

LIFE CYCLE ASSESSMENT OF ACTIVATED CARBON ADSORPTION AND
OZONATION TO REMOVE MICROPOLLUTANTS FROM TEXTILE
WASTEWATER

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AYŞE SENA AKDENİZ

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TEXTILE WASTEWATER**

submitted by **AYŞE SENA AKDENİZ** in partial fulfillment of the requirements for
the degree of **Master of Science in Environmental Engineering, Middle East
Technical University** by,

Prof. Dr. Halil Kalıpçılar
Director, Graduate School of **Natural and Applied Sciences** _____

Prof. Dr. Bülent İçgen
Head of the Department, **Environmental Engineering** _____

Prof. Dr. Ülkü Yetiş
Supervisor, **Environmental Engineering, METU** _____

Examining Committee Members:

Prof. Dr. Bülent İçgen
Environmental Engineering, METU _____

Prof. Dr. Ülkü Yetiş
Environmental Engineering, METU _____

Prof. Dr. Aysun Özkan
Environmental Engineering, Eskişehir Tech. Uni. _____

Prof. Dr. Niğmet Uzal
Civil Engineering., Abdullah Gül Uni. _____

Assist. Prof. Dr. Sema Sevinç Şengör
Environmental Engineering, METU _____

Date: 29.08.2022



I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : Akdeniz, Ayşe Sena

Signature :

ABSTRACT

LIFE CYCLE ASSESSMENT OF ACTIVATED CARBON ADSORPTION AND OZONATION TO REMOVE MICROPOLLUTANTS FROM TEXTILE WASTEWATER

Akdeniz, Ayşe Sena
Master of Science, Environmental Engineering
Supervisor : Prof. Dr. Ülkü Yetiş

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To avoid potential adverse effects by micropollutants in secondary textile wastewater, it is necessary to apply an advanced treatment process, among which activated carbon adsorption and ozone oxidation are the most attractive alternatives. There is still a lack of studies evaluating the environmental impacts of these processes for the tertiary treatment of textile wastewater. Using the life cycle assessment (LCA) methodology, this study assesses and compares the environmental impacts of ozone oxidation and GAC adsorption. Micropollutants were included in the study using the results from a literature survey on the concentration of micropollutants in secondary textile wastewater and also in the effluents from activated carbon adsorption and ozone oxidation treatment. SimaPro 9.2.0.2 was used to model the processes using background data from the Ecoinvent v3.6 database. Adopting the impact analysis method of Impact 2002+, the impacts of two scenarios: GAC adsorption and ozone oxidation, were assessed. Results show that the environmental impact of ozone oxidation is significantly higher than that of GAC adsorption for almost all impact categories due to higher energy consumption. The GAC adsorption shows almost 90 % lower impacts in 14 of 15 categories studied. It is worth noting that the environmental impacts of ozone oxidation are strongly related to energy consumption for ozone generation, which emphasizes the

importance of the source of electricity. The results from the study support GAC adsorption as a suitable process for removing micropollutants from secondary textile effluent.

Keywords: Life Cycle Assessment, Activated Carbon Adsorption, Ozone Treatment, SimaPro, Textile Wastewater



ÖZ

TEKSTİL ATIKSULARINDAN MİKROKİRLETİCİLERİN GİDERİLMESİ İÇİN AKTİF KARBON ADSPORSİYONUNUN VE OZONLAMAMANIN YAŞAM DÖNGÜSÜ ANALİZİ

Akdeniz, Ayşe Sena
Yüksek Lisans, Çevre Mühendisliği
Tez Danışmanı: Prof. Dr. Ülkü Yetiş

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İkincil tekstil atık sularında mikrokirleticilerin potansiyel olumsuz etkilerinden kaçınmak için, aktif karbon adsorpsiyonu ve ozon oksidasyonunun en cazip alternatiflerden sayılabileceği ileri bir arıtma prosesi uygulamak gereklidir. Tekstil atık sularının üçüncül arıtımı için bu proseslerin çevresel etkilerini değerlendiren çalışmalar halen yetersizdir. Yaşam döngüsü değerlendirmesi (LCA) metodolojisini kullanan bu çalışma, ozon oksidasyonunun ve granüler aktif karbon adsorpsiyonunun çevresel etkilerini değerlendirir ve karşılaştırır. Mikrokirleticiler, ikincil tekstil atık sularındaki ve ayrıca aktif karbon adsorpsiyonu ve ozon oksidasyon proseslerinden çıkan atıksulardaki mikrokirleticilerin konsantrasyonuna ilişkin bir literatür araştırmasının sonuçları kullanılarak çalışmaya dahil edildi. Ecoinvent v3.6 veritabanındaki arka plan verilerini kullanarak süreçleri modellemek için SimaPro 9.2.0.2 kullanıldı. Impact 2002+ etki analizi yöntemini kullanılarak, iki senaryonun etkileri değerlendirildi: granüler aktif karbon adsorpsiyonu ve ozon oksidasyonu değerlendirildi. Sonuçlar, daha yüksek enerji tüketimi nedeniyle neredeyse tüm etki kategorileri için ozon oksidasyonunun çevresel etkisinin granüler aktif karbon adsorpsiyonundan önemli ölçüde daha yüksek olduğunu göstermektedir. Granüler aktif karbon adsorpsiyonu, incelenen 15 kategoriden 14'ünde neredeyse %90 daha düşük etki göstermektedir. Ozon oksidasyonunun çevresel etkilerinin, ozon üretimi için enerji tüketimiyle güçlü bir şekilde ilişkili

olması, elektrik kaynağının önemini vurgulayan dikkat edilmesi gereken bir husustur. Çalışmadan elde edilen sonuçlar, mikrokirleticilerin ikincil tekstil atık suyundan uzaklaştırılması için uygun bir süreç olarak granüler aktif karbon adsorpsiyonunu desteklemektedir.

Anahtar Kelimeler: Yaşam Döngüsü Analizi, Aktif Karbon Adsorpsiyonu, Ozon Arıtımı, SimaPro, Tekstil Atıksuyu



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LIST OF ABBREVIATIONS

BOD:	Biological Oxygen Demand
CFs:	Characterization Factors
COD:	Chemical Oxygen Demand
DALY:	Disability Adjusted Life Year
EC:	Electrical Conductivity
EQSs:	Environmental Quality Standarts
EU:	European
GAC:	Granular Activated Carbon
ISO:	International Organization for Standardization
LCA:	Life Cycle Assessment
LCI:	Life Cycle Inventory
MP:	Micropollutant
NRDC:	Natural Resource Defense Council
PM:	Particulate Matter
SS:	Suspended Solids
T:	Tempreature
TA:	Total Alkalinity
TDS:	Total Dissolved Solids
TH:	Total Hardness
TKN:	Total Kjeldahl Nitrogen
TN:	Total Nitrogen
TOC:	Total Organic Carbon
TS:	Total Solids
TSS:	Total Suspended Solids
USD:	United States Dolar



CHAPTER 1

INTRODUCTION

1.1 General

The textile manufacturing industry started its production with traditional methods in the early periods of history; and turned to mass production with the industrial revolution. Today, with the support of technological developments, the textile industry continues to be an essential industry branch for all countries with a wide variety of functional products (Republic of Türkiye Ministry of Industry and Technology, 2020).

In 2020, the size of the world textile industry reached 999 Billion USD. While China, the United States, India, Germany, and Türkiye are the top five countries in textile exports, the Turkish textile industry's exports reached 12.34 Billion USD in 2020 (Republic of Türkiye Ministry of Industry and Technology, 2020).

Textile production involves converting fiber into the fabric using various processes, including desizing, scouring, bleaching, mercerizing, dyeing, printing, and finishing (Republic of Türkiye Ministry of Industry and Technology, 2022). In these processes, a vast amount of water is consumed. In addition, hundreds of different chemicals, such as dyes, surfactants, etc., are applied to textile products in water baths. While the average water consumption for producing various fabrics such as wool, woven, knit, carpet, stock/yarn, non-woven, and felted fabric finishing changes between 2.5 to 285 m³/ton of textile, the average water consumption is typically reported as around 200 m³/ton of textile produced (Karthik & Gopalakrishnan, 2014).

In addition to high water consumption, the industry consumes a wide variety of chemicals such as toxic organic chemicals, toxic anions, biocides, ionic metals and metal complexes, and surfactants. Because of high water and chemical consumption,

the textile industry generates a high amount of wastewater with a high chemical oxygen demand (COD), biological oxygen demand (BOD), suspended solids (SS), total dissolved solids (TDS), pH, phenols, sulfate, and chloride concentrations. Therefore, the high amount of wastewater production and the potential to cause severe water pollution when not treated properly can be listed as the main characteristics of textile effluents (Karthik & Gopalakrishnan, 2014).

In water pollution control, removing recalcitrant micropollutants such as dyes, chlorinated benzenes, phenol, chlorinated phenols, etc., from all the industrial effluents reaching into water bodies is needed (Lee et al., 2011). Preliminary, primary, secondary, and tertiary treatment stages are applied to remove all these and other conventional pollutants. Although the treatment steps and the choice of the process depend on the wastewater's characteristics, in most cases, all these treatment steps are needed for a good treatment of textile wastewater. The preliminary treatment removes the large solids, oils, and fats; the primary treatment eliminates suspended solids and organic matter from the wastewater; the secondary treatment removes biodegradable organics, suspended solids, and nutrients and the tertiary treatment removes residual suspended solids and micropollutants (States, 1998). Although different tertiary treatment methods are applied to remove micropollutants, activated carbon adsorption and ozonation are the most commonly applied tertiary treatment technologies for textile effluents.

The Turkish Water Pollution Control Regulation (Republic of Turkey Official Gazette, 2004) establishes discharge limits for industrial sources with specific limitations based on the type of activity generating the wastewater discharge. According to this regulation, industrial discharges should meet the technology-based discharge standards set for COD, TSS, pH, oil and grease, NH₄-N and other parameters listed. In complying with the discharge standards set in the regulation, secondary treatment is generally sufficient and there is no need for further treatment by advanced treatment methods. However, the textile industry will need to remove micropollutants from secondary textile wastewater in the future because of the possible future requirements of the Regulation of the Turkish Surface Water Quality and the need for water reuse.

The Turkish Surface Water Quality Regulation published by the Ministry of Agricultural and Forestry, 2016, within the scope of harmonization of Türkiye's legislation with the EU Legislation, requires that the concentrations of some micropollutants in surface and transitional waters be kept below the environmental quality standards (EQSs). This regulation defines EQSs for 45 priority and 250 river basin-specific pollutants. These 250 substances are mainly organic micropollutants and metals, identified based on their toxicity, persistency, bioavailability, and occurrence level in national surface waters. In line with the EQSs set for micropollutants, the micropollutant discharges with industrial wastewater are to be controlled and treated for the removal of micropollutants.

The textile industry, one of the industries with a high amount of micro-pollutants in its wastewater, is required to adopt tertiary treatment to remove micropollutants from its secondary effluents. In this regard, choosing the most suitable tertiary treatment processes is crucial. The suitability of a treatment method depends mainly on three main factors; effectiveness, economic feasibility, and environmental friendliness. The best way of evaluating the environmental friendliness of a process/product is to perform a life cycle assessment (LCA).

LCA, which has been in use since the 1970s, aims to measure potential adverse environmental impacts of a process or a product on different impact categories. In addition to calculating a process or product's potential adverse environmental impacts, this tool can compare multiple processes or products to determine which process/product has a less environmental impact. LCA contains an impact assessment step that contributes to determining the potential adverse effects of the product/process analyzed are concentrated. LCA identifies the potential impacts on the environment and human health, as impacts on the environment generally also affect humans.

While LCA is good for comparing distinct wastewater treatment processes and the volume of LCA studies on some wastewater treatment processes is extensive, there is no study published that focuses specifically on comparing activated carbon adsorption and ozonation processes for the removal of micropollutants from secondary textile wastewater.

1.2 The Objectives and Scope of the Study

The main objective of this study is to evaluate and compare the potential environmental impacts of two commonly used tertiary treatment methods, which are granular activated carbon (GAC) adsorption and ozone oxidation, for micropollutant removal from the secondary textile wastewater by the LCA.

The study was carried out for three different scenarios, LCA for GAC treatment, LCA for ozone treatment, and LCA for comparison of GAC treatment and ozonation. A sensitivity analysis was also carried out. The scenarios and the scope of the sensitivity analysis are explained below:

- GAC adsorption LCA scenario; to measure the potential adverse environmental impacts of GAC adsorption for the typical GAC dosage applied for the removal of the pollutant of concern
- Base-case Ozone treatment LCA scenario; to measure potential adverse environmental impacts of ozone treatment for typical ozone dosages
- Comparison of GAC adsorption and ozonation case; to compare these two treatment methods' potential adverse environmental impacts for the minimum, base, and maximum dosages
- Sensitivity analysis for the above-mentioned scenarios; to assess the impacts of incineration ratio in GAC adsorption, micropollutant concentrations in both treatment methods, and ozone dosages in ozone treatment parameters on environmental impacts.

In assessing the environmental impacts of the tertiary treatment of secondary treated textile wastewater by the GAC adsorption and ozonation processes, firstly, the micropollutants in the secondary treated textile wastewater and the concentrations of these pollutants in the secondary treated wastewater were compiled. For this purpose, a comprehensive literature review was conducted. Then, the doses of activated carbon and ozone that should be applied in tertiary treatment to remove these pollutants were determined. This step constituted the main phase of completing an inventory of the relevant inputs and outputs of the study.

SimaPro was used as software for LCA in the study. System boundaries were determined as the entrance of the tertiary treatment and the exit of the tertiary treatment process; in other words, a gate-to-gate approach was used in this study. The functional unit of the study was selected as 1 m³ secondary treated textile wastewater. The method of Impact 2002+ was used to conduct an LCA. In this thesis, Chapter 2 includes background information about the textile industry, textile wastewater treatment, and also about LCA. Chapter 3 deals with the methodology used in the study for the LCA study and the compilation of inventory data for the LCA of alternative tertiary treatment processes. The results of the LCA study are presented and discussed in Chapter 4. Chapter 5 presents the conclusion derived from the study.



CHAPTER 2

LITERATURE REVIEW

This chapter first presents a general overview of the textile industry, summarizing the production process, wastewater characteristics, and treatment methods. Then, a review of the LCA literature used in the present study is provided.

2.1 Textile Industry

Textile manufacturing which includes the creation of fabric materials, is one of the oldest human activities. Textile production, whether from natural fiber or synthetic fiber, begins with the conversion of fiber into yarn and continues with the transformation of yarn into fabric. The final step is to sew the fabric into clothes or other end products. Dyeing and various finishing processes are also part of textile manufacturing processes(The European Commission, 2003).

The industry interacts with agriculture and livestock farming due to the needed natural fibers such as cotton and wool. Also, it interacts with the petrochemical industry due to synthetic fibers. The industry is intertwined with the chemical industry because the paint-finishing processes cooperate with the ready-made clothing accessory industry. Moreover, the industry is technically related to many sectors, from automotive to construction, heavy industry to medicine. At the meeting point of the high value-added products obtained with the customer, retail and merchandising are the last links of the industry's supply chain. These areas' control is provided by the strong logistic sector (Republic of Türkiye Ministry of Industry and Technology, 2022).

The needs of the textile industry diversify with the development of the sectors interacting with the textile industry and the change in customer demands. In sports products, waterproof and sweat proof; in military areas, bulletproof and fireproof; or in medical sectors, antibacterial products are demanded. It is expected that the colors

of the products produced for the clothing industry will not fade for a long time, their form will not deteriorate, and they will not stain. In addition, the sector's product variety is increasing with rapidly changing trends. These changes will cause diversification in the industry's production stages and raw materials (Republic of Türkiye Ministry of Industry and Technology, 2022).

In this chapter of the thesis, firstly, the manufacturing processes applied in the textile industry are presented. Then, the characteristics of textile wastewater are given and the processes used in the treatment of textile wastewater; in particular, advanced treatment processes are described.

2.1.1 Production in the Textile Industry

The production of textiles begins with the harvesting of raw materials or the preparation of fibers, which can be cotton, wool, silk, jute, linen, and synthetic fibers such as rayon, nylon, and polyesters. The fibers are then spun for the production of yarn. Yarn production is mechanical and uses no chemicals. Yarn is then processed to make fabric. Fabric can be manufactured in many different ways, such as knitting, weaving, or through the production of non-woven fabrics (Figure 1) (The European Commission, 2003).

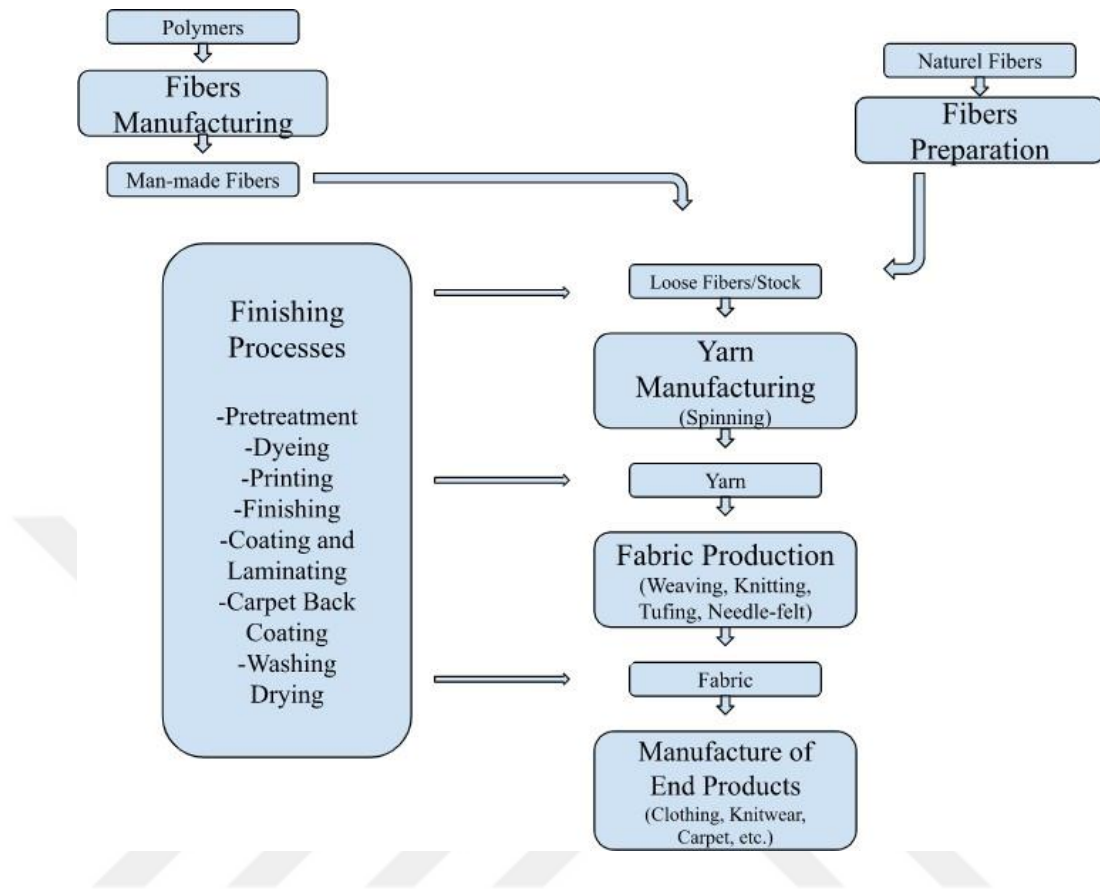


Figure 1. General Diagram of Processes in the Textile Industry (The European Commission, 2003)

During textile production, various chemicals are used to give the products the required properties. These chemicals are selected according to the type of fiber, desired aesthetic appeal, and unique technical properties. The usage of chemicals starts with the step of fiber production, which is vital to creating the needed durability, strength, texture, and appearance. Produced fibers can be listed into four main categories, which are plant-animal, man-made, and synthetic fibers. In this step, depending on the category of fiber and the needed quality, pesticides, insecticides, fertilizers, acids, bases, scouring chemicals, process chemicals, dyes, stabilizers, pigments, and catalysts can be used. The process of fiber production is followed by yarn production. Although the yarn production process is more mechanical compared to fiber production, it can need spinning oils to increase the strength of the fiber. Third and the main one of the main processes of textile production is called fabric

production. Sizing chemicals and lubricants can be added to fabrics to prevent yarn breaking (Ramos et al., 2021).

Finishing processes cover pretreatment, coating and laminating, and carpet back or washing steps according to the type of product. The process of pretreatment, which can be accepted as the main production step of textile production, is carried out with fabrics to prepare the fabric to receive dyes and functional chemicals. Step of pretreatment, which can be classified as wet processes of textile production, covers sizing, desizing, scouring, bleaching, and mercerizing activities. For this step, detergents, solvents, enzymes, bleaches, acids, and bases can be used according to the need for fabric. Activities in the pretreatment step are briefly explained in the following paragraphs.

Sizing: Sizing is generally the first wet process and is crucial for weaving. At this step, the yarn is coated with a thin adhesive film to improve its weave-ability. It is a weaving preparatory process. Starch, modified starch, carboxymethyl cellulose, polyvinyl acetate, and polyvinyl alcohol can be applied to raise the tensile strength and smoothness of the product.

Desizing: The aim of desizing is to remove the sizing agent from the fabric. The sizing agent on the weaved yarn can inhibit any subsequent wet processing of the fabric. Desizing, a hot washing process, varies according to the sizing materials used in the sizing step. Using enzymes, acids, etc., creates the pollution load.

Scouring: It is performed to remove residual reagents on natural and synthetic materials. Although the type and intensities of the used chemicals depend on the material, scouring waste liquors can be toxic and chemically aggressive. For example, used organophosphates in sheep dipping may find in raw wool scouring.

Bleaching: Bleaching increases the whiteness of the fabric, so it is needed if the fabric is white or light color. The process is mostly carried out by chemical oxidation with hydrogen peroxide or sodium hydrochloride.

Mercerizing: To increase tensile strength, dye affinity and luster of the product, the mercerization process is applied. It is mostly performed on pure cotton which is

treated by a concentrated caustic bath and final acid wash (Judd, S., & Jefferson, 2002).

At the end of pretreatment, dyes and pigments are used for dyeing and printing the fabric. As the last step of producing textiles, the finishing treatment step is applied. The step aims to add an aesthetic appeal and unique technical properties such as flame retardance, enhanced water resistance, and antibacterial property to the fabric. For this step variety of chemicals can be used. For example, halogenated, phosphorous-based chemicals are used for flame retardance, biocides such as silver and triclosan are used for antibacterial production, and waxes, silicones and fluorocarbons are used for water repellence. In addition to these steps, chemicals such as dimethyl fumarate and methyl bromide can be added to protect the fabric from molding during transportation (*Textile Guide.*, 2021).

2.1.2 Characteristics of the Textile Effluents

The textile industry is one of the biggest wastewater producers among manufacturing industries. According to NRDC (Natural Resource Defense Council) (Encourage Textile Manufacturers to Reduce Pollution, 2021), one-fifth of global industrial water pollution is caused by textile mills with 20,000 chemicals used in production. In addition to the various chemicals it uses, the industry consumes lots of water. This water consumption varies according to the fabric type. The amount of water consumed by the industry for different fabric types is given in Table 1.

Table 1. Water Consumption for Different Types of Fabric (Karthik & Gopalakrishnan, 2014)

Fabric	Minimum Water Consumption (m³/ton)	Maximum Water Consumption (m³/ton)
Wool	111	285
Woven	5	114
Knit	20	84
Carpet	8.3	47
Stock/Yarn	3.3	100
Non-Woven	2.5	40
Felted Fabric Finishing	33	213

Although the specific water consumption of the industry varies a low with the type of fabric produced, the average consumption is estimated at 200 m³ per ton of textile (Karthik & Gopalakrishnan, 2014). This high water consumption during production causes a vast amount of wastewater generation in the sector.

The wastewater of the industry is characterized by high concentrations of BOD, COD, suspended solids, nitrates, chlorides, dyes, metals (manganese, sodium, copper, lead, iron, chromium), and dark color. The typical characteristic of textile wastewater is given in Table 2.



Table 2. Typical Characteristics of Textile Wastewaters

Parameter	Reference							
	Al-Kdasi et al., (2004)	Avlonitis et al., (2008)	Eswaramoorthi & Chauhan, (2008)	Upadhye & Joshi, (2012)	Hussein, (2013)	Kehinde & Aziz, (2014)	Ananthashankari, (2014)	Pal, (2017)
T (°C)			35-45	35-45	33-45	21-62	35-45	
pH	7-9		6-10	6-10	5.5-10.5	6.95-11.8	6-10	10
Color (Pt-Co)	50-2500			50-2500		50-2500	50-2500	
COD (mg/L)	150-12000	100	1000-1500	150-10000	150-10000	150-30000	150-12000	1800
BOD (mg/L)	80-6000		300-500	100-4000	100-4000	80-6000	80-6000	360
EC (µS/cm)		1000						
TS (mg/L)	15-8000		200-400			6000-7000		
TSS (mg/L)	15-8000		8000-12000	100-5000	100-5000	15-8000	15-8000	
TDS (mg/L)	2900-3100			1800-6000	1500-6000	2900-3100	2900-3100	
Chlorine (mg/L)	1000-1600						1000-6000	
Chlorides (mg/L)			3000-6000	1000-6000	200-6000			15900
Free chlorine (mg/L)			<10				<10	
TA (mg/L) as CaCO ₃				500-800	500-800	17-22		
TKN (mg/L)	70-80			70-80	70-80	70-80	70-80	
TN (mg/L)			10-30				10-30	10-30
NO ₃ -N (mg/L)			<5				<5	<5
Free ammonia (mg/L)			<10				<10	<20
Na ₂ CO ₃ (mg/L)		20						

Table 2. Typical Characteristics of Textile Wastewaters (Continued)

Parameter	Reference							
	Al-Kdasi et al., (2004)	Avlonitis et al., (2008)	Eswaramoorthi & Chauhan, (2008)	Upadhye & Joshi, (2012)	Hussein, (2013)	Kehinde & Aziz, (2014)	Ananthashankar, (2014)	Pal, (2017)
NaOH (mg/L)		10						
NaCl (mg/L)		300						
Phosphate (mg/L)							<10	<20
Sulphates (mg/L)			600-1000		500-700		600-1000	1400
Sulphides (mg/L)					5-20			
Oil and grease (mg/L)			10-30		10-50	5-5.5	10-30	
Dye (mg/L)			70					700
Zink (mg/L)			<10		3-6		<10	
Nickel (mg/L)			<10				<10	
Manganese (mg/L)			<10				<10	
Iron (mg/L)			<10				<10	<10
Copper (mg/L)			<10		2-6		<10	
Boron (mg/L)			<10				<10	
Arsenic (mg/L)			<10				<10	
Silica (mg/L)			<15				<15	
Mercury (mg/L)			<10				<10	
Fluorine (mg/L)			<10				<10	
Chromium (mg/L)					2-5			
Potassium (mg/L)					30-50			
Sodium (mg/L)			7000	610-2175	400-2175		7000	2900

As shown in Table 2, the wastewater from the textile industry is rich in dyes and also in ionic content. Therefore, it is with high conductivity. In addition, the textile effluents are high in pollution load due to the sizing agents and also other chemicals used during production.

Textile wastewater typically needs secondary treatment to be discharged into the receiving environment or tertiary treatment to be reused. With the use of appropriate treatment methods, the pollution in the water can be decreased. In Table 3, the characteristics of raw textile effluents taken from different studies and also those of treated effluents by different wastewater treatment processes are given.

Table 3. Untreated and Treated Textile Wastewater Characteristics

Reference	Influent/ Effluent	COD (mg/L)	BOD (mg/L)	TOC (mg/L)	Color (mgPtCo/L)
Tanveer et al. (2022)	Influent	680	-	-	-
	Effluent (Ozonation)	160	-	-	-
Beyan et al. (2021)	Influent	960	490	-	1140
	Effluent (Activated Carbon)	56	23	-	-
Geraldino et al. (2020)	Influent	655.8	158.0	83.0	1715
	Effluent (Fenton Process)	120.1	15.8	24.65	51.45
Afanga et al. (2020)	Influent	325	35	52	-
	Effluent (Electro Fenton)	126	18	34	-
Trigueros et al. (2019)	Influent	6038	-	1162	1966
	Effluent (Fenton Process)	368	-	23	20
Salazar et al. (2019)	Influent	1762.89	-	642	-
	Effluent	116	-	48.4	-

Table 3. Untreated and Treated Textile Wastewater Characteristics (Continued)

Reference	Influent/ Effluent	COD (mg/L)	BOD (mg/L)	TOC (mg/L)	Color (mgPtCo/L)
	(Solar Photoelectro Fenton)				
GilPavas et al. (2019)	Influent	875	189.6	324	1366
	Effluent (Fenton Process)	208	87.9	93	121
GilPavas et al. (2018)	Influent	545	118	164	1248
	Effluent (Solar Photoelectro Fenton)	59.9	35	45.9	51.7

As presented in Table 3, textile wastewater treatment studies by applying different advanced treatment methods such as ozonation, activated carbon, and the Fenton process played an active role in reducing the COD value and removing the color. Moreover, advanced treatment methods are effective in the removal of micropollutants from textile wastewater. Removal of the micropollutants is essential because they have various adverse effects such as short-term or long-term toxicity, endocrine disruption, reproductive impairments, physical abnormalities, or fish species feminization if they are released into the environment uncontrollably (Bhatt et al., 2022).

2.1.3 Treatment of Textile Effluents

As presented above, the textile effluents are extremely polluted due to the presence of a high COD, color, and total dissolved solids. Moreover, some of the dyes and other chemicals used are not readily amenable to biological treatment. So, many treatment processes, including physical, chemical, and biochemical processes, are applied to treat textile wastewater in an efficient way. In the literature, there are numerous articles published on the treatment of textile effluent applying conventional treatment technologies. These articles indicate that the conventional

treatment processes are effective in removing conventional pollutants but not recalcitrant compounds (Zhang et al., 2021).

In the conventional treatment of textile effluents, to remove floating and settleable materials such as oil and grease, colloidal particles, pieces of fabric, yarn, fibers, rags, and lint, conventional primary treatment methods are used. Screening, sedimentation, equalization, chemical coagulation or mechanical flocculation are among the primary treatment methods applied. The chemical coagulation method is widely used for the efficient decolorisation of wastewater containing disperse dyes (Holkar et al., 2016). In this step, neutralization may also be applied.

To reduce BOD, COD, color, phenol and dissolved organic contents of the textile wastewater, secondary treatment methods are applied. Activated sludge process, aerated lagoon, oxidation ditch, and trickling filtration are among the methods commonly applied as secondary treatment methods.

To reduce the color content and remove specific contaminants from the wastewater, advanced treatment methods are used. Ion exchange, reverse osmosis, membrane technology, Fenton processes, adsorption, and ozonation can be used as advanced treatment methods (Senthil Kumar & Saravanan, 2017).

Ion exchange technology, which is used in water softening, purification or treatment processes, can also be used in textile effluent treatment as an advanced treatment method. Ion exchange is based on the principle of replacing unwanted ionic contaminants with another acceptable ion. It is generally applied in column reactors in industrial waters (Lacour et al., 2004). Reverse osmosis is the filtering process with pressure. The method which performs effective treatment is also used in cases where the reuse of the textile water is desired. It is effective in removing micropollutants, heavy metals, and color from water (Güneş & Gönder, 2021). In addition, to reverse osmosis, membrane technologies such as ultrafiltration, nanofiltration, and the membrane bioreactor can also be used in textile wastewater treatment. The membrane bioreactor is used in combination with biological treatment, increasing the treatment efficiency and reducing the use of space. Fenton Process, which is an advanced oxidation process, is used for the removal of non-

biodegradable materials. The method is also used for micropollutant removal in textile wastewater. Moreover, adsorption and ozonation are used in micropollutant removal from textile effluent as advanced treatment methods with high removal capacity.

2.1.3.1 GAC Treatment

Adsorption is used to remove soluble organic pollutants such as phenols, polychlorinated biphenyls, dyes, pesticides, etc., from textile effluent thanks to its high surface area and porous structure. The process is one of the physicochemical treatment techniques. The process's effectiveness depends on particle size, adsorbent surface area, adsorbate, and adsorbent concentration, contact time, temperature, and pH.

Activated carbon is one of the commonly used adsorbents in the adsorption process because of the adsorbing effectiveness in the removal of metal ions, cations, dyes, etc. It is produced from materials that have high carbon content, such as coconut husk, hazelnut shells, sawdust, coffee, and tea waste (Senthil Kumar & Saravanan, 2017).

Activated carbon has three main forms, which are extruded, powder, and GAC. The diameter of extruded activated carbon is between 0.8 to 5 mm. It is mostly used in air treatment applications due to its low dust content, high mechanical strength, and low-pressure drop. The diameter of the powdered one is less than 0.18 mm. It is mostly used in flue gas treatment and liquid phase applications. Lastly, GAC, which has a size range between 0.2 to 5 mm, has an irregular shape. It is used in water treatment applications, air treatment applications, and industrial processes. GAC is ideal for usage in various areas because of its adsorptive capacity. Also, it can be used multiple times by reactivated with the help of thermal oxidation, so it is an environmentally responsible product (*Granulated Activated Carbon*, 2022).

2.1.3.2 Ozonation

In ozone treatment, the oxygen (O_2) in the air is converted to ozone (O_3) form with the use of high voltage electricity. Ozonation which is occurred the infusion of ozone (O_3) into the water, is a type of chemical water treatment. Ozone, which is a colorless gas at room temperature and at normal pressure, is mixed with water in liquid form and given to the system in water treatment (Boner et al., 1999).

Injected ozone which causes oxidation reactions, decays in water. Also, emerged OH^\cdot radicals react with substances in the water. In other words, the reaction can be done directly with ozone or indirectly with OH^\cdot radicals.

Ozone which is one of the powerful oxidants, breaks down detergents, phenols, and organic molecules. It can easily break double bonds, so ozone has a wide range of applications in water treatment, advance oxidation processes, and disinfection of water and wastewater.

Ozone can react with molecules in two ways: it can have a direct molecule reaction or an indirect free radical-type reaction. It is effective over a wide pH range for organic degradation and inorganic removal. The method is widely applicable for various components. In addition, after oxidation, removal and disposal of the ozone are not needed. However, ozone needs to be produced at the point of use. In other words, it cannot be transported to another place because of this reason; ozone should be produced on-site. Also, the release of toxic molecules and carcinogenic aromatic amines should be controlled during dosage because ozone reaction with some substances can cause the formation of some toxic or carcinogenic chemicals (Mazille, 2022).

2.2 Micropollutants in the Secondary Textile Effluents and Their Removal by Activated Carbon Adsorption and Ozone Treatment

A comprehensive literature review was conducted to identify micropollutants that may present in untreated textile effluents and their concentrations in both secondary treated wastewater and in the effluents from tertiary treatment by the processes of activated carbon adsorption and ozone oxidation. The list of micropollutants that are likely to be found in textile wastewater that is taken as a basis for the study is given in Table 4, Table 5 and Table 6. This chapter presents the results of the literature review carried out for the determination of the micropollutants that are present in textile wastewaters and also their concentrations when treated by the activated carbon adsorption and ozone oxidation processes.

2.2.1 Micropollutants in Secondary Textile Wastewaters and Their Typical Concentrations

Although a small amount of micropollutants in textile wastewater is treated up to advanced treatment, the main treatment is carried out in the advanced treatment stage. Micropollutant concentrations in the secondary treated water entering the advanced treatment in textile wastewater are given below.

Table 4. Effluent Micropollutant Concentration from Secondary Treatment

Micropollutant	Concentration in effluent ($\mu\text{g/L}$)	Reference
Trimethoprim	236.75	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Diclofenac	668	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Ketoprofen	613.33	Muñoz et al., 2009

Table 4. Effluent Micropollutant Concentration from Secondary Treatment

(Continued)

Micropollutant	Concentration in effluent (µg/L)	Reference
		Li et al., 2019 Igos et al., 2021
Sulfadiazine	118	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021
Sulfamethoxazole	539.67	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Anthracene	11.9	Kucuk et al., 2021
Fluoranthene	10.0	Kucuk et al., 2021
Hexachlorocyclohexane	45.7	Kucuk et al., 2021
Nonylphenol	241.4	Kucuk et al., 2021
Dioxins	0.217	Kucuk et al., 2021
Cypermethrin	105.1	Kucuk et al., 2021
Acenaphthylene	12.5	Kucuk et al., 2021
Benzyl benzoate	161.9	Kucuk et al., 2021
Bisphenol A	17.9	Kucuk et al., 2021
Diphenyl ether	3685	Kucuk et al., 2021
Phenanthrene	83.2	Kucuk et al., 2021
Fluorene	22.3	Kucuk et al., 2021
Carbendazim	119.6	Kucuk et al., 2021
Epoxiconazole	55	Kucuk et al., 2021

2.2.2 The Typical Concentrations of Micropollutants in the Effluents from Activated Carbon Adsorption

A literature review study was conducted to obtain the effluent micropollutant concentrations from the secondary treatment and the amount of removal by activated carbon treatment in different case studies of the determined micropollutants for the activated carbon adsorption scenario. In the case of data from more than one study, the average value was taken. If there is only the effluent concentration from the secondary treatment, concentration values were found by calculating 80 % removal over the effluent concentration from the secondary treatment, considering that the activated carbon treatment would have a purification performance of more than 80

% and this treatment efficiency would be sufficient for micropollutants. Table 5 shows the micropollutants, the concentration values reached by the specified method, the method of obtaining the concentration value, and the references taken as the basis.

Table 5. Effluent Micropollutant Concentration from GAC Treatment

Micropollutant	Concentration in effluent ($\mu\text{g/L}$)	Type of data	Reference
Trimethoprim	11.46	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Diclofenac	171.34	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Ketoprofen	74.34	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021
Sulfadiazine	13.52	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021
Sulfamethoxazole	410.41	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Anthracene	2.38	80% Treatment Efficiency	Kucuk et al., 2021
Fluoranthene	2.0	80% Treatment Efficiency	Kucuk et al., 2021
Hexachlorocyclohexane	9.14	80% Treatment Efficiency	Kucuk et al., 2021
Nonylphenol	48.2	80% Treatment Efficiency	Kucuk et al., 2021
Dioxins	0.04	80% Treatment Efficiency	Kucuk et al., 2021
Cypermethrin	21.0	80% Treatment Efficiency	Kucuk et al., 2021
Acenaphthylene	2.5	80% Treatment Efficiency	Kucuk et al., 2021

Table 5. Effluent Micropollutant Concentration from GAC Treatment (Continued)

Micropollutant	Concentration in effluent (µg/L)	Type of data	Reference
Benzyl benzoate	32.38	80% Treatment Efficiency	Kucuk et al., 2021
Bisphenol A	3.58	80% Treatment Efficiency	Kucuk et al., 2021
Diphenyl ether	737.0	80% Treatment Efficiency	Kucuk et al., 2021
Phenanthrene	16.64	80% Treatment Efficiency	Kucuk et al., 2021
Fluorene	4.46	80% Treatment Efficiency	Kucuk et al., 2021
Carbendazim	23.9	80% Treatment Efficiency	Kucuk et al., 2021
Epoxiconazole	11.0	80% Treatment Efficiency	Kucuk et al., 2021

2.2.3 The Typical Concentrations of Micropollutants in the Effluents from Ozone Oxidation

A similar study was carried out for the determination of micropollutant concentration from secondary treated textile effluents and also for the determination of their concentrations after ozone treatment. In order to reach the correct results in the comparison scenario, the concentration data were taken from studies where GAC and ozonation treatment methods were used together.

Because of the close micropollutant treatment efficiencies, 80 % treatment efficiency has been accepted in ozone treatment for micropollutants whose effluent concentrations are only reached from the secondary treatment. Table 6 shows the micropollutants that are present in textile effluents, their concentrations in the secondary treated effluents and the sources of these concentration data.

Table 6. Micropollutants and Their Concentrations in the Effluents from Ozone Treatment of Textile Effluents

Micropollutant	Concentration in the effluent (µg/L)	Type of data	Reference
Trimethoprim	3.71	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Diclofenac	34.58	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Ketoprofen	198.66	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021
Sulfadiazine	61.5	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021
Sulfamethoxazole	52.29	Average Concentration	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Anthracene	2.38	80% Treatment Efficiency	Kucuk et al., 2021
Fluoranthene	2.0	80% Treatment Efficiency	Kucuk et al., 2021
Hexachlorocyclohexane	9.14	80% Treatment Efficiency	Kucuk et al., 2021
Nonylphenol	48.2	80% Treatment Efficiency	Kucuk et al., 2021
Dioxins	0.04	80% Treatment Efficiency	Kucuk et al., 2021
Cypermethrin	21.0	80% Treatment Efficiency	Kucuk et al., 2021
Acenaphthylene	2.5	80% Treatment Efficiency	Kucuk et al., 2021
Benzyl benzoate	32.38	80% Treatment Efficiency	Kucuk et al., 2021
Bisphenol A	3.58	80% Treatment Efficiency	Kucuk et al., 2021

Table 6. Micropollutants and Their Concentrations in the Effluents from Ozone Treatment of Textile Effluents (Continued)

Micropollutant	Concentration in the effluent (µg/L)	Type of data	Reference
Diphenyl ether	737.0	80% Treatment Efficiency	Kucuk et al., 2021
Phenanthrene	16.64	80% Treatment Efficiency	Kucuk et al., 2021
Fluorene	4.46	80% Treatment Efficiency	Kucuk et al., 2021
Carbendazim	23.9	80% Treatment Efficiency	Kucuk et al., 2021
Epoxiconazole	11.0	80% Treatment Efficiency	Kucuk et al., 2021

2.3 LCA Concept

Environmental concerns such as climate change, eutrophication, acidification, depletion of resources, and ozone depletion have come up with the increase in the manufacture and consumption of goods. The need to determine the magnitude of the problems encountered and to determine the contribution of the production activities to the environmental risks has emerged. In the 1960s and 1970s, LCA started to be used as a tool to conduct a systematic analysis of environmental impacts over the life cycle of a product, material, process, or other measurable activity (Guinée et al., 2011). To conduct a systematic examination of inputs and outputs of energy, water or materials of a product or a process throughout its life cycle is named LCA. This concept constitutes a common language in measuring and comparing the effect of different products and processes.

To conduct an LCA, for a product/material/process or other measurable activity, raw material extraction, manufacturing, distribution, use/operation/maintenance and disposal/recycling steps of the product or the process are taken into consideration. Although the analysis can be conducted from the extraction of natural resources to the final disposal of interlinked stages of the product or process with the cradle-to-grave approach, it can be conducted in limited stages of the product or process with the cradle-to-gate or gate-to-gate approach (Muralikrishna & Manickam, 2017).

The concept aims: (1) identification of environmental loads during stages with the entrance of consumed amount of raw material and energy, emission of gases and waste generated; (2) detection of potential adverse environmental impacts of the stages; and (3) determine the options to reduce adverse environmental impacts (*Life Cycle Assessment*, 2022). LCA assists in (1) reviewing the product's life cycle to identify opportunities to improve its environmental performance; (2) informing decision-making mechanisms, governmental or non-governmental organizations for strategic planning; (3) the selection of appropriate indicators for determining environmental performance; (4) the preparation of the environmental product declaration of the product and the appropriate eco-labeling during the marketing phase (*ISO 14040: 2006. ISO Principles and Framework*, 2006).

For the standardization and international acceptance of the LCA, International Organization for Standardization which is a worldwide federation for national standards bodies published some guidelines. The guidelines are (*Environmental Management — Life Cycle Assessment — Principles and Framework*, 2006);

- ISO 14040: Principles and Framework (1997)
- ISO 14041: Goal and Scope Definition and Inventory Analysis (1999)
- ISO 14042: Life Cycle Impact Assessment (2000)
- ISO 14043: Life Cycle Interpretation (2000)

With time, the need for formal and technical revision has arisen in the published international standardizations. As a result of the revision studies, guidelines of ISO 14040 and ISO 14044 were published. The guidelines, which are named “ISO 14040: Principles and Framework” and “ISO 14044: Requirements and Guidelines” include the definition of general methodologies of LCA and life cycle inventory (LCI) studies (*Environmental Management — Life Cycle Assessment — Principles and Framework*, 2006). The guidelines define reporting, critical review, and limitations of LCA, and the methodology to be applied in the four main phases of an LCA, which are goal and scope definition, inventory analysis, impact assessment, and interpretation. The phases of LCA are shown in Figure 2 Moreover, the guidelines explain the relation between the LCA Phases (*ISO 14044:2006 Environmental Management — Life Cycle Assessment — Requirements and Guidelines*, 2022).

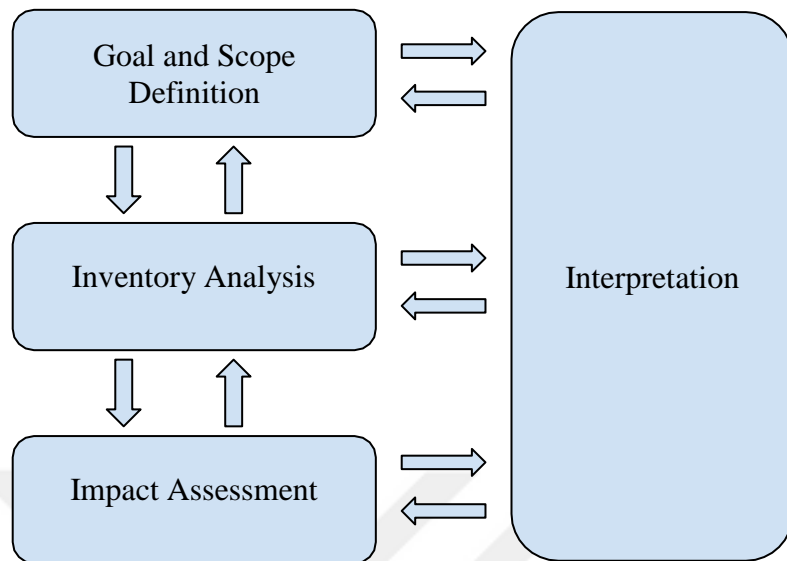


Figure 2. LCA Phases

The first phase, which is the goal and scope definition, includes the level of detail of the study and system boundary. The second phase, called inventory analysis, includes data collection to meet the study's goal. Thirdly, the impact assessment phase contains results to understand the system's environmental significance. Lastly, the interpretation phase summarizes and discusses the results; also, it contains recommendations related to the study result (*ISO 14040: 2006. ISO Principles and Framework, 2006*).

2.3.1 Goal and Scope Definition

The goal and scope section, which is the first part of the LCA methodology, defines the reasons for the study, intended application and audience, functional unit, system, and system boundary of the study. Moreover, the limitations and assumptions of the study are described in this section. The specification in the section is significant to the consistency of obtained result and aim. However, despite the determination of the goal and scope of the study, changes and modifications can be made during the analysis (Khasreen et al., 2009).

The section describes the aim and scope of the study and gives information about its level of detail. At this stage, defining a functional unit is essential to model a product in LCA. The functional unit, which is a reference basis for all calculations regarding impact assessment, is a quantified description. A functional unit can be based on different features of the product or process under study, such as mass, volume, cost, or technical quality (Arzoumanidis et al., 2020).

Determining the system boundaries is mandatory for the study. The boundaries of the studied system must be clearly drawn. Determined system boundaries in the life cycle of a product express the included unit processes in the modeled system. The product system should be modeled based on the inputs and outputs at its boundaries.

The life cycle of the product includes the extraction of raw material, transportation, processing, packaging of the product, consumption of the product, and the last step of the life cycle, which can be reuse, recycling, recovery, or disposal. The life cycle of a product is given in Figure 3.



Figure 3. Life Cycle of a Product (Frațila & Rotaru, 2017)

The boundary can be selected as the approach of cradle-to-grave, gate-to-gate, cradle-to-gate, gate-to-grave, and cradle-to-cradle. With the cradle-to-grave approach, the entire life cycle of the product is taken into account. Gate-to-gate approaches primarily focus on a specialized unit process, so it evaluates a particular section in the product's life cycle. The approach of cradle-to-gate boundaries which starts from natural material exploitation and covers transportation and production steps. Gate-to-grave approach contains processes after the production step of the product, which are distribution, use, and the last step of the life cycle (reuse, recycle, remanufacture, disposal). Lastly, the cradle-to-cradle covers the recycling activity at the end of the life span of the product as well. In other words, in the cradle-to-cradle approach, used raw materials are turned into another product rather than disposed of (Rebitzer et al., 2004). The change in the system boundaries according to the different approaches is shown in Figure 4.

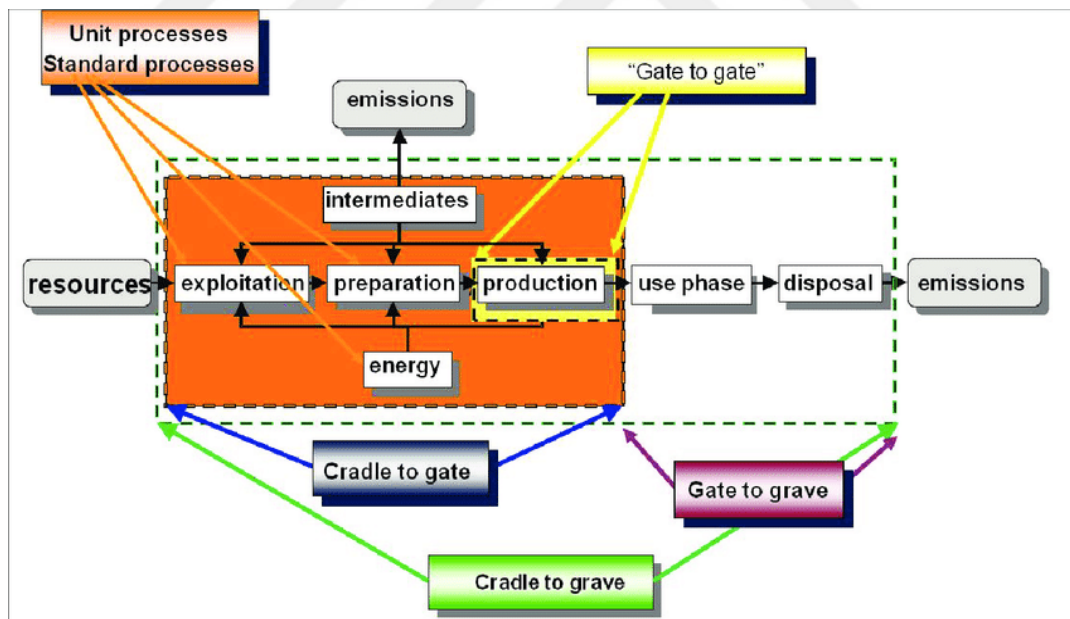


Figure 4. System Boundaries with Approaches (Klöpffer, 2012)

After determining the aim of the study and system boundaries, the need for data arises. The data collection stage is an important process that should be carried out meticulously in order to ensure the reliability of the study results. Also, the quality

of the data used in the study is directly related to the quality of the study. Time, geography, precision, used technology, representativeness, completeness, reproducibility, and consistency, which can be listed as data quality indicators, should be taken into consideration in a level of detail depending on the defined aim of the study (Ölmez, 2011).

2.3.2 Inventory Analysis

Inventory analysis, the second stage of an LCA, includes collecting main data to be used in calculating impacts. At this step of LCA; raw materials used, resources used, energy used, emissions into water and air, wastes produced and all the other releases for the entire life cycle of a product/process/activity are determined and quantified.

This quantification may be done using field studies, literature reviews, or available databases. If needed, the amounts of all inputs and outputs are calculated for the determined functional unit. As the result of the inventory analysis part, all inputs and outputs of the system in consideration are listed with the quantities.

The type and quantity of the system's inputs and outputs is an important factor in diversifying and customizing the study. To have an effective analysis, data should be provided from a reliable source; also, a sufficient amount of data should be used. Moreover, data must have been obtained from the region determined for the study, from the process or product under study, and in a short period of time. In other words, reliability, completeness, temporal correlation, geographical correlation, and technological correlation are important data quality indicators for LCA.

Obtained data should be evaluated, validated, and related to the functional unit of the system. If it is needed, allocation procedures which are relating the impacts to the unit processes can be done (Khasreen et al., 2009).

2.3.3 Impact Assessment

Impact assessment, the third step of the LCA, tries to show the relation between inputs and outputs of the system with impact indicators. The indicators state the

contribution of the determined impact categories to environmental load. Definition, classification, characterization, normalization, and weighting parts are located in this step. The normalization and weighting steps of the study are optional (Khasreen et al., 2009).

- **Definition:** Relevant impact categories with the aim of the study are selected and defined in this part.
- **Classification:** Inventories of the system are classified according to their contribution to the impact categories (Khasreen et al., 2009).
- **Characterization:** With the help of the characterization factor, the results of classification convert to a relative contribution to the environment.
- **Normalization:** The part provides impact indicators of the study for comparison by expressing in a way. In other words, all impacts of the system get the same unit.
- **Weighting:** The part which is based importance or relevance of the different impact categories depends on the incorporation of ethical, political, and social factors (Menoufi, 2011).

Commonly used impact categories, their classification and characterization are given in Table 7.

Table 7. Classification and Characterization of Common Impact Categories (Khasreen et al., 2009)

Impact Category	Classification	Characterization Factor
Global Warming	Carbon Dioxide (CO ₂) Nitrogen Dioxide (NO ₂) Methane (CH ₄) Chlorofluorocarbons (CFC _s) Hydro chlorofluorocarbons (HCFC _s) Methyl Bromide (CH ₃ Br)	Global Warming Potential
Acidification	Sulfur Oxides (SO _x) Nitrogen Oxides (NO _x) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH ₄)	Acidification Potential

Table 7. Classification and Characterization of Common Impact Categories
(Continued)

Impact Category	Classification	Characterization Factor
Eutrophication	Phosphate (PO ₄) Nitrogen Oxide (NO) Nitrogen Dioxide (NO ₂) Nitrates Ammonia (NH ₄)	Eutrophication Potential
Ozone Depletion	Chlorofluorocarbons (CFCs) Hydro chlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH ₃ Br)	Ozone Depletion Potential

Impact categories in which environmental issues caused by the product or process are expressed are divided into two; are categories called midpoint and endpoint (damage). While midpoint categories are more specific areas that input and output dosages contribute to, endpoint categories, which can include a contribution of more than one midpoint category, are the direct damage to areas such as human health, ecosystem quality, and resources, etc.

2.3.4 Interpretation

Interpretation, the last step of the LCA, analyses the results from the previous step, the impact assessment, to reach a conclusion. If it is needed, verification of the result of the study can be done. There are three perspectives on the verification of the results.

Completeness check: Completeness of the study is ensured about the defined significant environmental issues in the goal and scope of the study.

Sensitivity check: If the final results can be affected by uncertainties in the study, sensitivity analysis is done to check the confidence of the results. In the analysis, inventory is changed systematically by a type of what-if analysis.

Consistency check: Consistency of the procedures, methods, and data evaluated in this part. Also, their coherency with the goal and scope of the study is checked (Moresi et al., 2020).

2.3.5 LCA Software

To have a calculation for environmental impact of a product or process, software tools were developed. The softwares, which can be used in LCA studies, can be listed as SimaPro, GaBi, OpenLCA, One Click LCA, Umberto etc. (The European Product Bureau, 2020). SimaPro is one of the commonly used software to have an LCA. The software gives a chance to analyze the life cycles of a product or process in a systematic way. It measures the potential environmental impact of the system and identifies the hotspots of the supply chain from extraction of raw materials to disposal (*About Simapro*, 2022).

In short, SimaPro has a facilitating role in the inclusion of all life cycle steps of the product or process in the analysis and in modeling the effects of the determining system on the complex environmental system. Moreover, the software provides the user with correct and fast incorporation of the inventory of the study into the system with the help of the database.

2.4 LCA for the Textile Wastewater Treatment

With the emergence of the concept of LCA, studies have been started to examine the environmental impacts of the production processes or treatment processes of the products in different areas. The fact that there are lots of different industries, also each of these industries includes different processes and technologies, has increased the diversity of the studies.

LCA studies are carried out in order to calculate the environmental impact of the treatment processes. Different advanced treatment methods cause different environmental impacts due to their different energy, water, and chemical consumption.

To date, many different studies have been carried out regarding the LCA of tertiary treatment of micropollutants. In the present section, a short review of these studies is given.

In the study of Muñoz et al. (2007), where solar-driven-photo-Fenton oxidation, ozone oxidation, and GAC treatment methods combined with biological treatment were compared using alphanethyl-phenylglycine (MPG) as a target substance, it was found that the solar-driven-photo-Fenton process coupled with biological treatment has a lower environmental impact in six of nine impact categories (global warming, ozone depletion, human toxicity, freshwater aquatic toxicity, photochemical ozone formation, acidification, eutrophication, energy consumption, and land use). When ozone and GAC are compared, it has been observed that GAC has lower environmental impacts than ozone oxidation.

In the study of Igos et al. (2012), the effect of discharging micropollutants without treatment was not found to be very high. In addition, activated carbon treatment, ozonation, and UV, which are advanced treatment methods, were compared. Activated carbon and ozone treatment were found to be preferable to UV.

The study by Zepon Tarpani & Azapagic (2018) includes an LCA of 4 advanced treatment processes used to eliminate pharmaceutical pollutants. In the study, nanofiltration, GAC, ozonation, and solar photo Fenton processes were compared. It was seen that nanofiltration has the most negligible environmental impact in 13 of the 18 categories. Also, the GAC process follows nanofiltration with five categories out of 18.

In the study of Arzate et al. (2019), solar photo Fenton and ozone purification systems were compared, and it was observed that the solar photo Fenton process has about six times more environmental impact. It has been determined that this observed difference is due to the chemical reactants used in the solar photo Fenton process.

The study of Li et al. (2019), which was conducted with 126 micropollutants from pharmaceutical or personal care products, evaluated its environmental impacts of it. When treatment methods of activated carbon, ozone, and membrane are analyzed, it has been determined that electricity consumption is the input that creates the environmental impact.

In the study of Nakhate et al. (2020), textile wastewater is subjected to treatment processes, including activated carbon filter and ozone processes. The result of the

study, when activated carbon and ozone processes are compared, it is observed that the environmental impact of the ozone process is higher than the activated carbon process in nine of the nine mid-point impact categories.

In the study by Liu et al. (2020), an LCA of 110 micropollutants in the Yarlung Tsangpo river was made. It was seen that discharged micropollutants had the highest impact on the chronic and acute toxicology categories.

In the study of Risch et al. (2022), an LCA was conducted to compare the treatment with GAC and ozonation processes for 65 micropollutants in different chemical groups. In 13 of the 15 identified impact categories, treatment with ozone produced from oxygen had a higher environmental impact compared to treatment with GAC.

In contrast to the life cycle analysis studies conducted so far, this study is based on the micropollutants found in textile wastewater. Ozone and GAC processes, which are two commonly used methods in the treatment of micropollutants, have been compared. Inputs and outputs were obtained by literature review; also, average values were used rather than a case study. It is aimed that this study will form a basis for the work to be done in the sector.



CHAPTER 3

METHODOLOGY

The following chapter presents the study approach and the LCA methodology applied in the study.

3.1 Study Approach

In this study, the potential adverse environmental impacts of tertiary treatment methods, which are GAC and ozonation, applied for the removal of micropollutants from the secondary treated textile wastewater, were evaluated and compared using the LCA approach.

First, micropollutants that typically exist in textile wastewaters were identified by a comprehensive literature review. The achievable minimum, average and maximum effluent concentrations of these micropollutants' by the GAC adsorption and ozone treatment was determined by the literature review, as well. If there was not any data about the concentration of a micropollutant in the tertiary effluent, its effluent concentration was estimated by assuming the average removal efficiency for the tertiary treatment of the secondary effluent. In the following paragraph, the approach adopted to evaluate this average removal efficiency is provided.

Switzerland is one of the countries that fulfill the requirements of the "Water Framework Directive" which aims to protect and improve water quality in all waters. In this context, it has been determined that advanced treatment methods can provide at least 80% removal of micropollutants from the secondary urban wastewater treatment plants' effluents (Derco et al., 2021). Another study by Ateş (2019) reported that treatment methods of activated carbon and ozone oxidation could provide over 80% removal for most micropollutants that are present in textile effluent. In addition, 80% treatment efficiency was found reasonable and taken as a

basis in different studies, which are reported by Bonvin et al. (2016) and Eggen et al. (2014) on micropollutant treatment.

Considering all these background studies, the treatment performance for the micropollutants for which the removal efficiency is not available for activated carbon and ozone treatment was assumed as 80%.

To evaluate the validity of this assumption, two different sensitivity analyses were conducted. Conducted sensitivity analyses were Sensitivity Analysis in Micropollutant Concentration for GAC and Sensitivity Analysis in Micropollutant Concentration for Ozonation. The analyses were conducted between the minimum and maximum discharge concentrations of micropollutants. It was tested by changing the ratio of adverse environmental impacts of these two methods for changing micropollutant discharge concentration, which was affected by treatment efficiency, with the sensitivity analysis.

Secondly, after determining of micropollutant concentration, the inventories of the system were detected, which are dosages of GAC and ozone, consumed energy inputs of the treatment processes, used water and chemicals in the process, and emissions of the system. While these inventories were found, the average values from the literature review were taken as a basis.

The functional unit was selected as 1 m³ of secondary treated wastewater. The system boundary of the study is given in Figure 5. Also, the system boundary of GAC adsorption and ozone treatment is detailed in Figure 6 and Figure 7.

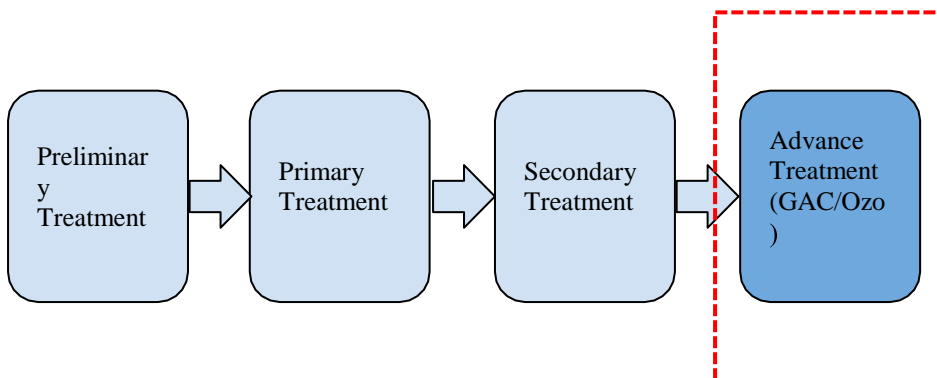


Figure 5. System Boundary

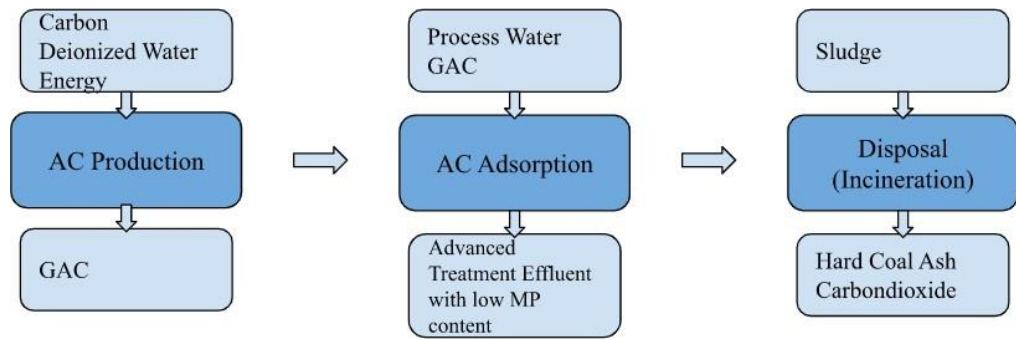


Figure 6. GAC Adsorption System Boundary

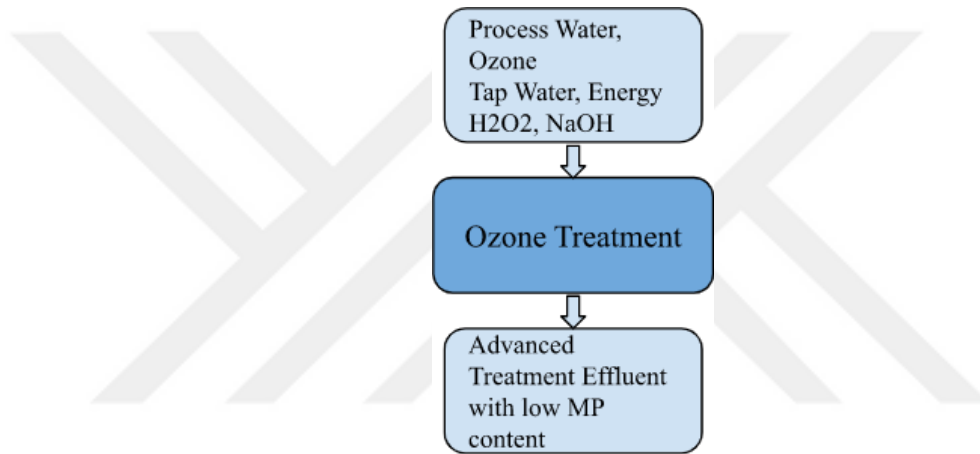


Figure 7. Ozone Treatment System Boundary

As shown, the system boundary starts at the beginning of the tertiary treatment processes, which are GAC adsorption and ozonation processes, and ends at the exit of the tertiary treatment process. In the study, the gate-to-gate approach was adopted.

3.2 LCA Methodology

The software of SimaPro PhD Version 9.2.0.2 was used to conduct an LCA of the GAC adsorption and ozone treatment of the secondary textile wastewater following the steps of goal and scope definition, inventory analysis, impact assessment, and interpretation of the study.

3.2.1 Goal and Scope Definition

The goal of the study is to make a gate-to-gate analysis of potential adverse environmental impacts of GAC adsorption and ozonation for removing micropollutants from the secondary treated textile wastewater. The functional unit of the study was set as 1 m³ secondary treated textile wastewater, and three different scenarios and sensitivity analyses were studied.

Table 8. The Goal of Scenarios and Sensitivity Analysis

Scenarios	Goal
GAC Adsorption	To evaluate the potential adverse impacts of the GAC adsorption for 15 different environmental impact categories for the removal of micropollutants.
Base-case Ozone Treatment	To measure the potential adverse environmental impacts of the base-case ozone treatment for 15 different impact categories.
Comparison of GAC and Ozonation	To compare potential adverse environmental impacts of GAC and ozone treatment for the base and minimum/base/maximum cases for 15 different impact categories is aimed.
Sensitivity Analysis	To test the sensitivity of the system to <ul style="list-style-type: none">• the incineration of used GAC,• The ozone dose• The effluent micropollutant concentration for 15 different impact categories.

The goal of the study according to the three scenarios and sensitivity analysis considered is given in Table 8. The sensitivity analysis was conducted separately for both GAC and ozone treatments. In GAC adsorption, the sensitivity of the system to the final disposal of used GAC and the micropollutant effluent concentration was evaluated. The disposal method for the used activated carbon was considered as incineration, taking into account the absence of an activated carbon regeneration facility in Türkiye. Also, sensitivity analysis has been conducted for disposal

methods with the limitations of complete incineration and non-incineration. The fact that the sensitivity of the incineration process is high means that the potential adverse impact of this process on the environment is high. The high sensitivity of incineration will indicate that alternative disposal methods should be evaluated in future studies. Also, in GAC adsorption, the sensitivity of micropollutant discharge concentration is evaluated. In ozone treatment, the sensitivity of ozone dosage and micropollutant discharge concentration is evaluated. The importance of the case of sensitivity of micropollutant discharge concentration in GAC and ozonation is explained in the Study Approach Part (Section 3.1). The case tests the reliability of the assumption of 80% micropollutant treatment efficiency of treatment methods of activated carbon and ozonation over the concentration of outlet of secondary treatment or discharge water. Otherwise, considering that the increase in micropollutant concentration in treated water would directly cause an increase in ozone dosage, the sensitivity of impacts to the ozone dosage is tested for the determining dosages.

3.2.2 Inventory Analysis

Inventory analysis is a crucial step of an LCA study to obtain accurate and reliable LCA analysis results. The primary inventory data source for the study was the literature. A comprehensive literature review was conducted to perform the LCA inventory analysis. When needed, the database of SimaPro was used as well, giving priority to the Ecoinvent v3.6 database. So, the data used for the inventory of LCA was partly from laboratory-scale studies and partly from large-scale applications. Therefore, it is worth noting that this feature of the LCA inventory data may limit the usefulness of the study results concerning full-scale applications.

Inputs and outputs of the systems of GAC and ozonation treatment are shown in Figure 8. In addition, The process stages to which the inputs and outputs are related are defined in Table 9.

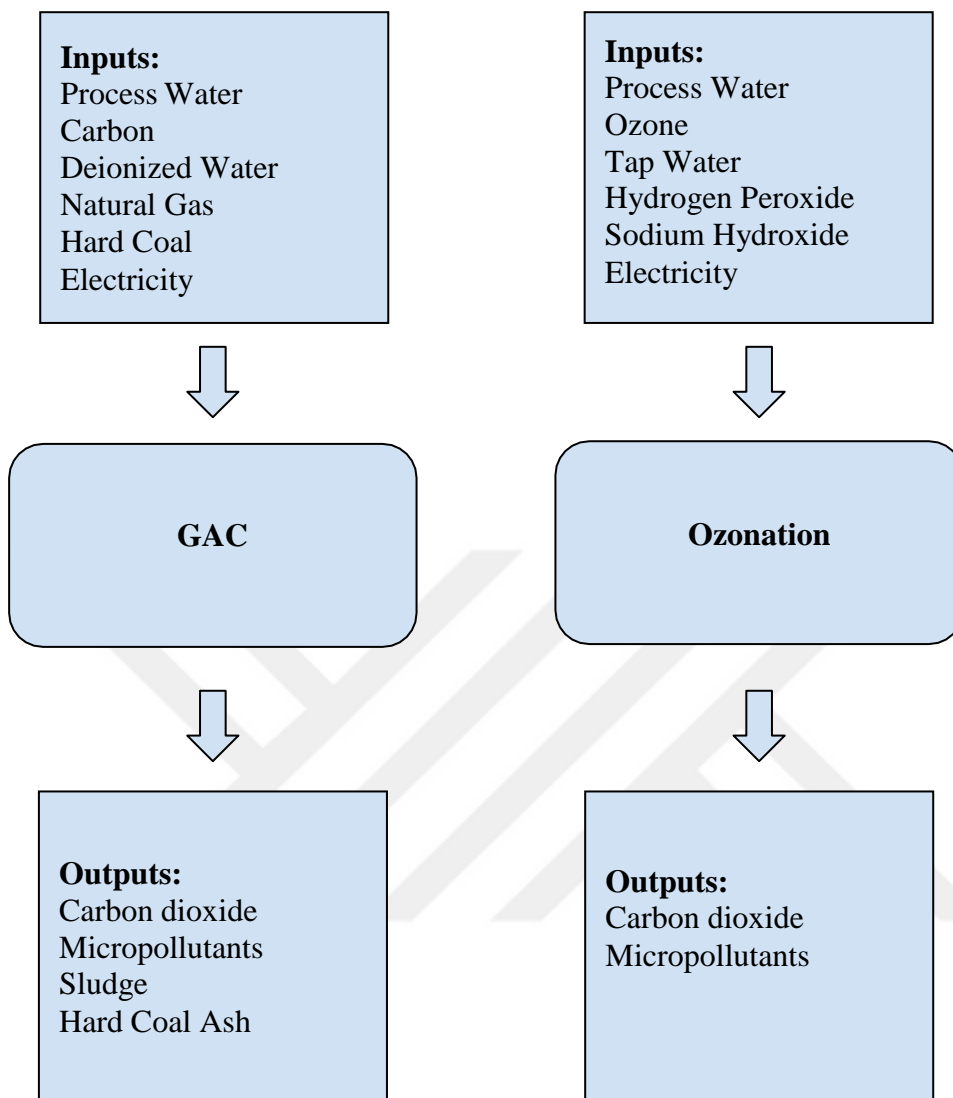


Figure 8. Input and Output of the Systems

Table 9. Relation of Input/Output to Process Stage

GAC Adsorption Input/Output	Related Process Stage
Process Water	Secondary Treated Water from the textile industry
Carbon	Used carbon for GAC production
Deionized water	Used water in the production of GAC
Natural Gas	Used energy in the production of GAC
Hard Coal	Used energy in the production of GAC
Electricity	Used energy in production and process
Carbon dioxide	The output of GAC production
Micropollutants	Discharged MP after advanced treatment
Sludge (hazardous waste incineration)	Used GAC with treated MP (entered the software as refinery sludge)
Hard Coal Ash	Ash remaining after incineration of sludge from used GAC
Ozonation Input/Output	Related Process Stage
Process Water	Secondary Treated Water from the textile industry
Ozone	Used ozone for ozonation (By entering the amount of used ozone, the inputs and outputs used for ozone production in the database of the software are included in the system.)
Tap water	Water used to add the produced ozone to secondary treated water
Hydrogen Peroxide	Chemicals used to improve the treatment process
Sodium Hydroxide	Chemicals used to improve the treatment process
Electricity	Used energy in the process
Carbon dioxide	The output of ozone usage (ozonation process)
Micropollutants	Discharged MP after advanced treatment

If there are different alternative codes for inputs and outputs in the database of SimaPro, the used codes in the study are listed below.

- De-ionized water, reverse osmosis, production mix, at plant, from surface water
- Tap water (CA-QC) market for
- Natural gas, high pressure (CZ) Import from RU

- Hard coal, from underground and open pit mining, consumption mix, at power plant
- Electricity, medium voltage Tr
- Hard coal ash (CH) treatment of, sanitary landfill
- Refinery sludge (CH) treatment of, hazardous waste incineration
- Ozone, liquid (RER) production
- Sodium hydroxide (50% NaOH), production mix/RER Mass
- Hydrogen peroxide, without water, in 50% solution state (GLO) market

3.2.2.1 GAC Adsorption

In this scenario, the inventory formed via the literature review was introduced into the software as inputs and outputs. Wastewater processed, activated carbon used, deionized water used, natural gas consumed, hard coal used, and electricity consumed was entered as input data for the scenarios studied. The wastewater expresses the secondary treated water from the secondary treatment processes. Activated carbon used is the carbon used in the tertiary treatment of the secondary effluent. The deionized water used is the water used during the activated carbon production process. Also, the energy demand of GAC production and process usage was entered into software as the inventory of the system. Since the GAC dosage could not be directly entered into the system as an input in the GAC adsorption, the energy, water, and carbon requirements to be used during the production of the GAC and the carbon dioxide emission to be generated were also entered into the system as basic input and output. In energy consumption inventories, electricity demand was entered separately as used electricity in the process (0.04 kWh) and used electricity in GAC production (0.0161 kWh). In addition to this, as the output of the system, carbon dioxide emission and discharged micropollutants, and produced sludge was entered into the software. Sludge in the system is organic-containing sludge that is produced due to the completion of the life of the activated carbon used in advanced treatment. Incineration was set as the disposal method of the produced sludge. It was assumed that the incineration process would take place at 80% efficiency. The efficiency expresses the combustion efficiency measure of the sludge in percentage. A 100% combustion efficiency is accepted as ideal, whereas in reality, the efficiency is affected by impurities, temperature, or air level. Also, the ashes remaining from

the combustion process were entered as the output of the system. The inventory table of the scenario of “GAC Adsorption” is given in Table 10.

Table 10. Life Cycle Inventory for GAC Adsorption, Normalized to the Functional Unit for Base Case Scenario

Inputs	Amount	Unit	Reference
GAC Production			
Process Water	1000 (1)	kg (m ³)	Functional Unit
Carbon	0.01	kg	Mailler et al., 2016
Deionized water	0.122	kg	Zepon Tarpani & Azapagic, 2018
Natural Gas	0.00348	m ³	Zepon Tarpani & Azapagic, 2018
Hard Coal	0.0209	kg	Zepon Tarpani & Azapagic, 2018
Electricity	0.04+0.0161	kWh	Muñoz et al., 2007
Outputs			
Emission to air			
Carbon dioxide	2.4	kg	Muñoz et al., 2007
Emission to Water			
Trimethoprim	11.46	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Diclofenac	171.34	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Ketoprofen	74.34	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021
Sulfadiazine	13.52	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021

Tablo 10. Life Cycle Inventory for GAC Adsorption, Normalized to the Functional Unit for Base Case Scenario (Continued)

Inputs	Amount	Unit	Reference
Sulfamethoxazole	410.41	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Anthracene	2.38	µg	Kucuk et al., 2021
Fluoranthene	2.0	µg	Kucuk et al., 2021
Hexachlorocyclohexane	9.14	µg	Kucuk et al., 2021
Nonylphenol	48.2	µg	Kucuk et al., 2021
Dioxins	0.04	µg	Kucuk et al., 2021
Cypermethrin	21.0	µg	Kucuk et al., 2021
Acenaphthylene	2.5	µg	Kucuk et al., 2021
Benzyl benzoate	32.38	µg	Kucuk et al., 2021
Bisphenol A	3.58	µg	Kucuk et al., 2021
Diphenyl ether	737.0	µg	Kucuk et al., 2021
Phenanthrene	16.64	µg	Kucuk et al., 2021
Fluorene	4.46	µg	Kucuk et al., 2021
Carbendazim	23.9	µg	Kucuk et al., 2021
Epoxiconazole	11.0	µg	Kucuk et al., 2021
Outputs to Technosphere			
Sludge (hazardous waste incineration)	0.008	kg	Mailler et al., 2016
Hard Coal Ash	0.002	kg	Mailler et al., 2016

3.2.2.2 Ozone Treatment

Scenario inventories were entered into software as inputs and outputs. The input of the scenario, process water, ozone, tap water, hydrogen peroxide, sodium hydroxide, and electricity inputs, was entered. The process water expresses the treated water, which exits from the secondary treatment process. The ozone dosage entered into the system considering ozone transfer efficiency. Ozone transfer efficiency was accepted

as 75% in the study. Therefore, for the base case, the transferred ozone dosage would be 20 g which is 75 % of 26.67 grams. Also, chemicals which were hydrogen peroxide and sodium hydroxide to enhance the ozone treatment efficiency were entered as the input. Used tap water and used energy to add ozone to treated water were taken into consideration as inputs. Unlike the GAC adsorption, the energy and other inputs used in the ozone production step have not entered the system. The reason was that when the ozone dosage was entered into the system as an input, the resources consumed during the production of this ozone were already included in the calculation step of the system. Also, used chemicals such as hydrogen peroxide and sodium hydroxide to improve the treatment efficiency of the system were entered as inputs. Otherwise, carbon dioxide and discharged micropollutant concentrations were entered as the output of the scenario. The inventory table of the scenario of “Base-case Ozone Treatment” is given in Table 11.

Table 11. Life Cycle Inventory for Ozone Treatment, Normalized to the Functional Unit for Base Case Scenario

Inputs	Amount	Unit	Reference
Process Water	1000 (1)	kg (m ³)	Functional Unit
Ozone	26.67	kg	Muñoz et al., 2007
Tap water	0.110	kg	Muñoz et al., 2009
Hydrogen Peroxide	25.0	g	Arzate et al., 2019 Kovalova et al., 2013
Sodium Hydroxide	0.08	kg	Shefet & Ben-Ghedalia, 1982
Electricity	0.6	kWh	Arzate et al., 2019 Wardenier et al., 2019
Outputs	Amount	Unit	
Emission to air			
Carbon dioxide	0.66	kg	Muñoz et al., 2007
Emission to Water			
Trimethoprim	3.71	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021

Inputs	Amount	Unit	Reference
			Zepon Tarpani & Azapagic, 2018
Diclofenac	34.58	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Ketoprofen	198.66	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021
Sulfadiazine	61.5	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021
Sulfamethoxazole	52.29	µg	Muñoz et al., 2009 Li et al., 2019 Igos et al., 2021 Zepon Tarpani & Azapagic, 2018
Anthracene	2.38	µg	Kucuk et al., 2021
Fluoranthene	2.0	µg	Kucuk et al., 2021
Hexachlorocyclohexane	9.14	µg	Kucuk et al., 2021
Nonylphenol	48.2	µg	Kucuk et al., 2021
Dioxins	0.04	µg	Kucuk et al., 2021
Cypermethrin	21.0	µg	Kucuk et al., 2021
Acenaphthylene	2.5	µg	Kucuk et al., 2021
Benzyl benzoate	32.38	µg	Kucuk et al., 2021
Bisphenol A	3.58	µg	Kucuk et al., 2021
Diphenyl ether	737.0	µg	Kucuk et al., 2021
Phenanthrene	16.64	µg	Kucuk et al., 2021
Fluorene	4.46	µg	Kucuk et al., 2021
Carbendazim	23.9	µg	Kucuk et al., 2021
Epoxiconazole	11.0	µg	Kucuk et al., 2021

3.2.3 Comparison of GAC and Ozonation

The scenario consists of two parts. In the first part, a comparison was made for the base cases of GAC and ozone treatment. In the second part, the comparison was made with the minimum, base, and maximum dosages of GAC and ozone treatment.

3.2.3.1 Comparison of GAC and Ozonation for the Base Case Scenarios

For the scenario, inventories of the scenario of GAC Adsorption LCA for Base Case and scenario of Ozone Treatment LCA for Base Case were used. In the scenario, two treatment methods were compared for the base case.

3.2.3.2 Comparison of GAC and Ozonation for Minimum/Base /Maximum Dosage Case

Detected common micropollutants minimum, average and maximum concentrations were used in this scenario. While the concentration of micropollutants was changed into three different categories as a minimum, base, and maximum, the dosages of GAC and ozone used were changed to a minimum, average and maximum. A literature review was conducted to determine the dosage of GAC and ozone. The amount of used water and energy in GAC production was changed at the required rate. Also, sludge produced as output has been changed. Otherwise, process water, which was the functional unit of the system, has not been changed. Also, the chemicals used in ozone treatment, which were hydrogen peroxide and sodium hydroxide, have not been changed because their dosages were related to the amount of process water. In addition to this, the energy used in the treatment process has not been changed because it was mostly related to the amount of process water. Inventories for the average concentration, inventories of the scenario of GAC Adsorption, and scenario of Base-case Ozone Treatment are used. Inventories for minimum and maximum dosages of GAC and ozone were given in Table 12 and Table 13.

Table 12. Inventories of GAC Minimum and Maximum Dosages

GAC Adsorption Minimum/Maximum Case					
GAC Minimum Dosage Inventories			GAC Maximum Dosage Inventories		
Inputs	Amount	Unit	Inputs	Amount	Unit
Process Water	1000 (1)	kg (m ³)	Process Water	1000 (1)	kg (m ³)
Carbon	0.005	kg	Carbon	0.02	kg
Deionized water	0.061	kg	Deionized water	0.244	kg
Natural Gas	0.00174	m ³	Natural Gas	0.00696	m ³
Hard Coal	0.0104	kg	Hard Coal	0.0417	kg
Electricity (for usage and production)	0.04+0.00805	kWh	Electricity (for usage and production)	0.04+0.0322	kWh
Outputs	Amount	Unit	Outputs	Amount	Unit
Emission to air			Emission to air		
Carbon dioxide	2.4	kg	Carbon dioxide	2.4	kg
Emission to Water			Emission to Water		
Trimethoprim	1.36	µg	Trimethoprim	34.2	µg
Diclofenac	45.60	µg	Diclofenac	418.95	µg
Ketoprofen	1.44	µg	Ketoprofen	256.5	µg
Sulfadiazine	3.8	µg	Sulfadiazine	43.3	µg
Sulfamethoxazole	122.4	µg	Sulfamethoxazole	820.66	µg
Anthracene	0.32	µg	Anthracene	8.04	µg
Fluoranthene	0.24	µg	Fluoranthene	8.0	µg
Hexachlorocyclohexane	1.12	µg	Hexachlorocyclohexane	59.6	µg
Nonylphenol	0.9	µg	Nonylphenol	555.0	µg
Dioxins	0.004	µg	Dioxins	0.4	µg
Cypermethrin	6.14	µg	Cypermethrin	75.0	µg
Acenaphthylene	1.1	µg	Acenaphthylene	6.8	µg
Benzyl benzoate	0.76	µg	Benzyl benzoate	305.8	µg
Bisphenol A	0.2	µg	Bisphenol A	21.6	µg
Diphenyl ether	2.46	µg	Diphenyl ether	5169.4	µg
Phenanthrene	0.3	µg	Phenanthrene	73.76	µg

Table 12. Inventories of GAC Minimum and Maximum Dosages (Continued)

GAC Adsorption Minimum/Maximum Case					
GAC Minimum Dosage Inventories			GAC Maximum Dosage Inventories		
Fluorene	0.3	µg	Fluorene	21.16	µg
Carbendazim	2.0	µg	Carbendazim	159.96	µg
Epoxiconazole	1.2	µg	Epoxiconazole	64.8	µg
Outputs to Technosphere			Outputs to Technosphere		
Sludge (hazardous waste incineration)	0.004	kg	Sludge (hazardous waste incineration)	0.016	kg
Hard Coal Ash	0.001	kg	Hard Coal Ash	0.004	kg

Table 13. Inventories of Ozone Minimum and Maximum Dosages

Ozone					
Ozonation Minimum Dosage Inventories			Ozonation Maximum Dosage Inventories		
Inputs	Amount	Unit	Inputs	Amount	Unit
Process Water	1000 (1)	kg (m ³)	Process Water	1000 (1)	kg (m ³)
Ozone	13.34	g	Ozone	53.33	g
Tap water	0.055	kg	Tap water	0.220	kg
Hydrogen Peroxide	25.0	g	Hydrogen Peroxide	25.0	g
Sodium Hydroxide	0.08	kg	Sodium Hydroxide	0.08	kg
Electricity	0.6	kWh	Electricity	0.6	kWh
Outputs	Amount	Unit	Outputs	Amount	Unit
Emission to air			Emission to air		
Carbon dioxide	0.66	kg	Carbon dioxide	0.66	kg
Emission to Water			Emission to Water		
Trimethoprim	0.68	µg	Trimethoprim	5.7	µg
Diclofenac	4.56	µg	Diclofenac	71.82	µg
Ketoprofen	33.12	µg	Ketoprofen	499.5	µg
Sulfadiazine	0.76	µg	Sulfadiazine	175.77	µg
Sulfamethoxazole	11.09	µg	Sulfamethoxazole	121.99	µg

Table 13. Inventories of Ozone Minimum and Maximum Dosages (Continued)

Ozone					
Ozonation Minimum Dosage Inventories			Ozonation Maximum Dosage Inventories		
Anthracene	0.32	µg	Anthracene	8.04	µg
Fluoranthene	0.24	µg	Fluoranthene	8.0	µg
Hexachlorocyclohexane	1.12	µg	Hexachlorocyclohexane	59.6	µg
Nonylphenol	0.9	µg	Nonylphenol	555.0	µg
Dioxins	0.004	µg	Dioxins	0.4	µg
Cypermethrin	6.14	µg	Cypermethrin	75.0	µg
Acenaphthylene	1.1	µg	Acenaphthylene	6.8	µg
Benzyl benzoate	0.76	µg	Benzyl benzoate	305.8	µg
Bisphenol A	0.2	µg	Bisphenol A	21.6	µg
Diphenyl ether	2.46	µg	Diphenyl ether	5169.4	µg
Phenanthrene	0.3	µg	Phenanthrene	73.76	µg
Fluorene	0.3	µg	Fluorene	21.16	µg
Carbendazim	2.0	µg	Carbendazim	159.96	µg
Epoxiconazole	1.2	µg	Epoxiconazole	64.8	µg

3.2.3.3 Sensitivity Analysis

Two different sensitivity analysis has been conducted for each treatment process which was GAC and ozonation. In the first sensitivity analysis of GAC adsorption, the incineration percentage was changed between 0-100 %. In the second sensitivity analysis of GAC adsorption, micropollutant concentration was changed between the minimum and maximum values. Otherwise, in the first sensitivity analysis of ozone treatment, ozone dosages were changed between the minimum to maximum dosages. In the second sensitivity analysis of ozone treatment, micropollutant concentration was changed between the minimum and maximum values.

In LCA studies, the number of runs is usually determined between 1000 and 10000. This number determines how many times the software will be run by taking reference

from the points located between the determined maximum and minimum value (Heijungs, 2020). In this study, the fixed number of run is determined as 5000, which is the average of the typical value, and was taken as a basis. All sensitivity cases run 5000 times.

Changed inventories for sensitivity analysis for GAC and ozone treatment are given in Table 14 and Table 15.

Table 14. Inventory of Sensitivity Analysis for GAC

Sensitivity Analysis for GAC		
Incineration		
Outputs to Technosphere	Range	Unit
Sludge (hazardous waste incineration)	0-0.01	kg
The Inventories are taken as the same as the base case		
Micropollutants	Range	Unit
Micropollutant dosages	Min-Max	µg
The Inventories are taken as the same as the base case		

Table 15. Inventory of Sensitivity Analysis for GAC

Sensitivity Analysis for Ozonation		
Ozone Dosage	Range	Unit
Ozone dosages are taken as a variable at the min-max range	13.34-53.33	g
The Inventories are taken as the same as the base case		
Micropollutants	Range	Unit
Micropollutant dosages are taken as a variable at the min-max range	Min-Max	µg
The Inventories are taken as the same as the base case		

3.2.4 Impact Assessment

Endpoint and midpoint methods are located in SimaPro. Midpoint ones contain fate, emissions, and exposure. In addition to this, endpoint ones contain fate emissions, exposure, effect, and damage. Although midpoint results have fewer uncertainties than endpoints, interpretation of midpoints is complicated. In other words, despite the uncertainties, interpretation of the result of endpoint methods is easier. Because of this reason, the method, which is IMPACT 2002+, has category indicators at the endpoint level based on this study. The method was developed by the authors of the impact assessment method. Also, in the software of SimaPro, it is possible to develop new methods and change the impact categories.

Indeed, the first step in the impact assessment is the selection of the impact assessment methods to be used. There are different assessment methods embodied in SimaPro software with different capabilities (Table 16). The IMPACT 2002+ was selected as the impact assessment method as it has all the assessment steps of Characterization, Damage Assessment, Normalization, Weighting, and Single Score.

Table 16. The Capabilities of Impact Assessment Methods Available in the SimaPro Software (Pré, 2020)

IMPACT ASSESSMENT METHODS	Characterization	Damage Assessment	Normalization	Weighting	Single Score
CML IA	+		+		+
Environmental Prices	+		+	+	
Ecological Scarcity 2013	+		+	+	+
EDIP 2003	+		+	+	+
EF Method	+		+	+	
EDP 2018	+		+	+	

IMPACT ASSESSMENT METHODS	Characterization	Damage Assessment	Normalization	Weighting	Single Score
EPS 2015d and EPS 2015dx	+		+	+	
ILCD 2011 Midpoint+	+		+		
IMPACT 2002+	+	+	+	+	+
ReCiPe 2016	+	+	+	+	+
BEES	+		+	+	
TRACI 2.1	+		+		
CUMULATIVE ENERGY DEMAND	+			+	+
CUMULATIVE ENERGY DEMAND (LHV)	+			+	+
CUMULATIVE EXERGY DEMAND	+		+	+	+
ECOSYSTEM DAMAGE POTENTIAL (EDP)	+			+	+
GREENHOUSE GAS PROTOCOL	+		+	+	
IPCC 2013	+		+	+	
Selected LCI Results	+				
USEtox 2	+	+			
CML 1992	+		+		
Eco-Indicator 95	+		+	+	
Eco-Indicator 99	+	+	+	+	
Ecological Footprint	+		+	+	
Ecological Scarcity 2006	+		+	+	
Ecopoints 97			+	+	+
EDIP/UMIP 97	+		+	+	+
EPD (2008)	+		+	+	
EPD (2013)	+		+	+	
EPS 2000	+		+	+	
IPCC 2001 GWP	+		+	+	
IPCC 2007	+		+	+	

Table 16. The Capabilities of Impact Assessment Methods Available in the SimaPro Software (Continued)

IMPACT ASSESSMENT METHODS	Characterization	Damage Assessment	Normalization	Weighting	Single Score
ReCiPe	+	+	+	+	+

Method of IMPACT 2002+ (Impact Assessment of Chemical Toxics), which was developed by the Swiss Federal Institute of Technology, is a method developed for the impact assessment of chemical toxicants. The method makes measurements in 15 different categories (Figure 9). Measuring the environmental effects of chemical toxicants, which is the purpose of the development of this method and considering the extensive measurements made at 15 categories (on human health in aquatic and terrestrial areas or on climate change, etc.) by IMPACT 2002+ it has been identified for the purpose of the study and found appropriate to be used.

Another method that can be used in the LCA of tertiary water treatment methods is the ReCiPe 2016 Endpoint method. Similar to the IMPACT 2002+, this method can do characterization, damage assessment, normalization, and a single score estimation. In the present study, scenarios of GAC Adsorption and the comparison of GAC Adsorption and Ozonation for Base Case were also run with the ReCiPe 2016 Endpoint method. The results were found to be similar to those of the method of IMPACT 2002+ for both GAC Adsorption and Comparison of GAC Adsorption and Ozonation for Base Case scenarios for similar midpoint impact categories such as global warming, ionizing radiation, and ozone depletion. However, the ReCiPe 2016 Endpoint method was not preferred in the study because the method does not include global warming evaluation in endpoint categories. It is important to measure the global warming impact in the study where the disposal of the used GAC is determined as incineration. The method has the capability to measure characterization, damage assessment, normalization, weighting, and single score, which are defined below.

Characterization: In the characterization part of the impact assessment section, the contribution of the number of substances used to the midpoint level was multiplied by the characterization factor, which is already located at SimaPro. Also, the results are summed. The summed result shows the impact category indicator at the midpoint level.

Damage Assessment: In the damage assessment part, the impact category indicators at the midpoint level are related to at least one endpoint level category. Using a common unit for an endpoint/damage category is important for the summation of related categories. Damage factor units for each endpoint category are given in Table 17.

Normalization: The normalization part aims to show the overall environmental impact. For the aim, the impact of the endpoint categories is added. Because they have different units, equalization of the units is needed. For equalization, impact category values are crossed with the normalization factor. The factor expresses the environmental load in a location (country or continent) per person annually. The normalization factor for IMPACT 2002+ is given in Table 17 (Ölmez, 2011).

Weighting: Weight refers to the importance of an impact category. In this section, the midpoint and endpoint categories are multiplied by the weight factor, while the total impact is found.

Single Score: Finally, the values in the normalization or weighting sections are summed to reach the single score value.

The selected method IMPACT 2002+ includes 15 different midpoint impact categories, which are human toxicity carcinogenic effects, human toxicity non-carcinogenic effects (these two categories are sometimes grouped in one category: human toxicity), respiratory effects (due to inorganics), ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nitrification, land occupation, global warming, non-renewable energy consumption, and mineral extraction.

During the study, it was realized that some impact categories could be called different names in different methods of the SimaPro. In this scope, the impact category of photochemical oxidation is called respiratory organics in the result and discussion part of the study. In addition to this, the impact category of human toxicity is separated as carcinogens and non-carcinogens in the result and discussion part. Also, the method includes four different damage categories, which are human health, ecosystem quality, climate change, and resources. The relationship between midpoint categories and damage categories is given in Figure 9.

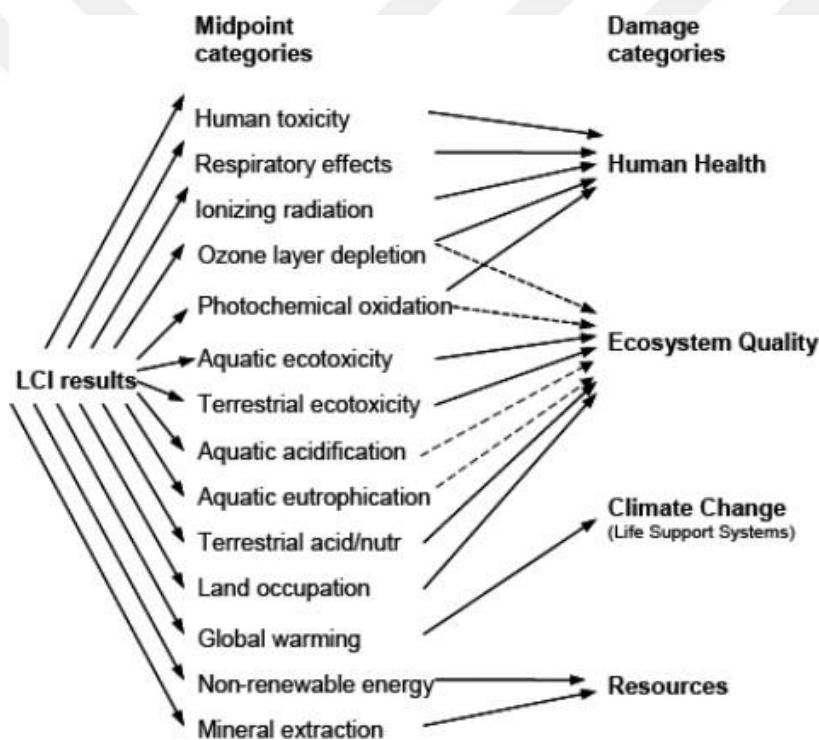


Figure 9. Relationship Between Midpoint Categories and Damage Categories (Pré, 2020)

Table 17. IMPACT 2002+ Impact Assessment Measure (Ölmez, 2011)

Midpoint category	Midpoint Reference Substance (Unit)	Endpoint/Damage category	Damage factor	Damage factor unit	Endpoint/Damage unit	Normalization factors in SimaPro	Normalized Damage Unit
Carcinogens	kg C ₂ H ₃ Cl eq	Human Health	2,8E-06	DALY / kg C ₂ H ₃ Cl eq	Disability Adjusted LifeYears (DALY)	141 Pt/DALY	Pt (Point) (1Pt=1000mPt)
Non-carcinogens	kg C ₂ H ₃ Cl eq		2,8E-06	DALY / kg C ₂ H ₃ Cl eq			
Respiratory inorganics	kg PM2.5 eq		0,0007	DALY / kg PM2.5 eq			
Ionizing radiation	Bq C-14 eq		2,1E-10	DALY / Bq C-14 eq			
Ozone layer depletion	kg CFC-11 eq		0,00105	DALY / kg CFC-11 eq			
Respiratory organics	kg C ₂ H ₄ eq		2,13E-06	DALY / kg C ₂ H ₄ eq			
Aquatic ecotoxicity	kg TEG water	Ecosystem Quality	5,02E-05	PDF*m ² *yr / kg TEG water	Potentially Disappeared Fraction (PDF)*m ² *yr	7,30E-5 Pt/PDF*m ² *yr	
Terrestrial ecotoxicity	kg TEG soil		0,00791	PDF*m ² *yr / kg TEG soil			
Terrestrial acid/nutrication	kg SO ₂ eq		1,04	PDF*m ² *yr / kg SO ₂ eq			
Land occupation	m ² org.arable		1,09	PDF*m ² *yr / m ² org.arable			
Aquatic acidification	kg SO ₂ eq		under development	under development	under development		
Aquatic eutrophication	kg PO ₄ eq		under development	under development	under development		
Global warming	kg CO ₂ eq	Climate Change	1	kg CO ₂ eq / kg CO ₂ eq	kg CO ₂ eq	0,000101 Pt/ kg CO ₂ eq	
Non-renewable energy	MJ primary	Resources	1	MJ primary / MJ primary	MJ	0,00000658 Pt/ MJ	
Mineral extraction	MJ surplus		1	MJ primary / MJ surplus			

The second column of the table shows the units which are used in Midpoint Level Analysis. Units are “kg substance S_{-eq}” (kg equivalent of a reference substance s) shows the reference substances amount that equals the impact of the determined pollutant. For example, for the impact category of global warming, all relevant substances turned to carbon dioxide equivalent to express the total impact. The fifth column of the table states the units which are used for Damage Level Analysis. Unit of DALY (Disability Adjusted Life Years) express the years of life lost because of premature death and the time of life which has lower quality due to an illness. Unit of PDF.m².y (Potentially Disappeared Fraction of Species Over a Certain Amount of m² during a certain amount of year) shows the fraction of species that disappeared on 1 m² area on earth's surface during the one year. MJ (Mega joule) expresses the needed energy to extract the resource. In the seventh column, the normalization factor is shown to convert all endpoints to a single score result. In the last column of the table, the unit of Normalized Damage Level Analysis is expressed. Unit of point (pers.y) measures the average impact in a category caused by a person during one year in Europe.

In addition to the unit of the categories, a description of midpoint categories is given in Table 18.

Table 18. Description of Midpoint Categories (Humbert et al., 2012)

Midpoint Category	Description
Human Toxicity (Carcinogens+ Non-carcinogens)	Represents all effects on human health, except respiratory effects caused by inorganics, effects of ozone layer depletion, ionizing radiation, photochemical oxidation. Estimated cumulative toxicity potentials expressed with specified mass (kg) of the chemical of Vinyl chloride (C ₂ H ₃ Cl).
Respiratory Inorganics	Measures to respiratory effects which are caused by air emitted inorganic substances. Measured damage for emissions into the air only is expressed as kg PM _{2.5} at the midpoint level

Midpoint Category	Description
Ionizing Radiation	Ionizing radiation potential because of emissions into air and water is measured. The midpoint characterization factor is expressed in Bq (Becquerel) Carbon-14 into air-eq.
Ozone Layer Depletion	US Environmental Protection Agency Ozone Depletion Potential List is used to obtain the midpoint damage. Also, the equivalent of the chemical Trichlorofluoromethane is used to express midpoint damage emitted into the air
Photochemical Oxidation (Respiratory Organics)	Damage of Photochemical Oxidation covers the impact on human health and impact on ecosystem quality. Impact on human health can be named effects of respiratory organics. Otherwise, impact on ecosystem quality refers to the impact of photochemical oxidation on growing plants. However, there is no available study to calculate the damage of photochemical oxidation on ecosystem quality, so only photochemical oxidations impact on human health part is calculated in this study. The characterization Factor of the midpoint impact is expressed in kg Ethylene eq.
Aquatic Ecotoxicity	The category quantifies the ecotoxicity effects on freshwaters (surface water). Midpoint Characterization Factor is expressed as Triethylene glycol in water. Also, the damaged unit is equal to PDF.m ² .y (Potential Disappeared Fraction of Species density with time).
Terrestrial Ecotoxicity	The category quantifies the ecotoxic effects of the substances in the aqueous phase of the soil. Characterization Factor is expressed as Triethylene glycol in the soil.
Terrestrial Acidification/nitrification	Terrestrial Acidification/ nitrification impact is measured in air only. Midpoint Characterization Factor is

Table 18. Description of Midpoint Categories (Humbert et al., 2012) (Continued)

Midpoint Category	Description
	expressed as kg sulfur dioxide eq into air.
Land Occupation	Damage of Land Occupation category is expressed in m ² org.arable (organic arable land).
Aquatic Acidification	Damage of Aquatic Acidification category is expressed in kg sulfur dioxide eq into the air.
Aquatic Eutrophication	Damage of the Aquatic Eutrophication category is expressed in kg Phosphate P-limited.
Global Warming	To quantify the global warming potential emissions into air, only the midpoint characterization factor of kg carbon dioxide equivalent is used.
Non-renewable Energy	To quantify the non-renewable energy consumption is calculated based on upper heating values. Midpoint Characterization Factor is expressed as Megajoule.
Mineral Extraction	To measure the impact category of mineral extraction midpoint Characterization Factor is expressed as Mega joule.

3.2.5 Interpretation

After the system's relevant input and outputs were compiled, the software was run to evaluate the potential adverse environmental impacts associated with the inventory of the system. To interpret the results of the study in relation to the objective of the study, the result of the study has been expressed as graphs and figures. Life Cycle Impact Assessment results of the first three scenarios evaluated under three main categories, which are characterization, damage assessment, normalization and the single score. The last part, which is called sensitivity analysis, is evaluated under the category of characterization.

CHAPTER 4

RESULT AND DISCUSSION

In this chapter, the results of the LCA study performed for two tertiary treatment scenarios, which are GAC adsorption and ozone oxidation treatment are given, and a comparison of the environmental impacts of GAC adsorption and ozonation treatment are presented.

The LCA study carried out is mainly based on the data gathered from the literature on the secondary treated textile effluent characteristics and the typical removal efficiencies for the two alternative tertiary treatment methods considered.

Section 4.1 presents an analysis of the life cycle impacts of GAC adsorption and ozonation treatment and also a comparison of these results. In the comparison of the scenarios, base dosage and minimum and maximum dosage cases were studied. During the analysis of the impacts of these treatment scenarios, the method of Impact 2002+ was used. For each scenario considered; characterization, damage assessment, and single score graphs are given.

Section 4.2 presents the results of the sensitivity analysis performed for both treatment methods. The sensitivity analysis part of the study was conducted with two different assumptions for each of the GAC adsorption and ozone oxidation.

4.1 LCA Results for Alternative Treatment Processes

The activated carbon adsorption with a carbon dose of 10 mg/L and ozone oxidation with an ozone dose of 20 mg/L was defined as the base case scenarios, and their life cycle impacts were evaluated first. In the following two sub-sections, the LCA results are presented for these two scenarios and then compared.

4.1.1 Base Case GAC Adsorption Treatment

In this scenario, potential adverse environmental impacts of the base-case activated carbon tertiary treatment of secondary textile wastewater were evaluated. The characterization, damage assessment, and single score analysis results are given in the following sections.

4.1.1.1 LCA Characterization Results for GAC Adsorption

Figure 10 presents the characterization graph that shows the potential adverse environmental impacts of the GAC adsorption at 15 different midpoint impact categories. Produced refinery sludge due to used GAC, produced hard coal ash due to incineration activity, consumed energy (electricity, hard coal, natural gas) for production and process of GAC and consumed deionized water are main contributors of the GAC adsorption. The impact categories considered are carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutrition, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, and mineral extraction. The results from the IMPACT 2002+ indicate that incineration and electricity usage are the two major contributors to the potential adverse environmental impacts (Figure 10). These two contributors constitute more than 90% of impacts in the categories of carcinogens, non-carcinogens, respiratory inorganics, terrestrial ecotoxicity, land occupation, aquatic eutrophication, and mineral extraction. Natural gas and hard coal consumption mainly contribute impact categories of ozone layer depletion and non-renewable energy, respectively. Used process water has a noticeable impact on the category of global warming. Otherwise, used activated carbon and deionized water are minor contributors to the scenario.

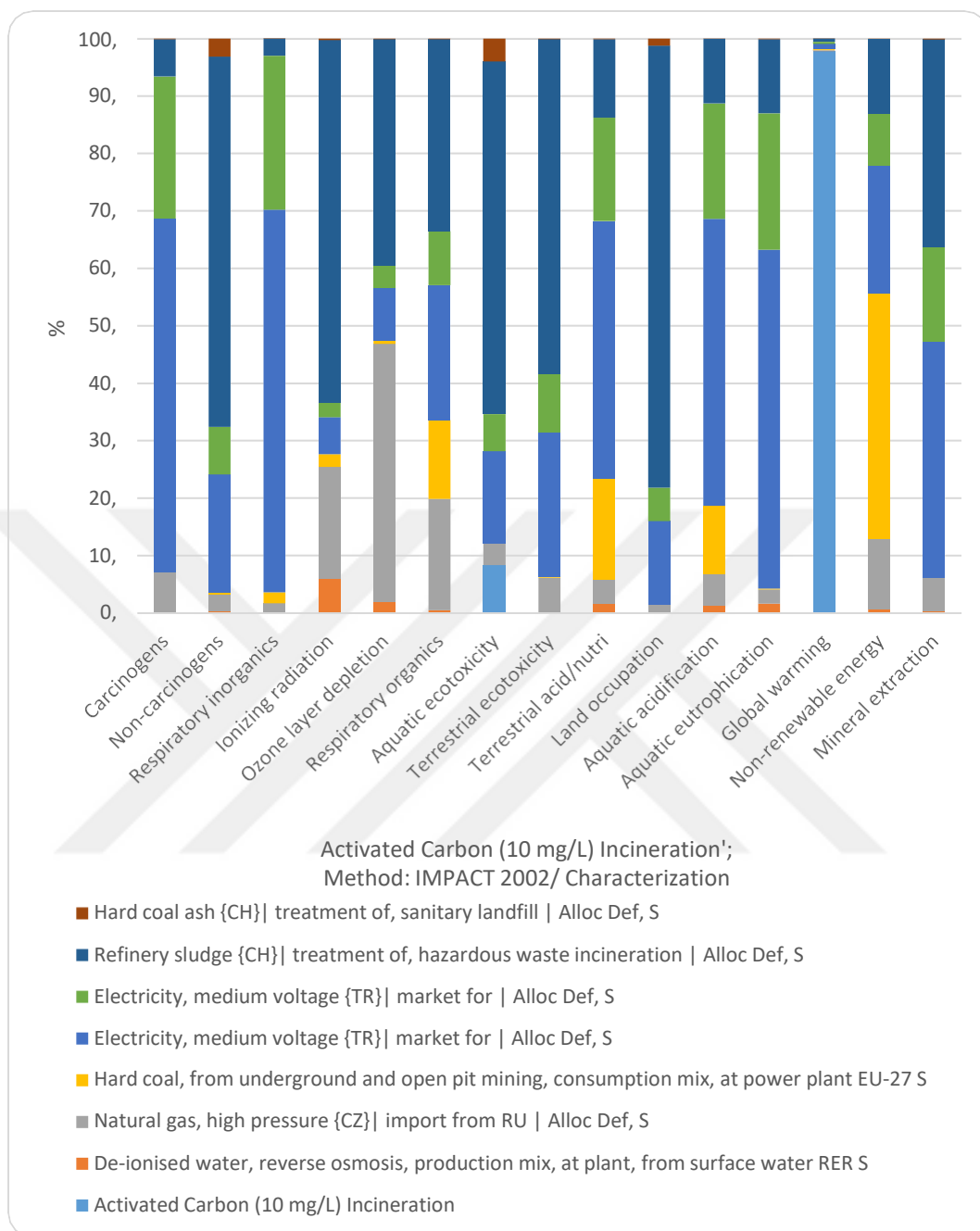


Figure 10. LCA Characterization Results for GAC Adsorption with the Dose of 10 mg/L

As shown by the characterization values, impact categories of aquatic ecotoxicity, terrestrial ecotoxicity, ionizing radiation, non-carcinogens, land occupation, and respiratory organics are the categories that are mostly affected by refinery sludge incineration. In addition, impact categories of carcinogens, terrestrial

acid/nitrification, mineral extraction, aquatic acidification, respiratory inorganics, and aquatic eutrophication are mostly affected by electricity consumption during the activated carbon treatment process. Also, the impact categories of global warming, non-renewable energy, and ozone layer depletion are mostly affected by activated carbon incineration, hard coal consumption, and natural gas consumption of the process, respectively. The expression of “activated carbon incineration” refers to the main input of the system, which is the treated process water of the industry. The values of the results of the characterization of GAC adsorption in 15 different environmental and health impact categories are given in Table A 1. Characterization Results for the GAC Adsorption Treatment (Activated Carbon Dose = 10 mg/L in Appendix A.

It is seen that for the scenario of GAC adsorption, electricity usage causes the highest adverse environmental impacts for six different impact categories out of 15. As it was mentioned in the study by Pesqueira et al. (2020), the energy consumption inputs of the treatment process cause the highest adverse impacts on the environment. The incineration process of the used activated carbon follows it with large impacts on five impact categories as the second highest adverse impact causing process.

4.1.1.2 Damage Assessment for the GAC Adsorption

Figure 11 shows potential adverse environmental impact contributions of the carbon adsorption to four damage categories which are climate change, resources, ecosystem quality, and human health in percentage. As can be depicted from this figure, similar to the high impacts in the global warming category shown in the characterization graph, activated carbon incineration has the highest contribution to the climate change category of the damage assessment graph. The potential environmental impact of energy usage of the system, which includes electricity usage, hard coal, and natural gas consumption, makes up most of the category of resources in the graph. Lastly, electricity usage and incineration of used GAC inventories of the scenario contribute to more than 90% of the damage assessment categories of ecosystem quality and human health.

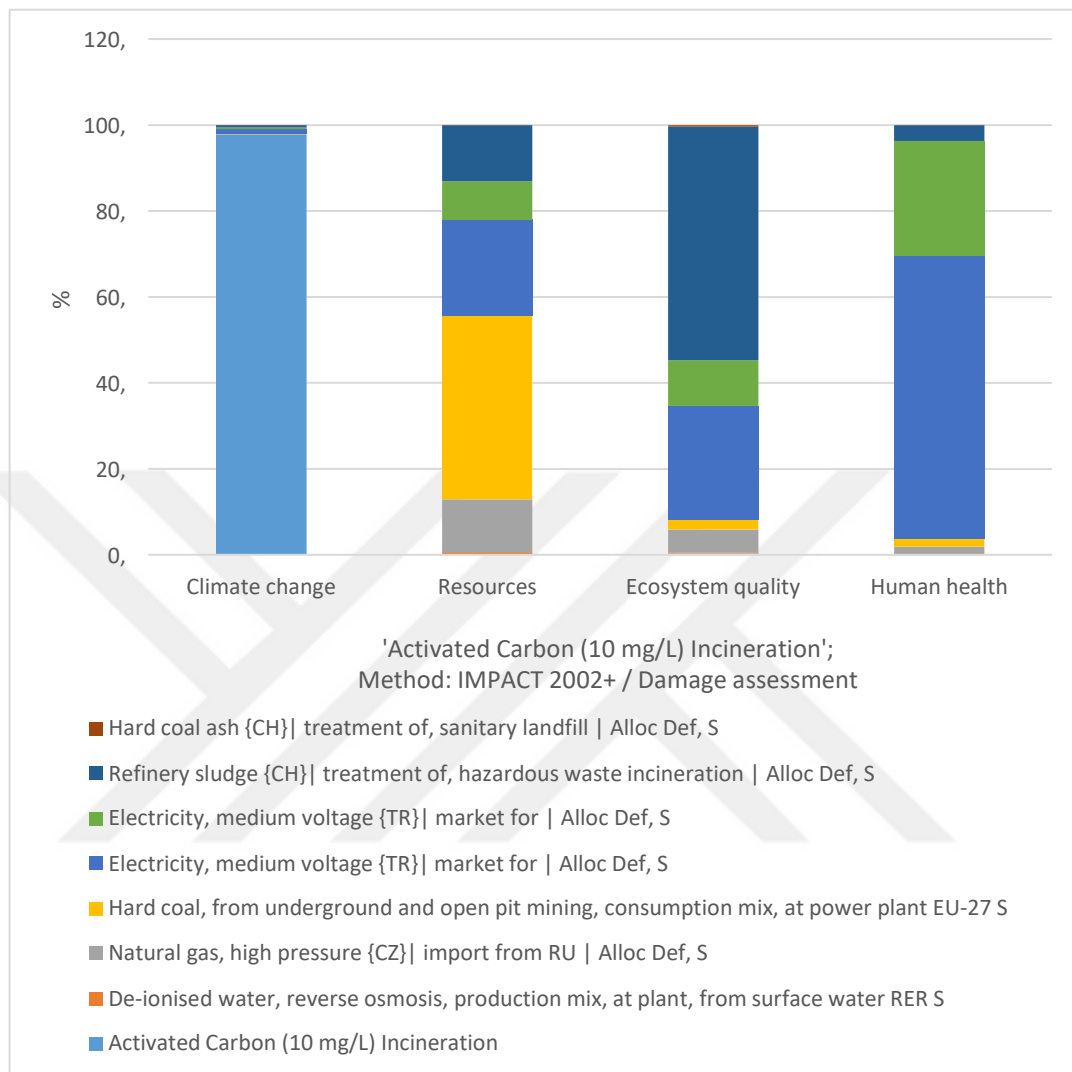


Figure 11. Damage Assessment of the GAC Adsorption with the Dose of 10 mg/L

It can be seen that the damage assessment graph supports the characterization graph by showing a high adverse environmental impact contribution of energy usage of the system for three categories, which are resources, ecosystem quality, and human health.

When the relation between the characterization and damage assessment graph is investigated, inventories of midpoint categories of carcinogens and non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, and respiratory organics contribute to the damage category of human health. Midpoint categories of

ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acid/nutria, and land occupation are the contributor to the damage category of ecosystem quality. Inventories of global warming are directly related to the climate change damage category. Lastly, midpoint categories of non-renewable energy and mineral extraction contribute to the damage category of resources.

4.1.1.3 Normalized Impacts for the GAC Adsorption

Figure 12 shows potential adverse environmental impact contributions of the GAC treatment to four damage categories which are climate change, resources, ecosystem quality, and human health in point. In the graph, the impacts of the inputs on damage categories are clearly seen. Unlike the damage assessment graph, it is seen in the normalization graph that the GAC adsorption process has the most impact on climate change and secondarily on human health categories. These two categories are followed by resource and ecosystem quality. In the category of climate change, impacts due to activated carbon incineration in the category of human health are the highest. This originates from the electricity consumption for incineration.

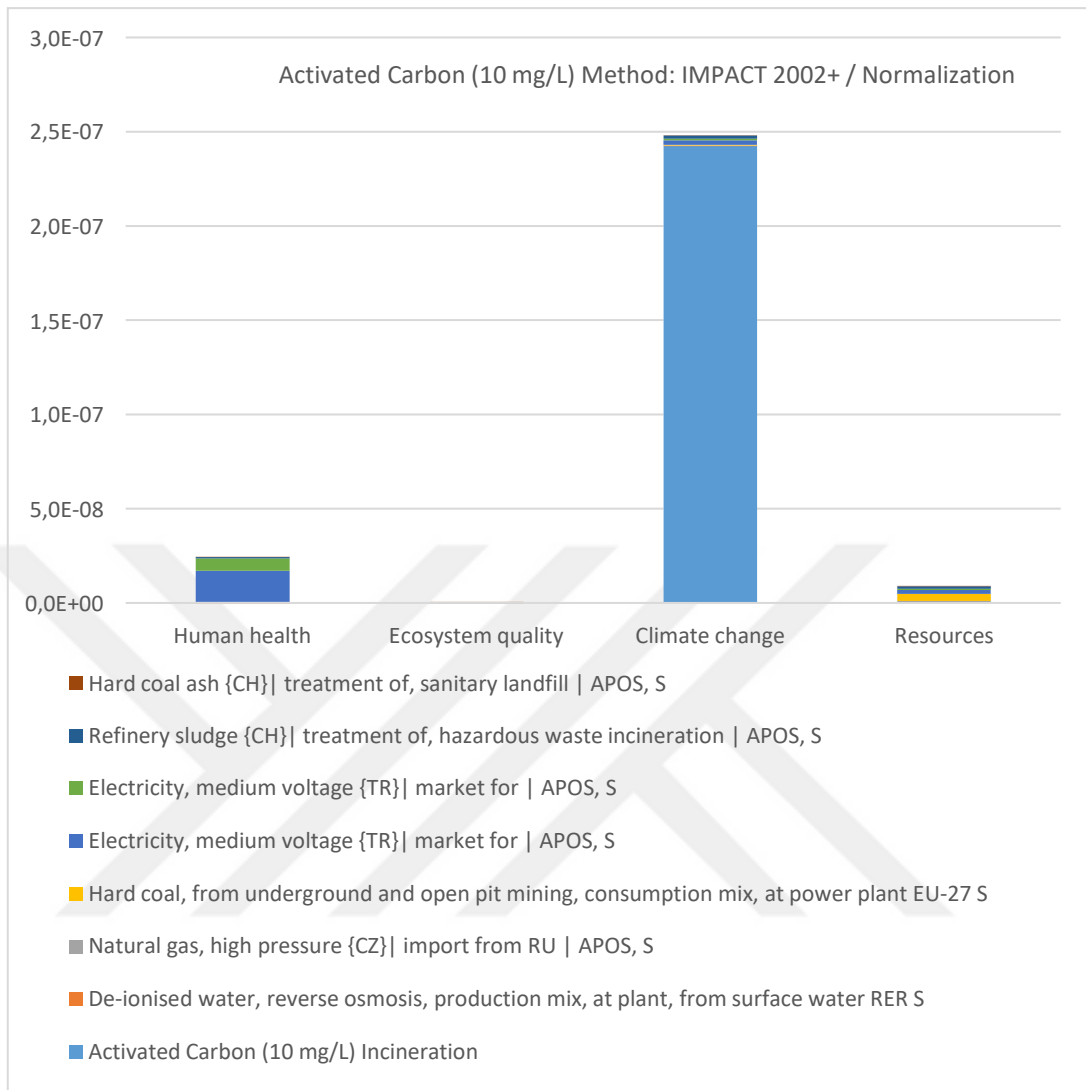


Figure 12. Normalization of the GAC Adsorption with the Dose of 10 mg/L

Similar to this study, Zepon Tarpani & Azapagic (2018) performed an LCA study for the GAC adsorption treatment of pharmaceuticals and personal care products from wastewater. Although the construction phase was taken into consideration in this study, the effect of the process on the human health category was high due to the operation of the process phase. Human toxicity was determined as the second highest impact category with the highest effects in this process. When the activated carbon treatment method is examined to reduce the impact of the category of human health, it is seen that changing the method of obtaining the energy used, especially

electricity, by taking into account the replaceable inputs of this process, will play a role in reducing the environmental impact.

4.1.1.4 Single Score Impacts of GAC Adsorption

Figure 13 shows the single score impacts for the GAC adsorption scenario. The data presented is a summary of the life cycle impacts where adverse environmental impact contributions are expressed in the unit of nPt. Thanks to this single unit impact, all inventories of the system can be compared.

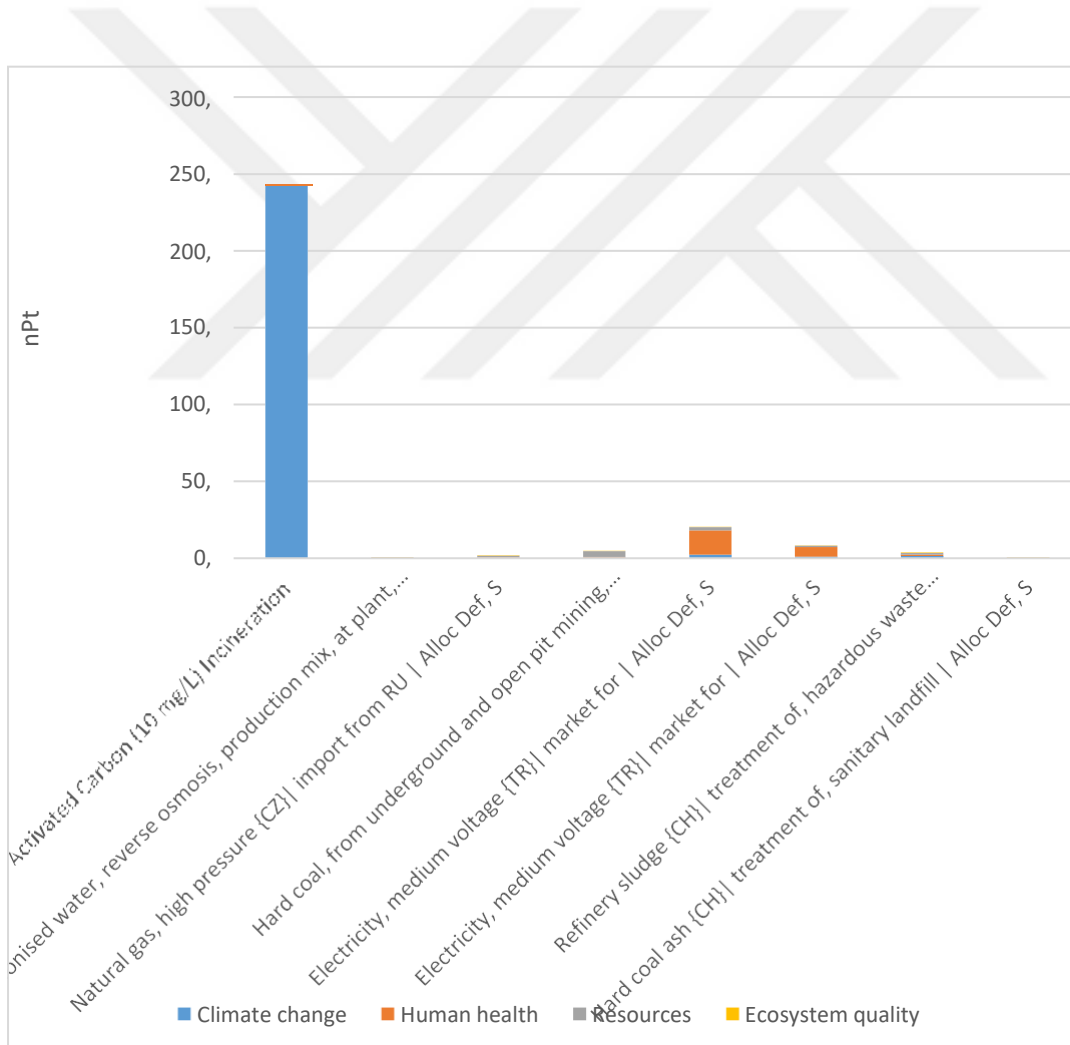


Figure 13. Single Score of the GAC Adsorption with the Dose of 10 mg/L

When the single score results for GAC adsorption were investigated, it was seen that the activated carbon incineration (treated industrial process water) is the main contributor to the climate change impact category, with a notable difference among inventories. With the value of 242,4 nPt treated, industrial process water has the highest impact among inventories for this case because the inventory of treated industrial process water covers the applications for the process water. When the impact of electricity usage in the system is assessed, it is seen as the main contributor to the human health category; also, it has a notable contribution to categories of resource and ecosystem quality. The main reason for the high impact of electricity is the low percentage of electricity generation from renewable sources. By increasing this percentage, the effect on the human health category can be reduced.

The table where single score values can be seen clearly is given in Table A 2 in Appendix A.

4.1.2 Base-case Ozonation Treatment

In this scenario, the potential adverse environmental impacts of ozonation applied with the ozone dose of 20 mg/L were evaluated. The characterization, damage assessment, and single score graphs are given and discussed as the results of the scenario.

4.1.2.1 LCA Characterization Results for the Base-Case Ozone Treatment

Figure 14 shows the life cycle impacts of the components of the base-case ozone treatment process for 15 different impact categories. Usage of electricity, sodium hydroxide and hydrogen peroxide, ozone production process, tap water usage, and ozonation process are taken into consideration in the inventory of the system. The same impact categories in the GAC treatment scenario were used. As can be seen from the figure, electricity consumption of the ozonation process and ozone production components of the system have higher percentages of potential adverse environmental impacts than the other components. Except for the impact category of

global warming, one of these two components are the main contributors of the impact categories. The impact of NaOH consumption for the improvement of rate of reaction appeared to have the highest potential impacts on the ionizing radiation impact category. On the other hand, the highest contribution to carcinogens was due to the use of hydrogen peroxide to increase oxidation of compounds and ozone transfer.

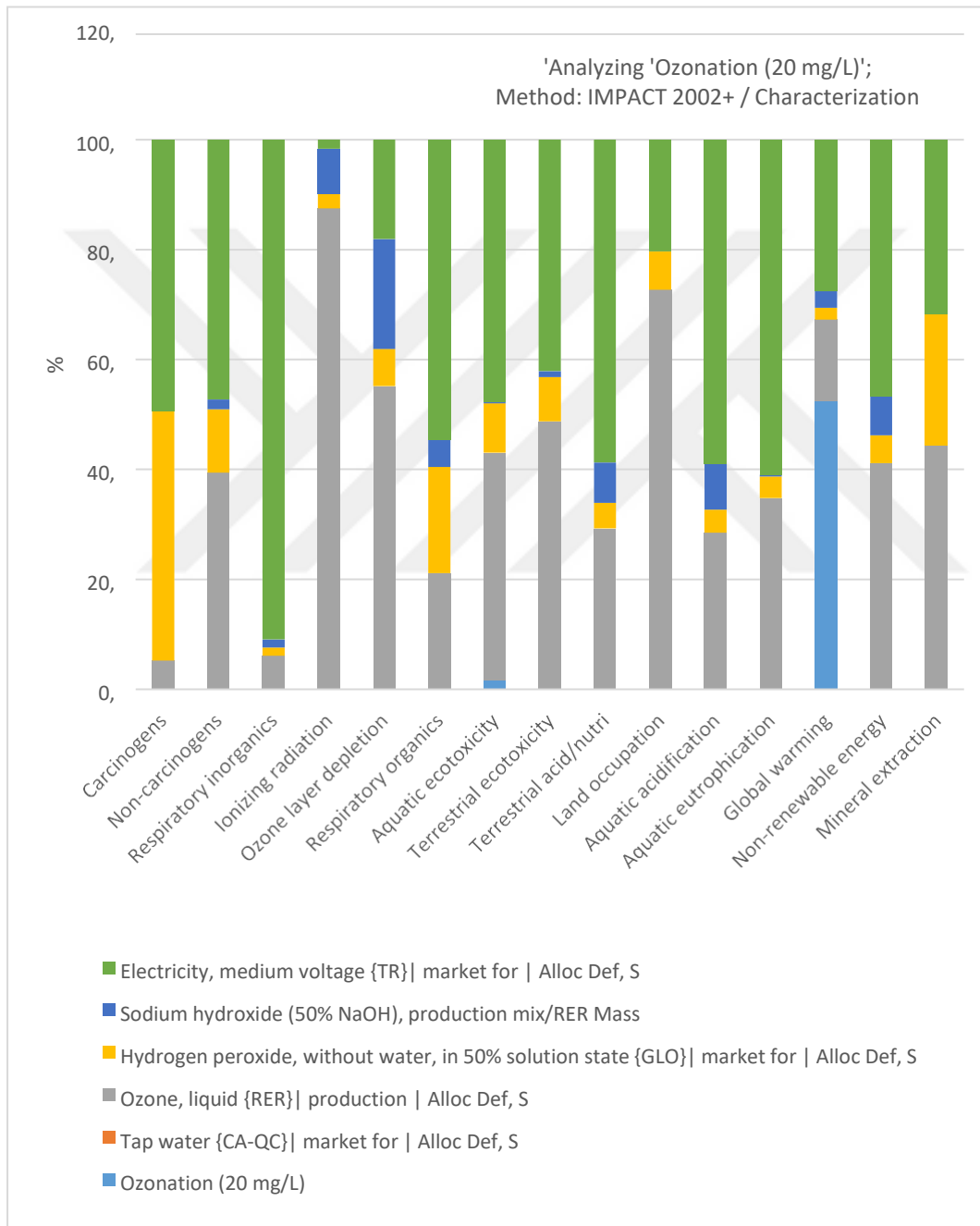


Figure 14. LCA Characterization Results for the Base-Case Ozone Treatment with the Dose of 20 mg/L

According to Figure 14, impact categories of carcinogens, non-carcinogens, respiratory inorganics, respiratory organics, aquatic ecotoxicity, terrestrial acid/nitrification, aquatic acidification, aquatic eutrophication, and non-renewable energy are mostly affected by electricity usage in the ozonation treatment. On the other hand, ionizing radiation, ozone layer depletion, terrestrial ecotoxicity, land occupation, and mineral extraction are mostly affected by the process of ozone production.

It is seen that for the scenario of base-case ozone treatment, the electricity usage causes the highest adverse environmental impacts for nine different impact categories out of 15. This high potential impact is due to the electricity use in the production of ozone. The ozone production process follows the electricity usage with five impact categories out of 15 as the second highest adverse impact.

The values of the results of the characterization for ozonation treatment in 15 different impact categories are given in Table B 1. Characterization Results for the Base-case Ozone Treatment (Ozone Dose = 20 mg/L) in Appendix B.

4.1.2.2 Damage Assessment of Base-Case Ozone Treatment

Figure 15 shows the potential adverse environmental impact contributions of different process components on four damage categories, which are human health, ecosystem quality, climate change, and resources. The graph shows that electricity usage has the most significant contribution to the human health and resources impact categories. The contribution of ozone production is the highest for the impact category of the ecosystem quality, due to it cause some direct and indirect reactions. Lastly, the impact category of climate change is affected at most by the ozonation process due to the release of greenhouse gas emissions from electricity consumption during the process.

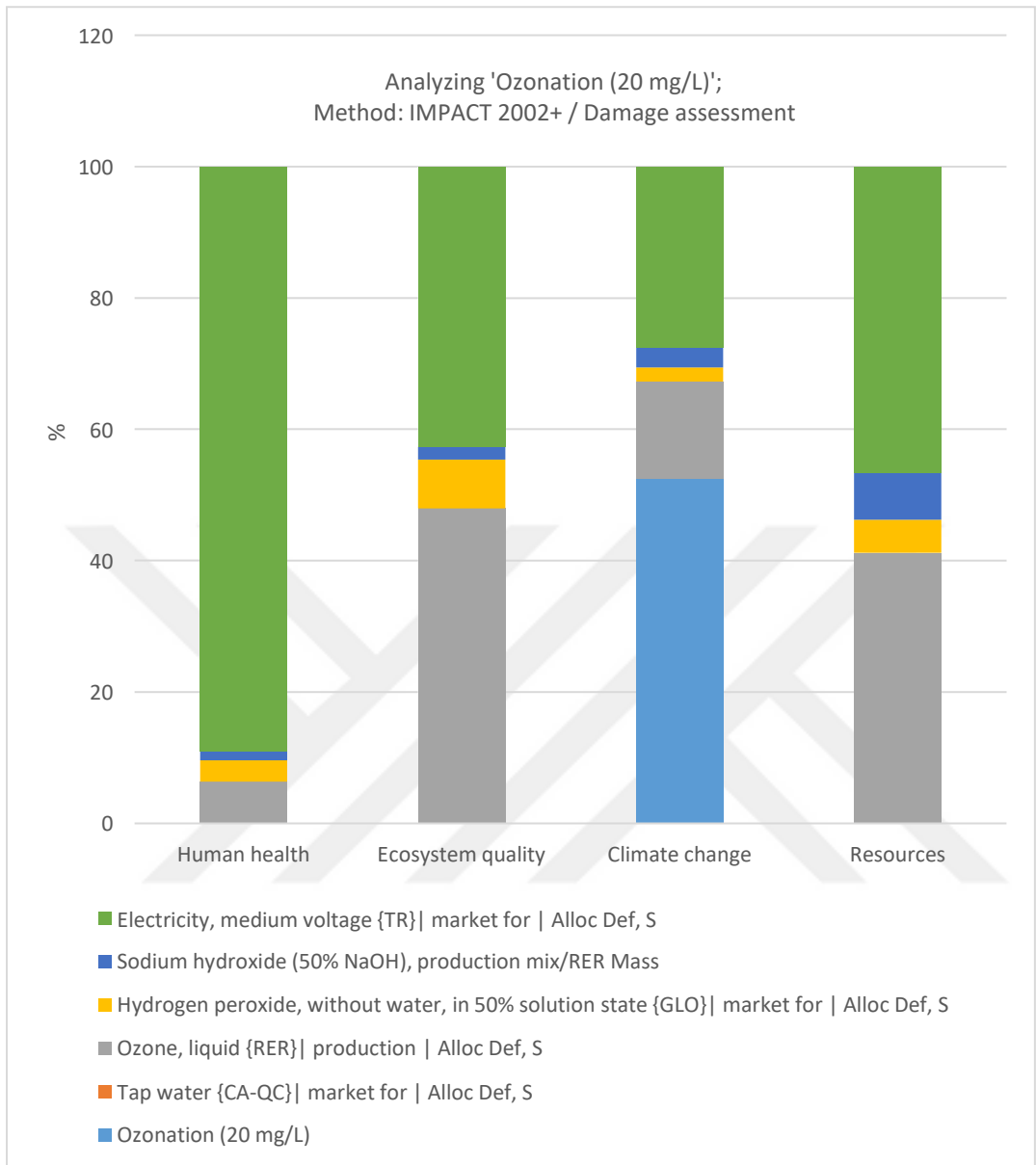


Figure 15. Damage Assessment of Base-case Ozone Treatment with the Dose of 20 mg/L

4.1.2.3 Normalized Impacts for the Ozone Treatment

Figure 16 shows potential adverse environmental impact contributions of the processes of the ozone treatment to four damage categories in point. Unlike the damage assessment graph, it is seen in the normalization graph that the ozone treatment process has the highest impact on human health and secondarily on climate change categories. The categories are followed by the resource and ecosystem quality categories, respectively. When the inputs are examined, the use of electricity stands out as the input that causes the most intense environmental impact.

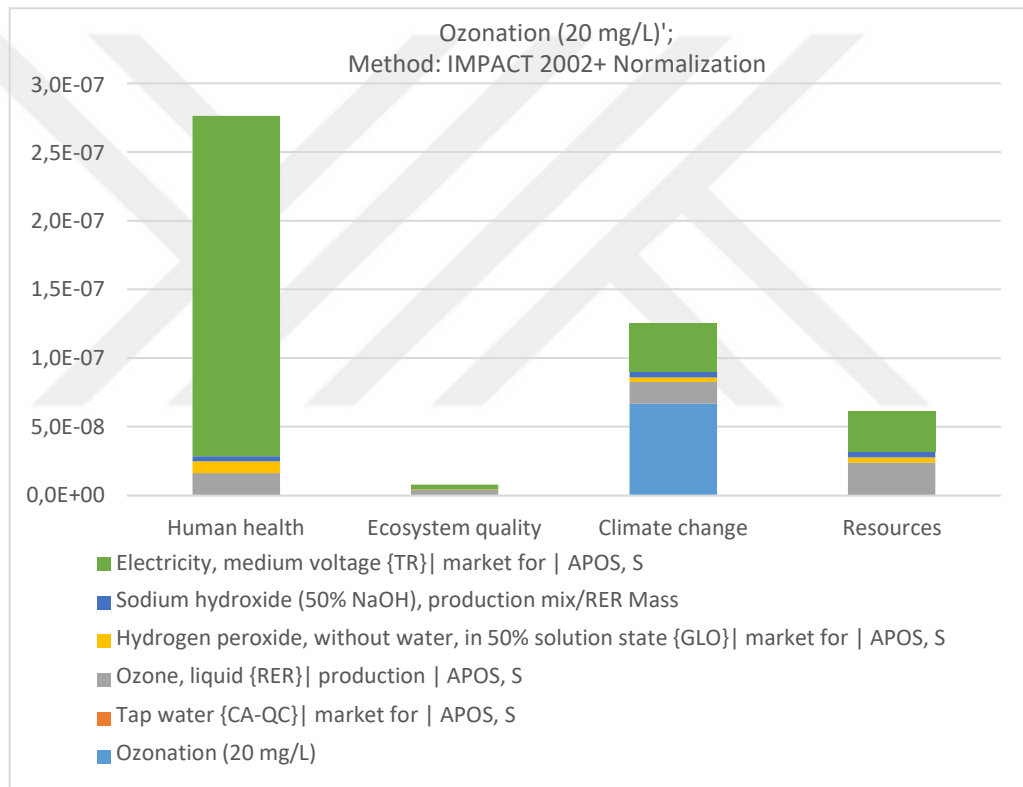


Figure 16. Normalization of Base-case Ozone Treatment with the Dose of 20 mg/L

Similar to this study, according to the LCA results performed for ozonation in the study by Muñoz et al., 2007, it was seen that the categories related to the human health endpoint category such as human toxicity, ozone layer depletion and photochemical oxidation were higher due to the use of electricity in the ozonation process.

4.1.2.4 Impact Base-case Ozone Treatment

Figure 17 shows the adverse environmental impact contributions of different components of the ozone oxidation treatment system as single scores. The single scores are expressed in unit of nPt.

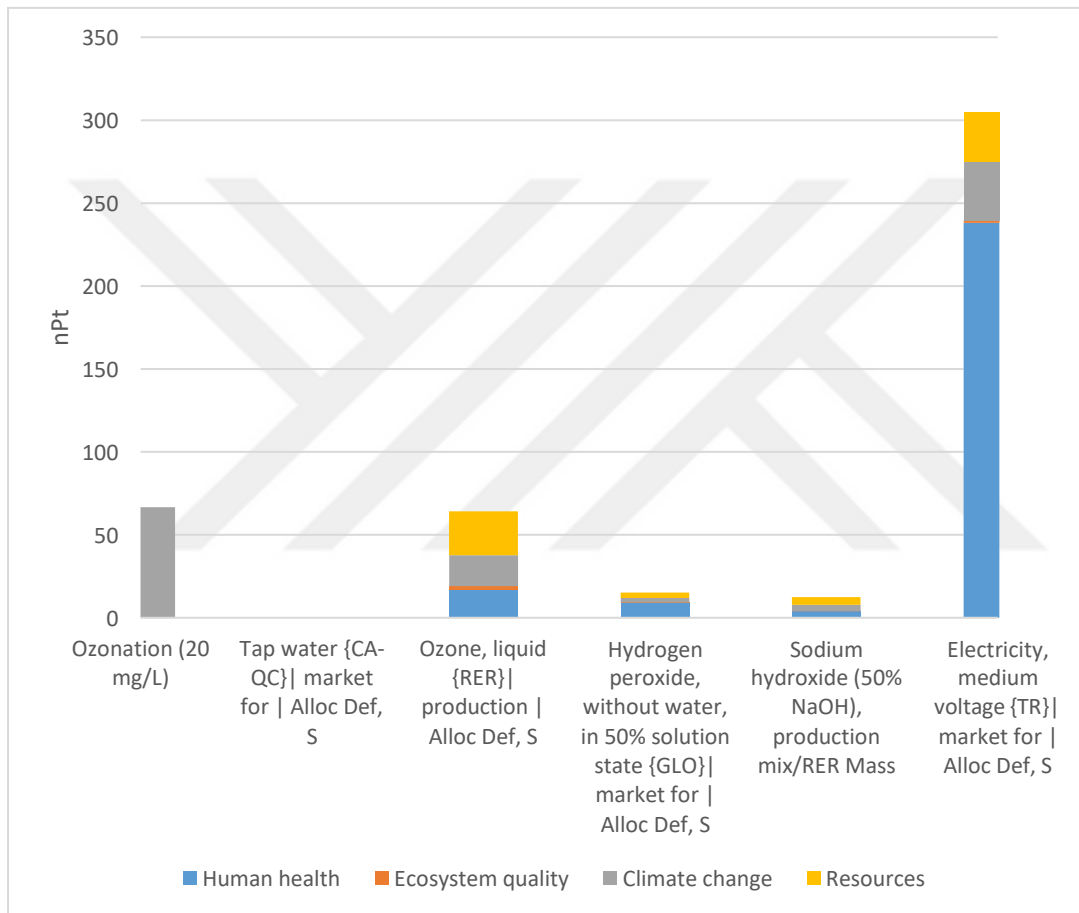


Figure 17. Single Score of Base-case Ozone Treatment with the Dose of 20 mg/L

When the single score results of the system for base-case ozone treatment are examined, it is seen that in terms of human health impacts, electricity is again the highest contributor among the other contributors. With the value of 237,91 nPt, electricity usage has the highest impact among the others for this case. When the impact of ozonation (express the input of treated industrial process water) of the system is observed, it is the main contributor to the climate change category, similar

to the high impact of input of treated industrial process water on the climate change category for the scenario of GAC adsorption.

It can be said that the energy consumption of the case is the main inventory in charge with potential adverse impact.

The table where single score values can be seen clearly is given in Table B 2 in Appendix B.

4.1.3 Comparison of GAC Adsorption and Ozonation

In this section, a comparison of potential adverse environmental impacts of GAC adsorption and ozonation in tertiary treatment of secondary textile wastewater for the base case and minimum/base/maximum dosage cases are given. For each dose case, the results are presented under the sub-titles of characterization, damage assessment, and single scores.

4.1.3.1 Comparison of GAC Adsorption to Ozonation for the Base Case Scenario

In this part, the comparison is made for the base case (10 mg/L GAC usage and 20 mg/L ozone usage). Also, micropollutant concentrations are given at Table 5 and Table 6.

4.1.3.1.1 Characterization Results for GAC and Ozonation for the Base Case

Figure 18 shows that the comparison of potential adverse environmental impact contribution percentage of GAC treatment and ozonation for 15 different impact categories for the tertiary treatment of 1 m³ secondary textile wastewater. In this comparison, the treatment method which has a higher potential adverse environmental impact on a category, is taken as the reference and its percentage impact is accepted as 100 for the category.

The impact categories considered are as carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutria, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, and mineral extraction. From Figure 18, it can be seen that GAC adsorption has less adverse environmental impact for 14 different impact categories out of 15 compared to ozonation. Also, it is seen that GAC's adverse environmental impacts are not more than 20% of the impact of ozonation for these 14 different categories. This clear difference in the impacts is due to high electricity consumption for the ozonation process. This finding is somewhat contrary to those of (Igos et al., 2021) who indicated that the advantage of GAC adsorption compared to ozonation is negligible. Nevertheless, they indicated that the difference could be significant in countries with significant shares of coal-based electricity, which is the case for Türkiye. The share of coal-based electricity is 31.4 % in Türkiye for the year 2021 (Ministry of Energy and Natural Resources, 2022).

As can be seen from Figure 17, only for the global warming impact category, the impact of GAC adsorption is twice that of ozonation. The higher impact of GAC adsorption on the global warming category is explained by the incineration process of used for GAC.

The characterization values are given in Table C 1 in Appendix C.

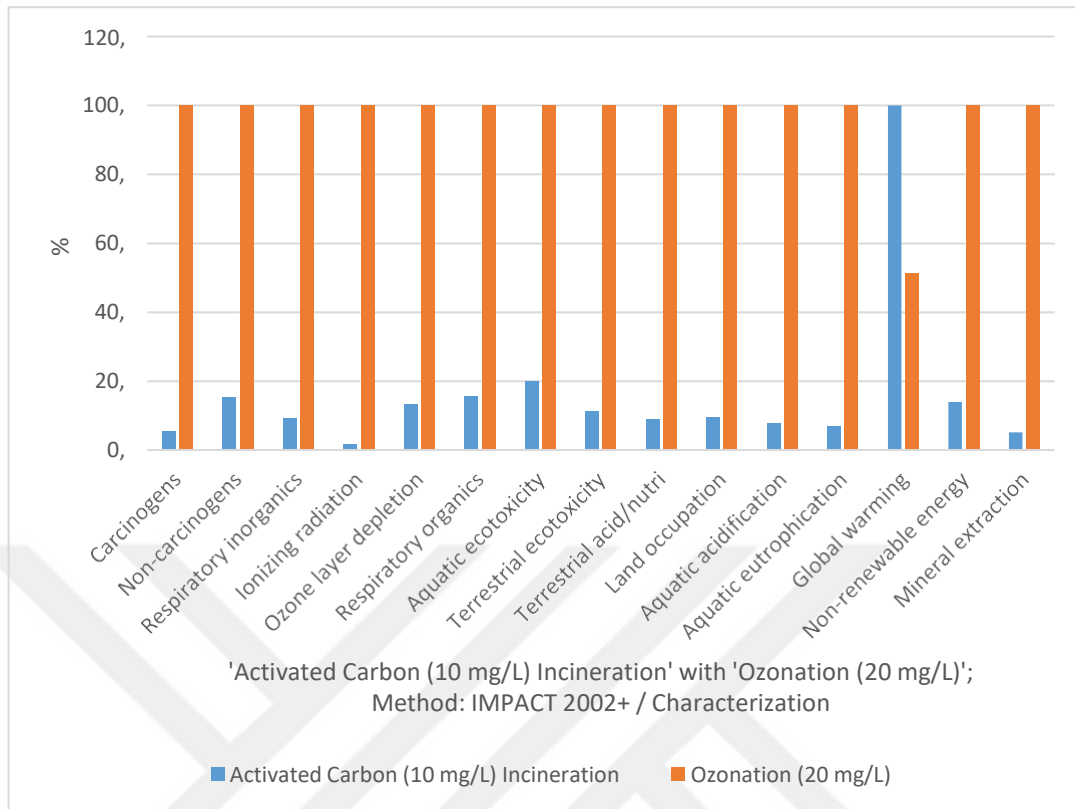


Figure 18. Characterization of GAC Adsorption and Ozonation for Base Case

4.1.3.1.2 Damage Assessment of GAC Adsorption and Ozonation for the Base Case

Figure 19 shows potential adverse environmental impact contribution percentages for these two methods for four damage categories. As can be depicted from this figure, ozonation has more adverse environmental impacts on human health, ecosystem quality, and resources impact categories with a clear difference. For these impact categories, the impacts of ozone treatment are 5-10 times that of ozonation. On the contrary, for the impact category of climate change, the potential adverse environmental impacts of GAC is twice those of ozonation because of its high electricity usage and chemical consumption

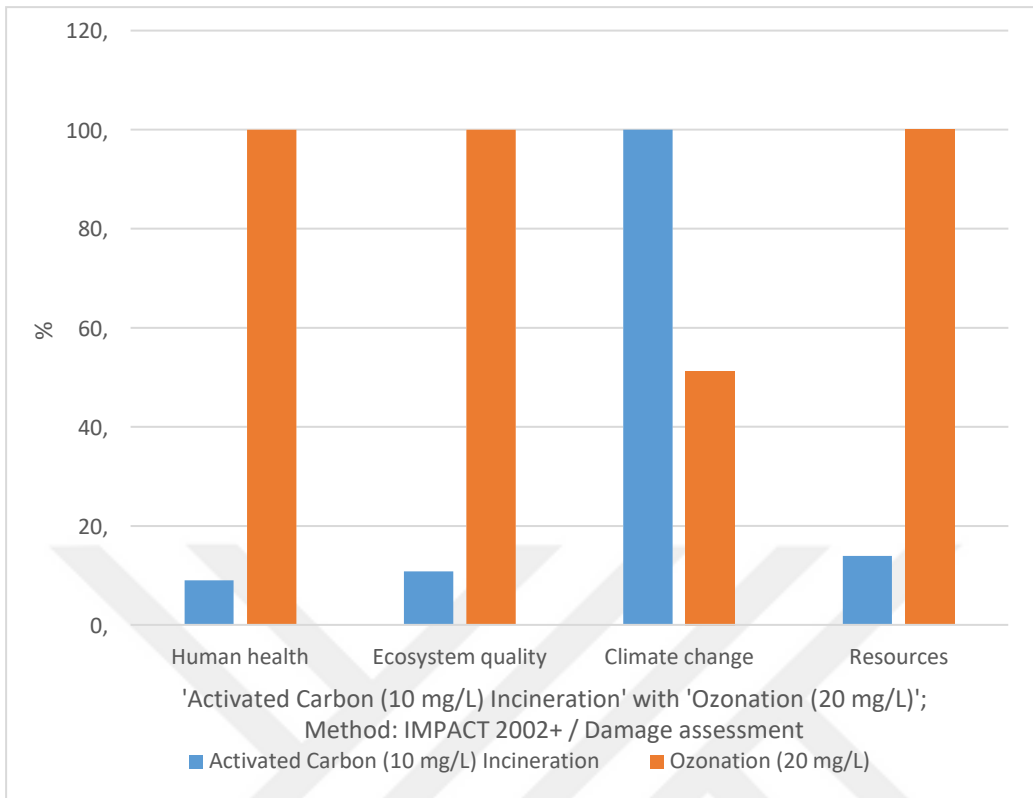


Figure 19. Damage Assessment of GAC Adsorption and Ozonation for Base Case

It can be seen that damage assessment graph supports the characterization graph by showing a high adverse environmental impact of ozonation compared to GAC for 3 impact categories out of 4.

4.1.3.1.3 Normalization of GAC Adsorption and Ozonation for Base Case

Figure 20 compares the potential adverse environmental impact contribution of GAC adsorption (10 mg/L) and ozone treatment (20 mg/L) for 4 damage categories in points. The graph shows that, unlike the damage assessment graph, both treatment methods contribute less to the ecosystem quality. Also, the impacts on the impact category of resources is lower as compared to the impacts on the human health and climate change categories. With its high electricity consumption, the environmental impact of the ozonation process (276 nPt) is quite higher than the environmental impact of GAC adsorption (24.4 nPt) in the human health category. On the other hand, impact of the GAC adsorption process (248 nPt) is more than the impact of ozonation (125 nPt) in the climate change category.

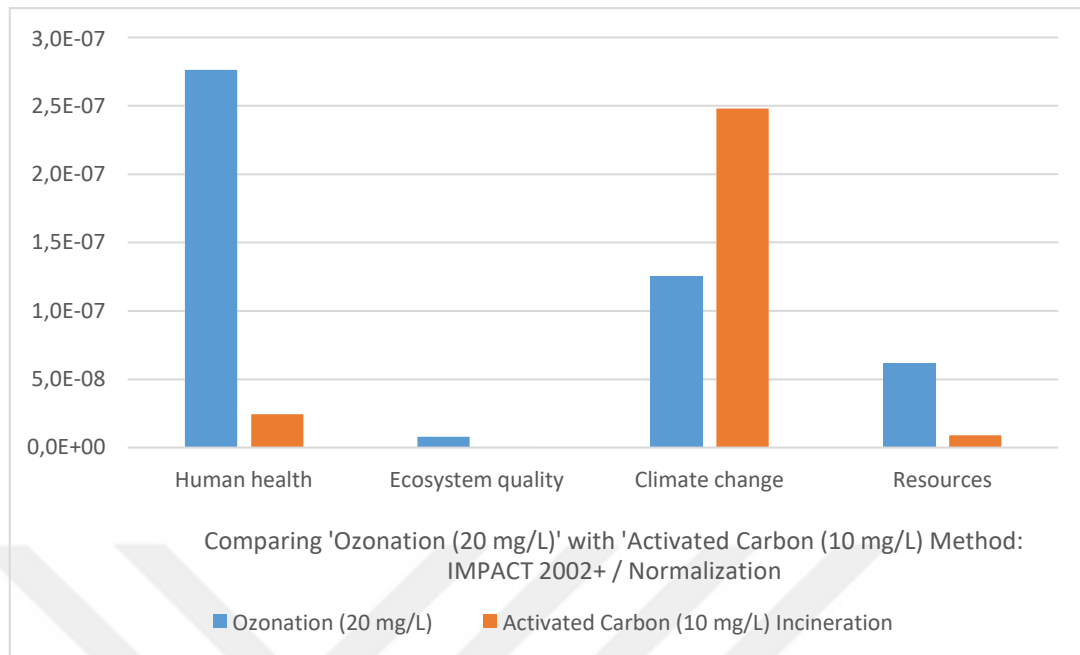


Figure 20. Normalization of GAC Adsorption and Ozonation for Base Case

A very recent LCA study by Risch et al. (2022) compared ozonation and activated carbon adsorption methods in the removal of 65 micropollutants from secondary urban wastewaters taking “the biologically pre-treated urban wastewater effluent generated from 50 000 PE during one year”. It was reported that air-fed ozone and GAC are better choices compared with oxygen-fed ozone on the ecosystems quality endpoint for the French electricity mix. For the human health category, air-fed ozone was the best option followed by GAC and finally pure oxygen-fed ozone. So, the findings of the study by Risch et al. (2022) support the present study concerning the high environmental impacts of ozonation in the endpoint of human health. In the same study, contrary to the present study, the effects of ozonation were found to be high at the global warming midpoint, which is associated with the climate change endpoint. It is considered that the reason for this is the selection of the regeneration method instead of incineration as the disposal method. Since this method is not used in Türkiye, incineration was chosen as the disposal method in this study.

4.1.3.1.4 Impact Comparison of GAC Adsorption and Ozonation for Base Case

Figure 21 demonstrates the contribution of the treatment methods to four impact categories in the unit of nPt. When the figure is analyzed, it is seen that treatment methods of GAC and ozonation make the biggest contribution to impact categories of climate change and human health, respectively. The total environmental impact of GAC is above 250 nPt, and the total environmental impact of ozonation is above 450 nPt.

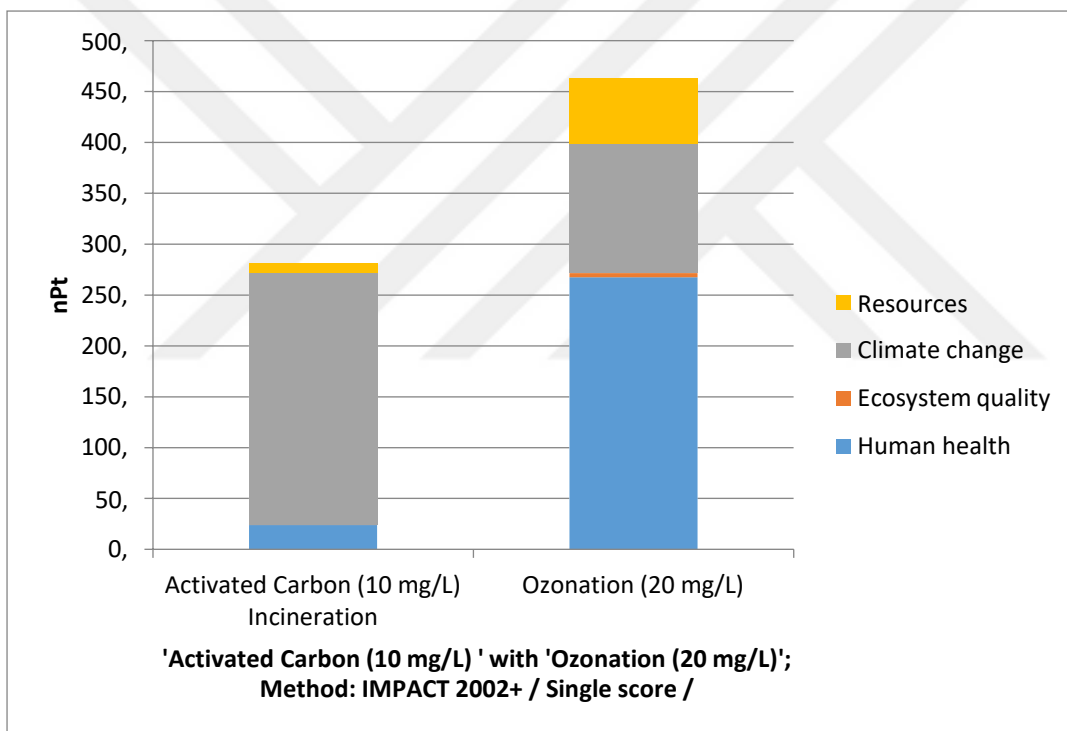


Figure 21. Single Score of GAC Adsorption and Ozonation for Base Case

The result indicates that GAC adsorption makes a 247.76 nPt contribution to the impact category of climate change. Also, ozonation makes 267.42 nPt and 127.02 nPt contributions to impact categories of human health and climate change, respectively.

The table where single score values can be seen clearly is given in Table C 2 in the Appendix C.

It is clear that a single score graph supports the graphs of characterization and damage assessment in this scenario by showing the higher environmental adverse impact of ozonation. Lower results of activated carbon adsorption compared to ozonation in the single score graph were found to be similar to results of Zepon Tarpani & Azapagic, 2018.

4.1.3.2 Comparison of GAC Adsorption and Ozonation for Minimum/ Base/ Maximum Dosage Cases

In part, the comparison is made for minimum/base/maximum dosage of GAC usage (5/10/20 mg/L) and Ozone usage (10/20/40 mg/L). In addition, micropollutant concentrations are taken as minimum/ average and maximum concentrations in this case.

4.1.3.2.1 Characterization of GAC Adsorption and Ozonation for Minimum/ Base/ Maximum Dosage Cases

Figure 22 shows that the comparison of potential adverse environmental impact contribution percentage of GAC adsorption and ozonation for minimum, base, and maximum dosages for 15 different impact categories for tertiary treatment of 1 m³ industrial water. In the scenario, the same impact categories are selected with the scenario of comparison on GAC adsorption and ozonation for the base case. In this scenario, a change in dosage of treatment method and how it affects the impact result is tested. Figure 22 demonstrates that both treatment methods show an increase in potential adverse environmental impact in all categories with the increase in dosage as it is expected. Categories of non-carcinogens, ionizing radiation, ozone layer depletion, aquatic ecotoxicity, terrestrial ecotoxicity, land occupation, non-renewable energy, and mineral extraction are more affected by this change compare to other seven categories.

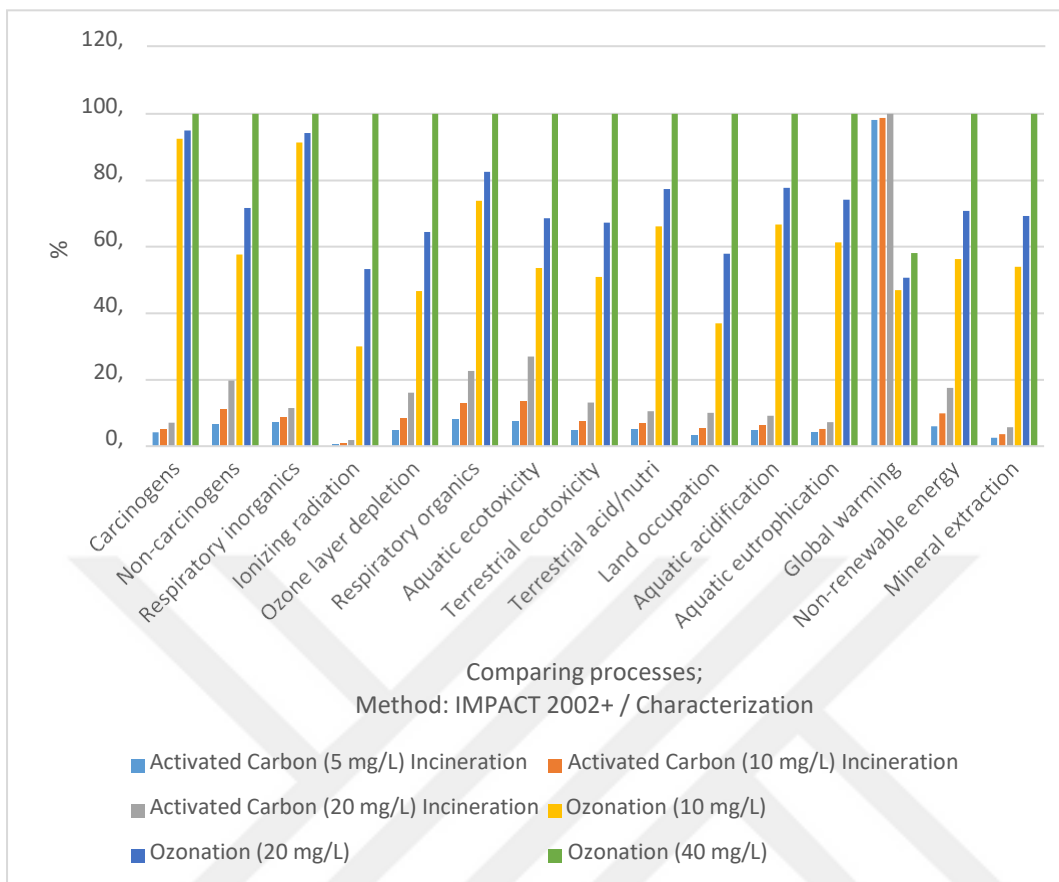


Figure 22. Characterization of GAC Adsorption and Ozonation for Minimum/Base/Maximum Dosage Case

It can be seen that the impact category of ionizing radiation is the most sensitive category for dosage change for the treatment of ozonation because of notably the change of it. In addition, aquatic ecotoxicity is the most sensitive category for dosage change for the treatment of GAC.

Values of characterization result of the GAC Adsorption and Ozonation for Minimum/Base/Maximum Dosage Case are given in Table C 3 in Appendix C.

4.1.3.2.2 Damage Assessment of GAC Adsorption and Ozonation for Minimum/ Base/ Maximum Dosage Cases

Damage assessment graph of the scenario of comparison on GAC and ozonation treatment for minimum/base/maximum dosage case shows potential adverse environmental impact contribution percentage of these two methods for different

dosages for 4 damage category. When the damage assessment graph is investigated, it shows that ozonation has a more adverse environmental impact on human health, ecosystem quality, and resources categories with a clear difference. The graph shows that the change in dosage of ozone and micropollutant concentration mostly affects the impact category of ecosystem quality. Also, dosage micropollutant concentration changes in GAC adsorption mostly affected the category of resources. Otherwise, human health and climate change categories are not as sensitive as methods of ecosystem quality and resources with different treatment material dosages and micropollutant concentrations.

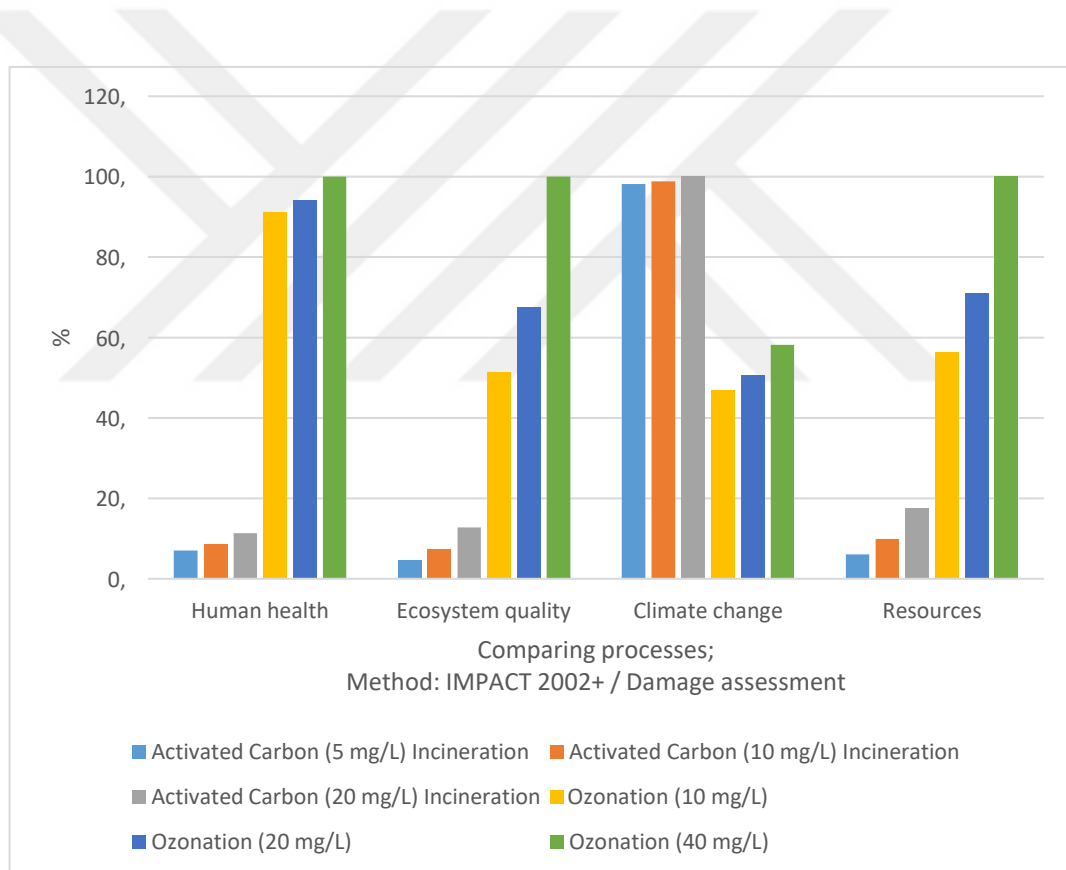


Figure 23. Damage Assessment of GAC Adsorption and Ozonation for Minimum/Base/Maximum Dosage Cases

4.1.3.2.3 Normalization of GAC Adsorption and Ozonation for Minimum/Base/ Maximum Dosage Cases

Figure 24 compares the potential adverse environmental impact contribution of GAC adsorption and ozone treatment for different dosages for 4 damage categories in point. The graphic shows that both treatment methods contribute the least to the ecosystem quality; also, the category is not much affected by the dosage change.

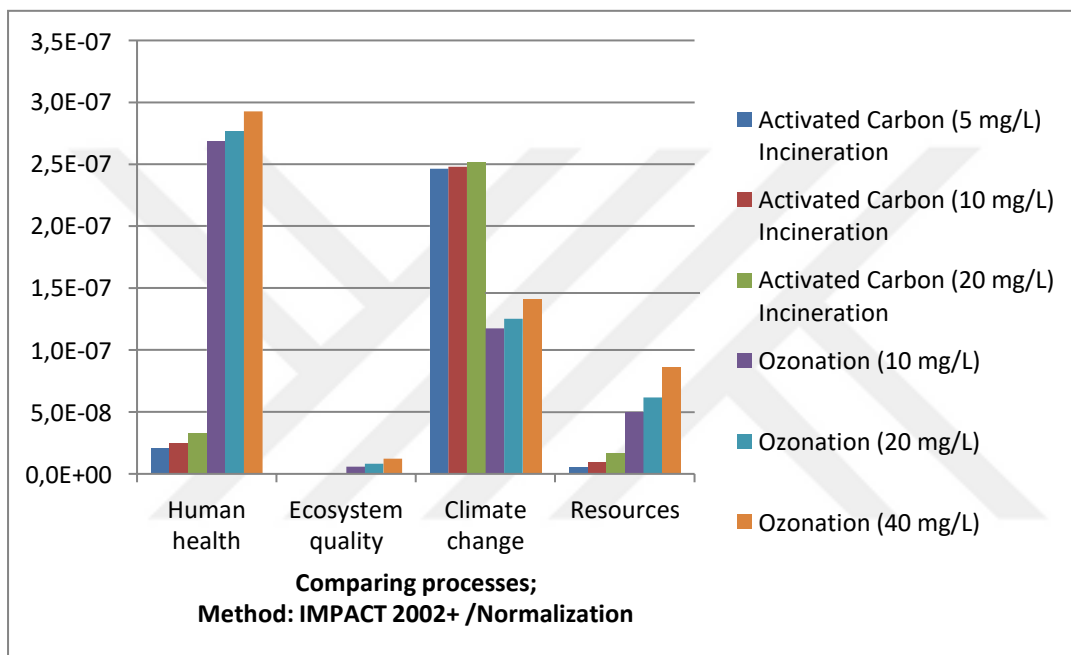


Figure 24. Normalization of GAC Adsorption and Ozonation for Minimum/Base/Maximum Dosage Cases

Considering the previous scenario, as expected, the highest environmental impact (293 nPt) is observed in the human health category at the maximum dosage of ozonation. The highest environmental impacts in other categories are 251, 85.5, 12.3 nPt and belong to the GAC adsorption, ozonation and ozonation respectively.

4.1.3.2.4 Comparison Impact of GAC Adsorption and Ozonation for Minimum/Base/Maximum Dosage Cases

Figure 25 indicates the contribution of the treatment methods in different dosages to four impact categories in the unit of nPt. When Figure 25 is analyzed, it is seen that

treatment methods of GAC and ozonation make the biggest contribution to impact categories of climate change and human health, respectively.

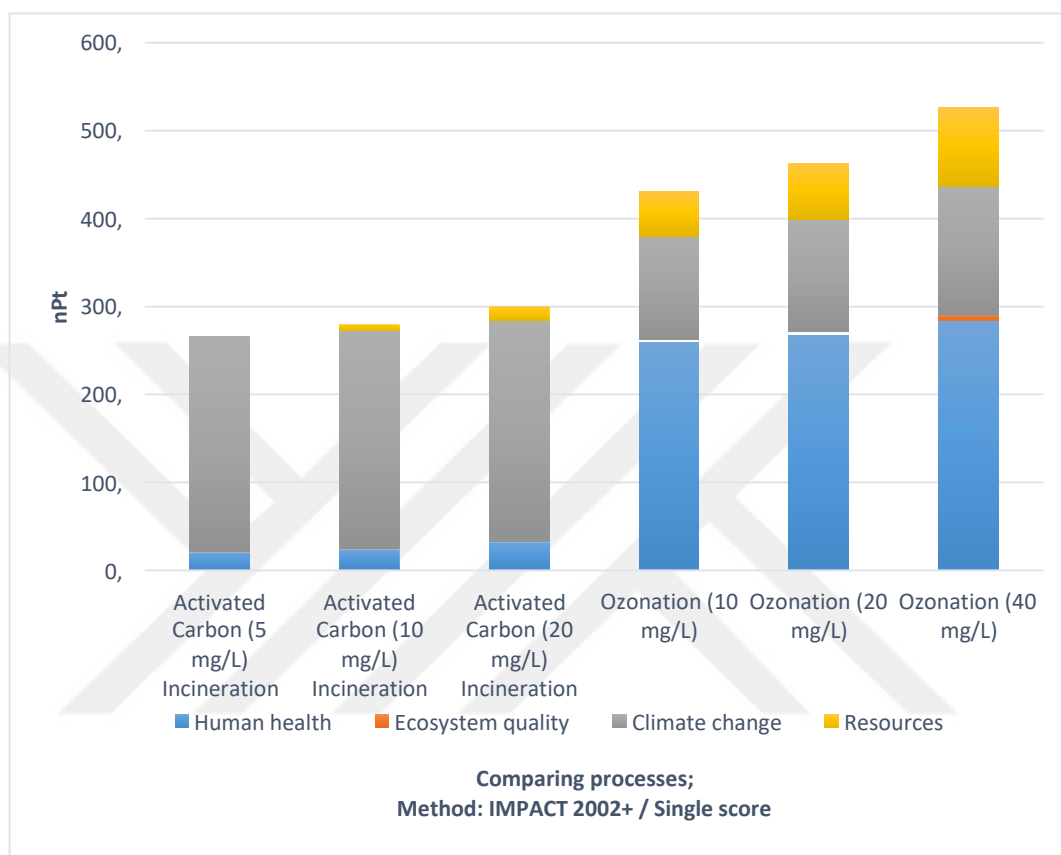


Figure 25. Single Score of GAC Adsorption and Ozonation for Minimum/Base/Maximum Dosage Cases

The result indicates that GAC adsorption makes a contribution to the impact category of climate change in the range of 246,25 to 250,79 nPt. Although the amount of the contribution to the impact category of climate change does not change too much, its amount is quite high compared to the contribution to other categories. Also, ozonation makes a contribution to impact categories of human health and climate change in the range of 258,96 to 284, 35 and 117,64 to 145, 78 respectively. In spite of that category of climate change being less contributed by the treatment of ozonation, the category is more sensitive to changes in ozone concentration compared to GAC. Table C 4 in Appendix C gives impact values of the case clearly.

4.2 Sensitivity Analysis

Sensitivity analysis is applied for both treatment methods separately. In the first part of the analysis, change in potential adverse environmental impacts of GAC adsorption with changing percentage of incineration of used GAC and changing micropollutant concentration was evaluated. In the second part, change in potential adverse environmental impacts of ozonation with changing ozone dosage and changing micropollutant concentration was evaluated. Characterization graphs and tables of the results are given as the result of the analysis.

4.2.1 Sensitivity Analysis for GAC

In this part, the results of sensitivity analysis done for GAC adsorption are presented. In the first part, the change in potential adverse environmental impacts of GAC adsorption when the incineration percentage is changed is analyzed. Incineration percentage changing interval is determined as 0-100%, which means the state of not incinerate and 100% fully efficient combustion are determined as limitations of the sensitivity interval. In the second part, the change in potential adverse environmental impacts of GAC adsorption when the micropollutant concentration in the treated water is changed is analyzed.

4.2.1.1 Sensitivity Analysis for the Incineration of Waste GAC

Figure 26 presents the sensitivity analysis carried out for the life cycle impact assessment characterisation phase for the incineration of waste GAC. As can be depicted, the potential environmental impact of GAC adsorption changes to a great extent when the percentage of the waste was incinerated changes between 0-100 %. According to the graph, the most sensitive impact category for the waste incineration component of the system is land occupation. In addition to this category, impact categories of non-carcinogens, ionizing radiation, aquatic ecotoxicity, and terrestrial ecotoxicity are affected notably by the change in the incineration percentage. Characterization result of impact category of land occupation can be higher 64.3%

and can be lower 58.1% than the current value with the change of incineration percentage of sludge of used GAC.

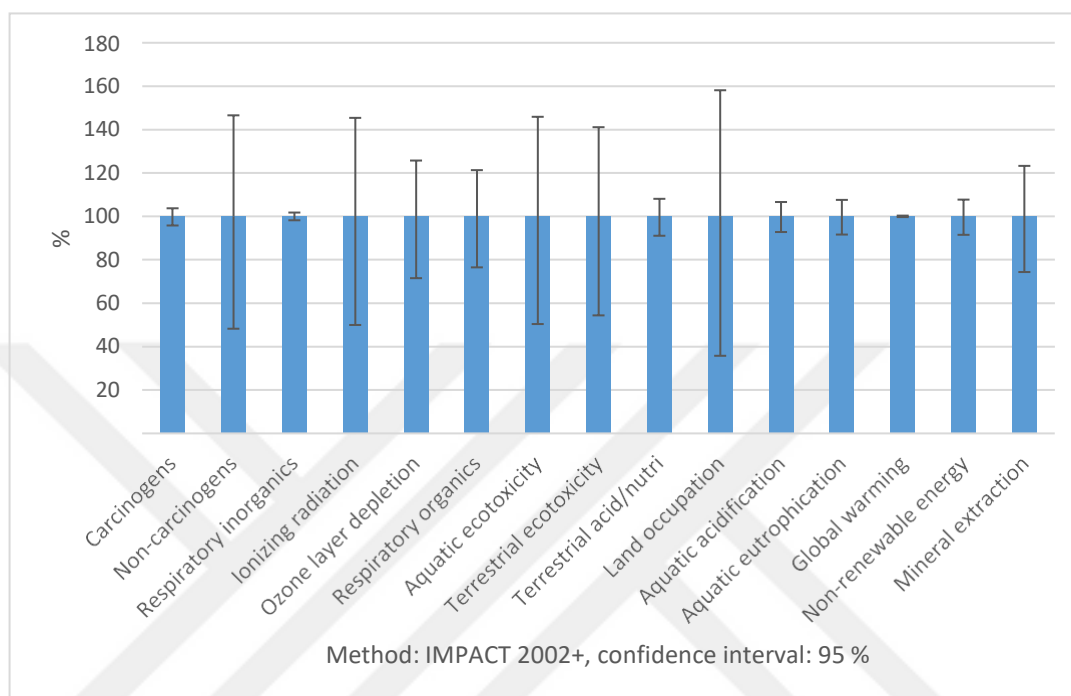


Figure 26. Sensitivity Analysis Results on the Impact Assessment Characterization Phase for the Incineration of Waste GAC (10 mg/L GAC)

The changes in the characterization results of these impact categories can be seen in Table D 1. Characterization of Sensitivity Analysis in Incineration in Appendix D as percentages.

This analysis shows that the incineration mostly contributes to the categories of land occupation, non-carcinogens, ionizing radiation, aquatic ecotoxicity, and terrestrial ecotoxicity. Although it is expected that change in the incineration activity will affect the result of the impact category of global warming, a clear change cannot be observed in this category because the main contributor of this category is electricity usage of the system. The electricity usage of the system is the main contributor to the system is observed in the characterization part of the scenario of GAC Adsorption in Figure 10.

4.2.1.2 Sensitivity Analysis in Micropollutant Concentration for GAC Adsorption

Graph of Characterization of Sensitivity Analysis in Micropollutant Concentration for GAC shows that change in the potential environmental impact of GAC adsorption when the amount of micropollutants is changed between the determined minimum and maximum values. According to the graph, the most sensitive impact category for the micropollutant concentration inventory of the system is aquatic ecotoxicity. In addition to this category, impact categories of carcinogens, non-carcinogens, and terrestrial ecotoxicity are affected slightly by the change in micropollutant concentration. Characterization result of the impact category of aquatic ecotoxicity can be higher 11,18% and lower 11,52% than the current value with the change of micropollutant concentration.

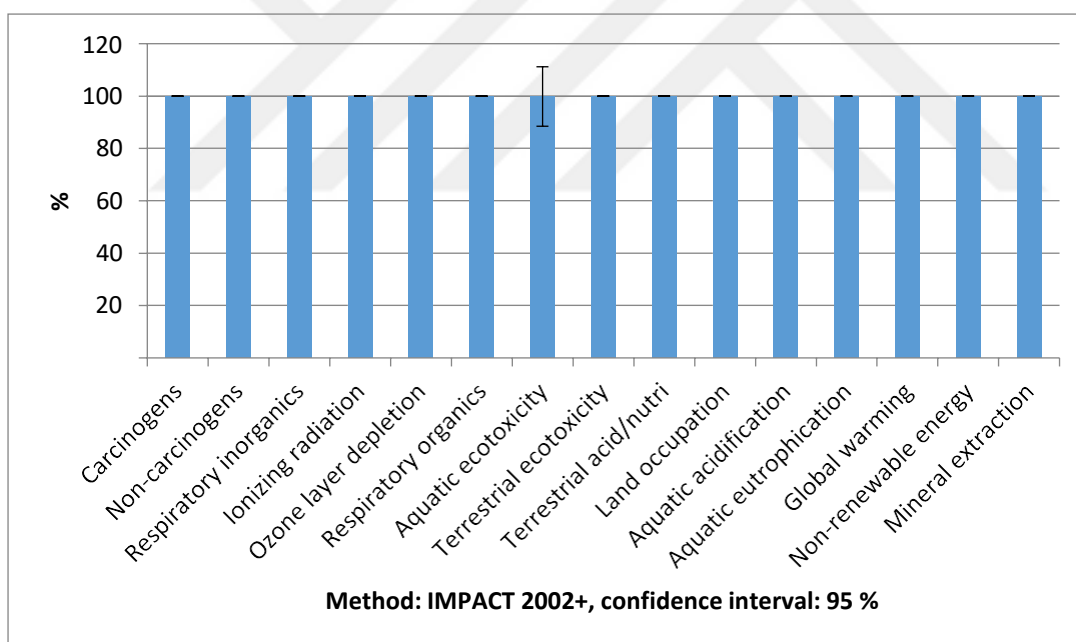


Figure 27. Characterization Graph of Sensitivity Analysis in MP Concentration for 10 mg/L GAC Adsorption

Changes in the characterization results of these impact categories can be seen in Table D 2. Characterization of Sensitivity Analysis in MP Concentration for GAC Treatment in Appendix D as percentage.

This analysis shows that the inventory of micropollutants mostly contributes to the category of aquatic ecotoxicity. It is one of the expected results because at the end of treatment, the untreated micropollutants in the water are discharge into the aquatic environment, so when the amount of micropollutants is increased, it mostly affects to impact category of aquatic ecotoxicity.

As explained in the methodology section, the treatment efficiency is accepted as 80% for the micropollutants whose output concentration from the tertiary treatment cannot be reached in the study. In the Sensitivity Analysis, the impact of this assumption on the study results for GAC adsorption is tested. Although it is not a sensitive parameter for 14 of the 15 categories, the assumption causes the deviation of (+/-)11-12% for the category of aquatic ecotoxicity in GAC treatment. It can be stated that the ratio is not low to ignore, so it has been determined as a limitation of the study.

4.2.2 Sensitivity Analysis for Ozonation

In this part, the results of sensitivity analysis carried out for ozonation treatment are presented. In the first part, the change in potential adverse environmental impacts of ozonation when the ozone dosage is changed is analyzed. In the second part, the change in potential adverse environmental impacts of ozonation when the micropollutant concentration in the treated water is changed is analyzed. Although increase and decrease in the inventories of ozone dosage and micropollutant concentration are dependent on each other, sensitivity analyses of these variables is made separately to see the sensitivity of the system for these two parameter.

4.2.2.1 Sensitivity Analysis for the Ozone Dosage in Ozonation Treatment

Graph of Characterization of Sensitivity Analysis in Ozone Dosage for Ozonation shows that change in the potential environmental impact of ozonation treatment when the amount of ozone dosage is changed between the determined minimum and maximum values. According to the graph, the most sensitive impact category for the

ozone dosage inventory of the system is ionizing radiation. In addition to this category, impact categories of ozone layer depletion, terrestrial ecotoxicity, land occupation, and mineral extraction are affected by the change in ozone dosage notably. The characterization result of the impact category of ionizing radiation can be higher 42.44% and can be lower 40.96% than the current value with the change of ozone dosage.

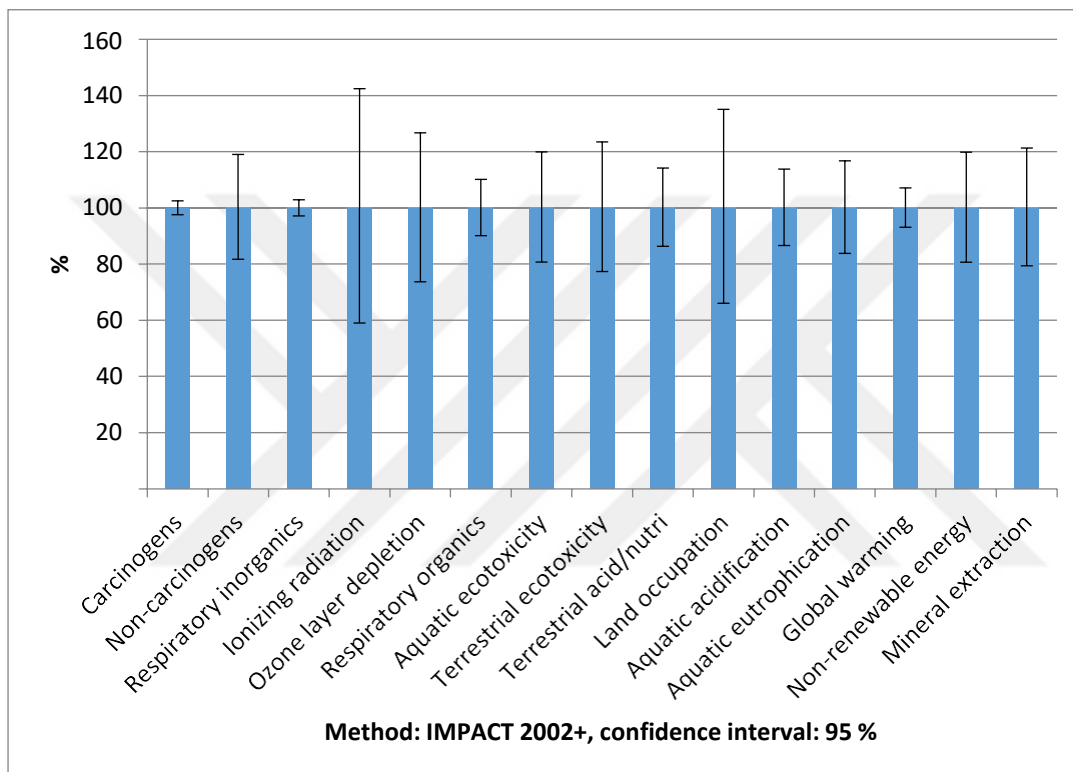


Figure 28. Characterization Graph of Sensitivity Analysis in Ozone Dosage for 20 mg/L Ozonation

This analysis shows that the inventory of ozone dosages mostly contributes to the category of ionizing radiation. Changes in the characterization results of these impact categories is given in Table D 3 in Appendix D as a percentage.

4.2.2.2 Sensitivity Analysis in MP Concentration for Ozonation

Graph of Characterization of Sensitivity Analysis in Micropollutant Concentration for Ozonation shows that change in the potential environmental impact of ozone

treatment when the amount of micropollutants is changed between the determined minimum and maximum values. According to the graph, the most sensitive impact category is ozone layer depletion for the inventory of micropollutant concentration in the system. In addition to this category, impact categories of ionizing radiation, aquatic ecotoxicity, and aquatic acidification are affected slightly by the change in micropollutant concentration. Characterization result of impact category of ozone layer depletion can be higher 3.42% and can be lower 2.99% than the current value with the change of micropollutant concentration. Changes in the characterization results of these impact categories is given in Table D 4 in Appendix D in detail.

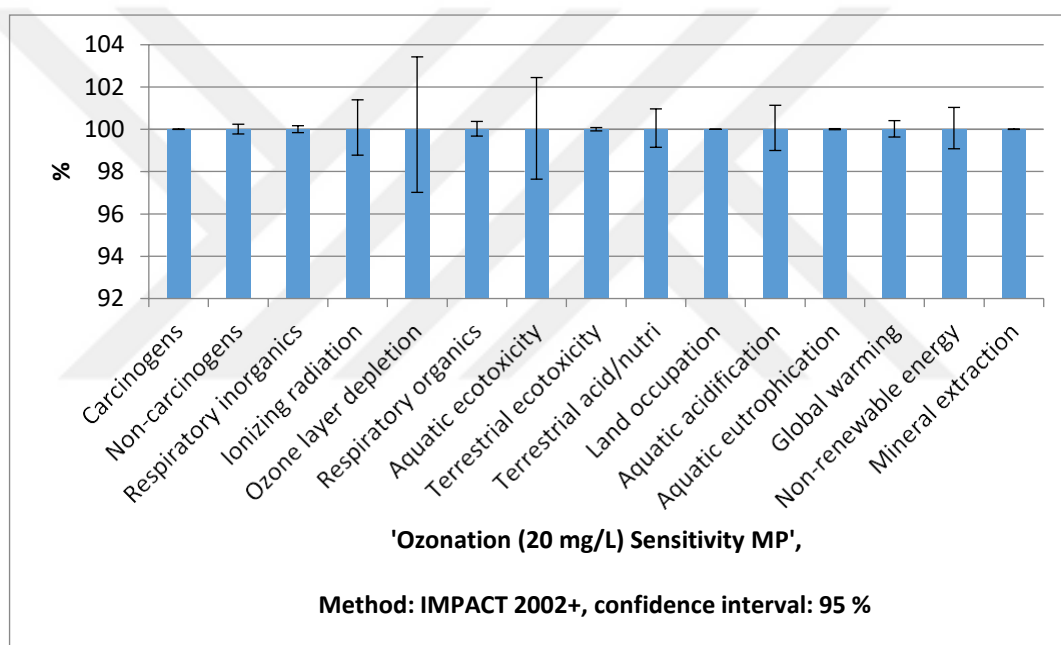


Figure 29. Characterization Graph of Sensitivity Analysis in MP Concentration for Ozonation

This analysis shows that the inventory of micropollutants mostly contributes to the category of ozone layer depletion although the most sensitive parameter of the case of Sensitivity analysis in micropollutant concentration for GAC adsorption is aquatic ecotoxicity. The reason for these difference is that the treatment efficiency of these two methods are different from each other, so discharged micropollutant amount to the environment is changed according to the treatment method. Different amounts micropollutants create different potential adverse impacts on the environment.

In this scenario, the assumption that the treatment efficiency is 80% for micropollutants whose output concentration from tertiary treatment cannot be reached is tested. It is seen that the relevant input affects 14 of the 15 categories given in the study results; also, does not cause a deviation of more than 3.42% in any impact category. Since the deviation created by the acceptance is less than 5%, it has been determined as a suitable assumption for ozone treatment scenarios for the study. The reason why the input caused much less deviation in the results compared to GAC adsorption is the higher adverse potential environmental impact is caused by the other inputs in ozone treatment. Therefore, it can be seen that micropollutant concentration is not a sensitive parameter in ozone treatment in the study.

CHAPTER 5

CONCLUSION

The textile industry, which is widespread and has a high pollution load, increases its product diversity day by day with developing technology and increasing demands. As a result of this, the amount of chemicals, raw materials, energy, and water used increases. With the increasing environmental awareness, various micropollutants in the industry's wastewater need to be treated. Since secondary treatment is not sufficient for the treatment of micropollutants in wastewater, advanced treatment methods should be used; also, it is significant to the preference of the right method for treatment. Activated carbon adsorption and ozonation are widely used advanced treatment methods to treat micropollutants with similar treatment efficiencies. This study compared the environmental impacts of these methods using the software SimaPro. The environmental impacts of advanced treatment methods, where the treatment of 1 m³ of water is considered as the functional unit, have been evaluated and compared with a gate-to-gate approach.

Three different scenarios, namely activated carbon adsorption, base-case ozone treatment, and comparison of GAC adsorption and ozonation, were analyzed for 15 different environmental impact categories, and the following findings were obtained in the study.

For GAC adsorption;

- The global warming endpoint is the impact category in which GAC treatment has the highest contribution.
- The electricity used in the GAC is the process component with the highest adverse environmental impact in almost all impact categories. Also, the incineration of the waste activated carbon appeared as the second most important component of the GAC treatment regarding its environmental impacts.

For ozone treatment;

- The human health endpoint is the impact category in which ozone treatment has the highest contribution.
- The electricity usage is the highest contributor to the environmental impacts of ozonation in all impact categories. The ozone generation process follows the electricity usage as the second highest contributor.

For the comparison of GAC adsorption and ozonation;

- GAC adsorption has much less adverse environmental impacts than ozonation in all impact categories except for global warming. GAC's adverse environmental impacts were generally found to be not more than 20% of the environmental impacts of ozonation.
- In the global warming category, the impact of GAC adsorption is twice as much as compared to ozonation. The higher impact of GAC adsorption on the global warming category is due to the incineration of waste GAC.
- The impact categories of non-carcinogens, ionizing radiation, ozone layer depletion, aquatic ecotoxicity, terrestrial ecotoxicity, land occupation, non-renewable energy, and mineral extraction were found to be affected more by the changes in the doses of GAC and ozone.
- The impact category of ionizing radiation is the most sensitive category for the change in ozone dose, and aquatic ecotoxicity for the change in GAC dose.

Moreover, sensitivity analysis was conducted for the incineration process of GAC adsorption, ozone dosage of ozone treatment, and micropollutant concentration for both treatment methods. It was seen that;

For the incineration of waste GAC;

- The most sensitive impact category of the system is land occupation; also, impact categories of non-carcinogens, ionizing radiation, aquatic ecotoxicity, and terrestrial ecotoxicity are affected notably by the change of incineration percentage.

For the micropollutant concentration of in GAC treatment;

- The category of aquatic ecotoxicity is the most sensitive impact category for the change in the micropollutant concentration.

For the ozone dosage in ozonation;

- Ionizing radiation is the most sensitive impact category for the ozone dosage; also, impact categories of ozone layer depletion, terrestrial ecotoxicity, land occupation, and mineral extraction are affected by the change notably.

For the micropollutant concentration in ozonation;

- The category of ozone layer depletion is the most sensitive impact category for micropollutant concentration change in ozone treatment.



CHAPTER 6

RECOMMENDATIONS

It is anticipated that the textile industry will need to remove micropollutants from secondary textile wastewater in the future to comply with environmental quality standards set by the Turkish Surface Water Quality Regulation published by the Ministry of Agricultural and Forestry in 2016, within the scope of harmonization of Türkiye's legislation with the EU Legislation. This requirement necessitates the selection of the most proper tertiary treatment method. This study was conducted to determine and compare the adverse environmental impacts of the tertiary treatment methods of activated carbon adsorption and ozonation for removing micropollutants from the secondary textile wastewater.

The following recommendations are made:

- The scope of the present study should be extended to the other advanced treatment processes such as the Fenton process, membrane processes, or ultraviolet disinfection for a better comparison of the tertiary treatment methods that can be applied for the removal of micropollutants from textile wastewater.
- LCA studies should be combined with socio-economic impact analysis to select the best tertiary treatment method for secondary textile wastewater.



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APPENDIX A- LCA RESULTS FOR THE BASE-CASE ACTIVATED CARBON TREATMENT

Table A 1. Characterization Results for the GAC Adsorption Treatment (Activated Carbon Dose = 10 mg/L)

Impact category	Unit	Total	Activated Carbon Incineration	De-ionised water	Natural gas	Hard coal	Electricity	Electricity	Sludge incineration	Ash lanfilling
Aquatic ecotoxicity	kg TEG water	4.73E-03	3.96E-04	2.50E-07	1.77E-04	9.83E-07	7.57E-04	3.05E-04	2.91E-03	1.89E-04
Global warming	kg CO2 eq	2.45E-03	0.0024	1.01E-06	2.33E-06	3.50E-06	2.31E-05	9.30E-06	1.38E-05	8.24E-08
Non-renewable energy	MJ primary	1.35E-03	0	8.68E-06	1.66E-04	5.77E-04	3.02E-04	1.22E-04	1.77E-04	5.41E-07
Terrestrial ecotoxicity	kg TEG soil	5.84E-04	1.99E-11	4.05E-07	3.53E-05	1.47E-06	1.47E-04	5.90E-05	3.41E-04	5.95E-07
Ionizing radiation	Bq C-14 eq	1.92E-04	0	1.16E-05	3.74E-05	4.29E-06	1.24E-05	5.00E-06	1.21E-04	5.06E-07
Carcinogens	kg C2H3Cl eq	1.42E-06	2.14E-10	5.14E-10	1.00E-07	5.39E-10	8.70E-07	3.50E-07	9.17E-08	1.95E-09
Terrestrial acid/nutri	kg SO2 eq	7.51E-07	0	1.24E-08	3.14E-08	1.32E-07	3.36E-07	1.35E-07	1.03E-07	8.19E-10
Non-carcinogens	kg C2H3Cl eq	5.40E-07	6.83E-12	1.31E-09	1.64E-08	2.13E-09	1.11E-07	4.45E-08	3.48E-07	1.71E-08
Land occupation	m2org.arable	4.84E-07	0	0	6.99E-09	0	7.03E-08	2.83E-08	3.72E-07	5.93E-09
Mineral extraction	MJ surplus	3.96E-07	0	1.23E-09	2.34E-08	1.20E-10	1.62E-07	6.53E-08	1.43E-07	6.08E-10
Aquatic acidification	kg SO2 eq	2.57E-07	0	3.29E-09	1.45E-08	3.03E-08	1.29E-07	5.17E-08	2.90E-08	1.37E-10

Impact category	Unit	Total	Activated Carbon Incineration	De-ionised water	Natural gas	Hard coal	Electricity	Electricity	Sludge incineration	Ash lanfilling
Respiratory inorganics	kg PM2.5 eq	2.35E-07	0	4.38E-10	3.59E-09	4.41E-09	1.57E-07	6.31E-08	7.00E-09	3.65E-11
Respiratory organics	kg C2H4 eq	1.45E-08	0	7.21E-11	2.80E-09	1.99E-09	3.39E-09	1.36E-09	4.83E-09	1.75E-11
Aquatic eutrophication	kg PO4 P-lim	1.21E-08	0	1.97E-10	3.01E-10	2.15E-11	7.15E-09	2.88E-09	1.56E-09	1.30E-11
Ozone layer depletion	kg CFC-11 eq	5.39E-12	0	1.07E-13	2.42E-12	3.72E-14	4.95E-13	1.99E-13	2.13E-12	5.75E-15

Table A 2. Single Score of the Base-Case GAC Adsorption Treatment (Activated Carbon Dose = 10 mg/L)

Label	Unit	Climate change	Human health	Resources	Ecosystem quality
Activated Carbon Incineration	nPt	242.4	8.72E-05	0	0.0015
De-ionised water	nPt	0.1018	0.0443	0.0571	0.0012
Natural gas	nPt	0.235	0.4026	1.0967	0.024
Hard coal	nPt	0.353	0.437	3.8007	0.0109
Electricity	nPt	2.3332	15.8608	1.9907	0.1186
Electricity	nPt	0.9391	6.384	0.8012	0.0477
Sludge Incineration	nPt	1.3918	0.8694	1.1626	0.2447
Ash Landfilling	nPt	0.0083	0.0111	0.0036	0.0016

APPENDIX B- LCA RESULTS FOR THE BASE-CASE OZONE TREATMENT

Table B 1. Characterization Results for the Base-case Ozone Treatment (Ozone Dose = 20 mg/L)

Impact category	Unit	Total	Ozonation	Tap water	Ozone Production	Hydrogen peroxide	Sodium hydroxide	Electricity
Carcinogens	kg C2H3Cl eq	2.64E-05	2.14E-10	2.31E-09	1.39E-06	1.20E-05	1.10E-08	1.31E-05
Non-carcinogens	kg C2H3Cl eq	3.51E-06	6.83E-12	1.19E-09	1.38E-06	4.05E-07	6.23E-08	1.66E-06
Respiratory inorganics	kg PM2.5 eq	2.59E-06	0	3.70E-11	1.57E-07	3.87E-08	3.84E-08	2.35E-06
Ionizing radiation	Bq C-14 eq	1.11E-02	0	1.93E-07	9.71E-03	2.91E-04	9.05E-04	1.86E-04
Ozone layer depletion	kg CFC-11 eq	4.11E-11	0	2.11E-15	2.27E-11	2.78E-12	8.22E-12	7.43E-12
Respiratory organics	kg C2H4 eq	9.30E-08	0	1.16E-11	1.96E-08	1.80E-08	4.57E-09	5.08E-08
Aquatic ecotoxicity	kg TEG water	2.38E-02	3.96 E-04	1.82E-06	9.85E-03	2.14E-04	5.28E-05	1.14E-02
Terrestrial ecotoxicity	kg TEG soil	5.22E-03	1.99E-11	6.16E-07	2.54E-03	4.21E-04	5.69E-05	2.20E-03
Terrestrial acid/ nutri	kg SO2 eq	8.58E-06	0	4.09E-10	2.51E-06	4.04E-07	6.27E-07	5.04E-06

Impact category	Unit	Total	Ozonation	Tap water	Ozone Production	Hydrogen peroxide	Sodium hydroxide	Electricity
Land occupation	m ² org.arable	5.18E-06	0	5.82E-10	3.77E-06	3.59E-07	0	1.05E-06
Aquatic acidification	kg SO ₂ eq	3.27E-06	0	1.14E-10	9.32E-07	1.36E-07	2.72E-07	1.93E-06
Aquatic eutrophication	kg PO ₄ P-lim	1.76E-07	0	4.08E-12	6.13E-08	6.90E-09	5.33E-10	1.07E-07
Global warming	kg CO ₂ eq	1.26E-03	6.60E-04	2.04E-08	1.86E-04	2.71E-05	3.82E-05	3.47E-04
Non-renewable energy	MJ primary	9.72E-03	0	2.63E-07	3.99E-03	4.91E-04	6.90E-04	4.54E-04
Mineral extraction	MJ surplus	7.68E-06	0	1.68E-09	3.40E-06	1.84E-06	4.31E-09	2.43E-06

Table B 2. Single Score of the Base-Case Ozone Treatment (Ozone Dose = 20 mg/L)

Label	Unit	Human health	Ecosystem quality	Climate change	Resources
Ozonation	nPt	8.72E-05	1.50E-03	66.66	0
Tap water	nPt	5.00E-03	4.00E-04	2.00E-03	1.7E-03
Ozone	nPt	16.9267	1.9963	18.7595	26.339
Hydrogen peroxide	nPt	8.7327	0.31	2.74	3.241
Sodium hydroxide	nPt	3.8473	0.0807	3.8607	4.5388
Electricity	nPt	237.9119	1.7785	34.9984	29.8598

APPENDIX C- COMPARISON OF GAC ADSORPTION AND OZONATION

Table C 1. Characterization of GAC Adsorption and Ozonation for the Base Case

Impact category	Unit	Activated Carbon (10 mg/L) Adsorption	Ozonation (20 mg/L)
Carcinogens	kg C2H3Cl eq	1.42E-06	2.64E-05
Non-carcinogens	kg C2H3Cl eq	5.40E-07	3.51E-06
Respiratory inorganics	kg PM2.5 eq	2.35E-07	2.59E-06
Ionizing radiation	Bq C-14 eq	1.93E-04	1.11E-02
Ozone layer depletion	kg CFC-11 eq	5.39E-12	4.11E-11
Respiratory organics	kg C2H4 eq	1.45E-08	9.30E-08
Aquatic ecotoxicity	kg TEG water	4.73E-03	2.38E-02
Terrestrial ecotoxicity	kg TEG soil	5.84E-04	5.22E-02
Terrestrial acid/nutri	kg SO2 eq	7.51E-07	8.58E-06
Land occupation	m2org.arable	4.84E-07	5.18E-06
Aquatic acidification	kg SO2 eq	2.57E-07	3.27E-06
Aquatic eutrophication	kg PO4 P-lim	1.21E-08	1.76E-07

Impact category	Unit	Activated Carbon (10 mg/L) Adsorption	Ozonation (20 mg/L)
Global warming	kg CO2 eq	2.45E-03	1.26E-03
Non-renewable energy	MJ primary	1.35E-03	9.72E-03
Mineral extraction	MJ surplus	3.96E-07	7.68E-06

Table C 2. Single Scores of the GAC Adsorption and Ozonation for the Base Case Scenarios

End-Point Impact Category	Unit	Activated Carbon (10 mg/L) Adsorption	Ozonation (20 mg/L)
Human health	nPt	24.0094	267.4236
Ecosystem quality	nPt	0.4501	4.1674
Climate change	nPt	247.7625	127.0207
Resources	nPt	8.9125	63.9803

Table C 3. Characterization Results for GAC Adsorption and Ozonation for Minimum/Base/Maximum Dosage Cases

Impact category	Unit	Activated Carbon (5 mg/L) Adsorption	Activated Carbon (10 mg/L) Adsorption	Activated Carbon (20 mg/L) Adsorption	Ozonation (10 mg/L)	Ozonation (20 mg/L)	Ozonation (40 mg/L)
Carcinogens	kg C2H3Cl eq	1.14E-06	1.42E-06	1.96E-06	2.58E-05	2.64E-05	2.78E-05
Non-carcinogens	kg C2H3Cl eq	3.25E-07	5.40E-07	9.69E-07	2.82E-06	3.51E-06	4.89E-06
Respiratory inorganics	kg PM2.5 eq	1.96E-07	2.35E-07	3.14E-07	2.51E-06	2.59E-06	2.74E-06
Ionizing radiation	Bq C-14 eq	1.03E-04	1.93E-04	3.73E-04	6.24E-03	1.11E-02	2.08E-02
Ozone layer depletion	kg CFC-11 eq	2.94E-12	5.39E-12	1.03E-11	2.98E-11	4.11E-11	6.38E-11
Respiratory organics	kg C2H4 eq	8.92E-09	1.45E-08	2.55E-08	8.32E-08	9.30E-08	1.13E-07
Aquatic ecotoxicity	kg TEG water	2.66E-03	4.73E-03	9.37E-03	1.86E-04	2.38E-02	3.47E-02
Terrestrial ecotoxicity	kg TEG soil	3.65E-04	5.84E-03	1.02E-03	3.95E-03	5.22E-03	7.77E-03
Terrestrial acid/nutri	kg SO2 eq	5.43E-07	7.51E-07	1.17E-06	7.33E-06	8.58E-06	1.11E-05
Land occupation	m2org.arable	2.77E-07	4.84E-07	8.97E-07	3.30E-06	5.18E-06	8.94E-06
Aquatic acidification	kg SO2 eq	1.93E-07	2.57E-07	3.86E-07	2.80E-06	3.27E-06	4.20E-06

Impact category	Unit	Activated Carbon (5 mg/L) Adsorption	Activated Carbon (10 mg/L) Adsorption	Activated Carbon (20 mg/L) Adsorption	Ozonation (10 mg/L)	Ozonation (20 mg/L)	Ozonation (40 mg/L)
Aquatic eutrophication	kg PO4 P-lim	9.64E-09	1.21E-08	1.71E-08	1.45E-07	1.76E-07	2.37E-07
Global warming	kg CO2 eq	2.44E-03	2.45E-03	2.48E-03	1.17E-03	1.26E-03	1.44E-03
Non-renewable energy	MJ primary	8.27E-04	1.35E-03	2.40E-03	7.72E-03	9.72E-03	1.37E-02
Mineral extraction	MJ surplus	2.79E-07	3.96E-07	6.29E-07	5.98E-06	7.68E-06	1.11E-05

Table C 4. Single Score of GAC Adsorption and Ozonation for the Minimum/Base/Maximum Dosage Cases

Label	Unit	Human health	Ecosystem quality	Climate change	Resources
Activated Carbon (5 mg/L) Incineration	nPt	19.934	0.284	246.247	5.4425
Activated Carbon (10 mg/L) Incineration	nPt	24.0094	0.4501	247.7625	8.9125
Activated Carbon (20 mg/L) Incineration	nPt	32.1563	0.784	250.79	15.8162
Ozonation (10 mg/L)	nPt	258.9609	3.1684	117.6435	50.8149
Ozonation (20 mg/L)	nPt	267.4236	4.1674	127.0207	63.9803
Ozonation (40 mg/L)	nPt	284.3495	6.1673	145.7753	90.3111

APPENDIX D- SENSITIVITY ANALYSIS

Table D 1. Characterization of Sensitivity Analysis in Incineration for GAC

Label	Activated Carbon (10 mg/L) Sensitivity in Incineration	Low	High
Carcinogens	100	4.1744	3.741
Non-carcinogens	100	51.8385	46.555
Respiratory inorganics	100	1.8696	1.6929
Ionizing radiation	100	50.077	45.3547
Ozone layer depletion	100	28.5257	25.718
Respiratory organics	100	23.5329	21.264
Aquatic ecotoxicity	100	49.6682	45.863
Terrestrial ecotoxicity	100	45.6426	41.0786
Terrestrial acid/nutri	100	8.9707	8.0711
Land occupation	100	64.3002	58.0978
Aquatic acidification	100	7.2755	6.598
Aquatic eutrophication	100	8.426	7.5825
Global warming	100	0.3512	0.3168
Non-renewable energy	100	8.515	7.6858
Mineral extraction	100	25.6715	23.2548

Table D 2. Characterization of Sensitivity Analysis in MP Concentration for GAC Treatment

Label	Activated Carbon (10 mg/L) Sensitivity in MP	Low	High
Carcinogens	100	0.0449	0.0467
Non-carcinogens	100	0.0013	0.0015
Respiratory inorganics	100	0	0
Ionizing radiation	100	0	0
Ozone layer depletion	100	0	0
Respiratory organics	100	0	0
Aquatic ecotoxicity	100	11.5178	11.1762
Terrestrial ecotoxicity	100	5.58E-06	5.07E-06
Terrestrial acid/nutri	100	0	0
Land occupation	100	0	0
Aquatic acidification	100	0	0
Aquatic eutrophication	100	0	0
Global warming	100	0	0
Non-renewable energy	100	0	0
Mineral extraction	100	0	0

Table D 3. Characterization of Sensitivity Analysis in Ozone Dosage for Ozonation

Label	Ozonation (20 mg/L) Sensitivity Ozone	Low	High
Carcinogens	100	2.4284	2.5168
Non-carcinogens	100	18.279	19.0299
Respiratory inorganics	100	2.8399	2.9298
Ionizing radiation	100	40.962	42.4437
Ozone layer depletion	100	26.2872	26.7207
Respiratory organics	100	9.848	10.1665
Aquatic ecotoxicity	100	19.2579	19.9306
Terrestrial ecotoxicity	100	22.64	23.5
Terrestrial acid/nutri	100	13.6397	14.1909
Land occupation	100	33.9337	35.1157
Aquatic acidification	100	13.3936	13.8386
Aquatic eutrophication	100	16.1764	16.759
Global warming	100	6.8916	7.118
Non-renewable energy	100	19.2939	19.8405
Mineral extraction	100	20.6104	21.3292

Table D 4. Characterization of Sensitivity Analysis in MP Concentration for Ozonation

Label	Ozonation (20 mg/L) Sensitivity MP	Low	High
Carcinogens	100	0.0059	0.0061
Non-carcinogens	100	0.2159	0.2439
Respiratory inorganics	100	0.1516	0.1721
Ionizing radiation	100	1.2193	1.3965
Ozone layer depletion	100	2.9887	3.4232
Respiratory organics	100	0.3251	0.3697
Aquatic ecotoxicity	100	2.3626	2.4417
Terrestrial ecotoxicity	100	0.0731	0.0821
Terrestrial acid/nutri	100	0.8503	0.9653
Land occupation	100	0	0
Aquatic acidification	100	1.0025	1.1374
Aquatic eutrophication	100	0.0235	0.0268
Global warming	100	0.3679	0.4093
Non-renewable energy	100	0.9270	1.0326
Mineral extraction	100	0.0059	0.0067