chosen as the software for modeling, which accommodates different environmental impact assessment methods. For this LCA study, ReCiPe 2016, developed by the Dutch National Institute for Public Health and the Environment, Radboud University, University of Leiden Department of Industrial Ecology and Pre-Consultants (Huijbregts et al. 2017), was chosen as the impact assessment method, which consists of 18 midpoint impact categories, together with 3 endpoint categories. In this paper, only midpoint impact categories are covered. Table 3.1 shows the ReCiPe midpoint impact categories and units.

Table 3.1 : ReCiPe midpoint impact categories and units.

Impact Category Indicator	Unit/Midpoint	Impact Category Indicator	Unit/Midpoint	Impact Category Indicator	Unit/Midpoint
Global warming	kg CO_2 eq	Terrestrial acidification	kg SO_2 eq	Human carcinogenic toxicity	kg 1.4-DCB
Stratospheric ozone depletion	kg CFC-11 eq	Freshwater eutrophication	kg P eq	Human non-carcinogenic toxicity	kg 1.4-DCB
Ionizing radiation	kBq Co-60 eq	Marine eutrophication	kg N eq	Land use	m^2a crop eq
Ozone formation, Human health	kg NO_x eq	Terrestrial ecotoxicity	kg 1.4-DCB	Mineral resources	kg Cu eq
Fine particulate matter formation	kg PM2.5 eq	Freshwater ecotoxicity	kg 1.4-DCB	Fossil resource scarcity	kg oil eq
Ozone formation, Terrestrial ecosystems	kg NO_x eq	Marine ecotoxicity	kg 1.4-DCB	Water consumption	m^3

3.2.4. Interpretation

The findings of the LCIA phase are examined in this final step of an LCA study. In general, the LCI and LCIA steps serve as information for the examined system, whereas the goal and scope, along with the interpretation phase, comprise the body (ISO 14044). The last step of this study covers recommendations based on the outcomes of the LCI/LCIA phases, limitations and conclusions. This paper covers the interpretation part of the LCA in the conclusion part of the paper.

3.3. Results

The highest contributor to the baseline scenario is energy consumption except for terrestrial ecotoxicity, mineral resource scarcity and water consumption. The production of gaseous chlorine had the highest contribution in these categories. The impacts gained from the transportation of gaseous chlorine were less than 2% in all impact categories, except terrestrial ecotoxicity at 4.65%, which can be considered negligible. When the production of gaseous chlorine was examined for the impact categories terrestrial ecotoxicity, mineral resource scarcity and water consumption, the mining operations for the material, production stage of the mined materials, chlorine alkali processes, treatment of waste caused by the production, decarbonized water production and processes for electricity production were observed. Figure 3.3 shows the impact distribution of energy consumption, chlorine production and transportation on the 18 midpoint impact categories for the baseline scenario and the percentage of each input on the total impact.

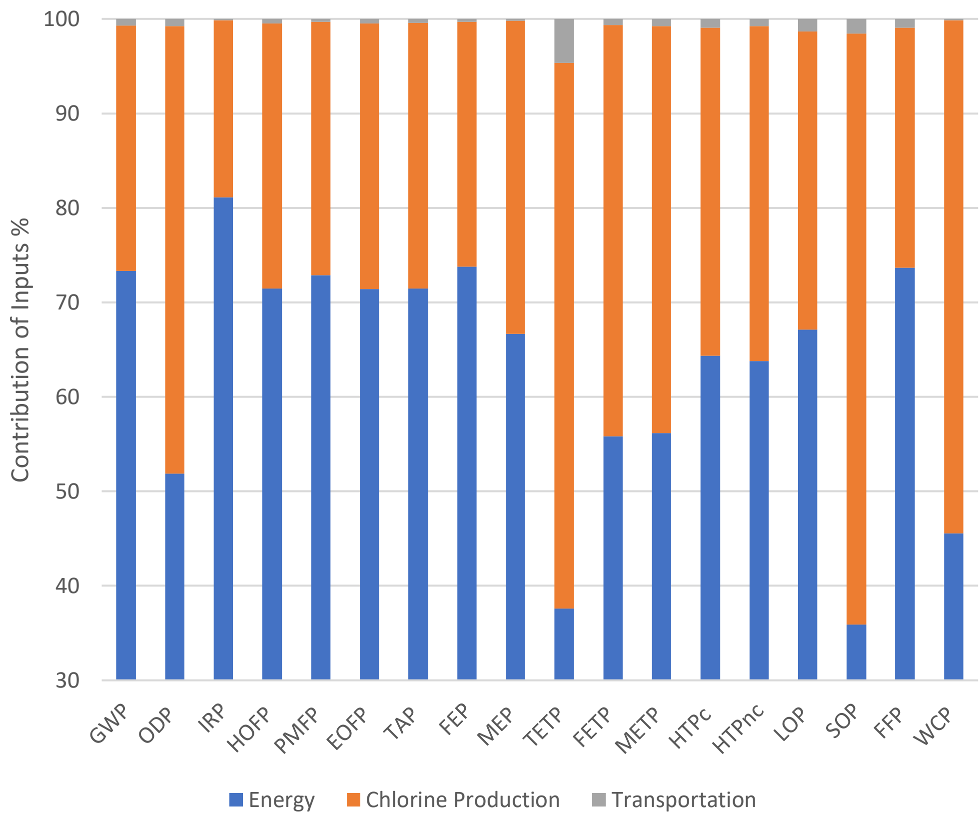

Figure 3.3 : Distribution of inputs for chlorination water disinfection system. (GWP: Global warming potential; ODP: Stratospheric ozone depletion; IRP: Ionizing radiation; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TETP: Terrestrial ecotoxicity; FETP: Freshwater ecotoxicity; METP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; LOP: Land use; SOP: Mineral resource scarcity; FFP: Fossil resource scarcity; WCP: Water consumption).

An ozone generator was used on-site to generate ozone for ozone disinfection. The energy consumption for the ozone disinfection system includes the energy used to generate ozone and the energy consumption of the air compressor system. Ozone production has the greatest influence across all impact categories. The major input that was responsible for the ozone generation process was electricity usage. Except for terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and mineral resource scarcity, electricity was responsible for more than 94% of impacts on ozone production. This result makes sense due to the fact that ozone production is an energy-intensive process. The air needed for the operation of the ozone disinfection system is supplied by compressors, which are also energy-driven. The air production stage had the second highest impact on all impact categories. Transportation of the ozone equipment had a very small impact in all categories, which was negligible compared to ozone and air production. Figure 3.4 shows the environmental impact contribution of the inputs for water disinfection with an ozone system on the 18 midpoint impact categories and the percentage of each input on the total impact.

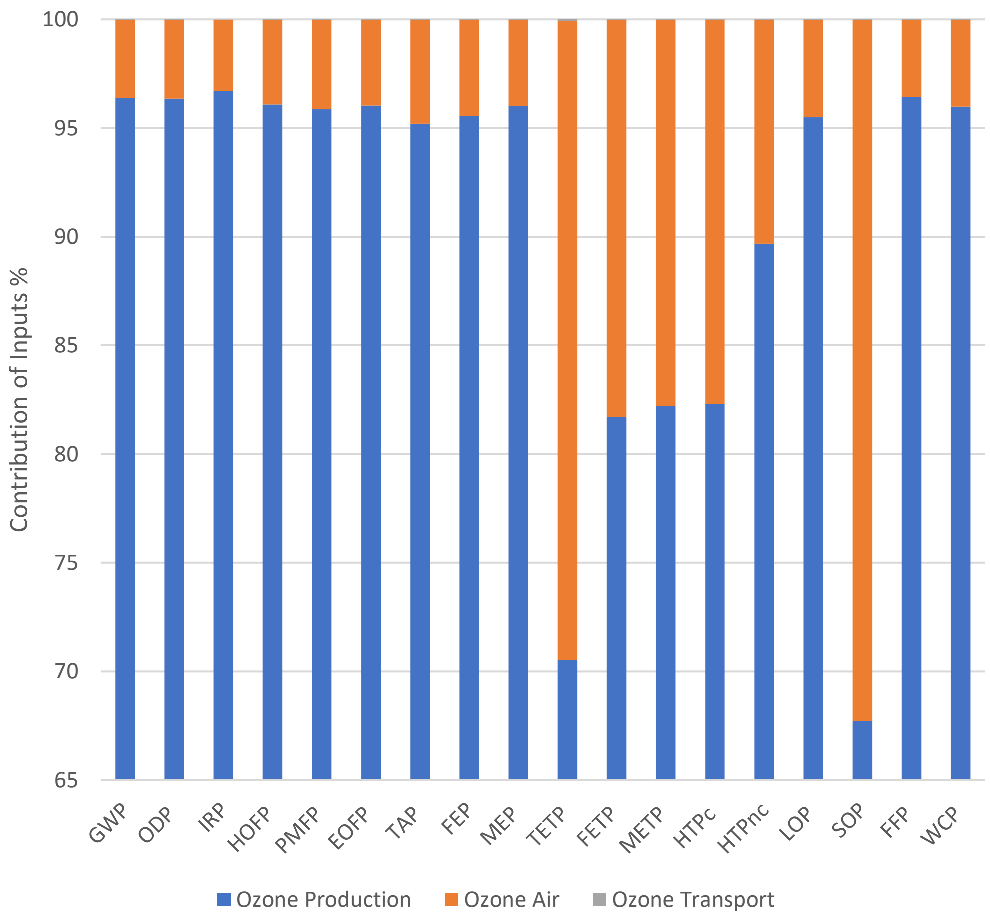

Figure 3.4 : Distribution of inputs for ozone water disinfection system. (GWP: Global warming potential; ODP: Stratospheric ozone depletion; IRP: Ionizing radiation; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TETP: Terrestrial ecotoxicity; FETP: Freshwater ecotoxicity; METP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; LOP: Land use; SOP: Mineral resource scarcity; FFP: Fossil resource scarcity; WCP: Water consumption).

The UV LP disinfection system employs vertically placed LP amalgam lamps in a closed vessel disinfection chamber. The use of energy for the operation of the UV LP system had the greatest impact across all 18 impact categories. The chemical (oxalic acid) used for cleaning the UV vessel had the second highest impact in all impact categories after energy. The highest contribution from the chemical cleaning agent is to stratospheric ozone depletion, ozone formation–terrestrial ecosystems and terrestrial acidification, with 12.87%, 7.55%, 7.51% and 3.09%, respectively. Environmental impacts caused by the transportation of the equipment were less than 1% in all impact categories. The environmental impacts due to UV LP disinfection and their distribution are depicted in Figure 3.5, with the percentage of each input on the total impact.

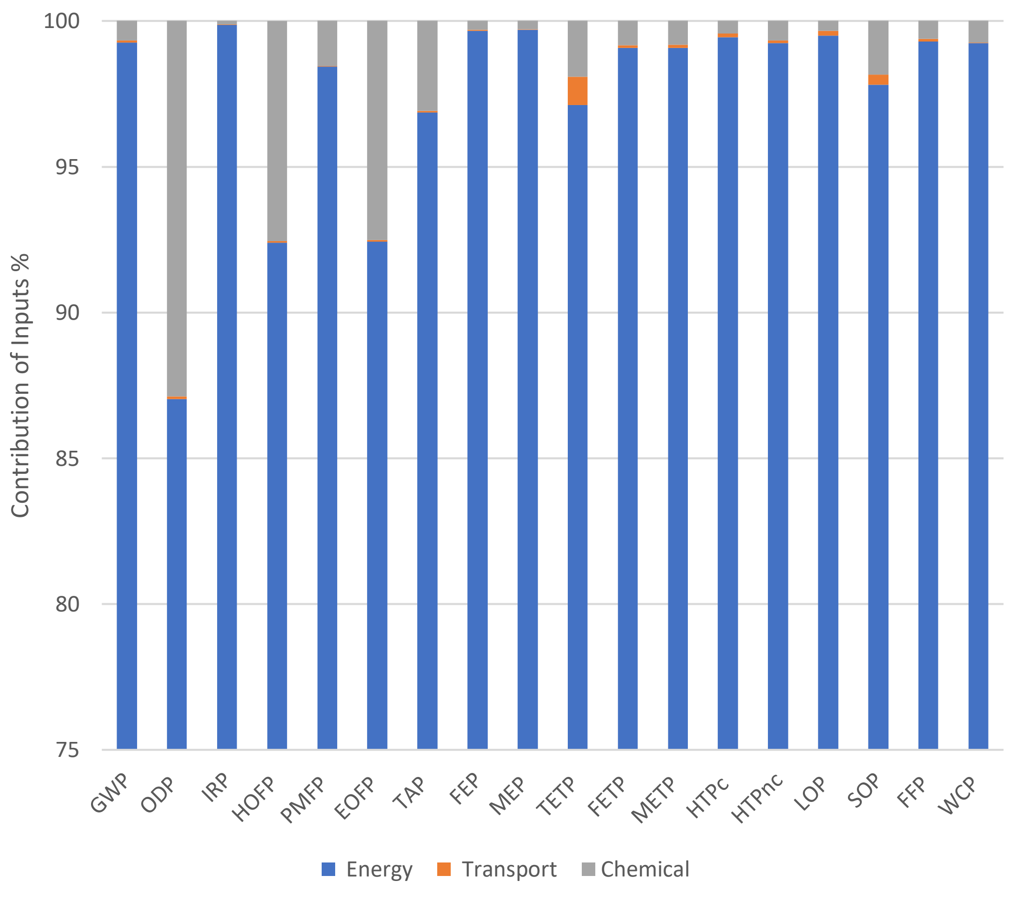

Figure 3.5 : Distribution of inputs for UV LP water disinfection system. (GWP: Global warming potential; ODP: Stratospheric ozone depletion; IRP: Ionizing radiation; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TETP: Terrestrial ecotoxicity; FETP: Freshwater ecotoxicity; METP: Marine

ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; LOP: Land use; SOP: Mineral resource scarcity; FFP: Fossil resource scarcity; WCP: Water consumption).

The UV LED system uses a closed vessel system similar to the UV LP system, but the UV LEDs mounted on the surface of the closed vessel disinfection chamber are used in the second UV disinfection system. As the UV disinfection process is reliant on the conversion of electric energy to UV light, electricity consumption is the most important aspect of the process. The LCA results of the UV LED system reveal that energy usage had the greatest influence on all impact categories. Transportation and cleaning chemical agents were together responsible for less than 1% of total impacts in all impact categories. Figure 3.6 shows the impact of inputs to disinfect one m^3 of treated drinking water using UV LED systems, with the percentage of each input on the total impact. In the ionizing radiation impact category, disinfection with gaseous chlorine had major impacts together with the ozone and UV LED systems.

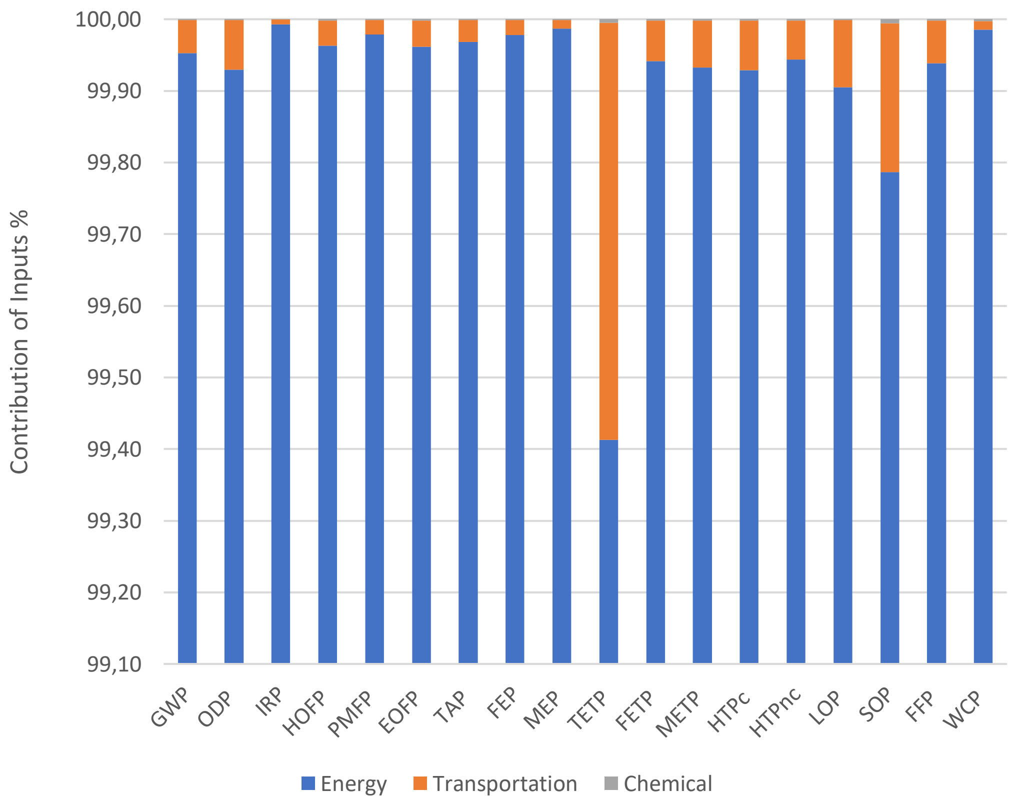

Figure 3.6 : Distribution of inputs for UV LED water disinfection system. (GWP: Global warming potential; ODP: Stratospheric ozone depletion; IRP: Ionizing radiation; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial

acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TETP: Terrestrial ecotoxicity; FETP: Freshwater ecotoxicity; METP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; LOP: Land use; SOP: Mineral resource scarcity; FFP: Fossil resource scarcity; WCP: Water consumption).

The calculated indicator results (characterization) provide numerical values for each impact category for the compared disinfection methods. LED UV disinfection had the highest overall impact in all categories when the four water disinfection technologies were evaluated. Due to their high energy consumption, the UV LED water disinfection system and ozone water disinfection system were responsible for the most environmental impacts in the impact categories generating the largest environmental footprints. The UV LP system was the most environmentally friendly disinfection technology, even though the energy demand was 22 times more than gaseous chlorine, with the least effect in all categories, followed by gaseous chlorine. The combined impact of chlorine production and its associated energy consumption contributed to this result. A study by Busse et. al. (2022), where four disinfection methods were evaluated from an LCA perspective for a water system with a max flow rate of 1 m^3/day, had similar results as the findings of our paper, showing that most impacts were caused by the UV LED disinfection system due to the higher energy consumption of other disinfection methods. One crucial point of the study was that the applied UV dosage was not the same in the UV systems, which does not provide a healthy comparison between the UV systems. In the study, chlorination was more environmentally friendly than the UV LP systems, which is not in line with this paper’s finding. Jachimowski and Nitkiewicz (2019) compared gaseous chlorine to a medium-pressure UV system with sodium hypochlorite, a residual disinfectant, for water disinfection at a municipal level. The results show that gaseous chlorination caused less environmental impact than the UV system, which is not in line with the result of this paper. The reason for the different results is due to the UV lamp type—medium-pressure lamps are less efficient compared to low-pressure high-output lamps—and additional chemical residual disinfectant usage after the UV disinfection process. The findings of this paper are consistent with other earlier LCA studies in terms of the effect of factors, which were limited in scope and focused on the impact of electrical energy and chemicals.

The articles that focus on the LCA of water disinfection technologies were very limited and applied to small-scale water treatment systems. In a study by Jones et al. (2018), the authors compared UV disinfection with chlorine disinfection. The distinctive part of this study is that it compares different scenarios based on the materials used for chlorination systems, such as tanks, baffles and pipes, with different UV dosages. In all scenarios, chlorination impacts on the environment were lower than UV systems. The outcome of this study shows that the major contributor to UV disinfection systems is caused by energy consumption, which is in agreement with our paper. The energy demand is based on the UV dosage applied to the water. A higher UV dosage requires more energy, which results in more environmental impacts. One critical element for UV disinfection systems is the manufacturers' technology, causing different energy consumption. In UV LP systems, for example, the UVC output of each UV lamp varies according to the manufacturer, resulting in more or less equipment and energy, which has a direct influence on the LCA results. Another important result found in this study shows the lamp production of UV light-emitting diodes. Compared to low-pressure lamps, the production of LED lamps causes many more environmental impacts. The production of UV LED lamps has an environmental impact that was 13-to-2860 times higher than the production of UV LP lamps across all impact categories on a functional unit basis. One of the difficulties faced in our LCA study was the lack of UV LED studies in the literature that could be used to analyze the environmental impacts of UV LED systems. Figure 3.7 shows a comparison of four disinfection methods on 18 midpoint impact categories with their impact values.

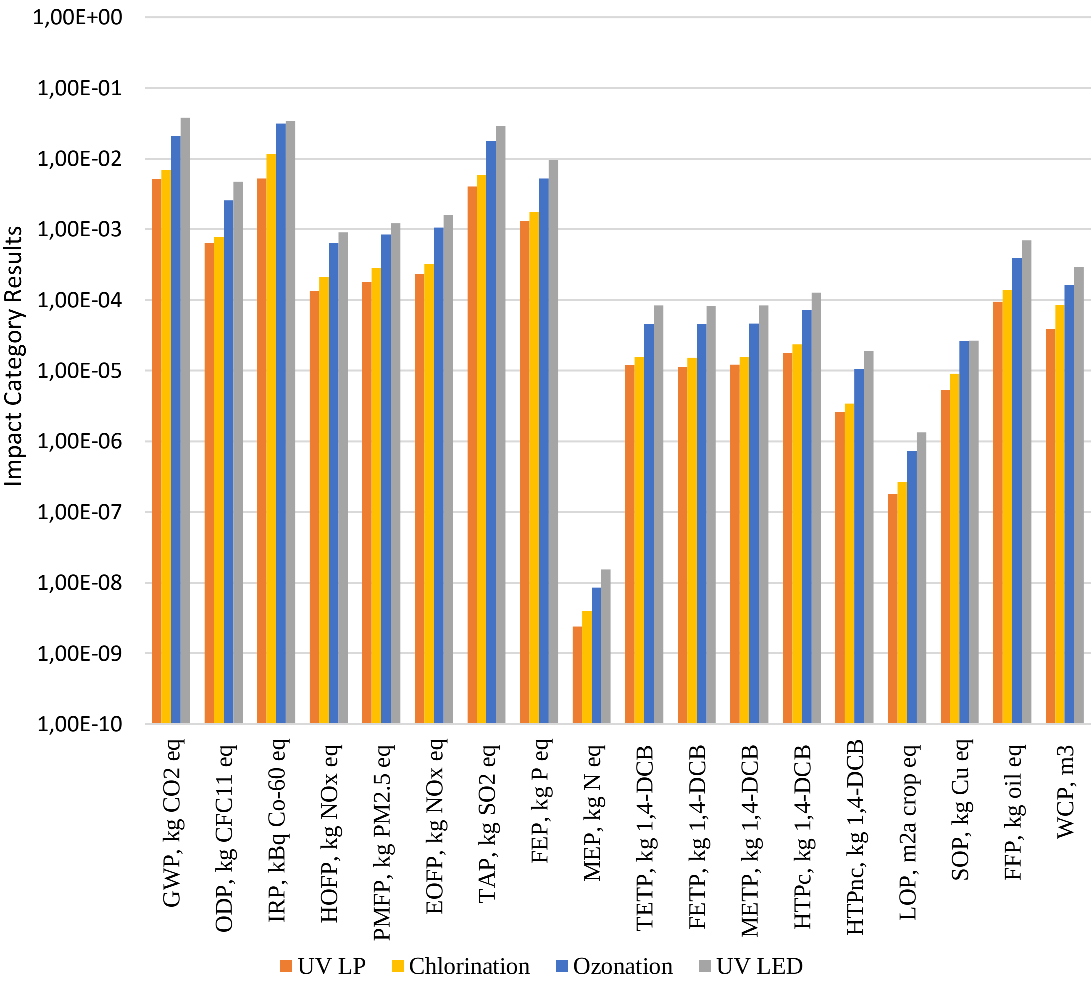

Figure 3.7 : Comparison of the four disinfection methods on midpoint impact categories. (GWP: Global warming potential; ODP: Stratospheric ozone depletion; IRP: Ionizing radiation; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TETP: Terrestrial ecotoxicity; FETP: Freshwater ecotoxicity; METP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; LOP: Land use; SOP: Mineral resource scarcity; FFP: Fossil resource scarcity; WCP: Water consumption).

The Ecoinvent database uses electricity mixes from different countries to obtain a median of electricity for the production of material and equipment for global value. The electricity used for operating the disinfection systems was chosen as the global medium voltage to obtain a global outlook. When the used electricity mix was changed to local conditions, the impact scores changed for the disinfection methods for all impact categories, together with a slight change in the gradation of the compared systems. The UV LED system was still the highest contributor in all impact categories except terrestrial ecotoxicity and mineral resource scarcity, whereas the ozone system had the highest impact and the UV LP system had the lowest impact in all categories. Another observation was that in all categories, improvements and deteriorations were seen for the disinfection methods. Table 3.2 presents the percentage of changes, both negative and positive, in the impact categories when utilizing international electricity mix data compared to local electricity mix data. The "+" symbol indicates an increase, and the "-" symbol indicates a decrease in the impact categories. These changes occur due to the methods used for electricity production and the electricity mix. The results gained by the change in the electricity mix show that the source of electricity is a critical issue in assessing the environmental impacts. The ANOVA test was conducted using the Minitab application to assess the statistical significance between the electricity mixes. Furthermore, SimaPro software was utilized to systematically adjust and model various electricity mix scenarios. When our study is compared with the current studies, it poses advantages due to its original data, which were gathered by the multiple site visits and archive searches of the LWA for verification. Another advantage is that the four main drinking water disinfection systems used widely around the world are compared in order to provide information for professionals in the field and at universities. When the literature is searched, it is seen that some studies are made comparing water disinfection systems at a lab-scale level or based on end users. This study focuses on large-scale water disinfection technologies that are operational. The main disadvantage faced in comparing these water disinfection systems is generating data that are now available from manufacturers.

Table 3.2 : Percentage change in the results due to electricity mix used.

Impact Category	Chlorine Disinfection	Ozone Disinfection	UV LED Disinfection	UV LP Disinfection
Global warming	+8.24	+11.42	+11.51	+11.39
Stratospheric ozone depletion	+19.82	+45.88	+46.36	+38.03
Ionizing radiation	+333.54	+1579.96	+1699.56	+1652.80

Table 3.2 (continued) : Percentage change in the results due to electricity mix used.

Ozone formation, Human health	+3.97	+5.54	+5.61	+5.13
Fine particulate matter formation	−61.46	−68.18	−68.50	−68.09
Ozone formation, Terrestrial ecosystems	+4.05	+5.65	+5.72	+5.24
Terrestrial acidification	−12.83	−16.62	−16.98	−16.50
Freshwater eutrophication	−39.29	−45.99	−46.56	−46.27
Marine eutrophication	−31.12	−39.93	−40.15	−40.10
Terrestrial ecotoxicity	+12.93	+20.84	+41.25	+32.00
Freshwater ecotoxicity	−19.38	−24.36	−29.60	−27.45
Marine ecotoxicity	−19.67	−24.78	−29.87	−27.72
Human carcinogenic toxicity	−19.93	−23.66	−27.56	−25.68
Human non-carcinogenic toxicity	−22.21	−28.04	−30.62	−29.47
Land use	+61.88	+118.55	+130.01	+12,614
Mineral resource scarcity	+16.38	+24.83	+56.37	+31.12
Fossil resource scarcity	+8.22	+11.35	+11.42	+11.30
Water consumption	+3.07	+6.74	+6.94	+6.87

At the municipal level, new and developing water disinfection technologies are being researched and implemented. Electrochemical disinfection (ED) is one of these technologies. Filho et al. (2021) conducted research that compared ED to chlorine and exhibited the results. It has been suggested that the electricity consumption of ED is substantially higher than that of chlorination, which would result in larger environmental impacts owing to energy consumption. Unlike Filho et al. (2021), Chaplin (2019) suggested that electrochemical technology might consume less energy than other approaches if utilized to treat numerous pollutants rather than simply pathogens. Advanced Oxidation Processes (AOPs), such as photocatalysis (Zhang et al. 2019), catalytic ozonation (Wang and Chen 2020), and sonolysis (Fetyan and Attia 2020), are also being investigated. Improvements in ozone disinfection are being researched in lab-scale experiments, which focus on increasing efficiency and decreasing energy use. According to Seridou and Kalogerakis (2021), using micro and nano ozone bubbles instead of macro bubbles in the typical ozone disinfection procedure can boost disinfection efficiency while using less energy. UV LEDs and xenon excimer lamps are being explored more and more in the context of UV disinfection (IWA 2022). Naunovic et al. (2008) investigated excimer lights and developed a lab-scale model to assess disinfection efficiency. The results were better than expected; however, the authors urged that further research should be conducted on this issue. Another significant characteristic of UV disinfection is that it may be utilized as a light source for photocatalysis water disinfection, which is an AOP (You et al. 2019). The effectiveness and functioning mechanism of developing water disinfection systems are being explored, but their environmental impacts are not being considered due to a lack of real-world applications. New methods of drinking water disinfection combine the elimination of several contaminants from water, resulting in an upgrade and modification in the traditional treatment procedure. It is safe to say that the environmental implications of the disinfection process can be reduced if treatment systems become more effective with new technology.

3.4. Conclusions

Since their first use at the beginning of the 20th century, UV disinfection systems have significantly evolved, combining various types of UV lamps for diverse applications. As these systems depend on electricity, it is crucial to focus on enhancing their energy efficiency and operational performance. Using materials with lower light absorption values than the current standards, such as stainless steel, high-density polyethylene and polypropylene, can increase the efficiency of UV LP systems, leading to reduced energy consumption. These improvements could expand the global use of UV LP water disinfection systems, which are known for their safety and reliability.

Currently, UV LED lamps have a higher environmental impact and energy consumption compared to UV LP systems for equivalent disinfection levels. The future of UV LED systems depends on advancements in lamp technology and greener production processes to make them viable for water disinfection. This research demonstrates that UV LP systems present the lowest environmental impacts among water disinfection methods. Although chlorination remains the most common method worldwide, transitioning to UV LP systems can reduce the environmental footprints of water treatment plants. Reducing energy consumption is critical; if achieved, ozone and UV LED systems could become more favorable.

With the advancement of water disinfection technologies and increasing support for renewable energy, it is crucial to continuously update the LCA of water disinfection technologies. The findings from this LCA study, along with others, emphasize the significance of energy as the primary contributor to environmental impacts. By adopting more energy-efficient products, it is possible to shift the factors contributing to environmental repercussions. The growing environmental awareness and establishment of regulatory frameworks, such as the EU Drinking Water Directive and the US Safe Drinking Water Act, necessitate periodic enhancements in water safety protocols. These updates require the re-evaluation of pollutant removal methods and the exploration of innovative treatment technologies. In this context, LCA serves as an essential tool for comprehensively assessing the environmental impacts of processes or technologies in water disinfection, thereby addressing public concerns about their potential ecological consequences.

Future studies on the LCA of municipal water disinfection should be evaluated, together with the environmental impacts associated with both the production and operation of equipment. Currently, obtaining detailed data on the materials used in the manufacture of disinfection equipment, such as stainless steel, amalgam components, electronic parts, wires, diodes, plastics and other materials, is challenging due to its limited availability. To bridge this gap, manufacturers should be encouraged to share comprehensive material data or conduct LCA studies to provide critical data for researchers. Such transparency will enhance the accuracy of environmental impact assessments and support the development of more sustainable water disinfection technologies.

To align the future of water disinfection more closely with sustainability goals, it is crucial to focus on improving energy efficiency, promoting transparency in production data and leveraging advancements in technology. Ongoing research and collaboration between industry and academia are critical to drive these advancements and ensure that water disinfection technologies evolve in an environmentally responsible manner.

4. LIFE CYCLE ASSESSMENT OF PACKAGE AND ULTRAFILTRATION DRINKING WATER TREATMENT SYSTEMS AT MUNICIPAL LEVEL

4.1. Introduction

Water has always been an important part of all the life due to its capability of being a solvent for many molecules and used by cells to transport the substances they need (Sargen and Utter, 2019), which is also essential part of human life. The historical findings shows that the earliest settlements were developed to locations that had access to fresh water (Vuorinen et al., 2007). Yet this day, more than 50% of the world population live closer to surface freshwater bodies, less than 3 km (Kummu, M. et al., 2011). It could be said that access to fresh water shaped how and where human beings live in the past but it is till continue to do so.

The water treatment process started with filtration of water and continued to develop by adding additional processes such as coagulation, flocculation, clarification and disinfection (Symons, 2006). Regulations for delivering clean water to the general population emerged at the same time as the treatment and knowledge of water. In 1974, the USA approved the Safe Drinking Water Act, which established national limitations and is still being updated today (CDC, 2019). Currently, the US EPA has set limits for more than 90 pollutants for the treatment of drinking water (CDC, 2022). Similar to the USA, EU also has been developing regulations for the drinking water. First directive for drinking water, covering the member states of the EU, was published in 1980 with the latest directive that was published on 23.12.2020 and came into force on 12.01.2021 (EU Directive, 2020). When this regulations and directives are reviewed, the common ground that they share is being updated with time parallel to understanding of new contaminations and health issues due to water consumption. Even though regulations on safe water had been around for a long time, it was not until 2010 that the access to safe water is a basic human right, which has to be provided by the states (UN, 2011).

Conventional water treatment process consists of following steps such as i) Coagulation ii) Flocculation iii) Sedimentation iv) Filtration v) Disinfection (Y. Wang et al., 2021). Various methodologies for water treatment have become viable, contingent upon the characteristics and origin of the water. A variety of options are available to choose a water treatment system such as conventional water treatment systems, PWTSs' with various processes, and membrane process water treatment systems. The decision to select a treatment system is based on a number of variables, including the water source quality (pollutants in the water), the location of the WTP, water demand, the effectiveness of the targeted treatment, contaminants, capital costs, operations and maintenance expenses, and environmental effects (Torpie et al., 2020). PWTSs' are complete drinking water treatment systems which consist of water treatment process that take place within the premanufactured tanks. These systems have some advantages over conventional WTPs such as requiring less area and construction, having the flexibility to increase plant capacity without major construction work and low operation and maintenance costs (Baddoo and Biddle, 2000). Membrane filtration employs several types of membrane processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) (Pendergast and Hoek, 2011). UF water treatment systems may have microfiltration followed by UF membranes to produce drinking water (Prézélus et al., 2021). Membranes can be used in variety of applications depending on their functions for capturing, separation and catalyzation (Drioli and Giorno, 2010).

Life Cycle Assessmentis a technique for assessing the environmental effect of a product or process (Ellis et al., 2023). It was standardized by the International Organization for Standardization (ISO), ISO 14040, in 1997 and has been modified several times, the most recent being in 2006, with a revision made in 2020. This standard outlines the general guidelines and structure for how to carry out an LCA study (ISO 14040) An LCA study has 4 stages i) Goal and Scope definition ii) Life Cycle Inventory Analysis iii) Life Cycle Impact Assessment iv) Interpretation (Corominas et al., 2020). There are different inputs and stages to evaluate the environmental impacts caused by WTPs. WTP LCA studies can include stages of construction, operation and dismantling of the plant. Each stage has its own inputs to calculate the environmental impacts (Zijp and H. van der Laan, 2015). LCA is also used for the comparison of different systems for a product or service (Stavropoulos et al., 2016).

Studies on LCA of water treatment began in the late 1990s, with the study of Sombeke et. al. (1997), being one of the earliest, in which conventional water treatment process was compared with nano filtration water treatment process. The goal of the study was to examine possible water treatment scenarios for their environmental impacts. Zine et al. (2013) carried out an LCA study for a conventional water treatment process that only focused on the Global Warming Potential (GWP). The study showed that the main contributors to emissions were the chemicals used in the processes and the electricity consumption. Studies by Friedrich (2002) and Saad et al. (2019) also stated that the major contributors are chemicals and electricity. Various studies (Goga et al. 2019, Tarnacki et al 2012, Raluy et al 2005) on the LCA of desalination using membranes indicates that the electricity consumption and chemical usage during the treatment are the main contributors on environmental impacts. The outcome of each study shows that energy and chemicals used for water treatment are the main points that needs to be focused and improved. Despite nearly three decades of research on LCA of water treatment, there are fewer studies compared to LCA of wastewater treatment and methodologies.

In this thesis two water treatment systems for a municipality were investigated. The existing system, combined PWTS with chemical disinfection, is compared with an alternative water treatment system, ultrafiltration water treatment system with chemical disinfection, in the means of operation and the production of main equipment (water treatment tanks, UF membrane and its supporting structure) from LCA perspective, following ISO 14040 guidelines. An impact assessment modeling software was used to calculate environmental impacts caused by the production and operation of the two water treatment systems.

4.2. Materials and Method

4.2.1. Goal and Scope

The goal of this study is to compare the environmental impacts of two municipal drinking water treatment systems (WTS). The first WTS is the existing Water Treatment Plant (WTP), located in Turkey, and operated by local water administration

(LWA). The maximum flow rates the of the WTP is 12.960 m^3/hour and the treatment is carried out by a package (modular) water treatment process that employs 36 modular water treatment tanks including physical and chemical processes. Water treatment begins with raw water entering the treatment tank from the bottom with an upflow, then passing through the clarifier section of the treatment tank for flocculation and clarifying. The tank's clarifier contains buoyant material clarification process. After clarification, water enters the filtration part of the treatment tank through the weir. The composition of the filtration media is made with anthracite, silica sand and garnet. After the filtration the treated water is disinfectant with gaseous chlorine and sent to the main storage tanks before distributed to the city. The limit for disinfection is having free chlorine between 0.2 mg/L and 0.5 mg/L before discharged to the supply line. Each tank features two backwash systems for clarifying and filtration, which are activated automatically when there is a head loss. The effluent from the backwash cycles is discharged into sewers and eventually ends up at the city's primary wastewater treatment facility. The alternative water treatment system is a virtually designed ultrafiltration plant (UFWTS). The raw water enters the system through cartridge filters, 300 µm pore size, before the UF membranes to hold the large particles and increase the lifespan of UF membranes. After raw water is filtered with cartridge filter, low dosages of coagulant are dosed to make colloidal particle's stick together and form larger sizes and then the water is processed with UF membranes. The UFWTS is comprised of 10 membrane trains each having 216 UF modules. The system is equipped with chemical backwash system for membrane cleaning and the effluent form backwash is store in a neutralization tank and discharged into sewage system. Table 1 provides details of the designed UF system that was used to compare with the existing PWTS.

Table 4.1 : Design data of the UF water treatment system.

Gross flux ($L/m^2.hr$)	Net filtration flux ($L/m^2.hr$)	Recovery (%)	Filtration time (min)	Backwash time (sec)	Backwash flux ($L/m^2.sa$)
66	60	95.4	45	45	120

Table 4.1 (continued) : Design data of the UF water treatment system.

System Configuration					
Total Membrane Area (m^2)	Number of total modules	Number of trains	Number of membranes on each train	Membrane type	Membrane material
151,200	2,160	10	216	Ultrafiltration	PVDF
Operational Configuration					
Design feed flow (m^3/hr)	Average inlet flow (m^3/hr)	Average permeate (m^3/hr)	Average backwash wastewater flow rate (m^3/hr)	Chemical backwash wastewater flow rate (m^3/hr)	Average wastewater flow rate (m^3/hr)
9,976	9,514	9,073	302.4	138.6	441

The functional unit of the study is 1m^3 treated and disinfected drinking water ready to be used by the public. The system boundary is the operational stage of both water treatment systems including chemicals and energy needed for the water treatment process together with the production of modular tanks concrete foundations for water treatment tanks, support structure for UF modules and UF membranes. The raw water intake structure, building construction, production of auxiliary treatment equipment (dosage pumps, compressors etc.), dismantling, generated wastewater from filter cleanings, waste and distribution to the water supply network are not included. ReCiPe midpoint impact assessment methodology is chosen to calculate the environmental impacts of both water treatment systems. Water treatment systems are assumed to have 30 years end of life (EoL). Thus, materials used for production of treatment tanks and UF membranes are calculated to meet the FU and additional material (with stainless steel frames) are taken in to account. UF filters are changed 4 times over the EoL period and additional 1% of filter material will be added each year to the modular water treatment tanks. Both water treatment systems are premanufactured and assembled at the water treatment plant. The equipment is installed on the site without major construction work which gives major advantage to both systems over traditional water treatment plants. Figure 4.1 shows the system boundary of the LCA study.

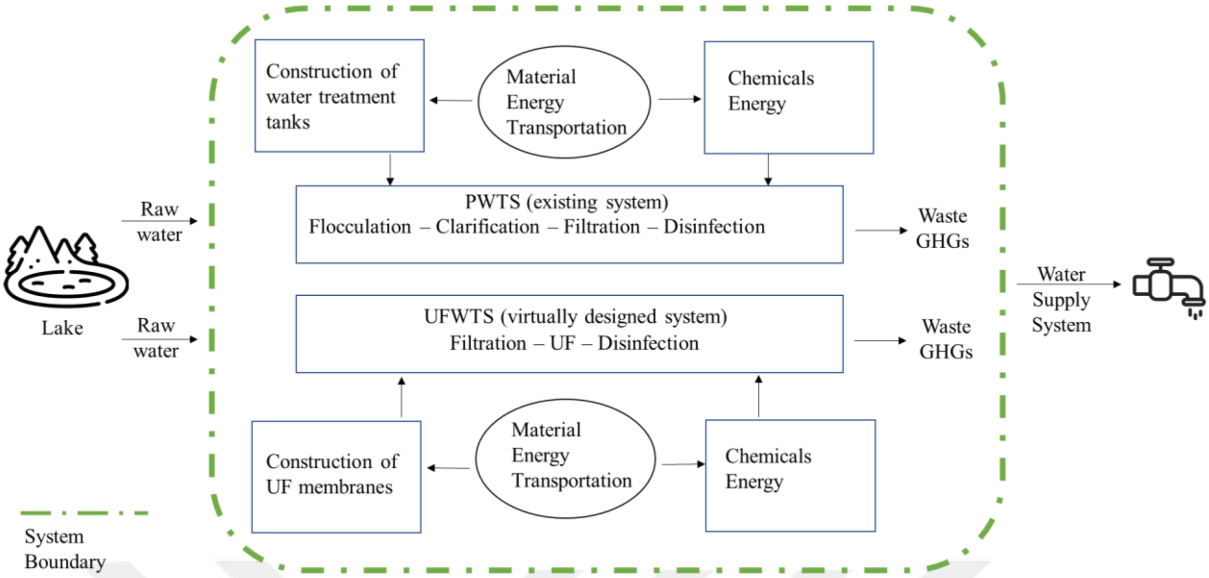

Figure 4.1 : System boundary of the compared water treatment methods.

4.2.2. LCI

The data collection of this LCA study is consisted of; operational data from LWA for the year 2021 for WTP, literature search and Ecoinvent database. In addition, unavailable data from mentioned sources was acquired from manufacturers. The data collected for operation includes total amount of treated water, electricity consumption, chemical consumptions, decrease in filter media, backwash cycles and transfer of chemicals. The data received was not suitable to imply to the impact assessment modelling program so site visits were carried out to break down the data to meet the FU. Collected data was grouped in 4 categories which are i) material needed for construction of the equipment ii) energy needed for operation iii) chemicals used in operation iv) materials needed for the operation. Materials needed for the construction includes components which are used to build package water treatment tanks and UF membranes. The items that are grouped for operational stage are divided into the chemicals, energy and the materials needed such as filter material or UF membranes. In case of PWTS materials needed for the operation consisted of filter material whereas for the UFWTS it is replacement of new membranes. The facility operated with an average flow rate of 9073 m^3/hour for the year 2021. The UFWTS was designed with the outlet water flow rate of 9073 m^3/hour using same raw water parameters and treated water to be comply with the drinking water regulations. Energy needed to produce the materials for production is included in the calculations though the data in the impact calculation modelling software and it will not be separately surveyed.

Table 4.2 : The water quality parameters on the scope of this thesis.

Parameter	Unit	Raw Water	Treated Water	Legal Requirements
Aluminum	µg/L	11 - 40	8 -15	< 200
Turbidity	NTU	0.9 – 1.2	< 1	Acceptable to consumers and no abnormal change
Odor, Taste				Acceptable to consumers and no abnormal change
Iron	µg/L	25 - 55	13- 24	< 200
Conductivity	µS/cm	280 - 300	< 300	< 2500
Manganese	µg/L	35 - 58	< 3	< 50
pH	-	7.59	7.5 - 8	6.5-9.5
Total Coliform Bacteria	CFU/100mL	5.78	0	0

As it can be seen from table 4.2 the raw water quality is below the required limits. In spring and fall the turbidity increases due to rain and runoff water. The studied water treatment plant used to improve the water parameters and provide the esthetical quality also it ensures the quality of water and a precaution step for unexpected contaminations. As it can be seen from the table 4.2 the raw water quality is very good based on the legal requirements. The main reason for treatment is due to the esthetics of water and for microbiological paramaters.

4.2.3. LCIA

Different methodologies for environmental impact calculations are available. Some of them such as Traci (USA) and LIME (Japan) are regional while ReCiPe and IMPACT World+ are global methodologies (SimaPro, 2022) which covers multiple impact categories. LCIA methodologies can be also distinguished based on their midpoint or endpoint impact category approach (Finnveden and Potting, 2014). Also, there are other impact assessment methodologies which covers only one category such as carbon footprint or water footprint (Ecoinvent, 2021).

ReCiPe environmental impact assessment methodology uses 18 midpoint impact categories and 3 endpoint area of protection to address the impacts to the environment with three 3 different perspectives; individualist, hierarchist and egalitarian. In this study, Recipe assessment methodology with hierarchist perspective will be used to address the environmental impacts caused by the water treatment scenarios on midpoint impact categories. Recipe midpoint impact categories includes global warming, stratospheric ozone depletion, ionizing radiation, ozone formation - human health, fine particulate matter formation, ozone formation - terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption. The data that are collected in LCI step is transferred to a modelling software to calculate the environmental impacts for the impact categories. SimaPro 9.4.0.1 classroom edition software is used to calculate the impacts on this paper's study. The modelling software provides different databases such as Agri-footprint economic, Ecoinvent, EU and DK input output, Industry data 2.0 and the U.S. Life Cycle Inventory Database with three calculation assessment methods, Impact World +, LC – Impact and ReCiPe 2016 (SimaPro, 2022).

4.2.4. Interpretation

Interpretation is the final step of an LCA study (ISO 14040). It includes the comment of the outcomes of LCI and LCIA phases in line with goal and scope of the study (EPLCA, 2021). The objective of this life cycle assessment (LCA) study is to compare the environmental impacts of two different municipal-scale water treatment systems. The final step of this study will provide recommendations based on the findings of the life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases, as well as to discuss the limitations of the study and draw conclusions. The interpretation of the LCA results will be presented in the conclusion section of this paper.

4.3. Results and Discussions

4.3.1. Environmental performance of Package and UF Water Treatment Systems

When the PWTS was analyzed, it was observed that the chemicals used for operating the package water treatment plant such as anionic polyelectrolyte, gaseous chlorine and polyaluminium chloride have the highest contribution in all impact categories except IR where the electricity used for the operation of the plant has the most impacts. Gaseous chlorine together with polyaluminium chloride is responsible for more than 80% of the impacts caused by chemicals used in the PWTS and the rest of the impacts are caused by the usage of polyacrylamide (PAM). In categories GWP, ODP, HOFP, PMFP, EOFP, TAP, FEP, MEP, HTPnc, LOP, FFP and WCP, electricity was the second major contributor after chemicals; whereas, TETP, FETP, METP, HTPc and SOP materials used for constructing the equipment had most environmental impacts after energy consumption. Contribution of the operational materials had impact less than 0.0001% percent in all impact categories which are negligible. In a conventional water treatment plant, the major energy consumption is from pumps which are used to transmit the raw water to the treatment plant, treated water to the supply lines and storage tanks around city. The energy consumption of water treatment processes is very low when it is compared with pumps. Bukhary et al. (2019) stated that the energy consumption of water treatment processes is only 2%; whereas, energy consumption of pumping is 98% in a conventional water treatment plant. In the studied PWTS with conventional process, the overall energy consumption of water treatment process is around 8% of total energy consumption of the whole water supply system is taken into account. Filter backwashing equipment uses the highest energy in the PWTS followed by poly preparation units and chlorine dosage units.

Materials used for constructing treatment tanks, including filtration media, have contributed between 3.88% and 35.13% in midpoint categories. The material, that had the most impacts in all categories, were ST37 steel used for the production of the tanks. Other materials such as glass fiber reinforced plastic (GFRP), ribbed iron, concrete and stainless steel (SS) were the other major contributors for construction material. Figure 4.2 shows the inputs and their overall impacts based on the FU.

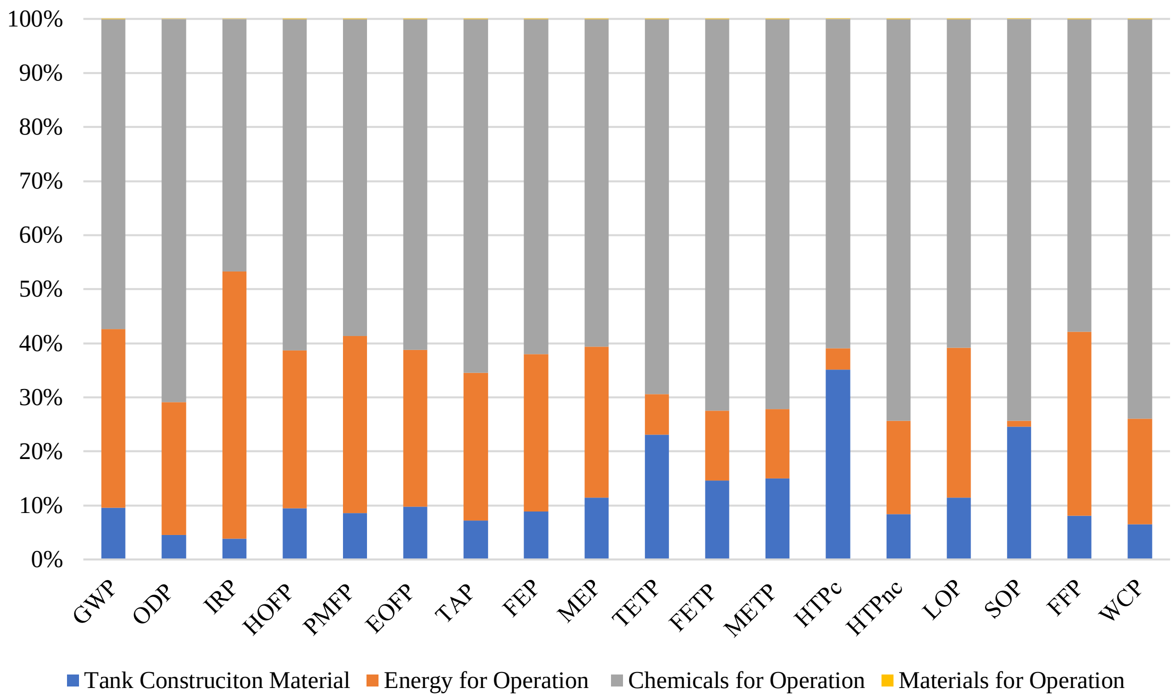

Figure 4.2 : Impacts of the package water treatment plant for midpoint impact categories. (GWP: Global warming potential; ODP: Stratospheric ozone depletion; IRP: Ionizing radiation; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TETP: Terrestrial ecotoxicity; FETP: Freshwater ecotoxicity; METP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; LOP: Land use; SOP: Mineral resource scarcity; FFP: Fossil resource scarcity; WCP: Water consumption).

Compared to water treatment plants with conventional process, water treatment plants with membrane processes consumes more energy (Grzegorzek et al., 2023). When the designed UFWTS was analyzed, electricity used for the treatment of water was the main contributor in all impact categories except SOP where chemicals used for the operation of the UFWTS was the main contributor. Materials used for operating the UFWTS had less than 2% effect in all categories except TETP and SOP which had overall impact 4 % and 12.5%, respectively. Materials considered as the part of the operation are polyvinylidenefluoride (PVDF), polyvinyl chloride (PVC) and polyurethane (PU) , which are used to produce UF modules, had less than 1% overall impact in all categories, only in SOP the impact was 3.19%. Prézélus et al. (2021)

carried out an LCA study for water treatment with UF and analyzed each process within the ultrafiltration. The results indicated that the chemicals used in the processes are the main contributors after energy consumption. The results were vice versa with the findings of this paper. The main reason for this result is due to the electricity consumption per m^3 that is used for UF systems which was higher in this paper. Within the chemicals used for operation, polyaluminium chloride was responsible for the greatest impacts followed by sodium hydroxide, gaseous chlorine and hydrochloric acid. The materials used to build UF membranes are responsible for the major impacts derived from constructing materials. PVDF, PVC and PU were the top 3 contributors for constructing material. Figure 4.3 presents the environmental impacts associated with the production of 1 cubic meter of water using the UF water treatment technique.

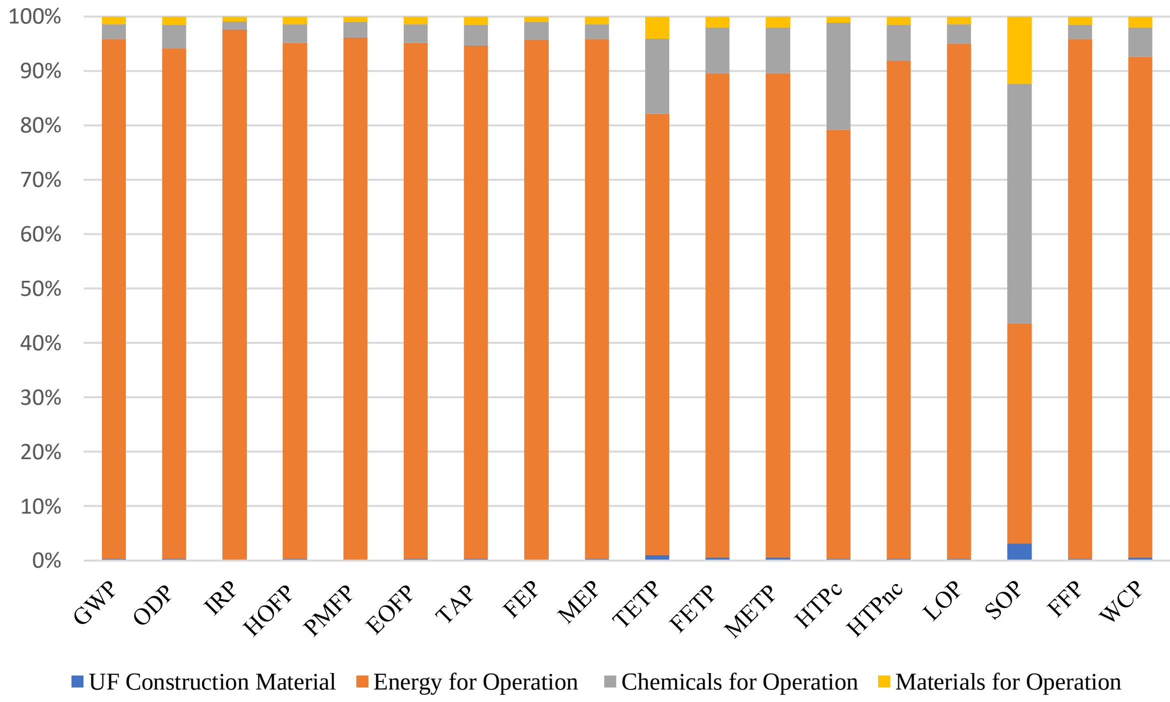

Figure 4.3 : Impacts of the UF water treatment plant for midpoint impact categories. (GWP: Global warming potential; ODP: Stratospheric ozone depletion; IRP: Ionizing radiation; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TETP: Terrestrial ecotoxicity; FETP: Freshwater ecotoxicity; METP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; LOP: Land use; SOP: Mineral resource scarcity; FFP: Fossil resource scarcity; WCP: Water consumption).

The production and operation of each water treatment system is consisted of different components. When both water treatment systems were compared using ReCiPe midpoint methodology it was observed that UFWTS system was responsible higher environmental impacts over PWTS. The main reason for this is due to electricity and amount of chemicals used in operation and production. In all 4 categories that the comparison is divided to, construction material, energy needed for operating the water treatment plant, chemicals needed for the water treatment processes and materials needed for the operating the plant, UFWTS had much more impact than PWTS in most of the impact categories. Materials that are required to construct and operate the UF membranes was much higher than the production and operation of package water treatment tanks. Energy consumption and the chemicals used for treatment process was again much higher than that in UFTWS. Since the materials needed for the operation of UFWTS consisted of UF membranes, due to the amount and producing new membranes, it is much higher compared to PWTS. Figure 4.4 presents a comparison of the PWTS and UFWTS across 18 midpoint impact categories, revealing significant differences in the environmental performances of two water treatment systems.

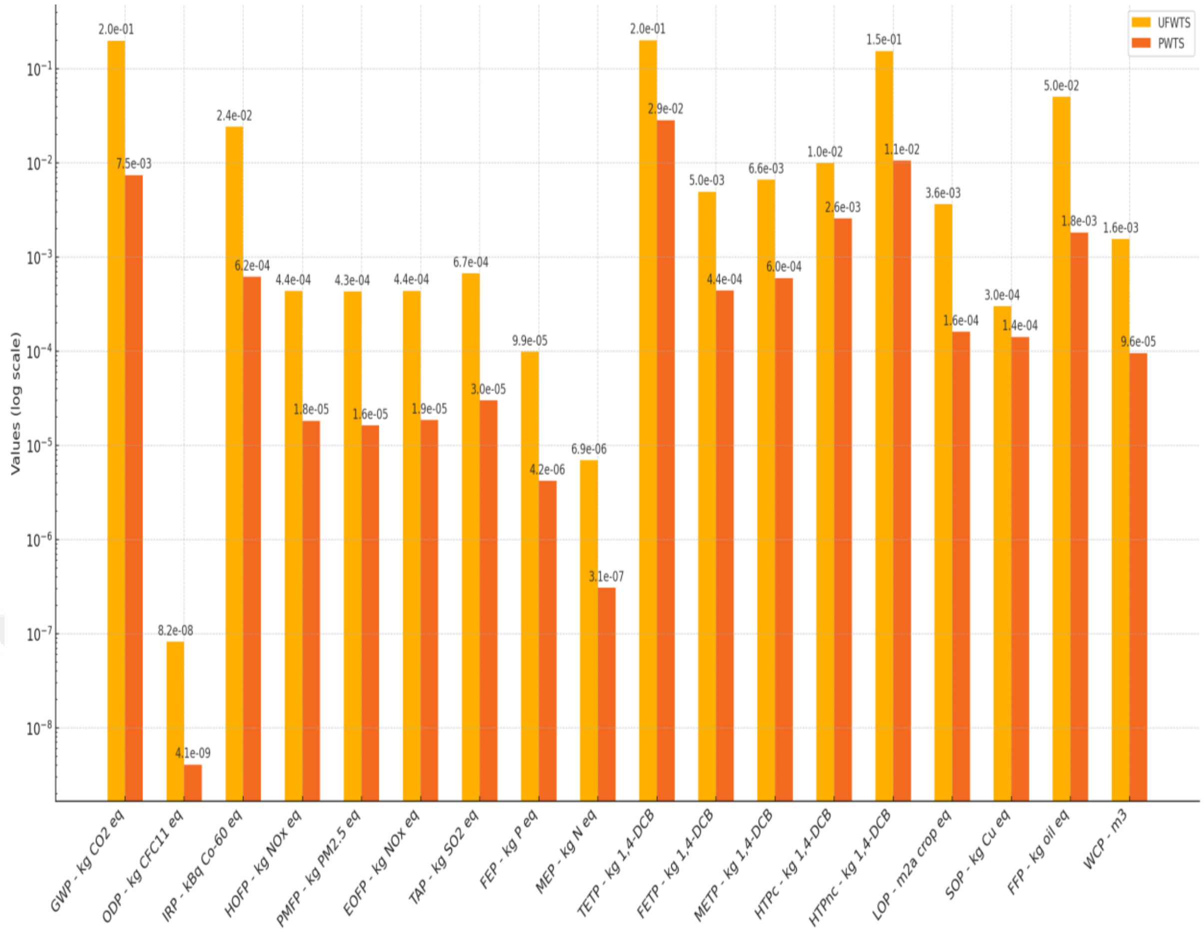

Figure 4.4 : Comparison of the analyzed water treatment methods. (GWP: Global warming potential; ODP: Stratospheric ozone depletion; IRP: Ionizing radiation; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TETP: Terrestrial ecotoxicity; FETP: Freshwater ecotoxicity; METP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; LOP: Land use; SOP: Mineral resource scarcity; FFP: Fossil resource scarcity; WCP: Water consumption).

According to findings of this study, natural resources and the methods used to turn these natural resources into a product are substantial contributors to the impact categories. Production phase of a product starts from the extraction of natural resources and all its disposal. The activities that are related to the production of the equipment used in PWTS and UFWTS consisted of activities such as mining operations, energy production (electricity/heat) needed for processing, transportation of raw material/finished product and waste/wastewater treatment.

Table 4.3 : Overview of the impact categories including the sources, results and interconnections between categories.

Impact category	**Source**	**Results**	**Other impact categories affected by this impact category**
Global warming	Combustion of fossil fuels, deforestation, industrial processes, chemical manufacturing	Release of greenhouse gases (CO_2, CH_4, N_2O)	Fossil resource scarcity and fine particulate matter formation
Stratospheric ozone depletion	Chlorofluorocarbons, carbon tetrachloride, nitrous oxide	Release of ozone-depleting substances (cfcs, halons)	Human carcinogenic toxicity and human non-carcinogenic toxicity
Ionizing radiation	Nuclear energy usage or other sources that emit ionizing radiation during electricity generation	Release of particles and electromagnetic waves	Human carcinogenic toxicity and human non-carcinogenic toxicity
Ozone formation, Human health	Vehicle emissions, industrial emissions, solvent use, power plants	Release of NOX and VOCS	Global warming and fine particulate matter formation
Fine particulate matter formation	Combustion sources, industrial processes, construction activities	Release of pm10 and pm2.5	Human health and ozone formation-human health
Ozone formation, Terrestrial ecosystems	Vehicle emissions, industrial emissions, urban sprawl	Release of NOX and VOCS	Global warming and fine particulate matter formation
Terrestrial acidification	Fossil fuel combustion, industrial processes, vehicle emissions	Release of acidifying substances like SO_2, NO_x, NH_3	Eutrophication and terrestrial ecotoxicity
Freshwater eutrophication	Sewage discharge industrial effluents	Nutrient runoffs and emissions affecting water bodies	Water consumption, terrestrial and freshwater ecotoxicity

Table 4.3 (continued): Overview of the impact categories including the sources, results and interconnections between categories.

Marine eutrophication	River discharge, wastewater discharge	Nutrient runoffs and emissions affecting marine water bodies	Marine ecotoxicity and water consumption
Terrestrial ecotoxicity	Industrial emissions, waste disposal, mining activities, accidental spills	Hazardous waste emissions	Human toxicity and land use
Freshwater ecotoxicity	Industrial effluents, mining discharges, sewage disposal	Chemical runoff and emissions	Human toxicity and marine ecotoxicity
Marine ecotoxicity	Industrial discharges, shipping activities, offshore drilling, runoff, waste disposal	Chemical runoff and emissions	Freshwater ecotoxicity and human toxicity
Human carcinogenic toxicity	Industrial emissions, occupational exposure, air pollution	Emissions and hazardous materials used in the process of energy production	Ionizing radiation and fine particulate matter formation
Human non-carcinogenic toxicity	Air pollution, water contamination, occupational exposure	Presence of non-carcinogenic toxic substances	Freshwater ecotoxicity and ozone formation-human health
Land use	Urban development, mining, deforestation, infrastructure development	Natural land transformation, biodiversity loss	Mineral resource scarcity and terrestrial ecotoxicity
Mineral resource scarcity	Mining activities, industrial demand, wasteful practices, technological advancements	The depletion of mineral resources and its impact on availability for future use.	Human toxicity and land use

Table 4.3 (continued): Overview of the impact categories including the sources, results and interconnections between categories.

Fossil resource scarcity	High fossil fuel consumption during energy production and chemical production. energy consumption, transportation, industrial processes	The depletion of fossil fuels and its impact on availability for future use.	Global warming and fine particulate matter formation
Water consumption	Industrial processes, energy production	The use of water resources and its impact on availability for future use.	Eutrophication and human toxicity

Relatively high environmental impacts from chemicals used in the water treatment are mainly caused by the phases in production process. Main activities for production, which are also major contributors, coal mining operations, heat generation with coal, electricity consumption, smelting operations, wastes from mining operations (landfill), chlor-alkali electrolysis, impact from other chemicals used in the production, gas/oil production and transportation activities. Some post activities such as wastewater treatment from production of ss, st37, PVDF and pig iron casting, use of tap water for concrete production and rehabilitation of mining sites added to impact calculations with a negative value in the modelling software resulting in a decrease in the calculated impact category.Table 4.3 shows the sources of each impact category which are surveyed in this thesis. sources and results are based on the production and operation of PWTS and UFWTS. The last column of the table shows the impact categories that are related and effecting each other.

Major activities that are responsible for the impacts of electricity production is caused by mining activities of coal, extraction of natural gas/oil, electricity production from coal/gas/hydro/ wastes and transportation. The research papers that were investigated during the preparation of this paper indicates that using green energy will reduce the impacts caused by the energy consumption and cause less contribution for environmental impacts. On the other hand, the study by Sonter et al. (2020) states that mining operations to gathered the resources needed to produce renewable energy equipment will put a pressure on biodiversity which will cause increase in of environmental impacts due to mining operations.

4.4. Conclusions

The findings of this study indicate the critical roles of materials, energy and chemicals in the water treatment process. The PWTS relies heavily on components from the steel industry, which demands substantial energy, primarily derived from coal. This reliance contributes significantly to environmental impacts from mining to usage in steel production. Substituting coal with alternative energy sources can markedly reduce these environmental impacts.

In the operational phase of water treatment systems, chemicals and electricity are predominant factors affecting the environment. The production of these chemicals involves extensive energy consumption from mining, transportation, water production, waste and related processes, driven by both fossil fuels and renewable sources. Variations in electricity production methods across different countries further influence environmental impacts, with differing electricity mixes leading to variations in these effects.

The LCA of the two water treatment systems reveals that the environmental burdens associated with the PWTS are lower compared to the UFWTS. The fabrication of the PWTS's components, particularly the treatment tanks, benefits from the use of recyclable materials, which reduce the overall environmental footprint at the end of their life cycle. In contrast, UF membranes used in UFWTS are not recyclable and are disposed of by burial in landfills, which contributes to more environmental impacts.

Additionally, the study highlights that the energy intensity of the water treatment processes plays a crucial role in determining their sustainability. The PWTS's lower energy demand during operation, coupled with its reliance on materials that can be more easily recycled, positions it as a more environmentally favorable option. Conversely, the UFWTS's higher energy requirements and the disposal needs of its membranes increase its environmental impacts.

It is also evident from the LCA that improvements in energy efficiency and the adoption of renewable energy sources could further reduce the environmental impacts of both water treatment plants. However, the integration of renewable energy must be carefully managed to avoid shifting environmental burdens. For instance, the production and disposal of renewable energy technologies themselves must be considered to ensure a net positive environmental impact.

The study suggests that future research should focus on advancing water treatment technologies to enhance their environmental performance. This includes developing more efficient equipment, exploring innovative disinfection methods, and optimizing treatment processes to minimize energy consumption and chemical use. Additionally, a comprehensive approach to resource management, including the use of life cycle thinking, is essential to achieve sustainable water treatment solutions.

In conclusion, the PWTS emerges as a more sustainable option compared to the UFWTS in terms of manufacturing, operation, and energy consumption. The recyclability of materials used in the PWTS and its lower operational energy demand contribute to its reduced environmental impacts. Given the considerations outlined in this study, the PWTS is recommended as a more sustainable choice for municipalities seeking to implement environmentally responsible water treatment solutions.

5. CONCLUSIONS AND FUTURE PERSPECTIVE

The landscape of life cycle assessment (LCA) in the field of drinking water treatment and disinfection is continually changing, offering a promising opportunity for enhancing sustainability within this essential sector. The systematic examination of numerous LCA studies underscores the significant environmental impacts associated with water treatment, particularly during the operational phase. Addressing these impacts necessitates a multifaceted approach that includes adopting renewable energy sources, enhancing technological capabilities, and utilizing eco-friendly materials.

Future LCA studies must prioritize the integration of renewable energy into water treatment systems. This shift will not only reduce the carbon footprint but also enhance the overall sustainability of the processes involved. Advancements in UV and ozone disinfection technologies, despite their current higher energy demands compared to traditional chlorination, indicate a potential for reduced environmental impacts through continuous technological innovations. These innovations should be rigorously evaluated through updated LCA studies to provide a comprehensive understanding of their environmental benefits and drawbacks.

The use of materials such as stainless steel and high-density polyethylene has already demonstrated significant improvements in system efficiency and energy consumption. Future research should explore the potential of these and other advanced materials in further reducing the environmental footprint of water treatment systems.

A critical aspect of future LCA studies is the need for detailed data on the production and operation of disinfection equipment. Manufacturers must be encouraged to share comprehensive material data or conduct their own LCA studies to facilitate a thorough assessment of environmental impacts. Transparency in data and collaboration between industry and academia are vital for advancing sustainable practices in water treatment and disinfection.

Regulatory frameworks mandating periodic updates to water safety protocols will continue to play a pivotal role in driving these advancements. These frameworks should emphasize the importance of LCA in environmental impact assessments, ensuring that technological progress is aligned with sustainability goals. Future LCA studies must include comprehensive data on equipment production, operation, and maintenance, focusing on enhancing energy efficiency and reducing chemical usage.

The transition towards greener technologies, such as UV LP systems and Package Water Treatment Systems (PWTS), offers a viable path to sustainable water treatment. PWTS, with its use of recyclable materials and lower operational energy demand, presents a lower environmental impact compared to Ultrafiltration Water Treatment Systems (UFWTS). The challenges associated with UFWTS, including the disposal of UF membranes and higher energy requirements, highlight the need for continued research and optimization of water treatment technologies.

In conclusion, achieving sustainability in water treatment and disinfection requires a concerted effort to enhance energy efficiency, embrace renewable energy sources, and utilize eco-friendly materials. Continuous collaboration between industry and academia, supported by regulatory backing and innovative research, is essential for driving advancements in this vital sector. Through these efforts, the water treatment industry can move towards more sustainable practices, ensuring the provision of safe and environmentally responsible water treatment solutions.

REFERENCES

Ahmadi, A., & Tiruta-Barna, L. (2015). A Process Modelling-Life Cycle Assessment-MultiObjective Optimization tool for the eco-design of conventional treatment processes of potable water. *Journal of Cleaner Production*, *100*, 116–125

Amini, A., Kim, Y., Zhang, J., Boyer, T., & Zhang, Q. (2015). Environmental and economic sustainability of ion exchange drinking water treatment for organics removal. *Journal of Cleaner Production*, *104*, 413–421

Amores, M. J., Meneses, M., Pasqualino, J., Antón, A., & Castells, F. (2013). Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. *Journal of Cleaner Production*, *43*, 84–92

AquiSense (2023). *UV-C LED case Studies - AquiSense New Zealand*. Retrieved June 11, 2024, from https://aquisense-newzealand.co.nz/remote-rural/

Baddoo, N., Biddle, T. (2000). Steel Package Water and Waste Water Treatment Units. The Steel Construction Institute. Retrieved October 24, 2023 from https://www.nickelinstitute.org/media/1819/steelpackagewaterscip254.pdf

Barjoveanu, G., Comandaru, I. M., Rodriguez-Garcia, G., Hospido, A., & Teodosiu, C. (2013). Evaluation of water services system through LCA. A case study for Iasi City, Romania. T*he International Journal of Life Cycle Assessment*, *19*(2), 449–462

Barjoveanu, G., Teodosiu, C., Gilc, A, F., Roman, I., Fiore, S. (2019). Environmental performance evaluation of a drinking water treatment plant: A life cycle assessment perspective. *Environmental Engineering & Management Journal,* 18 (2), 513–522.

Barrios, R., Siebel, M., Van Der Helm, A., Bosklopper, K., & Gijzen, H. (2008). Environmental and financial life cycle impact assessment of drinking water production at Waternet. *Journal of Cleaner Production*, *16*(4), 471–476

Bolton J. R., & Cotton C. A. (2008). *The Ultraviolet Disinfection Handbook.* American Water Works Assn, Denver, USA

Bonton, A., Bouchard, C., Barbeau, B., & Jedrzejak, S. (2012). Comparative life cycle assessment of water treatment plants. *Desalination*, *284*, 42–54

Bukhary, S., Batista, J., & Ahmad, S. (2019). An analysis of energy consumption and the use of renewables for a small drinking water treatment plant. *Water*, *12*(1), 28

Bull, R. J. (1999). Water. In: H. Marquardt, S. G. Schäfer, R. McClellan, F. Welsch. (ed) *Toxicology* (pp. 1041-1050). Massachusetts, USA: Academic Press

Busse, M. M., Hawes, J. K., & Blatchley, E. R. (2022). Comparative Life cycle Assessment of water disinfection Processes applicable in Low-Income Settings. *Environmental Science & Technology*, *56*(22), 16336–16346

Capitanescu, F., Rege, S., Marvuglia, A., Benetto, E., Ahmadi, A., Gutiérrez, T. N., & Tiruta-Barna, L. (2016). Cost versus life cycle assessment-based environmental impact optimization of drinking water production plants. *Journal of Environmental Management*, *177*, 278–287

Cashman S., Gaglione A., Mosley J., Weiss L., Hawkins T. R., Ashbolt N. J., Cashdollar J., Xue X., Ma C., Arden S. (2014). EPA National Homeland Security Research Center Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Drinking Water Treatment (EPA 600/R-14/376). United States Environmental Protection Agency.

CDC (2019). *History of Drinking Water Regulations*. Retrieved September 29, 2023, from https://www.cdc.gov/healthywater/surveillance/drinking-water-reg-history.html

CDC (2022). *Drinking Water Standards and Regulations.* Retrieved September 11, 2023 from https://www.cdc.gov/healthywater/drinking/public/regulations.html

Chaplin, B. P. (2019). The prospect of electrochemical technologies advancing worldwide water treatment. *Accounts of Chemical Research*, *52*(3), 596–604

Chen, J.P., Yang, L., Wang, L.K., Zhang, B. (2006). Ultraviolet Radiation for Disinfection. In: L.K. Wang, Y.T. Hung, N. K. Shammas (Eds.), *Advanced Physicochemical Treatment Processes. Handbook of Environmental Engineering* (vol 4., pp.317-366). Humana Press.

City of San Diego (2022). *Fact Sheet*. Retrieved June 11, 2024, from https://www.sandiego.gov/sites/default/files/water_treatment_plants_fact_sheet.pdf

Collado-Ruiz, D., & Ostad-Ahmad-Ghorabi, H. (2010). Comparing LCA results out of competing products: developing reference ranges from a product family approach. *Journal of Cleaner Production*, *18*(4), 355–364

Collier, S. A., Deng, L., Adam, E. A., Benedict, K. M., Beshearse, E. M., Blackstock, A. J., Bruce, B. B., Derado, G., Edens, C., Fullerton, K. E., Gargano, J. W., Geissler, A. L., Hall, A. J., Havelaar, A. H., Hill, V. R., Hoekstra, R. M., Reddy, S. C., Scallan, E., Stokes, E. K., . . . Beach, M. J. (2021). Estimate of burden and direct healthcare cost of infectious waterborne disease in the United States. *Emerging Infectious Diseases*, *27*(1), 140–149

Corominas, L., Byrne, D. M., Guest, J. S., Hospido, A., Roux, P., Shaw, A., & Short, M. D. (2020). The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review. *Water Research*, *184*, 116058

DEC (2005). *Environment and Climate Change*. Retrieved March 19, 2023, from https://www.gov.nl.ca/ecc/waterres/waste/groundwater/report

De Sousa Filho, J. W., Lenza, G. A., Tonhela, M. A., De Araújo, K. S., Fernandes, D. M., & Malpass, G. R. P. (2021b). Full-scale application of an electrochemical disinfection solution in a municipal drinking water treatment plant. *WEJ/Water and Environment Journal*, *36*(1), 86–95

Del Borghi, A., Strazza, C., Gallo, M., Messineo, S., & Naso, M. (2013). Water supply and sustainability: life cycle assessment of water collection, treatment and distribution service. *The International Journal of Life Cycle Assessment*, *18*(5), 1158–1168

Drioli, E., Giorno, L. (2010). *Comprehensive Membrane Science and Engineering.* United Kingdom: Elsevier Science

Ecoinvent (2021). *Impact Assessment*. Retrieved May 19, 2023 from https://ecoinvent.org/the-ecoinvent-database/impact-assessment

Ellis, A. C., Boyer, T. H., Fang, Y., Liu, C. J., & Strathmann, T. J. (2023). Life cycle assessment and life cycle cost analysis of anion exchange and granular activated carbon systems for remediation of groundwater contaminated by per- and polyfluoroalkyl substances (PFASs). *Water Research*, *243*, 120324

EU Directive (2020). Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption. Retrieved December 3, 2023, from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020L2184

European Commission - Joint Research Centre - Institute for Environment and Sustainability (2010). *International Reference Life Cycle Data System ILCD Handbook - Review Schemes for Life Cycle Assessment*. Luxembourg: Publications Office of The European Union

European Platform on LCA, EPLCA (2021). Life Cycle Assessment. Retrieved October 24, 2022, from https://eplca.jrc.ec.europa.eu/lifecycleassessment.html

Fetyan, N. a. H., & Attia, T. M. S. (2020). Water purification using ultrasound waves: application and challenges. *Arab Journal of Basic and Applied Sciences*, *27*(1), 194–207

Finnveden, G., Potting, J. (2014). Life cycle assessment. In P. Wexler (Eds.*)*, *Encyclopedia of Toxicology*, (3rd ed., pp. 74–77). New York: Academic Press

Fish, K. E., Reeves-McLaren, N., Husband, S., & Boxall, J. (2020). Uncharted waters: the unintended impacts of residual chlorine on water quality and biofilms. *Npj Biofilms and Microbiomes*, *6*(1)

Fitzhenry, K., Clifford, E., Rowan, N., & Del Rio, A. V. (2021). Bacterial inactivation, photoreactivation and dark repair post flow-through pulsed UV disinfection. *Journal of Water Process Engineering*, *41*, 102070

Foglia, A., Andreola, C., Cipolletta, G., Radini, S., Akyol, Ç., Eusebi, A. L., Stanchev, P., Katsou, E., & Fatone, F. (2021). Comparative life cycle environmental and economic assessment of anaerobic membrane bioreactor and disinfection for reclaimed water reuse in agricultural irrigation: A case study in Italy. *Journal of Cleaner Production*, *293*, 126201

Friedrich, E. (2002). Life-cycle assessment as an environmental management tool in the production of potable water. *Water Science & Technology*, 46 (9), 29–36.

Garfí, M., Cadena, E., Sanchez-Ramos, D., & Ferrer, I. (2016). Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. *Journal of Cleaner Production*, *137,* 997–1003

Gelete, G., Gokcekus, H., Ozsahin, D. U., Uzun, B., & Gichamo, T. (2020). Evaluating disinfection techniques of water treatment. *DESALINATION AND WATER TREATMENT*, *177*, 408–415

Godskesen, B., Hauschild, M., Rygaard, M., Zambrano, K., & Albrechtsen, H. (2013). Life-cycle and freshwater withdrawal impact assessment of water supply technologies. *Water Research*, *47*(7), 2363–2374

Goga, T., Friedrich, E., & Buckley, C. (2019). Environmental life cycle assessment for potable water production – a case study of seawater desalination and mine-water reclamation in South Africa. *Water S.A./Water SA*, *45*(4 October)

Griffiths, J. K. (2017). Waterborne diseases. In: Quah SR (ed) *International Encyclopedia of Public Health (*2nd edn. pp 388–401). Oxford, UK: Academic Press

Grzegorzek, M., Wartalska, K., & Kaźmierczak, B. (2023). Review of water treatment methods with a focus on energy consumption. *International Communications in Heat and Mass Transfer*, *143*, 106674

Hambsch, B., Böckle, K., & Van Lieverloo, J. H. M. (2007). Incidence of faecal contaminations in chlorinated and non-chlorinated distribution systems of neighbouring European countries. *Journal of Water and Health*, *5*(S1), 119–130

Hauschild, M. Z. (2018). Introduction to LCA Methodology. In M. Hauschild, R. Rosenbaum, S. Olsen (Eds.) *Life Cycle Assessment* (1st ed., pp. 59-66). Heidelber: Springer

Hofs, B., Van Den Broek, W., Van Eckeveld, A., & Van Der Wal, A. (2022b). Carbon footprint of drinking water over treatment plant life span (2025–2075) is probably dominated by construction phase. *Cleaner Environmental Systems*, *5*, 100079

Holloway, R. W., Miller-Robbie, L., Patel, M., Stokes, J. R., Munakata-Marr, J., Dadakis, J., & Cath, T. Y. (2016b). Life-cycle assessment of two potable water reuse technologies: MF/RO/UV–AOP treatment and hybrid osmotic membrane bioreactors. *Journal of Membrane Science*, *507*, 165–178

Huijbregts, M. a. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & Van Zelm, R. (2016b). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. T*he International Journal of Life Cycle Assessment*, *22*(2), 138–147

Humphreys, E, H., Tiemann, M. (2021). *Safe Drinking Water Act (SDWA): A Summary of the Act and Its Major Requirements*. Retrieved December 3, 2022, from https://sgp.fas.org/crs/misc/RL31243.pdf

Hunt, R. G., Franklin, W. E., & Hunt, R. G. (1996). LCA — How it came about. T*he International Journal of Life Cycle Assessment*, *1*(1), 4–7

Hunt, R. G., Sellers, J. D., & Franklin, W. E. (1992). Resource and environmental profile analysis: A life cycle environmental assessment for products and procedures. *Environmental Impact Assessment Review*, *12*(3), 245–269

Igos, E., Dalle, A., Tiruta-Barna, L., Benetto, E., Baudin, I., & Mery, Y. (2014). Life Cycle Assessment of water treatment: what is the contribution of infrastructure and operation at unit process level? *Journal of Cleaner Production*, *65*, 424–431

ISO (2006). *Environmental management — Life cycle assessment — Principles and framework (ISO/DIS Standard No. 14040)*. Retrieved from https://www.iso.org/standard/37456.html

ISO (2006*). Environmental management — Life cycle assessment — Requirements and guidelines (ISO/DIS Standard No. 14044)*. Retrieved from https://www.iso.org/standard/38498.html

IWA (2016). *Desalination past, present and future*. Retrieved September 22, 2022, from https://iwa-network.org/desalination-past-present-future/

IWA (2022). Global Trends Report, Third Edition. In *Global Trends and Challenges in Water Science, Research and Management*. Retrieved April 4, 2023, from https://iwa-network.org/wp-content/uploads/2022/09/IWA_2022_Global_Trend_SG_WEB.pdf

Jachimowski, A., & Nitkiewicz, T. (2023). Comparative analysis of selected water disinfection technologies with the use of life cycle assessment. *Archives of Environmental Protection*

Jiménez, S., Micó, M., Arnaldos, M., Medina, F., & Contreras, S. (2018). State of the art of produced water treatment. *Chemosphere*, *192*, 186–208

Joint Research Centre, Institute for Environment and Sustainability, ILCD (2010). *International Reference Life Cycle Data System (ILCD) Handbook: general guide for life cycle assessment: detailed guidance*. Luxembourg: Publications Office of The European Union

Jones, C. H., Shilling, E. G., Linden, K. G., & Cook, S. M. (2018). Life cycle environmental impacts of disinfection technologies used in small drinking water systems. *Environmental Science & Technology*, *52*(5), 2998–3007

Jones, E., Qadir, M., Van Vliet, M. T., Smakhtin, V., & Kang, S. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment*, *657*, 1343–1356

Kaiser, H.-P. & ex Water Supply Zurich (2018). Analytical Chemistry Strategic exercise: Drinking Water. In *Analytical Strategies Exercise of WS 2018/19* (pp. 1–3). Retrieved June 11, 2024, from https://ethz.ch/content/dam/ethz/special-interest/chab/organic-chemistry/zenobi-group-dam/documents/Education/LecturesExercises/Analytical%20Strategy%202018/Kaiser%20Description.pdf

Kulkarni, K., Raja, W., Kumar, P. (2022). Introduction to modular drinking water treatment system. In S. K. Kaur, P. Kumar, A. Cuprys (Eds.) *Modular Treatment Approach for Drinking Water and Wastewater* (1st ed., pp. 225–237). Heidelberg: Elsevier

Kumar, J. K., Pandit, A. B. (2013). *Drinking Water Disinfection Techniques*. Florida: CRC Press.

Kummu, M., De Moel, H., Ward, P. J., & Varis, O. (2011). How close do we live to water? A global analysis of population distance to freshwater bodies. *PloS One*, *6*(6), e20578

Lakho, F. H., Qureshi, A., Igodt, W., Le, H. Q., Depuydt, V., Rousseau, D. P., & Van Hulle, S. W. (2022). Life cycle assessment of two decentralized water treatment systems combining a constructed wetland and a membrane based drinking water production system. *Resources, Conservation and Recycling*, *178*, 106104

Leão, A. S., Sipert, S. A., Medeiros, D. L., & Cohim, E. B. (2022). Water footprint of drinking water: The consumptive and degradative use. *Journal of Cleaner Production*, *355*, 131731

Lee, K., Yu, S., Choi, Y., & Lee, M. (2012). Environmental assessment of sewage effluent disinfection system: electron beam, ultraviolet, and ozone using life cycle assessment. *The International Journal of Life Cycle Assessment*, *17*(5), 565–579

Lesimple, A., Ahmed, F. E., & Hilal, N. (2020). Remineralization of desalinated water: Methods and environmental impact. *Desalination*, *496*, 114692

Li, G., Wang, W., Huo, Z., Lu, Y., & Hu, H. (2017). Comparison of UV-LED and low pressure UV for water disinfection: Photoreactivation and dark repair of Escherichia coli. *Water Research*, *126*, 134–143

Linden, K. G., Hull, N., & Speight, V. (2019). Thinking outside the treatment plant: UV for water distribution system disinfection. *Accounts of Chemical Research*, *52*(5), 1226–1233

Lippi, D., & Gotuzzo, E. (2014). The greatest steps towards the discovery of Vibrio cholerae. *Clinical Microbiology and Infection*, *20*(3), 191–195

LIT UV (2020). *Use cases - LIT-UV*. LIT-UV. Retrieved June 11, 2024, from https://lit-uv.de/use-cases/

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., Costanza, M., & Chen, Y. S. (2009). Life cycle assessment of three water supply systems: importation, reclamation and desalination. *Water Supply*, *9*(4), 439–448

Manda, B. K., Worrell, E., & Patel, M. K. (2014). Innovative membrane filtration system for micropollutant removal from drinking water – prospective environmental LCA and its integration in business decisions. *Journal of Cleaner Production*, *72*, 153–166

Maryam, B., & Büyükgüngör, H. (2019). Wastewater reclamation and reuse trends in Turkey: Opportunities and challenges. *Journal of Water Process Engineering*, *30*, 100501

Mazhar, M. A., Khan, N. A., Ahmed, S., Khan, A. H., Hussain, A., Rahisuddin, N., Changani, F., Yousefi, M., Ahmadi, S., & Vambol, V. (2020). Chlorination disinfection by-products in municipal drinking water – A review. *Journal of Cleaner Production*, *273*, 123159

MDH, (2023). *Drinking Water Protection Fact Sheets*. Retrieved March 17, 2023, from https://www.health.state.mn.us/communities/environment/water/factsheet.

Meron, N., Blass, V., & Thoma, G. (2020). A national-level LCA of a water supply system in a Mediterranean semi-arid climate—Israel as a case study. T*he International Journal of Life Cycle Assessment*, *25*(6), 1133–1144

Mery, Y., Barna, L., Benetto, E., & Baudin, I. (2013). An integrated "process modelling-life cycle assessment" tool for the assessment and design of water treatment processes. *The International Journal of Life Cycle Assessment*, *18*(5), 1062–1070

Miller, G., Rice, R., Robson, C., Scullin, R. & Kuhn, W. (1978). *An Assessment of Ozone and Chlorine Dioxide Technologies for Treatment of Municipal Water Supplies* (EPA/600/8-78/018). Washington, D.C.: U.S. Environmental Protection Agency

Mo, W., Cornejo, P. K., Malley, J. P., Kane, T. E., & Collins, M. R. (2018). Life cycle environmental and economic implications of small drinking water system upgrades to reduce disinfection byproducts. *Water Research*, *143*, 155–164

Mohamed-Zine, M., Hamouche, A., & Krim, L. (2013a). The study of potable water treatment process in Algeria (boudouaou station) -by the application of life cycle assessment (LCA). *Journal of Environmental Health Science & Engineering*, *11*(1)

Mohapatra, P. K., Siebel, M. A., Gijzen, H. J., Van Der Hoek, J. P., & Groot, C. A. (2002). Improving eco-efficiency of Amsterdam water supply: A LCA approach. *Aqua*, *51*(4), 217–227

Monaghan, S., Wall, B., Page, D., Fitzgerald, J., McGuigan, N., Kerr, H. (2011). *Water Treatment Manual: Disinfection*. Wexfort: EPA Environmental Protection Agency. Retrieved February 15, 2023, from https://www.epa.ie/publications/compliance--enforcement/drinking-water/advice--guidance/Disinfection2_web.pdf

Naunovic, Z., Lim, S., & Blatchley, E. R. (2008). Investigation of microbial inactivation efficiency of a UV disinfection system employing an excimer lamp. *Water Research*, *42*(19), 4838–4846

Nessi, S., Rigamonti, L., & Grosso, M. (2012). LCA of waste prevention activities: A case study for drinking water in Italy. *Journal of Environmental Management*, *108*, 73–83

New York City Department of Environmental Protection (2019). *Croton Water Treatment Plant Final Supplemental Environmental Impact Statement*. Retrieved June 11, 2024, from https://www.nyc.gov/assets/dep/downloads/pdf/environmental-reviews/croton-water-filtration-plant-project/execsumm.pdf

NREL (2020). *Best research-cell efficiency chart*. Retrieved August 3, 2022, from https://www.nrel.gov/pv/cell-efficiency.html

Pendergast, M. M., & Hoek, E. M. (2011). A review of water treatment membrane nanotechnologies. *Energy & Environmental Science*, *4*(6), 1946

Pirnie, M., Linden, K. G., Malley, J. P. J. (2006) *Ultraviolet disinfection guidance manual for the final long term 2 enhanced surface water treatment rule*. Environ Prot 2(11):1-436

Prézélus, F., Tiruta-Barna, L., Remigy, J., & Guigui, C. (2021). Process-based LCA of ultrafiltration for drinking water production. *Water Research*, *199*, 117156

Raluy, R. G., Serra, L., & Uche, J. (2004). Life Cycle Assessment of Water Production Technologies - Part 1: Life Cycle Assessment of Different Commercial Desalination Technologies (MSF, MED, RO) (9 pp). T*he International Journal of Life Cycle Assessment*, *10*(4), 285–293

Raluy, R. G., Serra, L., Uche, J., & Valero, A. (2004). Life Cycle Assessment of Water Production Technologies - Part 2: Reverse Osmosis Desalination versus the Ebro River Water Transfer (9 pp). T*he International Journal of Life Cycle Assessment*, *10*(5), 346–354

Renzoni, R., & Germain, A. (2006). Life Cycle Assessment of Water: From the pumping station to the wastewater treatment plant (9 pp). T*he International Journal of Life Cycle Assessment*, *12*(2), 118–126

Romanovski, V., Claesson, P. M., & Hedberg, Y. S. (2020). Comparison of different surface disinfection treatments of drinking water facilities from a corrosion and environmental perspective. *Environmental Science and Pollution Research International*, *27*(11), 12704–12716

Roth, C., Wünsch, R., Dinkel, F., Hugi, C., Wülser, R., Antes, R., & Thomann, M. (2022). Micropollutant abatement with UV/H2O2 oxidation or low-pressure reverse osmosis? A comparative life cycle assessment for drinking water production. *Journal of Cleaner Production*, *336*, 130227

Saad, A., Elginoz, N., Babuna, F. G., & Iskender, G. (2018). Life cycle assessment of a large water treatment plant in Turkey. *Environmental Science and Pollution Research International*, *26*(15), 14823–14834

Sargen, M., Utter, D., (2019). *Biological Roles of Water: Why is water necessary for life? Science in the News*. Science in the News. Retrieved March 17, 2023, from https://sitn.hms.harvard.edu/uncategorized/2019/biological-roles-of-water-why-is-water-necessary-for-life/

Schalk, S., Adam, V., Arnold, E., Brieden, K., Voronov, A. (2006). *UV lamps for disinfection and advanced oxidation, lamp types, technologies and applications*. IUVA News, 8 (1), 32–37

Scott II R. D. (2009). *The Direct Medical Costs of Healthcare-Associated Infections in U.S. Hospitals and the Benefits of Prevention. In Healthcare-Associated Infections (HAIs)* (No. CS200891-A). Centers for Disease Control and Prevention. Retrieved December 13, 2022, from https://www.cdc.gov/hai/pdfs/hai/scott_costpaper.pdf.

Seridou, P., & Kalogerakis, N. (2021). Disinfection applications of ozone micro- and nanobubbles. *Environmental Science. Nano*, *8*(12), 3493–3510

Sharaai, A, H., Mahmood, N, Z., Sulaiman, A, H. (2010). Life cycle impact assessment (LCIA) of potable water production in Malaysia: A comparison among different technology used in water treatment plant. *Environmentasia*, 1 (3)

SimaPro, (2022). *SimaPro database manual Methods library*. Retrieved October 29, 2023, from https://simapro.com/wp-content/uploads/2022/07/DatabaseManualMethods.pdf

Smeets, P. W. M. H., Medema, G. J., & Van Dijk, J. C. (2009). The Dutch secret: how to provide safe drinking water without chlorine in the Netherlands. *Drinking Water Engineering and Science*, *2*(1), 1–14.

Smith, K. A. (2012). Louis Pasteur, the father of immunology? *Frontiers in Immunology*, *3*.

Sombekke, H., Voorhoeve, D., & Hiemstra, P. (1997). Environmental impact assessment of groundwater treatment with nanofiltration. *Desalination*, *113*(2–3), 293–296.

Sonter, L. J., Dade, M. C., Watson, J. E. M., & Valenta, R. K. (2020). Renewable energy production will exacerbate mining threats to biodiversity. *Nature Communications*, *11*(1).

Stavropoulos, P., Giannoulis, C., Papacharalampopoulos, A., Foteinopoulos, P., & Chryssolouris, G. (2016). Life Cycle Analysis: Comparison between Different Methods and Optimization Challenges. *Procedia CIRP*, *41*, 626–631.

Su, D. (2021). *Sustainable product development: Tools, Methods and Examples*. Berlin: Springer.

Svarog UV (2007). *Water Disinfection, Sewage Disinfection, Ultrasound, Ultraviolet, Pure Water*. Retrieved June 11, 2024, from https://svarog-uv.ru/English/index.htm

Swyngedouw, E., & Williams, J. (2016). From Spain’s hydro-deadlock to the desalination fix. *Water International*, *41*(1), 54–73

Symons, G. E. (2006). Water treatment through the ages. *Journal of the American Water Works Association/Journal - American Water Works Association*, *98*(3), 87–98

Tarnacki, K., Meneses, M., Melin, T., Van Medevoort, J., & Jansen, A. (2012). Environmental assessment of desalination processes: Reverse osmosis and Memstill®. *Desalination*, *296*, 69–80

Tarpani, R. R. Z., Lapolli, F. R., Recio, M. Á. L., & Gallego-Schmid, A. (2021). Comparative life cycle assessment of three alternative techniques for increasing potable water supply in cities in the Global South. *Journal of Cleaner Production*, *290*, 125871

Tokyo Water News (2020). *Tokyo Metropolitan Government Welcome to TOKYO Waterworks*. Retrieved June 11, 2024, from https://www.waterworks.metro.tokyo.lg.jp/eng/news/archive-48

Torpie, S., Feagin, N., Pell, D., Anderson, A., Johnson, J., Mallery, S., Perry, S. (2020). *Water System Design Manual* (L. Waring, Ed.; DOH Pub 331-123). Washington State Department of Health

UBA (2023). Renewable energies in figures. Renewable Energies. Retrieved February 3, 2023, from https://www.umweltbundesamt.de/en/topics/climate-energy/renewable-energies/renewable-energies-in-figures

UN (2010). Resolution adopted by the general assembly. 64/292. The human right to water and sanitation. A/RES/64/292. New York: United Nations. Retrieved October 13, 2022, from https://documents-dds-ny.un.org/doc/UNDOC/GEN/N09/479/35/PDF/N0947935.pdf?OpenElement

UN (2011). *The human right to water and sanitation*. Retrieved September 22, 2023, from https://www.un.org/waterforlifedecade/human_right_to_water.shtml

UN (2015). Water and sanitation - united nations sustainable development. Retrieved March 17, 2023, from https://www.un.org/sustainabledevelopment/water-and-sanitation/

UN (2021). *Sustainable Development Goals. The Sustainable Development Goals*. Retrieved March 17, 2022, from https://www.un.org/sustainabledevelopment/blog/tag/193-member-states/

UN (2022). *Hundreds of Children Die Each Day from Poor Sanitation, Secretary-General Says on World Toilet Day, Urging Action to Deliver Safe Conditions Worldwide* | UN Press. United Nations Meetings Coverage and Press Releases. Retrieved January 6, 2023, from https://press.un.org/en/2022/sgsm21577.doc.htm

UNICEF (2024). *Triple Threat*. Retrieved January 3, 2024, from https://www.unicef.org/reports/triple-threat-wash-disease-climate

US EPA (2000). The History of Drinking Water Treatment (EPA-816-F-00-006). United States Environmental Protection Agency

US EPA (2020). SDWA evaluation and rulemaking process. Safe Drinking Water Act. Retrieved July 19, 2022, from https://www.epa.gov/sdwa/sdwa-evaluation-and-rulemaking-process

Vince, F., Aoustin, E., Bréant, P., & Marechal, F. (2008). LCA tool for the environmental evaluation of potable water production. *Desalination*, *220*(1–3), 37–56

Vuorinen, H., Juuti, P., & Katko, T. (2007). History of water and health from ancient civilizations to modern times. *Water Supply*, *7*(1), 49–57

Walsh, T., & Mellor, J. (2020). Comparative life cycle assessment of four commonly used point-of-use water treatment technologies. *Journal of Water, Sanitation and Hygiene for Development*, *10*(4), 862–873

Wang, C., & Lin, W. (2021). Combination of ultraviolet-C light-emitting diodes and a spiral-channel configuration in a water disinfection reactor. *Journal of Water Process Engineering*, *42*, 102160

Wang, J., & Chen, H. (2020). Catalytic ozonation for water and wastewater treatment: Recent advances and perspective. *Science of the Total Environment*, *704*, 135249

Wang, Y., Shang, Y., Gao, Z., Qi, Y., Li, M., Men, Y., & Huang, H. (2021). Modulation of reduced graphene oxide membrane for low-fouling wastewater filtration: Membrane structure, wastewater property, and DFT calculation. *Journal of Cleaner Production*, *321*, 128982

Weiner, R., & Matthews, R. (2003). Environmental Engineering. Oxford: Butterworth-Heinemann.

WHO, (2007). *Outbreaks of Waterborne Diseases.* Retrieved December 13, 2023 from https://iris.who.int/handle/10665/366437

You, J., Guo, Y., Guo, R., & Liu, X. (2019). A review of visible light-active photocatalysts for water disinfection: Features and prospects. *Chemical Engineering Journal*, *373*, 624–641

Younos, T., & Tulou, K. E. (2009). Overview of desalination techniques. *Journal of Contemporary Water Research & Education/Journal of Contemporary Water Research and Education*, *132*(1), 3–10

Zhang, C., Li, Y., Shuai, D., Shen, Y., Xiong, W., & Wang, L. (2019). Graphitic carbon nitride (g-C3N4)-based photocatalysts for water disinfection and microbial control: A review. *Chemosphere*, *214*, 462–479

Zijp, M, C., H, van der Laan. (2015). Life Cycle Assessment of two drinking water production schemes (Letter Report 2015–0209; p. 34). National Institute for Public Health and the Environment

CURRICULUM VITAE

Adı-Soyadı **:** Mehmet Zahid DEMIR

EDUCATION:

- **B.Sc.** **:** 2008, SakaryaUniversity, Faculty of Engineering, Environmental Engineering Department
- **M.Sc.** **:** 2012, New Jersey Institute of Technology, Environmental Engineering Department

PROFESSIONAL EXPERIENCE AND REWARDS:

- LIT UV Elektro, Technical & Marketing Consultant, 2017 – 2022

  Provided strategic guidance and advisory services to management, business, and technical teams, focusing on domain-specific solutions and advanced technologies. My contributions included offering valuable insights for strategic planning in technology and platform development, assessing complex business requirements to formulate targeted solutions, and delivering compelling ROI projections to aid project prioritization and planning with senior executives. Additionally, I collaborated closely with upper management to define strategic directions and implement new operational protocols. Engaging in consultative dialogues with clients, I addressed intricate business concerns and developed innovative proposals. I also created detailed reports and presentations to convey insights and recommendations to relevant stakeholders.

- Ekolojik Energy Group Co. Inc, Purchasing Manager, 2016 – 2017

  Responsible for purchasing equipment for biogas, refrigerator-recycling, electronic recycling, and sludge incineration plants. This included all materials and services for four operating plants and the Waste Transportation Company of the Group. I developed comprehensive standard operating procedures for departmental operations, evaluated vendor performance against quality standards, and conducted monthly reconciliation of open purchase orders to manage inventory levels effectively. I formulated improvement plans to address service-related concerns, resolved complex supply chain issues, and engaged with location managers and departmental supervisors to ascertain requirements. My efforts in streamlining contract bidding and procurement processes resulted in cost reductions, while thorough review and authorization of purchase orders and invoices ensured precision. Additionally, I adeptly negotiated favorable pricing and terms with vendors, researched potential suppliers for alignment with company requirements, and identified ways to reduce lead times and improve inventory management.

- LIT TURKEY Environment, Engineering, Contracting, Trade & Management Co. Inc., Partner & Technical Manager, 2012 – 2017

  Led team efforts in designing various environmental projects, including water treatment plants, boiler water treatment systems, and UV disinfection systems. I created and delivered training materials on UV disinfection systems to local government officials. I oversaw partnerships and key accounts with entities such as the Ministry of Environment and Urbanization, Ministry of Forestry and Water Affairs, and major Water and Sewerage Administrations in Istanbul, Ankara, and Izmir. Facilitating communication between cross-functional teams, I promoted collaboration among technology leaders throughout project phases. I initiated client interactions to gather and interpret project requirements, working closely with system administrators and directors to coordinate project tasks. Additionally, I managed administrative operations to ensure regulatory compliance and foster enduring business relationships. I negotiated contracts and project management strategies, ensuring fairness for all parties involved, and stayed abreast of industry developments and market trends to capitalize on competitive advantages. Collaborating extensively with legal counsel, I drafted contracts, agreements, and legal documents to minimize risk exposure and provide expert guidance on business operations and strategic initiatives.

- MGH Environment / MGH Group, Project Manager, 2015 - 2016

  Controlled the development and execution of environmental projects within the MGH Group, negotiating with international environmental technology companies to secure distributorship in Turkey. I prepared tenders for projects in the water and wastewater sector, including designing a capacity increase project for a glass production facility wastewater treatment plant. I implemented plans to ensure projects were completed on time and within budget, managed costs, and monitored performance, leading to successful outcomes. Additionally, I planned, designed, and scheduled different phases of large-scale projects with a team, developing and executing strategic project plans aligned with business objectives. I negotiated contracts with third-party vendors to benefit the company and regularly reported to managers on project budgets, progress, and technical issues. Through well-defined project plans and budgets, I ensured the successful realization of projects.

- Istanbul Environmental Protection and Waste Material Recycling Inc., Environmental Field Engineer, 2008 – *2009*

  Implemented a comprehensive health and safety plan for the operations of the Komurcuoda Landfill site, including leachate sampling and monitoring at the leachate treatment plant to ensure discharge limits were met. I prepared bid documents for the operation of the leachate treatment plant and oversaw the daily operations of contractors handling earthmoving and concrete work at hazardous waste facilities. Leading a team of engineers and technicians, I identified and resolved issues during construction projects and managed all aspects of these projects, including budgeting, scheduling, quality assurance, safety, and coordination with contractors. I developed project schedules, reviewed plans for feasibility, obtained necessary permits and approvals, tracked project progress, and ensured all documentation was current. Additionally, I prepared detailed progress reports, evaluated the technical feasibility of engineering designs and test results, and collaborated with other departments to ensure successful project completion. I established and maintained supplier relationships to ensure timely delivery of quality materials, monitored engineering team performance, made recommendations for improvement, and motivated teams to complete projects on time and within budget.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- Comparative Life Cycle Assessment of Four Municipal Water Disinfection Methods. Mehmet Zahid Demir, Huseyin Guven, Mustafa Evren Ersahin, Hale Ozgun, Mehmet Emin Pasaoglu and Ismail Koyuncu. Sustainability. https://doi.org/10.3390/su16146104