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LCA, s-LCA and LCC & main outcomes from CSS3

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Lead beneficiary:	**19 - NTUA**
Lead author:	**Antonis Peppas, Chrysa Politi, Konstantinos Baldoukas**
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Executive Summary

Deliverable D5.4 presents the sustainability assessment of Scenario 3.1 within Circular Systemic Solution 3 (CSS3), which focuses on the valorization of wastewater through a microalgae-based process. The assessment includes environmental, economic and social impact evaluations. Scenario 3.1 was compared against a conventional baseline scenario representing current wastewater treatment and disposal.

The Life Cycle Assessment results show that Scenario 3.1 significantly outperforms the baseline in most environmental impact categories. Notable improvements are observed in Abiotic Depletion – Fossil (–4.06 MJ vs +4.08 MJ), Global Warming Potential (0.33 kg CO_2 eq. vs 1.01 kg CO_2 eq.) and Acidification Potential (–3.72 × 10^{-3} kg SO_2 eq. vs 1.01 × 10^{-3} kg SO_2 eq.). Scenario 3.1 also yields net-negative results in eutrophication and ecotoxicity indicators, highlighting the system's ability to reduce environmental burdens through the production of valuable bio-based outputs.

The Life Cycle Cost analysis reveals that, while the baseline incurs lower direct costs, Scenario 3.1 has the potential for long-term cost recovery through resource valorization. The main cost contributors in Scenario 3.1 are energy and input materials used in key stages such as harvesting and enzymatic hydrolysis.

The social Life Cycle Assessment evaluation indicates positive social performance for Scenario 3.1, particularly in relation to worker safety, job creation and technology development. Benefits are also observed for the local community and society at large, although minor gaps remain in areas such as certification uptake and public environmental engagement.

Overall, the results demonstrate that Scenario 3.1 offers a technically feasible and environmentally beneficial solution for wastewater treatment, with promising economic and social co-benefits. The findings support its potential scalability and contribution to sustainable regional transformation under the FRONTSH1P project.

Contents

1 Introduction

1.1 Purpose of the deliverable

The goal of this deliverable is to identify key actions with the highest potential for improving the eco-design of specific products, such as soil improvers, biofertilizers, and bio stimulants. As the primary tool for eco-design, NTUA will assess the environmental impact of the developed microalgae technology using Life Cycle Assessment (LCA) and Social Life Cycle Assessment (s-LCA). The study will focus on the specific environmental footprint of the biobased products in CSS3, particularly in terms of greenhouse gas emissions, human health, climate impact, and ecosystem quality. A sensitivity analysis will be conducted to identify key bottlenecks that must be addressed during the eco-design process. This analysis will be carried out in phases, initially providing feedback during the eco-design stage, and later demonstrating the benefits of the finalized demonstration process.

The LCA will follow ISO 14040/44, 21930, and other applicable standards using Sphera software. The inventory sources will include standardized and readily available data, as well as data generated throughout the project. Specific sources for the inventory (LCI) will include:

1. Integrated Sphera databases for raw materials, waste, products, and processes (such as ELCD of EC-Joint Research Centre).
2. Chemical characterization data from real stream analyses in Task 5.2.
3. Biological system modelling results from Task 5.3.
4. Actual demo plant performance data, including power consumption, mass and energy balances, from Task 5.3.

Additionally, the life cycle thinking approach will be extended to include costing for the developed wastewater treatment processes via Life Cycle Costing (LCC). The process results will inform the LCC analysis, while equipment, operation and maintenance costs will be derived from the demo plant construction phase. Other assumptions needed for calculating costs related to waste disposal, system replacements and decommissioning will be based on LNEG's experience with long-term operation of microalgae-based facilities. The study will also include a cost assessment for scaling up facility capacity, with process optimization evaluated through sensitivity analysis.

1.2 Trends in water waste management: A European and regional perspective

1.2.1 Water waste in Europe

Water is essential for life; it is an indispensable resource for the economy and also plays a fundamental role in the climate regulation cycle. The management and protection of water

resources, of fresh and saltwater ecosystems, and of the water we drink and bathe in is therefore one of the cornerstones of environmental protection. This is why the EU's water policy over the past 30 years is focused on the protection of water resources, ensuring that good quality water, in sufficient quantity, is available for all legitimate uses. The state of play is described by the fifth implementation report (2019) of the Water Framework Directive (2000), the central piece of environmental legislation concerning European waters. Recent insight about the quality of existing water related EU legislation and perspectives for its future development is offered by the Fitness check of the Water Framework Directive and related legislation (2019) [1]. A number of countries receive a significant proportion of their renewable freshwater resources as external inflow (see Figure 1). Among the EU Member States, there are five countries with ca. 80% and more dependency on transboundary water resources.

Share of external inflow from neighbouring territories in renewable freshwater resources - long-term average
(%)
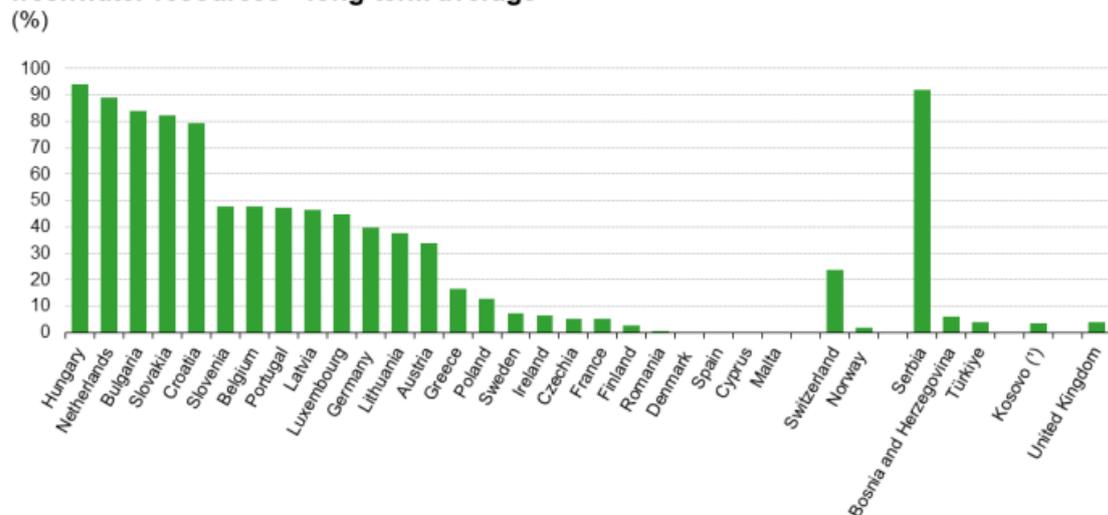
Note: The minimum period taken into account for the calculation of long term averages is 30 years.
(¹) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence
Source: Eurostat (online data code: env_wat_ltaa)

eurostat

Figure 1 Share of external inflow from neighbouring territories in renewable freshwater resources - long-term average [1]

Water resources refer to the freshwater available for use in a territory and include surface waters (lakes, rivers and streams) and groundwater. Renewable water resources are calculated as the sum of internal flow (which is precipitation minus actual evapotranspiration) and external inflow. Freshwater availability in a country is primarily determined by climate conditions and transboundary water flows (in other words, external inflows), while for total amounts, the size of the country matters. Freshwater resources per inhabitant are considered an important indicator for measuring the sustainability of water resources. For EU Member States, the average water resources are about 4-5 thousand m³

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[1] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Water_statistics

per inhabitant. In water-rich countries an inhabitant's share can be as high as around 30 thousand m³ (Croatia) or close to 70 thousand m³ as in Norway. According to the World water development report of the United Nations, a country experiences "water stress" when its annual water resources are below 1 700 m³ per inhabitant; among the EU Member States, this is the case in Poland, Czechia, Cyprus and Malta.

Table 1 Renewable freshwater resources - long-term annual average (million m³) [1]

Renewable freshwater resources - long-term annual average
(million m³)

	A. Precipitation	B. Evapo-transpiration	C. Internal Flow C=A-B	D. External Inflow	E. Renewable freshwater resources E=C+D	F. Renewable freshwater resources per 1000 inhabitants
Belgium	27 264	15 745	11 288	10 563	25 011	2.1
Bulgaria	73 344	57 460	15 884	83 957	99 841	15.0
Czechia	53 454	39 082	14 372	829	15 201	1.4
Denmark	38 485	22 145	16 340	0	16 340	2.8
Germany	309 000	205 000	104 000	69 000	173 000	2.1
Estonia	29 018	:	12 347	:	12 347	9.2
Ireland	89 491	38 182	51 308	3 526	54 834	10.6
Greece	115 000	55 000	60 000	12 000	72 000	6.9
Spain	322 754	222 358	100 396	0	100 396	2.1
France	512 864	312 003	200 860	11 000	206 236	3.0
Croatia	63 805	39 275	24 530	93 783	118 313	30.7
Italy	285 270	151 815	133 455	:	:	:
Cyprus	2 869	2 496	374	0	374	0.4
Latvia	43 220	23 573	19 647	16 992	36 639	19.5
Lithuania	44 731	30 713	14 018	8 522	22 539	8.0
Luxembourg	2 030	1 125	905	739	1 644	2.5
Hungary	56 172	50 592	5 580	91 500	:	:
Malta	172	89	83	0	83	0.2
Netherlands	32 017	22 311	9 706	78 355	88 061	5.0
Austria	99 800	43 100	56 700	29 300	:	:
Poland	201 116	150 796	50 319	7 504	57 823	1.6
Portugal	82 164	43 571	38 593	35 000	73 593	7.2
Romania	158 884	119 599	39 285	284	39 569	2.1
Slovenia	29 448	13 026	16 422	15 074	31 496	14.9
Slovakia	39 612	25 531	14 081	66 086	80 192	14.8
Finland	222 000	115 000	107 000	3 200	110 000	19.8
Sweden	349 790	169 512	170 330	14 678	194 750	18.6
Norway	554 149	188 815	365 334	6 532	371 866	68.1
Switzerland	61 207	21 382	39 825	12 560	52 385	6.0
Bosnia and Herzegovina	55 863	25 940	29 922	2 000	31 922	:
North Macedonia	19 533	:	:	1 014	:	:
Serbia	57 578	44 093	13 485	153 084	166 569	24.8
Türkiye	449 170	275 700	173 470	6 900	180 370	2.1
Kosovo (¹)	763	478	285	11	296	:
United Kingdom	287 607	127 290	161 369	6 454	172 861	2.9

(:) not available
The minimum period taken into account for the calculation of long term averages is 30 years.

(¹) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence.
Source: Eurostat (online data codes: env_wat_ltaa and demo_gind)

eurostat

The overall use of water resources can be considered sustainable in the long-term in most of Europe. However, specific regions may face problems associated with water scarcity; this is the case particularly in parts of southern Europe, where it is likely that efficiency gains in agricultural water use (as well as other uses) will need to be achieved in order to prevent seasonal water shortages. Regions associated with low rainfall, high population density or intensive agricultural or industrial activity may also face sustainability issues in the coming years, which could be exacerbated by climate change impacts on water availability and water management practices.

Water is provided either by public water supply (public or private systems with public access) or is self-supplied (for example, private drills). While the share of the public water supply

sector in total water abstraction depends on the economic structure of a given country and can be relatively small, it is nevertheless often the focus of public interest, as it comprises the water volumes that are directly used by the population.

Table 2 presents households' water use from public supply. It varies across European countries - the median is around 40-50 cubic metres per inhabitant and has been slightly decreasing over the last decades.

Table 2 Household water use from public water supply, 1990-2022 (m³ per inhabitant) [1]

Household water use from public water supply, 1990-2022
(m³ per inhabitant)

	1990	2000	2010	2020	2021	2022
Belgium ([2])	:	32	35	32	32	:
Bulgaria	48	36	36	37	37	:
Czechia	53	34	31	32	33	31
Denmark ([2])	66	47	42	43	42	40
Germany ([2])	52	46	44	46	:	:
Estonia	:	:	:	:	:	:
Ireland	:	:	:	:	:	:
Greece ([2])	:	32	:	107	109	110
Spain	:	61	59	47	:	:
France	:	:	:	:	:	:
Croatia	:	41	44	42	43	45
Italy ([2])	78	74	:	:	:	:
Cyprus	:	69	96	98	105	:
Latvia	:	37	38	38	20	18
Lithuania	:	:	19	27	28	27
Luxembourg	:	:	:	:	:	:
Hungary	56	38	34	37	38	39
Malta	:	37	41	43	42	41
Netherlands	47	51	47	49	46	:
Austria	46	44	46	43	44	44
Poland	50	36	31	34	35	35
Portugal ([2])	38	67	59	:	:	:
Romania	52	49	:	31	30	32
Slovenia	43	44	41	40	40	41
Slovakia	:	:	:	:	:	:
Finland ([2])	85	78	:	:	:	:
Sweden	63	59	52	48	:	:
Iceland ([2])	:	108	:	:	:	:
Norway	71	66	73	66	66	65
Switzerland	95	92	72	61	59	59
Bosnia and Herzegovina	:	:	31	:	:	:
Montenegro	:	:	:	55	55	55
North Macedonia ([2])	34	36	:	:	:	:
Albania	:	:	:	49	40	40
Serbia	:	48	45	47	48	49
Türkiye	:	:	33	44	:	44
Kosovo ([1]) ([2])	:	:	21	27	:	:
United Kingdom ([2])	:	:	46	:	:	:

(:) not available

([1]) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence.
([2]) Partly neighbouring reference years if not available
Source: Eurostat (online data codes: env_wat_cat and demo_gind)

eurostat ▣

Overall, there is a development towards a higher proportion of the population being connected to wastewater treatment. Table 3 presents information on the proportion of the population connected to at least secondary wastewater treatment plants, which typically is an acceptable level of environmental protection unless the receiving waters are in a sensitive area. This share has been generally increasing over the past decades and was above 80% in half of the EU Member States for which recent data are available (mixed reference years). The share of the population connected to at least secondary wastewater treatment plant even rose to 95% and above in six Member States (Denmark, Germany, Greece, the Netherlands, Austria and Sweden), as well as Switzerland and the United Kingdom. At the other end of the range, less than one in two households were connected to at least secondary

urban wastewater treatment plants only in Malta and Croatia, while the same was also true in Iceland, Albania, Serbia and Bosnia and Herzegovina.

Table 3 Share of the population connected to at least secondary urban wastewater treatment, 2000-2022 (%)[1]

Share of the population connected to at least secondary urban wastewater treatment, 2000-2022 (%)

	2000	2005	2010	2015	2020	2021	2022
European Union	68	73	76	79	81	81	81
Belgium	41	54	75	82	84	84	84
Bulgaria	36	38	45	61	65	65	:
Czechia	:	73	77	81	83	85	85
Denmark	93	:	93	97	98	98	98
Germany	:	97	96	96	:	:	:
Estonia	69	78	79	83	83	82	82
Ireland	:	:	65	61	64	64	65
Greece	:	:	87	93	95	95	95
Spain	80	88	93	86	87	87	:
France	:	:	78	80	80	80	80
Croatia	:	:	:	37	37	31	:
Italy	:	54	58	60	:	:	:
Cyprus	14	30	:	:	83	:	:
Latvia	53	63	59	73	77	76	77
Lithuania	:	47	64	72	77	77	76
Luxembourg	:	:	:	:	:	:	:
Hungary	30	42	70	76	81	82	82
Malta	11	13	7	0	7	7	7
Netherlands	98	99	99	99	100	100	100
Austria	85	90	94	95	99	99	99
Poland	50	58	65	73	75	75	76
Portugal	:	43	:	:	:	:	:
Romania	:	17	23	40	52	53	54
Slovenia	12	32	52	57	69	68	68
Slovakia	:	:	:	:	69	70	71
Finland	80	82	83	84	85	85	85
Sweden	94	94	94	95	96	96	:
Iceland	0	2	1	:	:	:	:
Norway	:	:	48	51	67	68	71
Switzerland	96	97	98	:	:	:	:
Bosnia and Herzegovina	9	10	11	12	:	:	:
Albania	:	:	:	8	31	22	23
Serbia	5	6	9	11	14	15	15
Türkiye	18	29	38	55	61	61	61
Kosovo (¹)	:	:	:	:	:	:	:
United Kingdom	91	99	100	:	:	:	:

(:) not available

(¹) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence.

Source: Eurostat (online data code: sdg_06_20)

eurostat

1.2.2 Water waste in Lodzkie region

During research in Lodzkie region [2], in the case of most standard parameters for wastewater discharged to the sewer system in Lodz, exceedances were observed. The results show that only pH, concentration of Zn, Pb, HOI and PC always met the requirements given in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**.

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[2] https://link.springer.com/article/10.1007/s40095-021-00455-4

Table 4 Tested parameters of wastewater quality—methodology of analysis and emission standards[2]

No	Parameter	Analytical method; detection limit	Emission standards in Lodz	
			Discharge of industrial wastewater into the sewer system according to local regulation in Lodz	Discharge into water and soil according to Regulation of the Minister of Maritime Economy and Inland Navigation
1	pH	PN-EN ISO 10523:2012; potentiometric method	$6.5 \div 9.5$	$6.5 \div 12.0*$
2	CD	PN-EN 27,888:1999; conductometric method; 10 μS/cm	–	–
3	TSS	PN-EN 872–2007-1; gravimetric method; 2 mg/L	600 mg/L	35 mg/L
4	BOD_5	PN-EN 1899–2:2002; dilution technique; 3 mg/L	$600 \text{ mgO}_2/\text{L}$	$15 \text{ mgO}_2/\text{L}$
5	COD	PN-ISO 6060-2006; titration method; 30 mg/L	$1200 \text{ mgO}_2/\text{L}$	$125 \text{ mgO}_2/\text{L}$
6	NH_4–N	PN ISO 5664:2002; titration method; $0.5 \text{ mg } NH_4$–N/L	$100 \text{ mg } NH_4$–N /L	$10 \text{ mg } NH_4$–N /L*
7	TKN	PN-EN 25,663:2001; titration method; 2 mg N/L	100 mgN/L	–
8	TP	PN-EN ISO 6878:2006; UV/VIS spectrometry; 0,04 mgP/L	15.0 mgP/L	1 mgP/L
9	S^{2-}	Sulfide test; colorimetric method; 0.1 mgS^{2-}/L	1 mgS/L	0.2 mgS/L*
10	Zn	PN-EN ISO 8288:2002, mineralization and FAAS; 25 μg/L	2 mg/L	2 mg/L*
11	Cu	PN-EN ISO 15586:2005; mineralization and GFAAS; 0.5 μg/L	0.3 mg/L	0.1; 0.5 mg/L**
12	Cr	PN-EN ISO 15586:2005; mineralization and GFAAS; 1 μg/L	0.3 mg/L	0.5; 1,0 mg/L**
13	Pb	PN-EN ISO 15586:2005; mineralization and GFAAS; 2 μg/L	0.2 mg/L	0.1; 0.5 mg/L**
14	CS	cuvette tests HACH; UV/VIS spectrometry; 0.2 mg/L	–	–
15	AS	cuvette tests HACH; UV/VIS spectrometry; 0.1 mg/L	15 mg/ L	5 mg/L*
16	NIS	cuvette tests HACH; UV/VIS spectrometry; 6 mg/L	20 mg/L	10 mg/L*
17	HOI	PN-EN ISO 9377–2; solvent extraction and gas chromatography; 0.1 mg/L	15 mg/L	5;15 mg/L**
18	BTX	ISO 11423–2; extraction and gas chromatography; 5 μg/L	1 mg/L	0.1 mg/L*
19	PC	SPE and UV/VIS spectrometry; 0.02 mg/L	15 mg/L	0.1 mg/L*
20	NAP	SPE and HPLC; 1 μg/L	–	–

*Limits for industrial wastewater; **depending on the type of industry

The median values were exceeded only in sample cases, the median COD was equal to 1283.5 mg/L and 705 mg/L while the median BOD5 was equal to 642 mg/L. Summarizing the results of the analysis, it can be concluded that at some sampling points, the wastewater has the highest levels of organic compounds. The concentration of TSS was also high and the limit values for wastewater discharged into the sewage system were sometimes exceeded. The conducted research has shown that the quality parameters of wastewater discharged into the sewer system in Lodz sometimes exceed the legislative requirements. At most sampling points, such cases occurred only sporadically, but at 3 points, the median content of organic substance in the sewage was higher than the permissible values (BOD5 and COD). During the measurement campaign, several high exceedances of the concentration of one or more pollutants were identified, which may indicate illegal discharge of industrial wastewater. No situations were observed, in which the composition of wastewater flowing into the treatment plant would endanger the treatment process and its

efficiency. However, such situations occurred outside the period of the measurement campaign.

In the samples of sewage collected from combined sewers during wet weather, significant exceedances of the pollutant concentrations established for sewage discharged into the waters were found, which indicates that during combined sewer overflow, small rivers in Lodz are exposed to the discharge of large loads of pollutants.

Wastewater composition was rather typical for municipal sewage, but the BOD5 and COD values were quite high. Most of the investigated wastewater quality parameters were characterized by medium to high coefficient of variation. The study carried out showed high Pearson correlations between selected indicators of wastewater quality, which can be used in the development of a future wastewater composition testing plan and allow a reduction in the number of parameters to be controlled.

The multivariate statistical analysis carried out identified some similarities in the composition of wastewater collected at different points in the sewerage system, but the results are not conclusive. Obtaining full knowledge of the wastewater characteristics in the sewage system would require a significant extension of the scope of monitoring.

Traditional monitoring of wastewater quality, based on laboratory tests, does not allow for WWTP warning about the inflow of wastewater that may threaten the treatment process. It seems that continuous monitoring with the use of online sensors is becoming a necessity, especially in the case of large hybrid sewage systems. The use of data from online quality monitoring stations and other measurement systems—of wastewater flow in sewers and rainfall—allows the development of modern tools helpful in the operation and modernization of sewage disposal system in cities.

1.3 Description of CSS3 solutions

The Circular Systemic Solution 3 (CSS3) focuses are designed to address sustainability challenges by integrating circular economy principles into the development of biobased products and processes. These solutions aim to optimize resource use, reduce environmental impacts and create a closed-loop system where waste is minimized and resources are continually reused. Below are key solutions under CSS3:

1. Integration of wastewater treatment and bioproduct production
    i.   Solution overview: Wastewater treatment is integrated into CSS3 solutions, where wastewater is not only cleaned but also used as a resource for the production of biobased products. This creates a dual benefit of treating water and generating biofertilizers.
    ii. Key process: Wastewater is processed through biological treatment systems (such as microalgae and bacteria), where contaminants are removed, and useful byproducts like biofuels, bioplastics or bio stimulants are produced. The treated water can then be returned to the ecosystem or reused in industrial processes.

     iii.   Benefits: Reduced water pollution, conservation of water resources and the generation of renewable bioproducts from waste.

2. Microalgae-based technologies for bioproducts

     i.   Solution overview: Microalgae are harnessed as a sustainable and versatile resource for the production of biobased products. They can be used to produce bio stimulants and other high-value chemicals. Microalgae-based solutions are particularly attractive due to their rapid growth rates, ability to capture CO_2 and potential to grow in various environments.

     ii.   Key process: Microalgae are cultivated using wastewater or other nutrient-rich waste streams, then processed to extract oils, proteins and other valuable compounds. These extracts are then used in the formulation of bioproducts like biodegradable plastics and plant-based fertilizers.

     iii.   Benefits: Microalgae-based systems offer a renewable, high-efficiency process for producing bioproducts. They also help mitigate environmental issues like nutrient pollution in water bodies and carbon sequestration.

2 Methodologies

2.1 Life Cycle Assessment

LCA is a systematic method used to evaluate the environmental, social, and economic impacts of a product, process, or service throughout its entire life cycle, from raw material extraction to disposal (Figure 2). Its primary objective is to enhance resource-use efficiency while minimizing environmental liabilities, making it invaluable for environmental decision support.
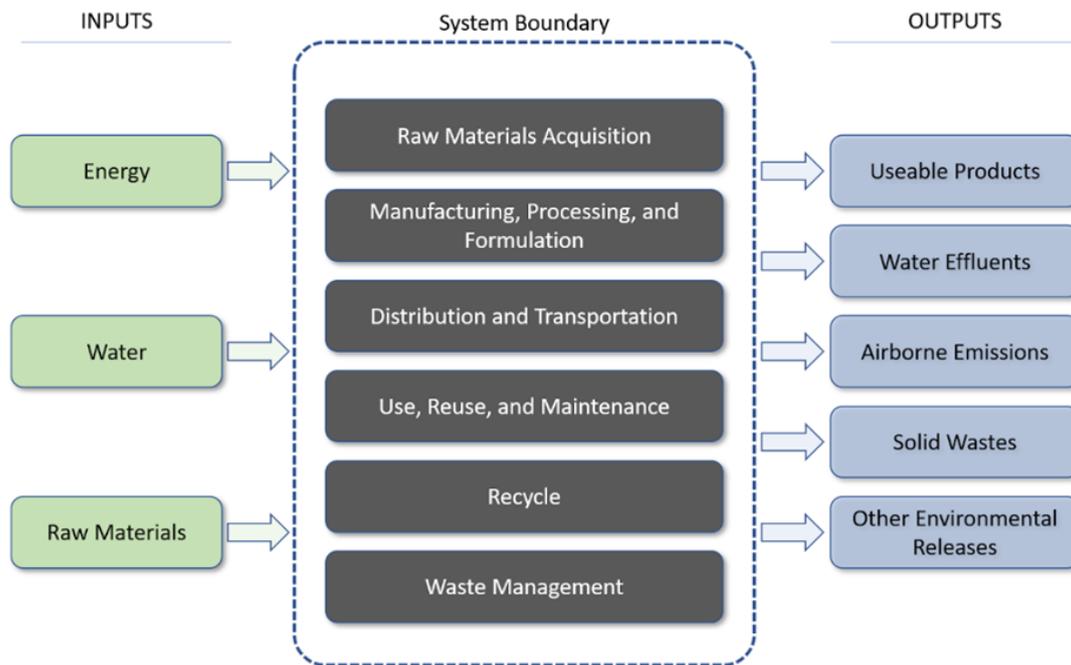
Figure 2 LCA input-output example process

The several life cycle stages are examined in depth by LCA, which identifies the impact types that are most common and focuses on those that have the greatest environmental consequence. This gives stakeholders the information they need to maximize environmental efforts. This optimization may involve prioritizing certain actions based on their potential effect and putting them in place where they can have the biggest impact. LCA came up as a result of increased business, public, and governmental concerns of how activities and products affect the environment. Its foundations include global modelling and energy audits, which looked at the impact of changes to the environment and natural resources. The two main ISO Standards that are commonly applied are 14040:2006 [3] and 14044:2006/A1:2018 [4]. Adhering to these ISO standards ensures that LCA analyses are conducted in a precise and standardized manner, making their results comparable and internationally accepted.

ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Framework: These standard lays down the fundamental principles and framework for conducting LCA. It provides guidance on the definition of the goal and scope of an LCA, selection of appropriate methodologies, data quality requirements, and reporting. ISO 14040 defines the four main phases of an LCA.

ISO 14044 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines: Building upon ISO 14040, ISO 14044 provides detailed requirements and guidelines for implementing the LCA methodology. It offers guidance on data collection, data

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[3] ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework. Accessed December 4, 2023. https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en
[4] ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines. Accessed December 4, 2023. https://www.iso.org/standard/38498.html

quality assessment, data normalization, and allocation procedures. ISO 14044 also addresses the importance of sensitivity analysis and uncertainty assessment.

According to ISO 14040:2006, ISO 14044:2006 and the ILCD Handbook, the LCA is carried out in four stages:

1. Goal Definition and Scope definition. In the Goal and Scope phase of an LCA, the goal definition clarifies what, why, how, and for whom the study is relevant, ensuring clear and useful results. The scope outlines the study's detail and limits, ensuring the goal can be achieved within these boundaries.

2. Life cycle inventory. In the inventory analysis phase, data is collected from various sources (industry databases, literature, and direct measurements), quantified (usually by mass or energy), and organized into a detailed inventory of inputs and outputs.

3. Life cycle impact assessment. The LCIA evaluates the potential environmental impacts of the inputs and outputs quantified in the inventory analysis. Using impact assessment methods, it translates data into impacts across categories like climate change, toxicity, ecosystem quality, and resource depletion, helping to identify and assess their significance.

4. Interpretation of the results. The interpretation phase analyses data from the inventory and LCIA, assessing environmental impacts, identifying key contributors, and evaluating overall sustainability. It combines quantitative results with qualitative insights to inform decision-making and improvements.

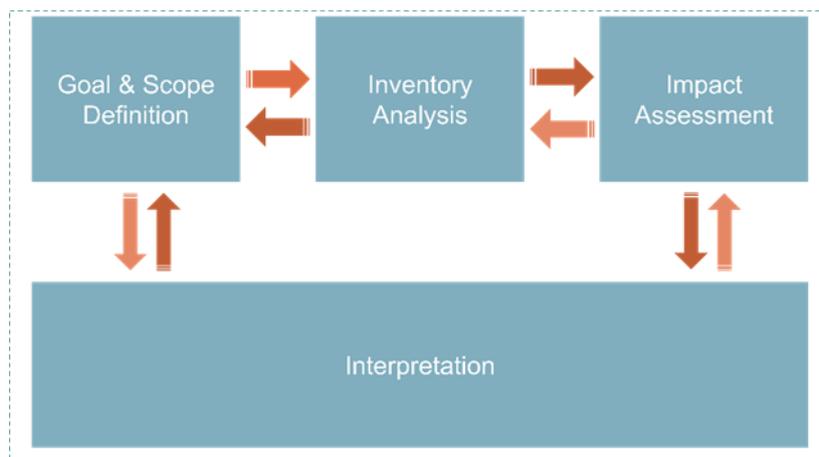These stages as well as their interaction are presented in the Figure 3.

Figure 3 LCA framework

2.2 Life Cycle Costing

Life Cycle Costing (LCC) is an analysis tool based on the principles of economic analysis to evaluate the overall long-term economic feasibility for specific investment options. Through LCC, it is possible to determine whether a project is economically viable and cost-effective.

Besides that, alternative solution that is available throughout the project from cradle-to-grave can be identified.

The EU Directive 2014/24 in the article 68 gives a precise definition of LCC: "Life Cycle Costing shall to the extent relevant cover parts or all the following costs over the life cycle of a product, service or works:

1. Costs, borne by the contracting authority or other users, such as:
   - Costs related to acquisition
   - Costs of use, such as consumption of energy and other resources
   - Maintenance costs
   - End-of-life costs, such as collection and recycling costs

2. Costs imputed to environmental externalities linked to the product, service or works during its life cycle, provided their monetary value can be determined and verified; such costs may include the cost of emissions of greenhouse gases and of other pollutant emissions and other climate change mitigation costs.

Additionally, ISO 15686-5 is available for LCC of buildings and constructed assets. According to this, LCC is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. In particular, it is an economic assessment considering all projected relevant cost flows over a period of analysis expressed in monetary value.

LCC analysis follows five simple steps and this general framework is presented below (Figure 4). While the steps are generally sequential, the sequence can be altered as per following the requirements of each project.
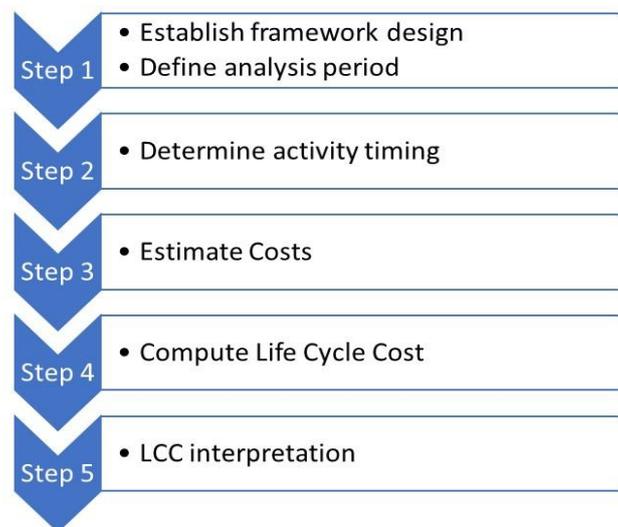

Step 1
- Establish framework design
- Define analysis period

Step 2
- Determine activity timing

Step 3
- Estimate Costs

Step 4
- Compute Life Cycle Cost

Step 5
- LCC interpretation

Figure 4 General framework of LCC analysis process.

Step 1: Establish framework design & define analysis period. A detailed framework and an analysis period are crucial for the LCC, because it involves the use of time value of money.

Therefore, setting the duration of the analysis is provided a clear understanding of the overall analysis.

Step 2: Determine activity timing. This step is attributed to the determination of timing in respect with all activities that need to be done for running LCC. For instance, collecting financial data, visit a case study site, collect case study data, analyse data as well as data interpretation.

Step 3: Estimate costs. The third step in this analysis is to identify and estimate all costs involved in each phase. Among the costs involved will be the cost of materials, equipment, electricity, labour, etc. The cost elements are the cash flows that occur over the life of the system. The cost structure describes the allocation of costs into groups i.e. engineering and development, construction, operation, transportation, disposal.

Step 4: Compute life cycle costs. Once, all data is available, the LCC calculation can be done in the fourth step. It is performed by taking into account system lifetime, capital expenditure, operation and maintenance expenditure, labour as well as any additional cost for waste management.

Step 5: Analyse results and evaluate alternatives. In the last step is to analyse all the results. Through this, where the cause of high-cost contributors can be identified. Based on the status of each case study, alternatives can be identified if it is possible based on the data available.

2.3 Social Life Cycle Assessment

A Social and socio-economic Life Cycle Assessment (s-LCA) is a social impact assessment methodology that aims at assessing the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling and final disposal [5].

s-LCA methodology follows the UNEP / SETAC guidelines: "Guidelines for Social Life Cycle Assessment of products and organizations 2020" which, in turn, is based on the ISO 14040 and ISO 14044 framework [6, 7]. Therefore, this methodology complements the LCA and LCC with social and socio-economic aspects.

Following the 4 steps described by the ISO 14040, the s-LCA can be developed as follows:

Step 1: Definition of the objective and application fields, i.e. function, functional unit, system boundaries. In this phase, the "stakeholder categories" are defined, being a cluster of stakeholders that are expected to have shared interests due to their similar relationship to the investigated product systems. For each stakeholder category, particular themes or areas

[5] UNEP – SETAC – Life Cycle Initiative – Guidelines for Social Life Cycle Assessment of products and organizations 2020, United Nations Environment Programme, 2020

[6] ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework. Accessed December 4, 2023. https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

[7] ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines. Accessed December 4, 2023. https://www.iso.org/standard/38498.html

of interest, which are called "sub-categories", are defined, referring to the categories of impact.

Step 2: Inventory analysis, which involves the collection of characteristic and functional data for the development of the s-LCA analysis.

Step 3: Evaluation of social impacts.

Step 4: Interpretation of results and identification of critical points.

The s-LCA method to be performed in the project is described below:

1. Identification of element(s), system(s) to be analysed, including system boundaries; in order to perform a sustainability assessment, this information is the same as for LCA and LCC.

2. For each life cycle phase (EN 15804:2012)[8], a stakeholders' analysis has to be performed in order to identify the main group of stakeholders related to a specific life cycle phase. The UNEP/SETAC guidelines identify five stakeholders' categories: workers, local community, society, consumers, and value chain actors (Figure 5). For each case study, depending on the phase analysed and on the type of system considered, the most relevant and significant stakeholders' categories are considered (Figure 6).
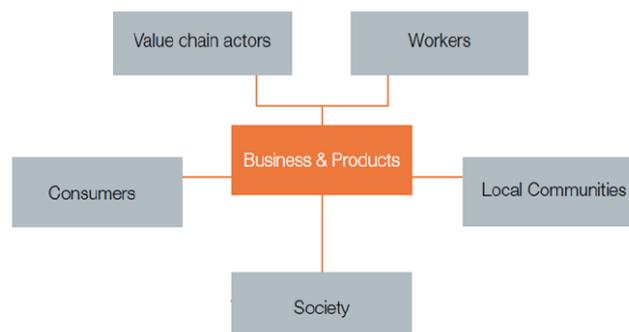
Figure 5 Stakeholders involved in the products life-cycle.
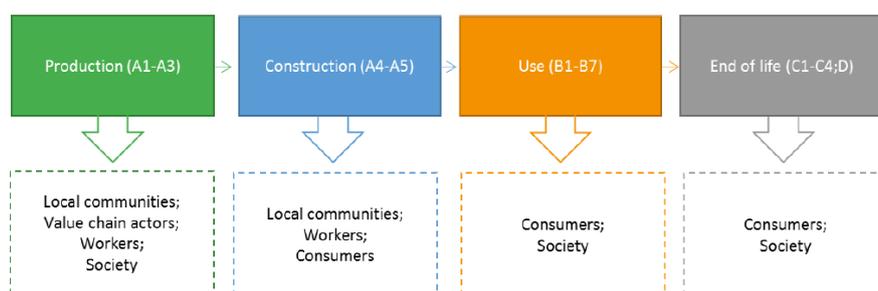
Figure 6 Indicative categories of stakeholders involved in each stage of the product life-cycle.

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3 LCA methodology

3.1 Goal and Scope

Goal and scope definition is one of the most important steps in any LCA/LCC/s-LCA analysis. This section outlines the purpose of the study, the functional unit (FU), the reference flow, system boundaries and any assumptions and limitations. Clear and precise definitions at this stage ensure the study provides credible results, enabling appropriate comparisons and informed decision-making.

3.1.1 Goal

The primary goal of the LCA for CSS3 is to evaluate the environmental impacts and costs of processing water waste through the proposed CSS3 in the region of Lodzkie. The study aims to assess the CO_2 footprint reduction, energy preservation and potential for carbon black production. It compares traditional water waste management practices, that have been used for centuries to treat and dispose of water waste with the CSS3 modern solutions. These traditional methods are typically based on simple, often low-cost techniques that have been passed down through generations. However, they may not always meet modern standards of efficiency and sustainability.

CSS3 (Circular Systematic Solutions 3) introduces advanced, sustainable and integrated solutions for wastewater management that aim to optimize water use, reduce environmental impacts, and promote resource recovery. These modern approaches emphasize circular economy principles, where wastewater is treated and reused, while valuable resources are recovered in the process. Below are key modern solutions for wastewater management under CSS3:

1. **Microalgae-based wastewater treatment**
   Microalgae-based technologies use algae to treat wastewater while simultaneously producing valuable bioproducts such as biofuels, bioplastics and bio stimulants. Wastewater is introduced into ponds or photobioreactors, where microalgae consume nutrients like nitrogen and phosphorus, reducing pollution. Algae also produce oxygen, helping break down organic matter. After treatment, the microalgae can be harvested to create bioproducts.

2. **Constructed wetlands for wastewater treatment**
   Constructed wetlands replicate natural wetlands' ability to filter and clean wastewater using plants, soil, and microbial communities. Wastewater flows through a series of plants and substrates (e.g., sand, gravel) in a constructed wetland system. The roots of the plants and microorganisms in the substrate filter out pollutants, while also promoting the breakdown of organic matter.

3. **Membrane Bioreactor (MBR) systems**

MBR technology combines biological treatment (activated sludge) with membrane filtration, providing highly efficient wastewater treatment. Wastewater is treated in a bioreactor, where microorganisms degrade organic matter. The treated water is then filtered through a membrane that separates clean water from residual solids and microbes, resulting in high-quality effluent.

4. **Electrocoagulation (EC) for pollutant removal**

   Electrocoagulation is an electrochemical process that uses electrical currents to destabilize and remove contaminants in wastewater, including heavy metals, oils and suspended solids. Electrodes are placed in the wastewater and an electric current is passed through, which causes pollutants to aggregate (coagulate) and then separate out of the water. This process is often used as a pre-treatment before other filtration methods.

5. **Anaerobic Membrane Bioreactor (MBR) for energy recovery**

   An MBR integrates anaerobic digestion with membrane filtration to treat wastewater while recovering energy in the form of biogas. In the absence of oxygen, microorganisms break down organic waste to produce biogas (methane). The treated water is filtered through membranes to separate solids from the clean effluent. The biogas can then be used for energy generation.

6. **Resource Recovery from wastewater (phosphorus, nitrogen and biogas)**

   Modern wastewater treatment increasingly focuses on recovering valuable resources, such as phosphorus, nitrogen and biogas, instead of simply treating the water and discarding the byproducts.

   - Phosphorus recovery: Advanced technologies like struvite crystallization or algae-based systems capture phosphorus, which can be used as a fertilizer.
   - Nitrogen recovery: Technologies like anammox (anaerobic ammonium oxidation) or membrane contactors recover nitrogen, reducing the need for chemical treatments.
   - Biogas production: Anaerobic digestion converts organic waste into biogas, which can be used for energy production.

7. **Integrated wastewater treatment and resource recovery systems**

   Integrated systems combine multiple treatment processes and resource recovery in a holistic approach to maximize efficiency and sustainability. These systems typically combine biological, chemical and physical treatments to remove pollutants while recovering resources like energy, water and nutrients. A combination of technologies (e.g., activated sludge, anaerobic digestion, filtration and electrocoagulation) is used to treat wastewater while capturing energy, recycling water and recovering nutrients for reuse in agriculture or industry.

3.1.2 Scope

The scope of this study outlines the processes and boundaries considered in the LCA. The product system under evaluation addresses the reduction of water waste at a regional scale (Lodzkie). The scope will cover the collection, processing and valorisation of water waste into soil improver, biofertilizers and biostimulants.

3.1.3 Functions of product system

The CSS3 system is designed to process wastewater and convert it into valuable by-products such as biofertilizers and biostimulants, reducing the waste volume sent to landfills. Functions of the product system include:

- **Valorisation of wastewater**: The system processes wastewater to recover valuable by-products, including biofertilizers and biostimulants.
- **Nutrient extraction**: The system extracts essential nutrients from wastewater, which can be reused for agricultural and industrial applications.
- **Nutrient reuse**: Extracted nutrients are repurposed to create biofertilizers and biostimulants, enhancing sustainability and reducing waste.

3.1.4 Functional Unit

The functional unit (FU) for this study is defined as the treatment of 1 ton of water waste through the CSS3 system. This FU serves as a reference flow to which all input and output data in the LCA are related, ensuring consistency in the analysis. The FU accounts for the mass of the waste untreated.

3.1.5 System boundary

LCA is a complex process that involves several stages for assessing the environmental impact of a product/service/technology referred to the upstream processes, downstream manufacturing, use stage, recycling and end-of-life processes.

The Circular Systematic Solution (CSS3) approach to water waste is developed into one scenario. Outputs of this scenario are final products or intermediate resources for integration with other Circular Systematic Solutions in the FRONTSH1P project. The scenario focuses on method and process for biostimulants and biofertilizers production.

Scenario 3.1 (CSS3_S3.1 Microalgae-based wastewater treatment):

Microalgae-based wastewater treatment is an innovative and environmentally sustainable process that uses the natural abilities of microalgae to purify wastewater, remove pollutants and even generate valuable byproducts. This method leverages the photosynthetic and metabolic capabilities of microalgae to treat wastewater while simultaneously producing bioproducts such as biostimulants and biofertilizers.

3.1.6 Impact Assessment Method Description and Impact Categories Description

The CML (Centrum voor Milieukunde Leiden) 2001 standard for LCA is a method for evaluating the environmental consequences of a product or process throughout its entire life cycle. It was developed by the Centre of Environmental Science of Leiden University and was published in a guide to the ISO standards in 2001[9]. The method is divided into baseline and non-baseline, the baseline being the most common impact categories used in LCA. The following table shows the categories it contains, according to last update in August-2016[10]. These indicators collectively provide insights into resource use, emissions and impacts on health and the environment across the assessed system's life cycle.

Table 2 Impact categories included in the method CML.

Method: CML	
Impact category group	**Name of the impact category in the method**
Acidification	Acidification potential - average Europe
Climate change	Climate change - GWP100
Depletion of abiotic resources	Depletion of abiotic resources - elements, ultimate reserves
	Depletion of abiotic resources - fossil fuels
Ecotoxicity	Freshwater aquatic ecotoxicity - FAETP inf
	Terrestrial ecotoxicity - TETP inf
Eutrophication	Eutrophication - generic
Human toxicity	Human toxicity - HTP inf
Ozone layer depletion	Ozone layer depletion - ODP steady state
Photochemical oxidation	Photochemical oxidation - high Nox

By adding more indicators with the EN 15804 +A2 (based on EF 3.1) method, the modular approach to LCA is strengthened, enhancing transparency and comparability among EPDs. The implementation of EN 15804 +A2 advances the industry toward a more standardized and reliable environmental assessment framework, supporting sustainable decision-making. A more comprehensive evaluation is achieved through the inclusion of impact categories such as 1. Resource use indicators and 2. Human toxicity, along with their subcategories (see Table 3).

Table 3 Impact categories of EN 15804 +A2 (based on EF 3.1) method.

Impact category group
1. Resource use indicators
Use of renewable primary energy (PERE) [MJ]
Total use of renewable primary energy resources (PERT) [MJ]
Use of non-renewable primary energy (PENRE) [MJ]
Total use of non-renewable primary energy resources (PENRT) [MJ]
Use of net fresh water (FW) [m³]

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[9] R. Frischknecht et al., 'Swiss Centre for Life Cycle Inventories A joint initiative of the ETH domain and Swiss Federal Offices Implementation of Life Cycle Impact Assessment Methods Data v2.0 (2007)', 2007. [Online]. Available: www.ecoinvent.org

[10] A. P. Acero, C. Rodríguez, and A. C. Changelog, 'LCIA methods Impact assessment methods in Life Cycle Assessment and their impact categories', 2016. [Online]. Available: http://www.openlca.org/files/openlca/Update_info_open

2. Human toxicity
Hazardous waste disposed (HWD) [kg]
Non-hazardous waste disposed (NHWD) [kg]

3.1.7 Assumptions and limitations

The quality of data used in this study plays a crucial role in ensuring reliable and meaningful results. The data used for the LCI analysis was evaluated based on several key aspects: technological relevance, consistency, completeness, representativeness and location specificity.

1. Technological relevance

The data collected in this study is highly relevant to the specific technologies employed in the CSS3 system for wastewater treatment, including microalgae cultivation, harvesting, high-pressure homogenization (HPH), enzymatic hydrolysis, and centrifugation. These data were derived from the actual operational conditions and experimental setup at the LNEG (Laboratório Nacional de Energia e Geologia) facility in Portugal. Therefore, the data reflects the technologies in their current form and captures the real-world performance of these systems under the study's scope. The use of these processes in wastewater treatment directly aligns with industry practices and the operational conditions at the pilot-scale plant at LNEG.

2. Consistency

The data used in this study is consistent with international standards and methodologies, such as ISO 14040/44 guidelines for conducting Life Cycle Assessment (LCA). Data was collected and processed using industry-standard software tools, including Sphera FE for LCA modelling. These methodologies ensure that the data and results are consistent and comparable with similar studies in the field of wastewater treatment. Furthermore, the operational data from the different stages of microalgae cultivation, harvesting, HPH, enzymatic hydrolysis, and centrifugation were gathered systematically and followed consistent protocols across all stages of the processes.

3. Completeness

The data collected for the LCI and LCA analysis is comprehensive within the boundaries set by the study. All relevant inputs and outputs for the core processes of the CSS3 system— microalgae cultivation, harvesting, HPH, enzymatic hydrolysis, and centrifugation—are included in the analysis. This includes energy consumption, emissions, and material flows (e.g., wastewater input and recovered biofertilizer output). However, the exclusion of wastewater collection, transportation, and post-processing stages means that the environmental impacts from these stages were not considered in this assessment, which could limit the overall completeness of the analysis.

4. Representativeness

The data used in this study is representative of the CSS3 wastewater treatment system as implemented at the LNEG facility in Portugal. The data reflects the actual performance and operational conditions of the system during the study period, providing a realistic snapshot of wastewater treatment through microalgae cultivation and subsequent processes. However, since the study focuses on pilot-scale operations, it may not fully represent the potential for scaling up to industrial levels. The assumptions made about the stability and efficiency of the system also limit the representativeness of future technological developments or variations that may arise in full-scale deployments.

5. Location specificness

The study acknowledges that the data used in the LCA analysis reflects the operational context of the LNEG (Portugal) facility, where the CSS3 system was designed and operated. The energy mix, infrastructure and wastewater management practices in this region are embedded in the data. Although, the electricity, water, fuels and other resources used in the model have been applied from Polish (PT) and European (RER) sources in the Sphera model, with adjustments made to account for regional variations. This ensures that the data remains specific to the location where the system is implemented while still reflecting broader European contexts.

3.2 Life Cycle Inventory Analysis of the current study

3.2.1 CSS3_3.1 Wastewater treatment

Description of Scenario 1

The main goal of Scenario 3.1 is to transform wastewater into valuable by-products through an innovative and environmentally sustainable process. In this scenario, microalgae are used to purify wastewater, removing pollutants and contributing to the recovery of valuable by-products such as biofertilizers and biostimulants.

Main stages included in the scenario

The system of converting wastewater into biofertilizers and biostimulants using microalgae involves six main stages, which are described as follows:

> **Stage 1: Pre-treatment (Preparation cultivation medium)**
> In this initial stage, the cultivation medium is prepared by mixing the necessary nutrients and minerals to create an optimal environment for microalgae growth. This ensures that the microalgae can effectively treat the wastewater in the later stages.

	Flow	Quantity	Unit
Inputs	Nitrogen	63.76	mg
	Phosphorus	50.18	mg
	Wastewater	1	L
	Electricity	0.00003	kWh

Outputs	Wastewater	1	L

Stage 2: Microalgae production

Microalgae are cultivated in the prepared medium, utilizing the nutrients from wastewater to support their growth. Fertilizers are also added to promote the optimal production of microalgae biomass.

	Flow	Quantity	Unit
Inputs	Wastewater	1000	kg
	CO_2	2.61	kg
	Nitrogen	0.06	kg
	Phosphorus	0.05	kg
	Electricity	0.5	kWh
Outputs	Water	1000	kg

Stage 3: Harvesting, dewatering and stabilization

After the microalgae have been grown, they are harvested through various techniques, such as filtration or flocculation. The microalgae biomass is then dewatered to reduce its water content, followed by stabilization to maintain its quality and prevent degradation.

	Flow	Quantity	Unit
Inputs	Chlorella culture	1000	kg
	Flocculant ($FeSO_4$)	0.15	kg
	Electricity	0.616145	kWh
Outputs	Chlorella concentrate (TSS)	12.9	kg
	Water + salts	1000	kg

Stage 4: High Pressure Homogenizer (HPH)

The microalgae biomass is processed in a High-Pressure Homogenizer (HPH), which breaks down the microalgae cells and releases valuable compounds for further processing.

	Flow	Quantity	Unit
Inputs	Water	213.66	kg
	Electricity	0.001148723	kWh
	TSS	52.95	kg
Outputs	Water	213,66	kg
	TSS	52,95	kg

Stage 5: Enzymatic Hydrolysis

In this stage, enzymes are added to the homogenized biomass to break down the complex molecules into simpler, valuable bioactive compounds. These compounds can later be used to produce biofertilizers and biostimulants.

	Flow	Quantity	Unit
Inputs	TSS	52.95	kg
	$H2SO_4$	0.86	kg
	$Ca(OH)_2$	1.4	kg
	Electricity	2.97	kWh
Outputs	TSS	39.18	kg
	$Ca(OH)_2$	0,75	kg
	Amino acids	13.77	kg
	$CaSO_4$	1.2	kg

Stage 6: Centrifugation

Centrifugation is used to separate the solid and liquid phases of the biomass. The solid phase contains valuable by-products, while the treated wastewater is separated and can be further processed or disposed of.

	Flow	Quantity	Unit
Inputs	TSS	39.18	kg
	Aminoethylethanolamine (AEEA)	13.77	kg
	Calcium hydroxide	0.75	kg
	Calcium Sulphate (CaSO4, ore)	1.2	kg
	Electricity	0.0061	kWh
Outputs	TSS	82.1	g
	Aminoethylethanolamine (AEEA)	37.87	kg
	Calcium hydroxide	1.28	kg
	Calcium Sulphate (CaSO4, ore)	0.75	kg
	Water	1.2	kg

CSS3_S3.1_Wastewater treatment
ocess plan Reference quantities
e names of the basic processes are shown.
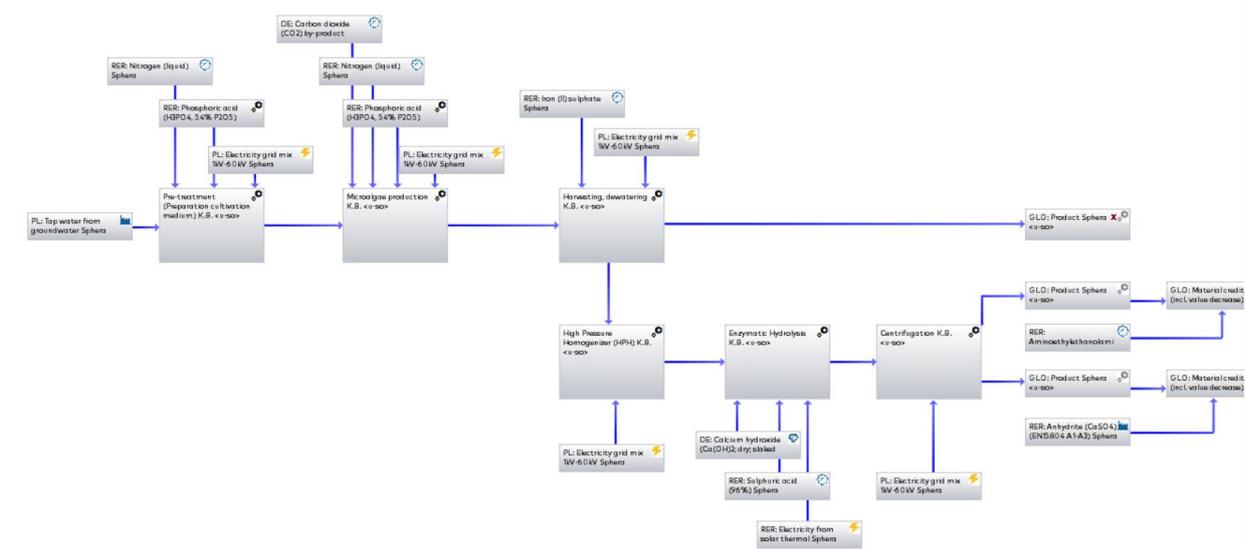
Figure 7 Flowsheet of the Sphera CSS3_S3.1 Wastewater treatment.

3.3 Life Cycle Impact Assessment and Interpretation

3.3.1 Abiotic Depletion

The reduction of abiotic (non-living) resources, such as minerals and metals, important for industrial and societal operations, is estimated by the Abiotic Depletion Potential (ADP). The impact in this category is represented in kilograms of antimony equivalent (kg Sb eq.), with antimony (Sb) being used as the benchmark element to indicate total abiotic resource depletion.

In Figure 8, the ADP impact of the Baseline scenario and Scenario 3.1 (converting wastewater into biofertilizers and biostimulants) is compared. The Baseline scenario shows a lower ADP value of 4.51E-07 kg Sb eq., reflecting minimal abiotic resource depletion due to the lack of additional processes or materials. In contrast, Scenario 3.1 exhibits a higher ADP value of 3.65E-06 kg Sb eq., indicating a greater level of abiotic resource depletion caused by the increased use of materials and energy for the wastewater treatment process. The categorical impact breakdown shows that materials contribute the most to this resource depletion (304.32%), with electricity accounting for a smaller proportion (3.97%) and credits offsetting the impact substantially (-208.29%). This suggests that while the process consumes more resources, there is also some recovery that mitigates its environmental impact (Figure 9).
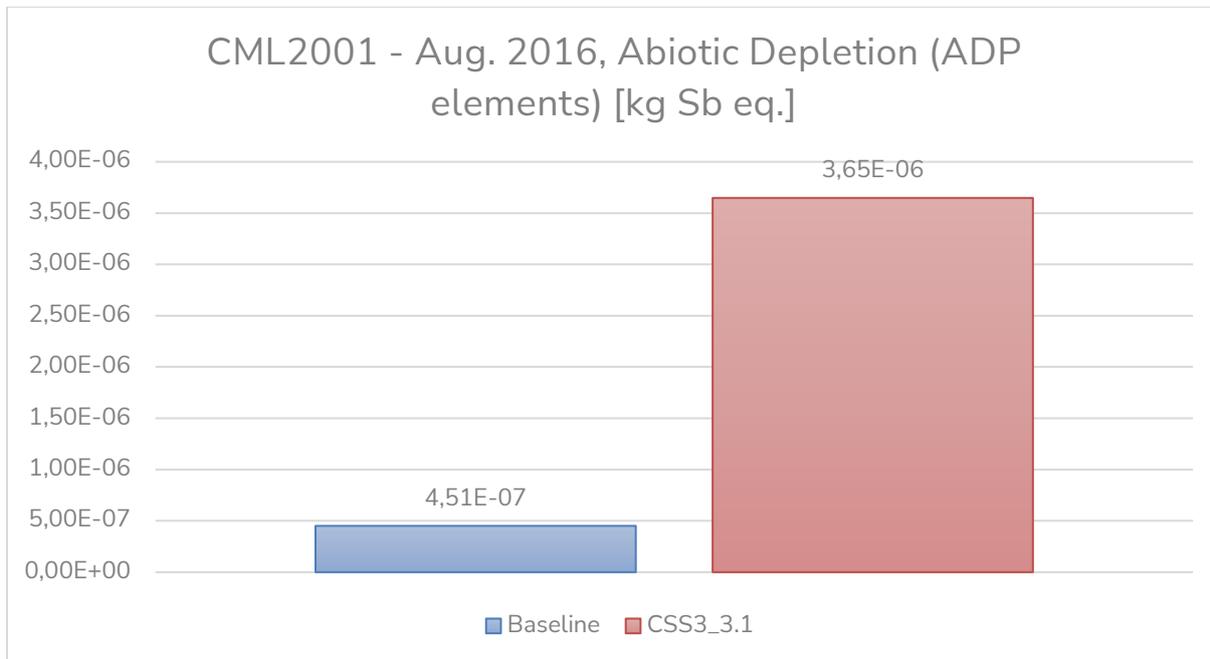
Figure 8 Abiotic Depletion [kg Sb eq.] for each scenario.
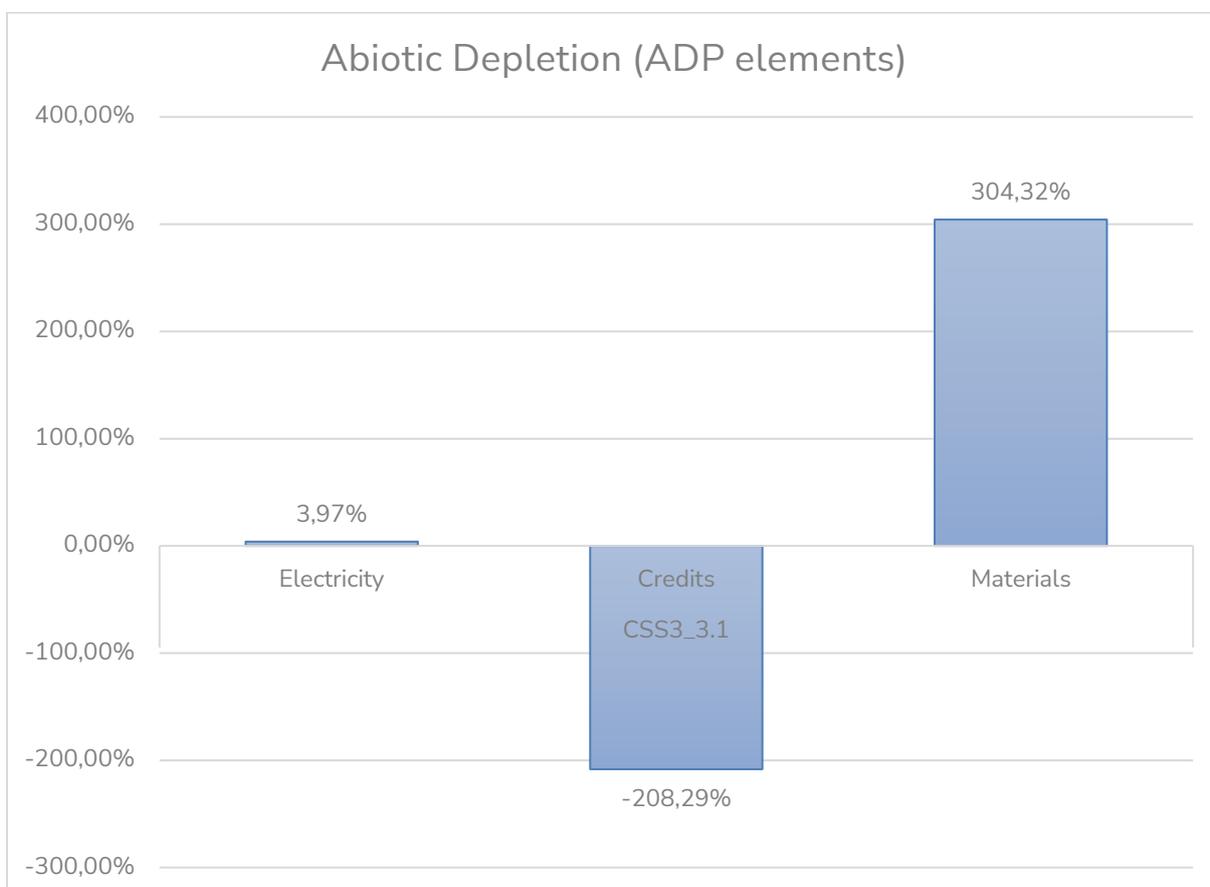
Figure 9 Categorical impact for Abiotic Depletion of each scenario.

3.3.2 Abiotic Depletion - Fossil

The consumption of non-renewable fossil fuels is measured by the Abiotic Depletion Potential for fossil resources (ADP-fossil). The ultimate reserve methodology is used to base this assessment, which estimates total available resources by analysing their average concentration in the Earth's crust and the mass of the crust itself. ADP-fossil is expressed in megajoules (MJ) and is used to provide a quantifiable indicator of the impact of energy consumption on fossil resource depletion. The need for sustainable resource management and the adoption of alternative energy solutions is highlighted by this, with the aim of reducing dependency on finite fossil fuels.

In Figure 10, he ADP-fossil impact of the Baseline scenario and Scenario 3.1 (converting wastewater into biofertilizers and biostimulants) is compared. The Baseline scenario shows a low ADP-fossil value of 4.08E+00 MJ, indicating minimal fossil fuel consumption due to the low energy requirements of the process. In contrast, Scenario 3.1 has a negative ADP-fossil value of -4.06E+00 MJ, which indicates that energy recovery processes contribute positively by offsetting fossil fuel consumption. The categorical impact, inFigure 11, breakdown reveals that materials are the primary contributors to the impact (463.16%), followed by electricity at 216.96%, while credits provide a substantial negative offset (-780.12%). This suggests that the resource recovery process in Scenario 3.1 plays a key role in reducing the depletion of fossil resources, despite the significant energy input required for the conversion process.
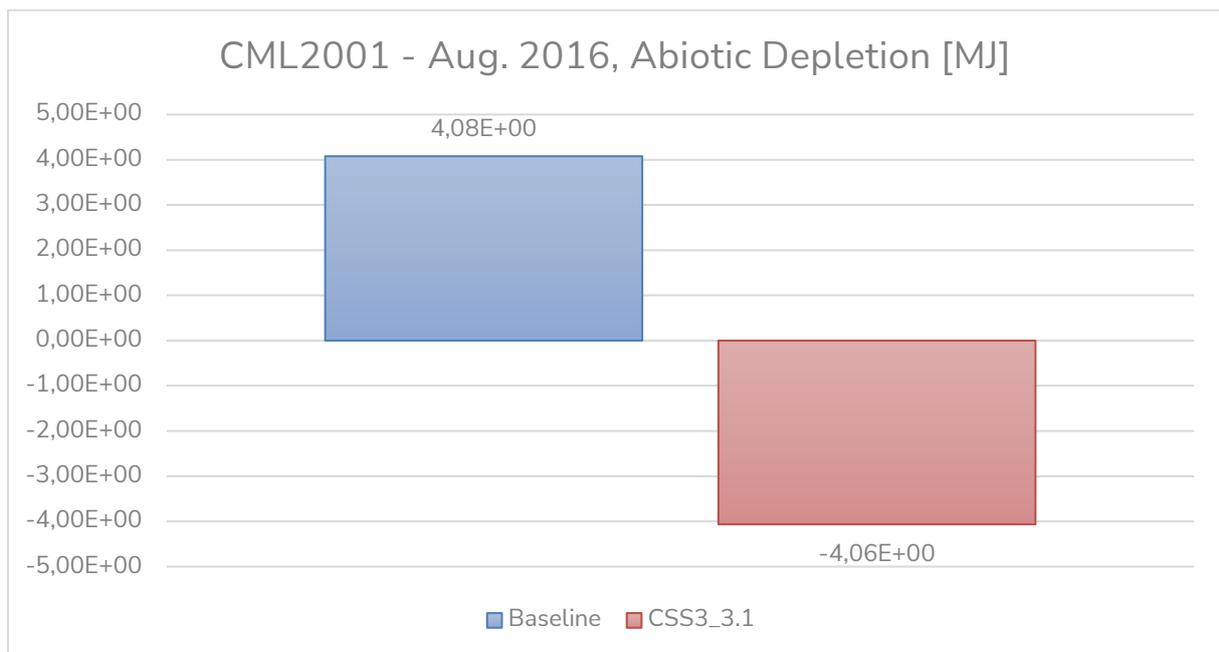
Figure 10 Abiotic Depletion [MJ] impact for each scenario.
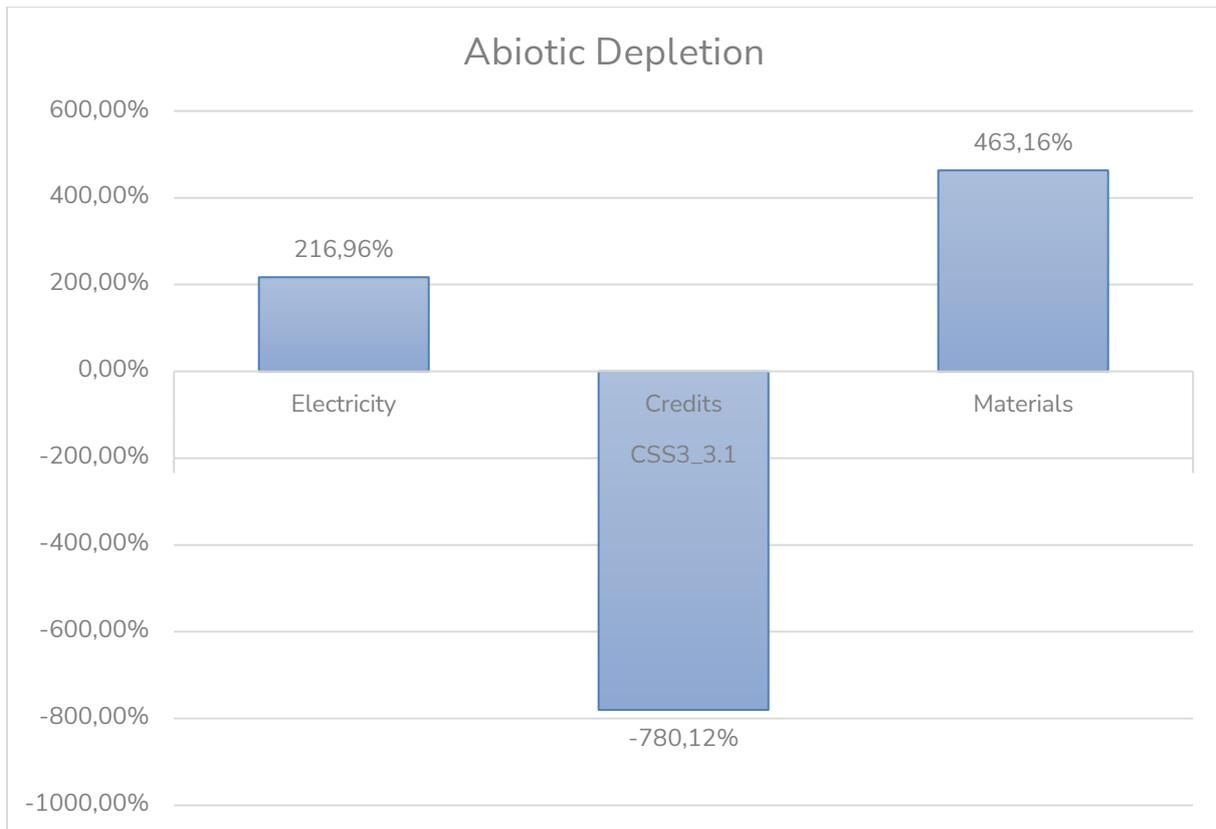
Figure 11 Categorical impact contribution (%) for Abiotic Depletion of each scenario.

3.3.3 Acidification Potential

The acidifying effect of substances in water and soil is described by acidification potential, highlighting the environmental impact of increased acidity due to substances like carbon dioxide dissolving in water. The reduction of pH levels, leading to acid rain and the consequent degradation of surface waters and forests, is primarily noted on a local scale within the LCA context. Beyond local implications, global concerns are extended by acidification, particularly ocean acidification, which threatens marine biodiversity and by extension, human food sources by jeopardizing the survival of certain species. The acidifying effects of these emissions are quantified by AP, which is expressed in terms of kilograms of SO_2-equivalents.

In Figure 12, the diagram compares the AP impact across different wastewater management scenarios. The Baseline scenario shows an AP value of 1.01E-03 kg SO2 eq., indicating a relatively lower acidifying impact. However, Scenario 3.1 shows a more significant AP value of -3.72E-03 kg SO2 eq., reflecting a negative impact, which corresponds to a beneficial environmental effect of reducing acidification. The categorical impact, in Figure 13, breakdown shows that materials contribute the most to the acidification impact at 99.97%, followed by electricity at 37.24%. Notably, credits provide a significant offset, with a contribution of -37.22%, further mitigating the environmental impact.
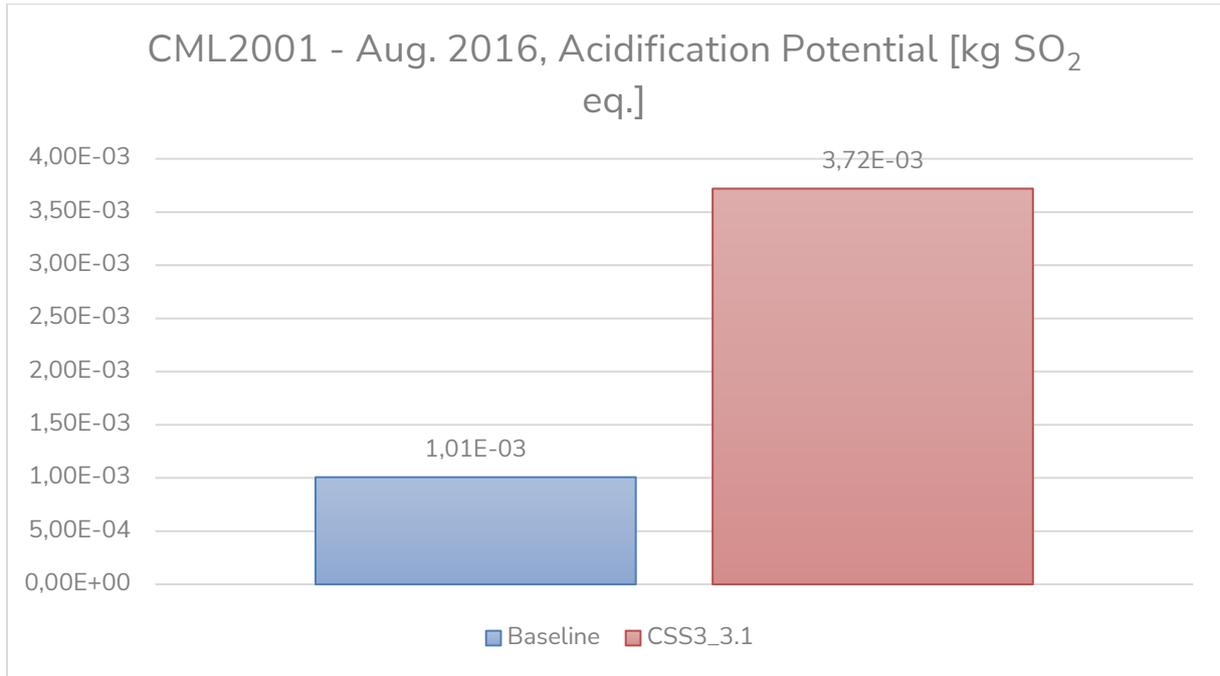
Figure 12 Acidification Potential [kg SO$_2$ eq.] impact for each scenario.
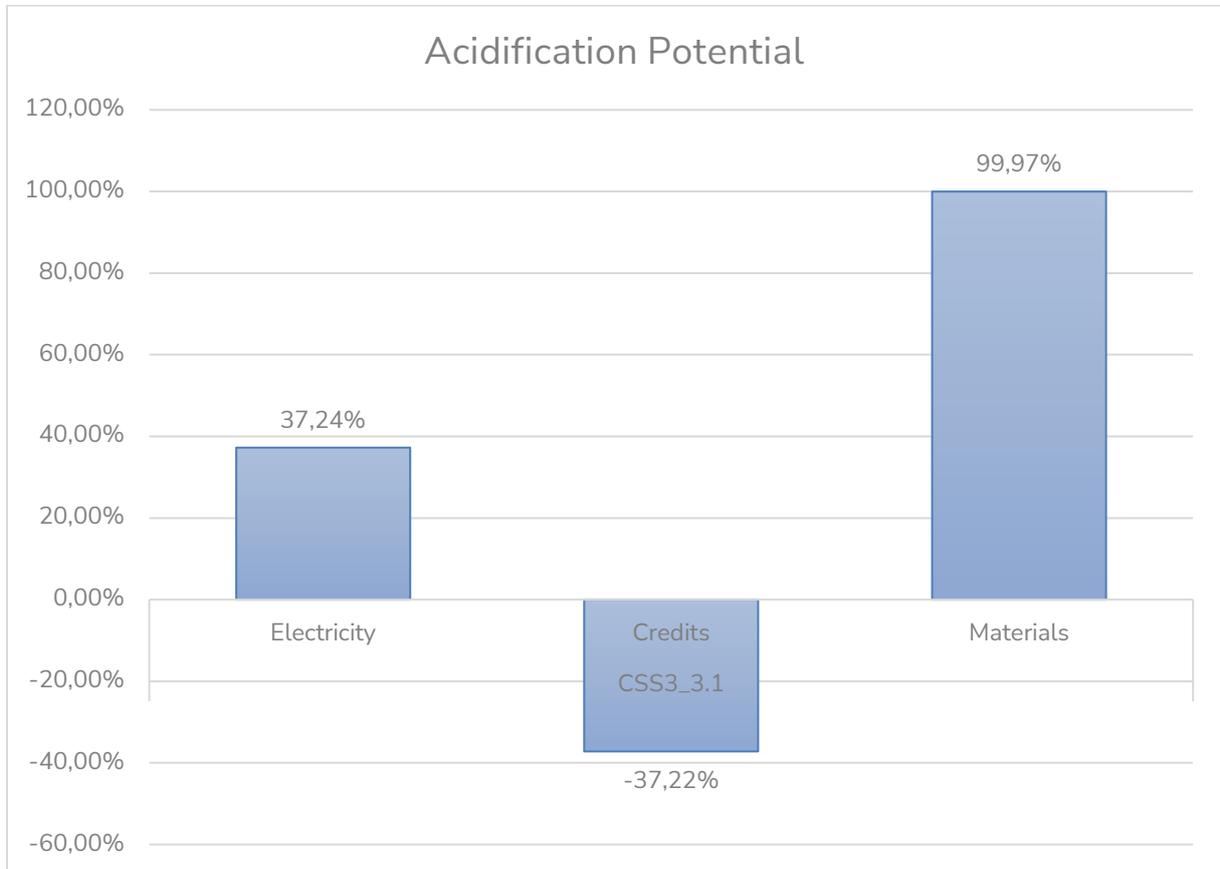
Figure 13 Categorical impact contribution (%) for Acidification Potential of each scenario.

3.3.4 Eutrophication Potential

The environmental impact arising from the enrichment of soil and water bodies with nutrients, leading to imbalances in ecosystems, is referred to by Eutrophication Potential (EP). This process, primarily triggered by the addition of nitrogenous and phosphatised compounds, often through agricultural fertilizers, which promote the unchecked growth of certain species, such as algae. Oxygen levels in aquatic environments are depleted by the resultant algal blooms, which endanger the survival of aquatic flora and fauna by significantly reducing the dissolved oxygen content necessary for their existence. Phosphate (PO_4) equivalents are preferred for characterization and quantification, though nitrogen oxide (NO_3) and oxygen (O_2) equivalents can also serve as interchangeable metrics.

In Figure 14, the EP impact across different scenarios for wastewater management is compared. The Baseline scenario has the highest EP value of 4.88E-05 kg PO_4 eq., primarily due to the release of organic nutrients during wastewater landfilling, which increases eutrophication potential by promoting excessive algae growth. In contrast, Scenario 3.1 shows a negative EP value of -3.34E-05 kg PO_4 eq., reflecting a beneficial environmental impact by reducing eutrophication. The reduction in eutrophication potential is primarily due to the lower impact from the process. As shown in Figure 15, the categorical contributions for Scenario 3.1 indicate that materials have the highest contribution at 841.94%, followed by electricity at 476.47%. Credits, which provide a significant offset, have a contribution of -1418.41%, indicating a substantial environmental benefit from the credits associated with the process.
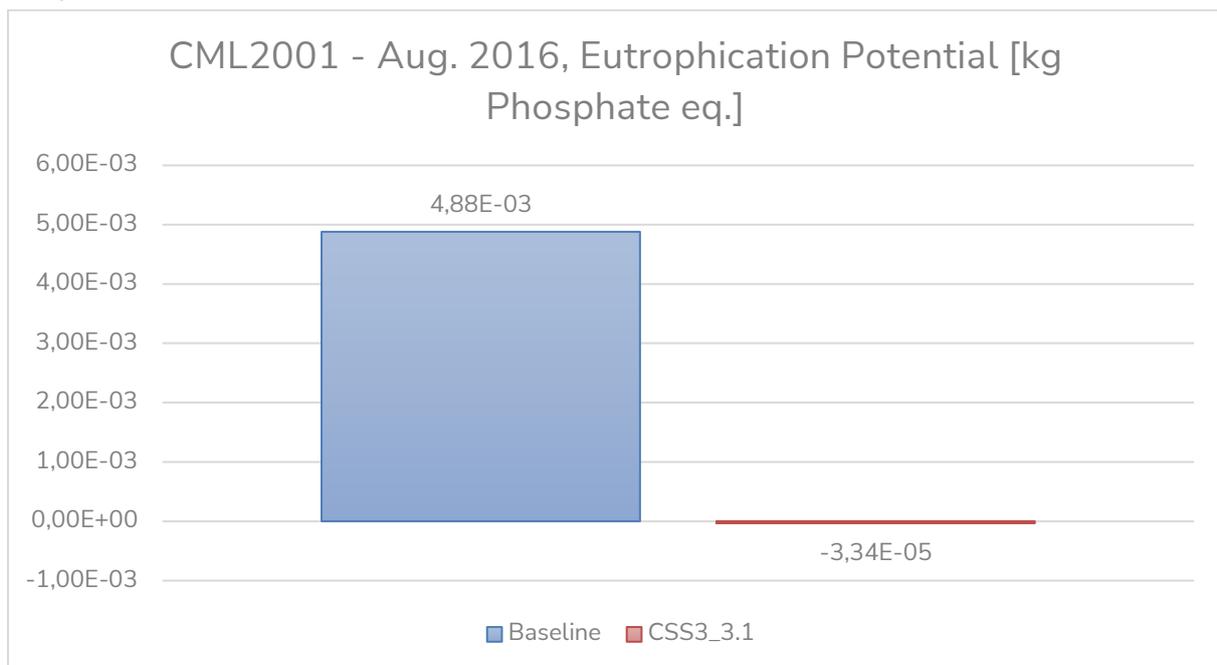

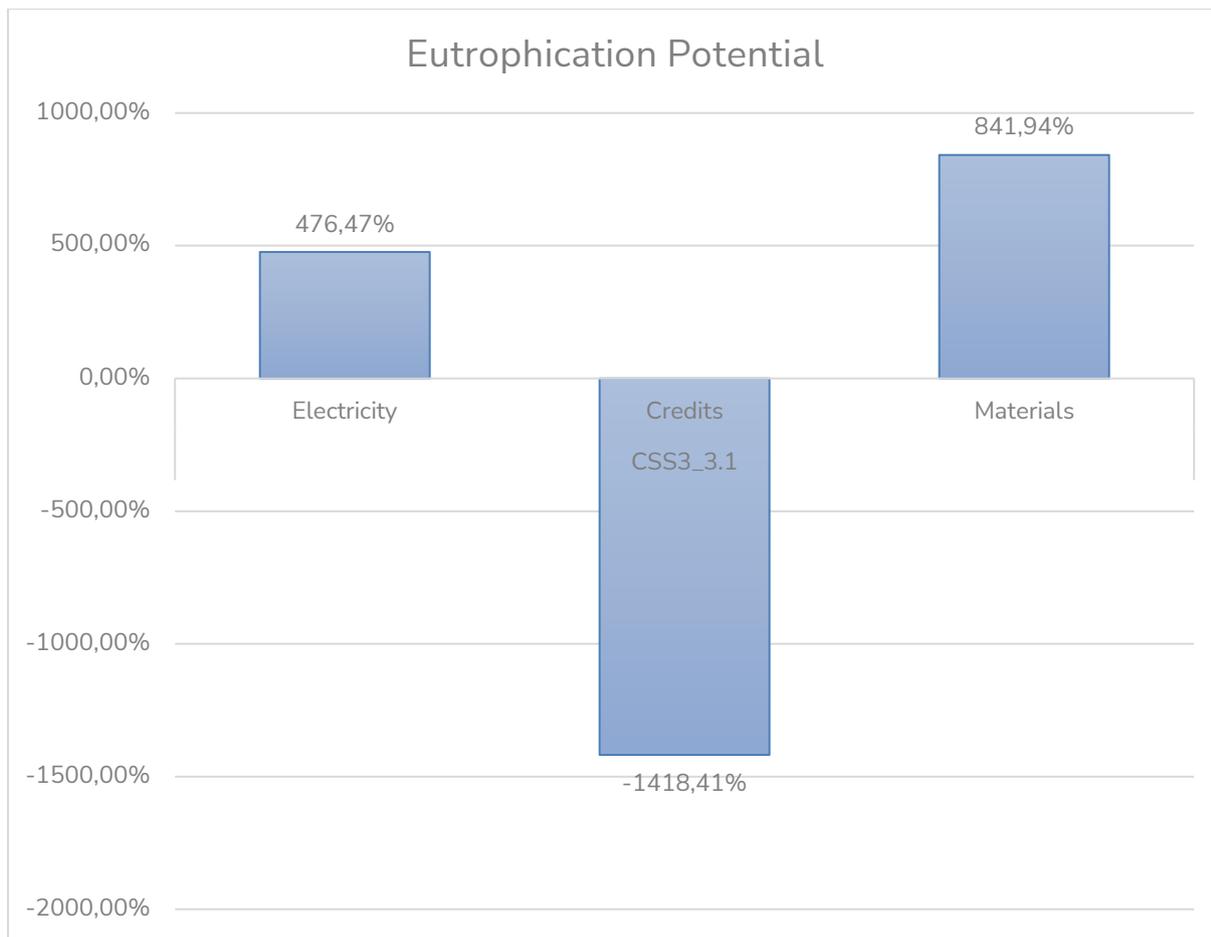*Figure 14 Eutrophication Potential (EP) [kg Phosphate eq.] impact for each scenario.*

Figure 15 Categorical impact contribution (%) for Eutrophication Potential (EP) of each scenario.

3.3.5 Freshwater Aquatic Ecotoxicity Potential

Freshwater Aquatic Ecotoxicity Potential (FAETP) is used as an environmental impact category in LCA and environmental impact assessments. The potential impact of a substance or activity on freshwater aquatic ecosystems is analysed by it. More specifically, the potential toxicity of substances released into freshwater environments and their potential harm to aquatic life is evaluated by FAETP. Kilograms of 1,4-dichlorobenzene (DCB) equivalent (kg DCB eq.) is typically used as the unit of measurement for FAETP. DCB is employed as a reference substance to represent the overall impact on freshwater aquatic ecotoxicity. Various factors, including the toxicity of substances, their environmental fate and their potential to harm aquatic organisms, are taken into account when calculating FAETP.

In Figure 16, the FAETP impact across different wastewater treatment scenarios is compared. The Baseline scenario shows a FAETP value of 6.44E-02 kg DCB eq., indicating a moderate level of potential harm to freshwater aquatic ecosystems. In contrast, Scenario 3.1 shows a significantly lower FAETP value of -2.99E-03 kg DCB eq., reflecting a beneficial impact on freshwater ecosystems. The categorical impact breakdown in Figure 17 shows that Materials contribute the most to the FAETP impact at 108.61%, while Electricity accounts for 24.44%.

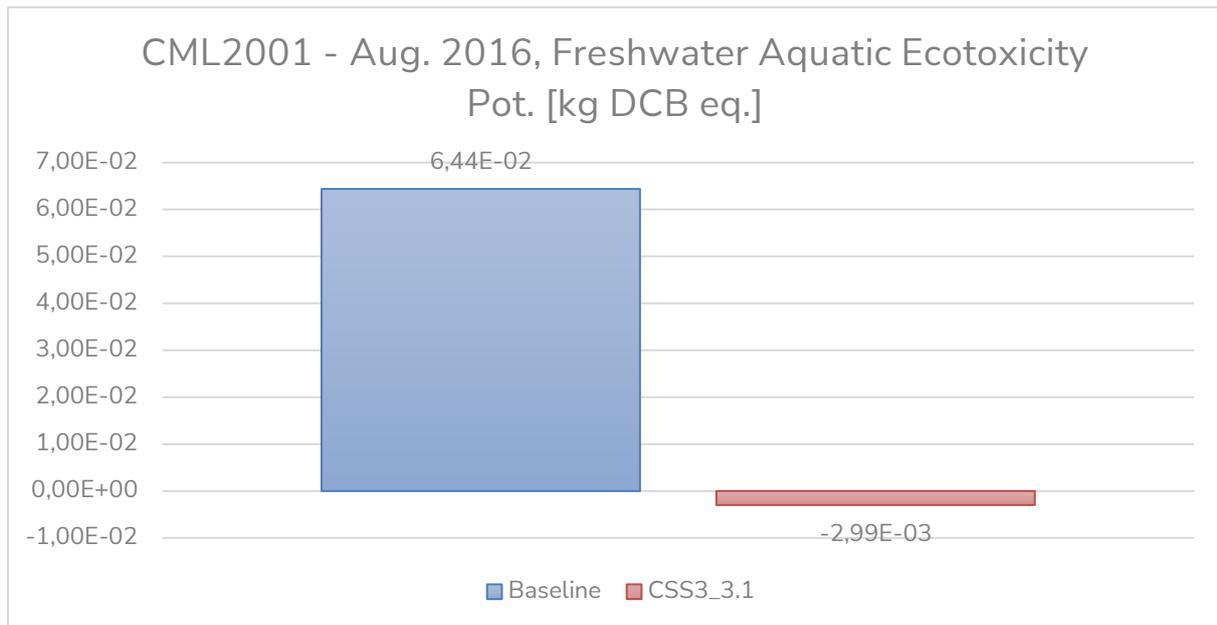Notably, Credits provide a substantial offset, contributing -233.06%, reducing the overall impact of the scenario.

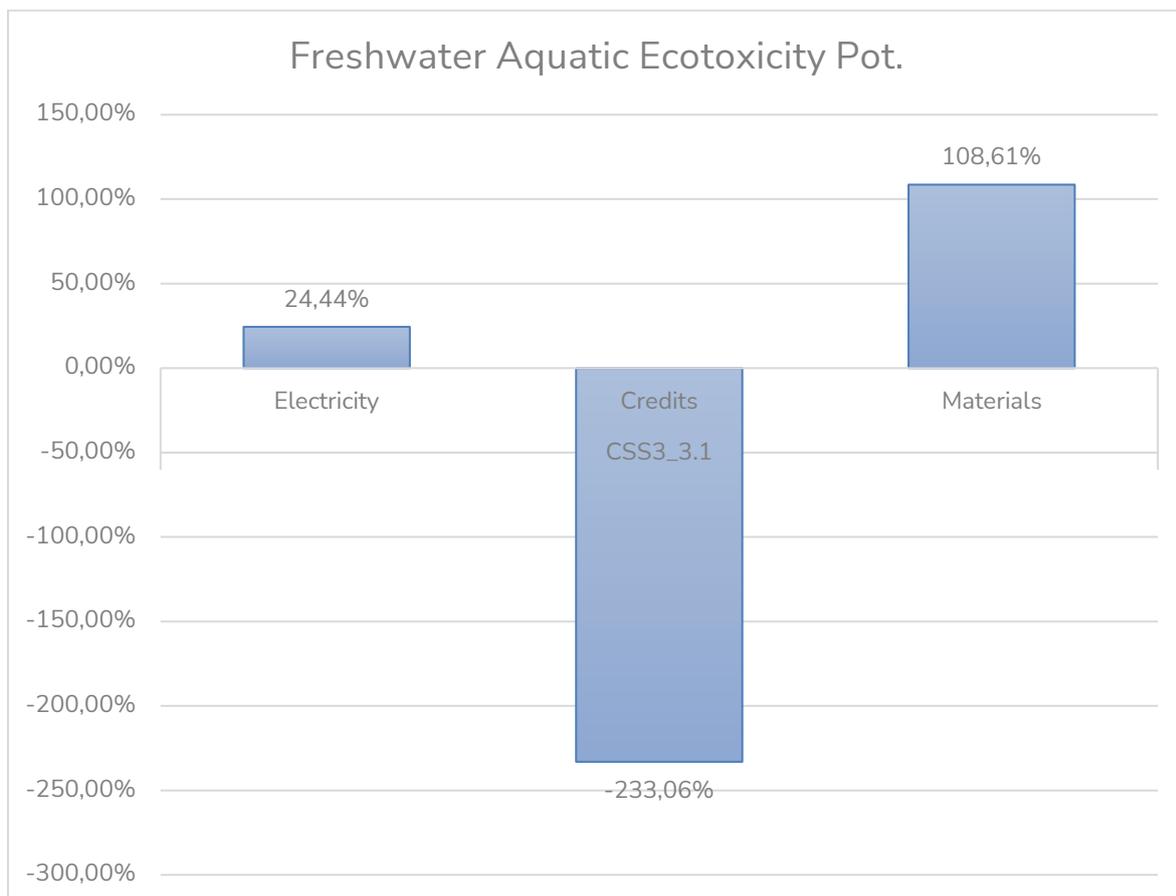*Figure 16 Freshwater Aquatic Ecotoxicity Pot. [kg DCB eq.] impact for each scenario.*

Figure 17 Categorical impact contribution (%) for Freshwater Aquatic Ecotoxicity Pot.

3.3.6 Global Warming Potential

Global Warming Potential (GWP) is examined as an environmental impact category that looks at the potential for a substance or activity to contribute to global warming or climate change. The total emissions of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are measured over a specific time frame, typically 100 years. GWP is expressed in units of kilograms of carbon dioxide equivalent (kg CO_2 eq.), which represents the amount of CO_2 emissions that would have the same warming effect as the emissions of the examined greenhouse gases. If a certain activity or substance has a GWP of 10 kg CO_2 eq., it means that its emissions over a 100-year period are equivalent to the warming effect of emitting 10 kilograms of carbon dioxide. Global Warming Potential (GWP 100 years) is used for these purposes.

In Figure 18the GWP impact across different wastewater treatment scenarios is compared. The Baseline scenario shows the highest GWP value of 1.01E+00 kg CO_2 eq., indicating the greatest contribution to global warming. In contrast, Scenario 3.1 exhibits a significantly lower GWP value of 3.31E-01 kg CO_2 eq., suggesting a reduced impact compared to the Baseline. The breakdown of categorical impacts shows that Electricity contributes the most to the GWP at 272.89%, while Materials follow at 287.49%, and Credits provide a notable offset at -460.47% (Figure 17).

Regarding the processes contributing to the overall GWP impact (Figure 20), the Pre-treatment process stands out with the highest contribution at 41%. Additionally, Microalgae production (247%), Harvesting, Dewatering (155%) and Enzymatic Hydrolysis (116%) all play significant roles in GWP, with Centrifugation contributing negatively at -460%, helping to offset some of the overall impact.
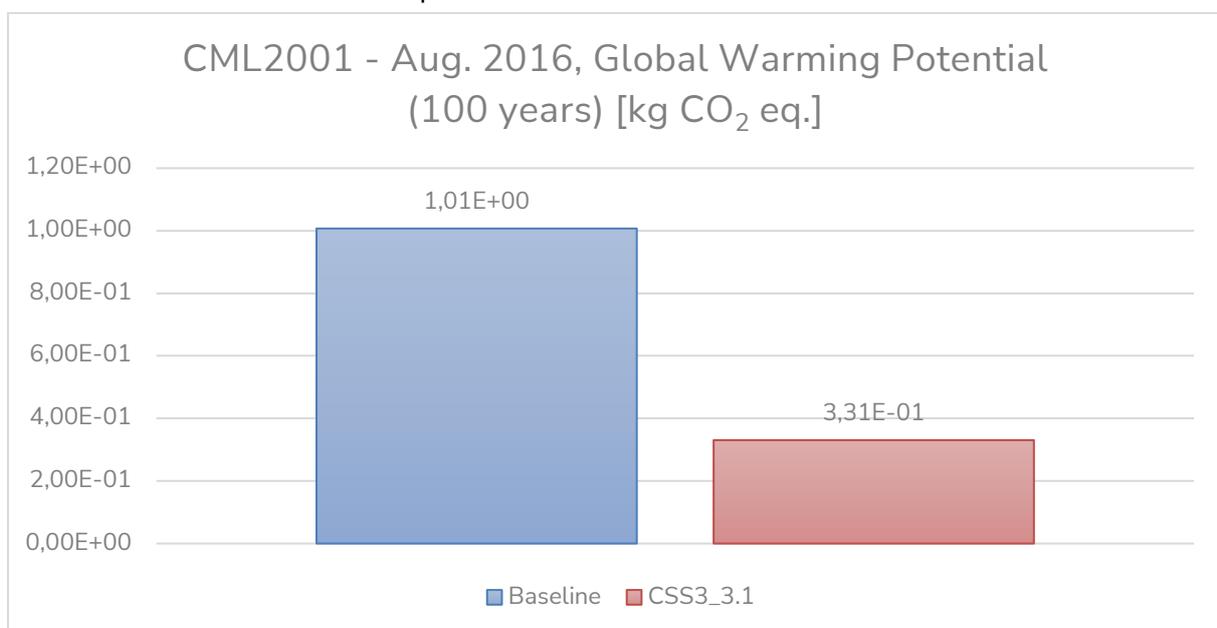

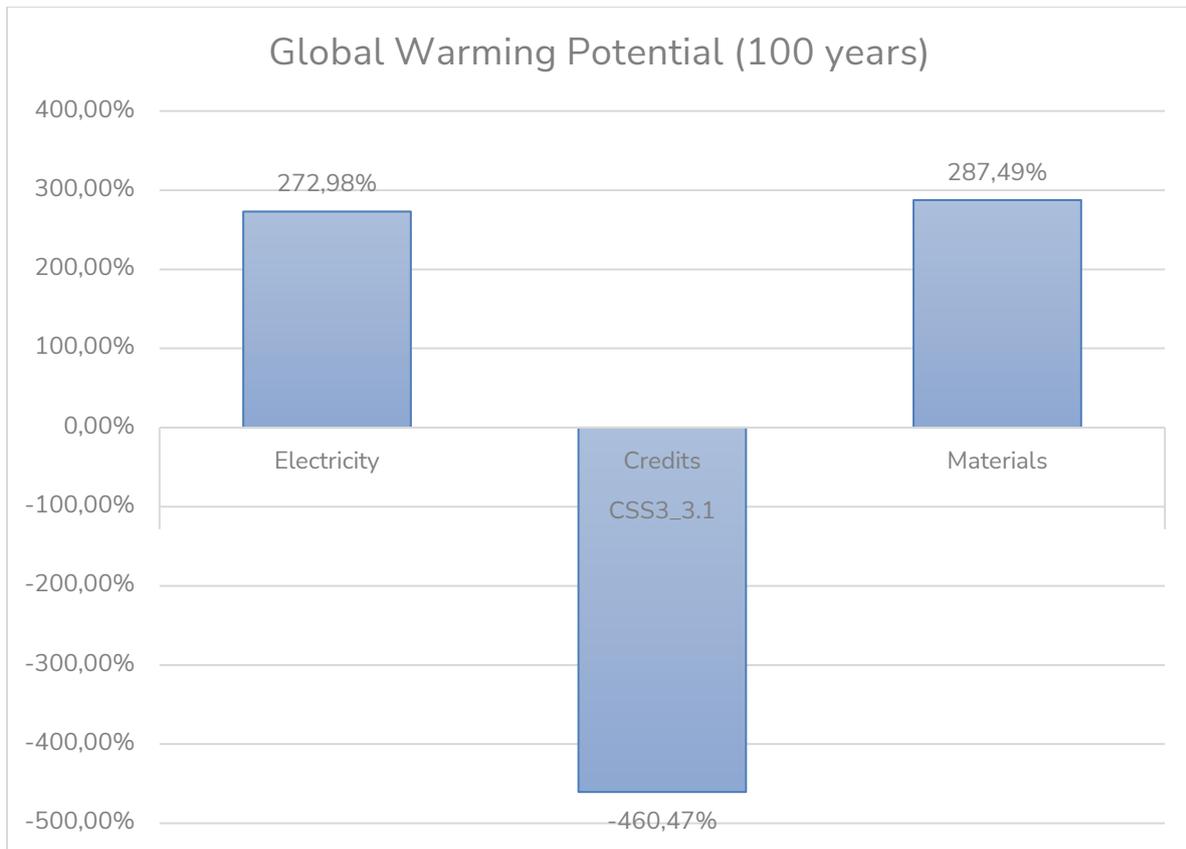*Figure 18 Global Warming Potential [kg CO_2 eq.] impacts.*

Figure 19 Categorical impact contribution (%) for Global Warming Potential.
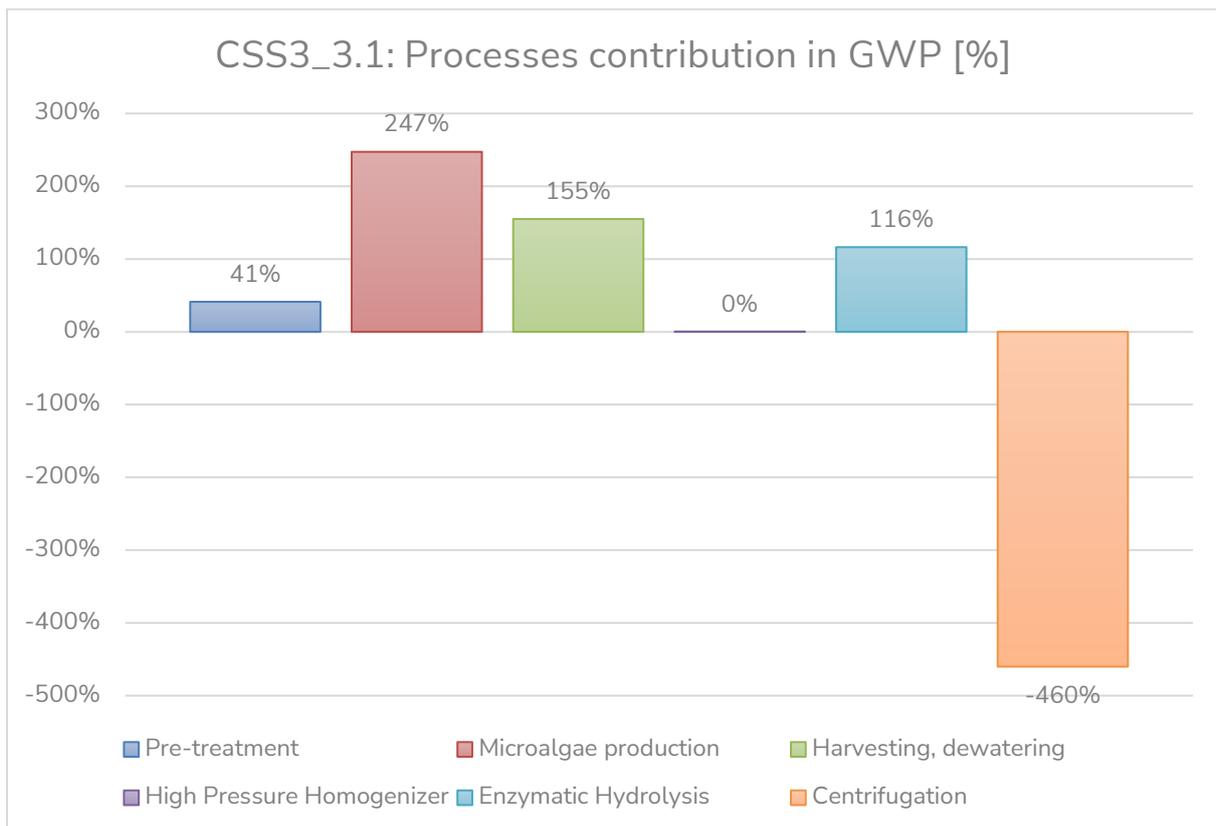

Figure 20 Contribution (%) to GWP impact per process.

3.3.7 Human Toxicity Potential

Human Toxicity Potential (HTP) is used to evaluate the potential human health impacts of substances or activities in terms of their toxicity, exposure, and persistence in the environment. The results are expressed in kilograms of DCB equivalent.

In Figure 21, the HTP impact across different wastewater treatment scenarios is compared. The Baseline scenario has an HTP impact of 1.30E-01 kg DCB eq., indicating a moderate human toxicity potential. In comparison, Scenario 3.1 shows a reduced HTP value of 3.92E-02 kg DCB eq., suggesting a lesser human health impact. The categorical impact breakdown reveals that Electricity is the largest contributor to HTP (126.96%), followed by Materials (55.81%) and Credits, which provide a negative offset of -82.78%, helping to reduce the overall human toxicity impact. The negative values in Scenario 1.2 and Scenario 1.3 reflect a more beneficial environmental impact. For Scenario 1.3, recovery processes lead to a reduction in HTP, with Credits significantly contributing to the offset of toxicity (Figure 22).
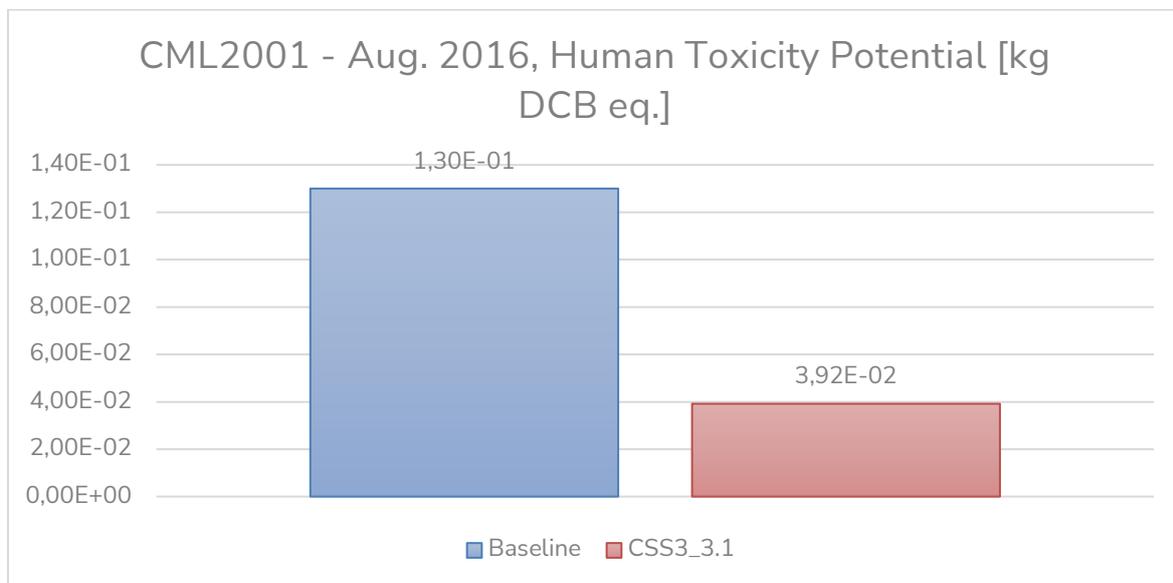

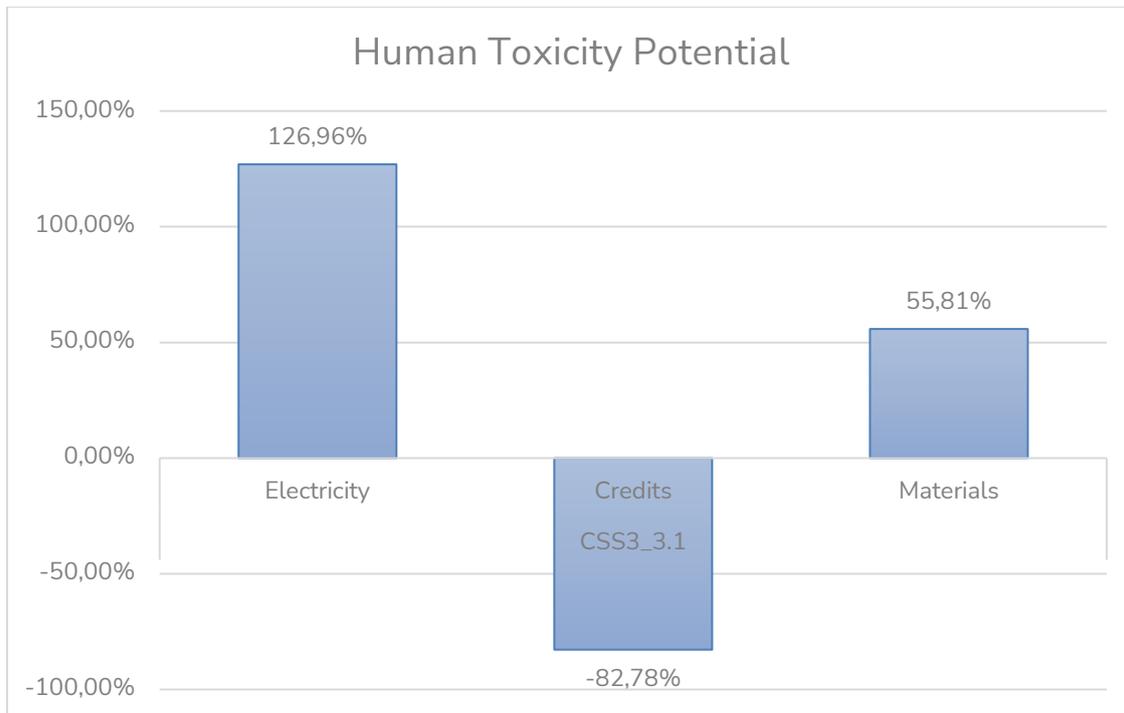*Figure 21 Human Toxicity Potential [kg DCB eq.] impact for each scenario.*

Figure 22 Categorical impact contribution (%) for Human Toxicity Potential

3.3.8 Ozone Layer Depletion Potential

Ozone Depletion Potential is used as a measure to describe the adverse effects of certain substances on the ozone layer in the stratosphere, particularly their role in diminishing the layer's capacity to block excessive ultraviolet radiation from reaching the Earth's surface. The significance of this issue has been globally recognized, which has led to concerted efforts under the Montreal Protocol to mitigate the impact through international cooperation. Although the impact of building materials on ozone depletion is generally minimal, the use of refrigerants in mechanical systems is a notable concern due to their potential for contributing to ozone layer damage. ODP is quantified in terms of kilograms of R11-equivalents, reflecting the global commitment to reducing the emission of ozone-depleting chemicals and safeguarding the ozone layer.

In Figure 23, the Ozone Layer Depletion Potential (ODP) impact across different wastewater treatment scenarios is illustrated. The Baseline scenario has an ODP value of 4.36E-12 kg R11 eq., while Scenario 3.1 shows a reduced ODP value of 1.47E-12 kg R11 eq., indicating a lesser negative impact on the ozone layer. The categorical impact breakdown, in Figure 24, reveals that Electricity is the largest contributor to ODP (242.86%), followed by Materials (373.62%) and Credits, which provide a significant negative offset of -516.49%, helping to reduce the overall ozone depletion impact. This suggests that while electricity and materials

have a considerable impact on ozone depletion, credits in the recovery process contribute substantially to minimizing this effect.
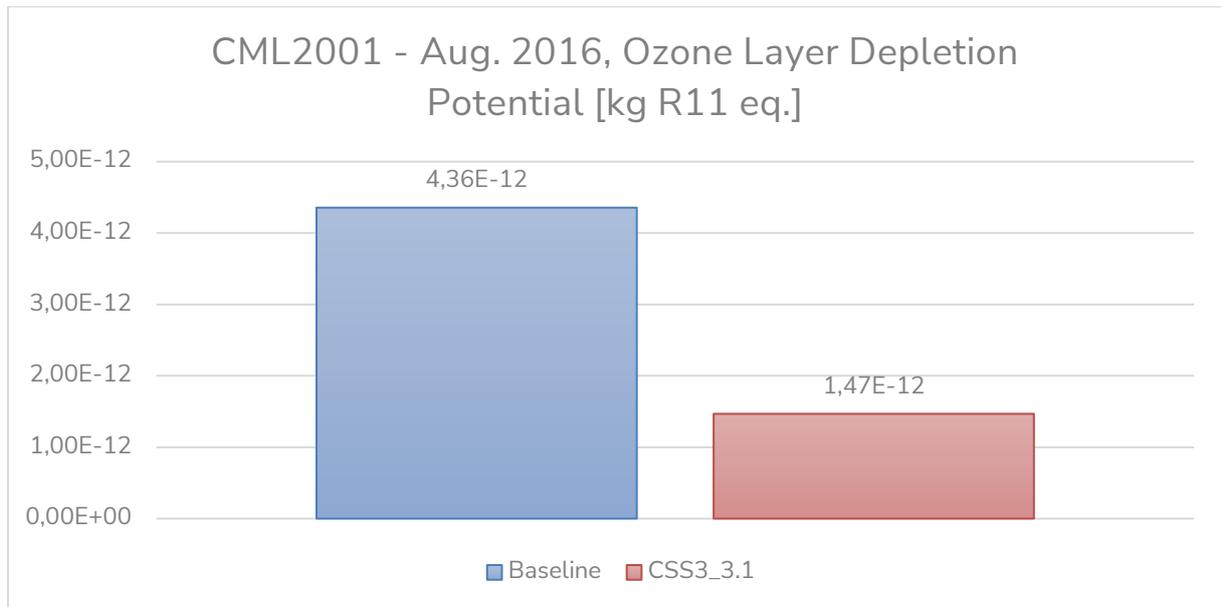

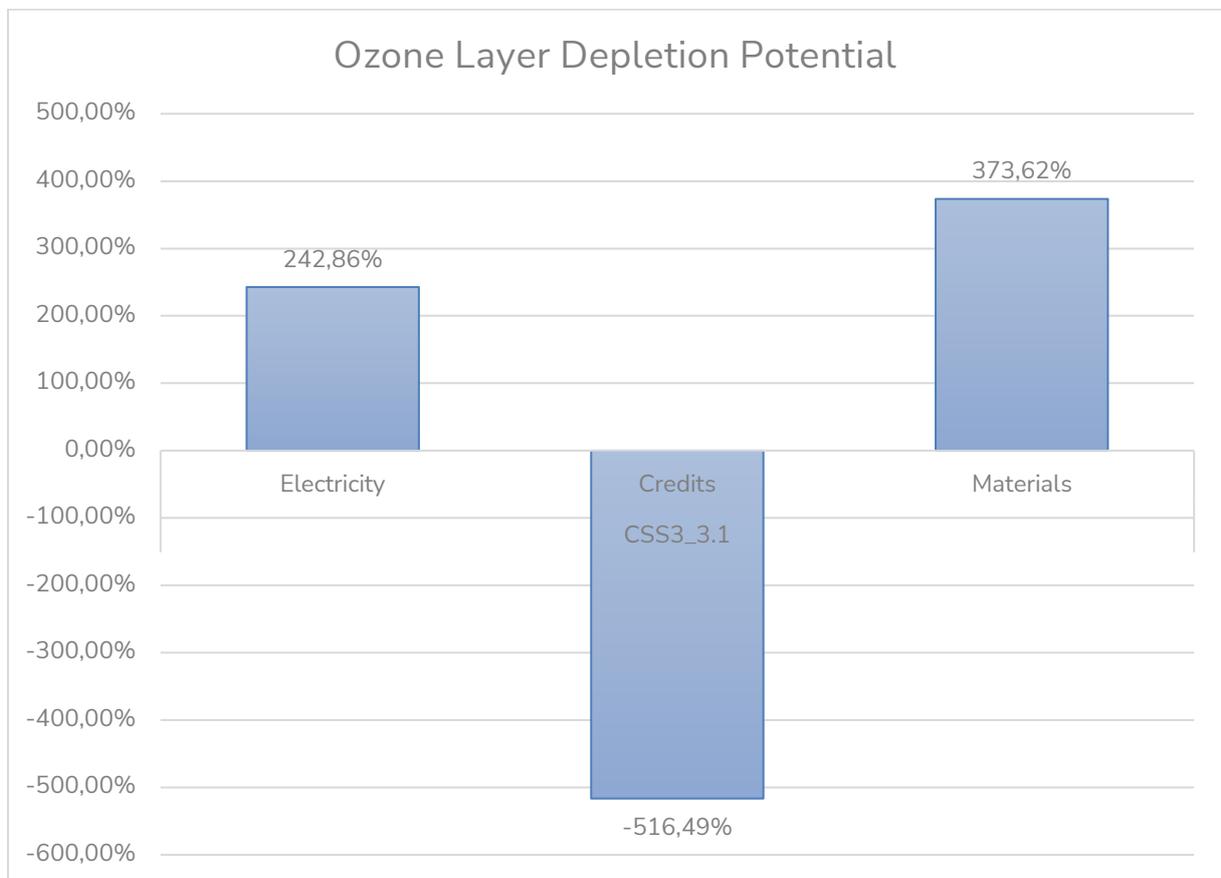*Figure 23 Ozone Layer Depletion Potential [kg R11 eq.] impact for each scenario.*

Figure 24 Categorical impact contribution (%) for Ozone Layer Depletion Potential (ODP, steady state) of each scenario.

3.3.9 Photochemical Ozone Creation Potential

The majority of tropospheric ozone formation occurs when NO_x, CO and VOCs, such as xylene, react in the atmosphere in the presence of sunlight. NO_x and VOCs are referred to as ozone precursors. A great deal of evidence exists to show that high concentrations (ppm) of ozone, created by high concentrations of pollution and daylight UV rays at the Earth's surface, can harm lung function and irritate the respiratory system. Photochemical Ozone Creation Potential (POCP) is expressed in terms of kg C_2H_4 equivalent.

In Figure 25, the Photochemical Ozone Creation Potential (POCP) impact across different wastewater treatment scenarios is compared. The Baseline scenario shows a high POCP value of 1.10E-04 kg C_2H_4 eq., mainly due to the release of volatile organic compounds (VOCs) during the decomposition of wood packaging waste in landfills. In Scenario 3.1, the POCP value is reduced to -1.20E-04 kg C_2H_4 eq., indicating a lower potential for photochemical ozone creation, likely due to energy recovery processes. The categorical impact breakdown (Figure 26) reveals that Electricity is the largest contributor to POCP (81.81%), followed by Materials (196.35%), with Credits providing a significant negative offset (-378.16%), helping to reduce the overall POCP impact despite fuel and electricity consumption. This suggests that energy recovery processes and credits in these scenarios significantly mitigate the photochemical ozone creation potential.
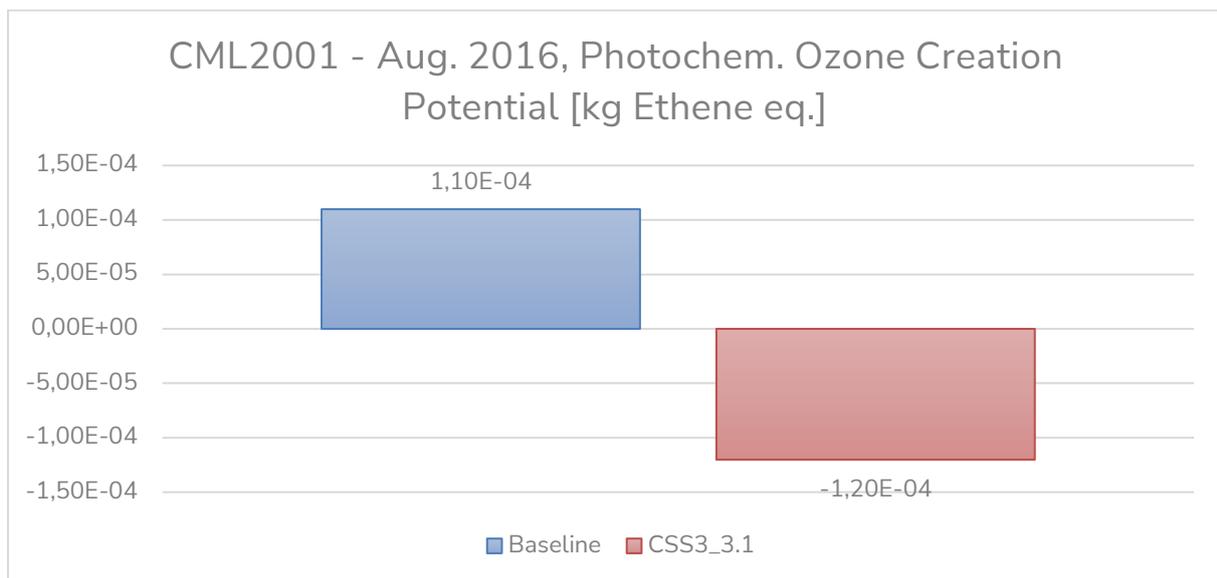

Figure 25 Photochemical Ozone Creation Potential [kg Ethene eq.] for each scenario.
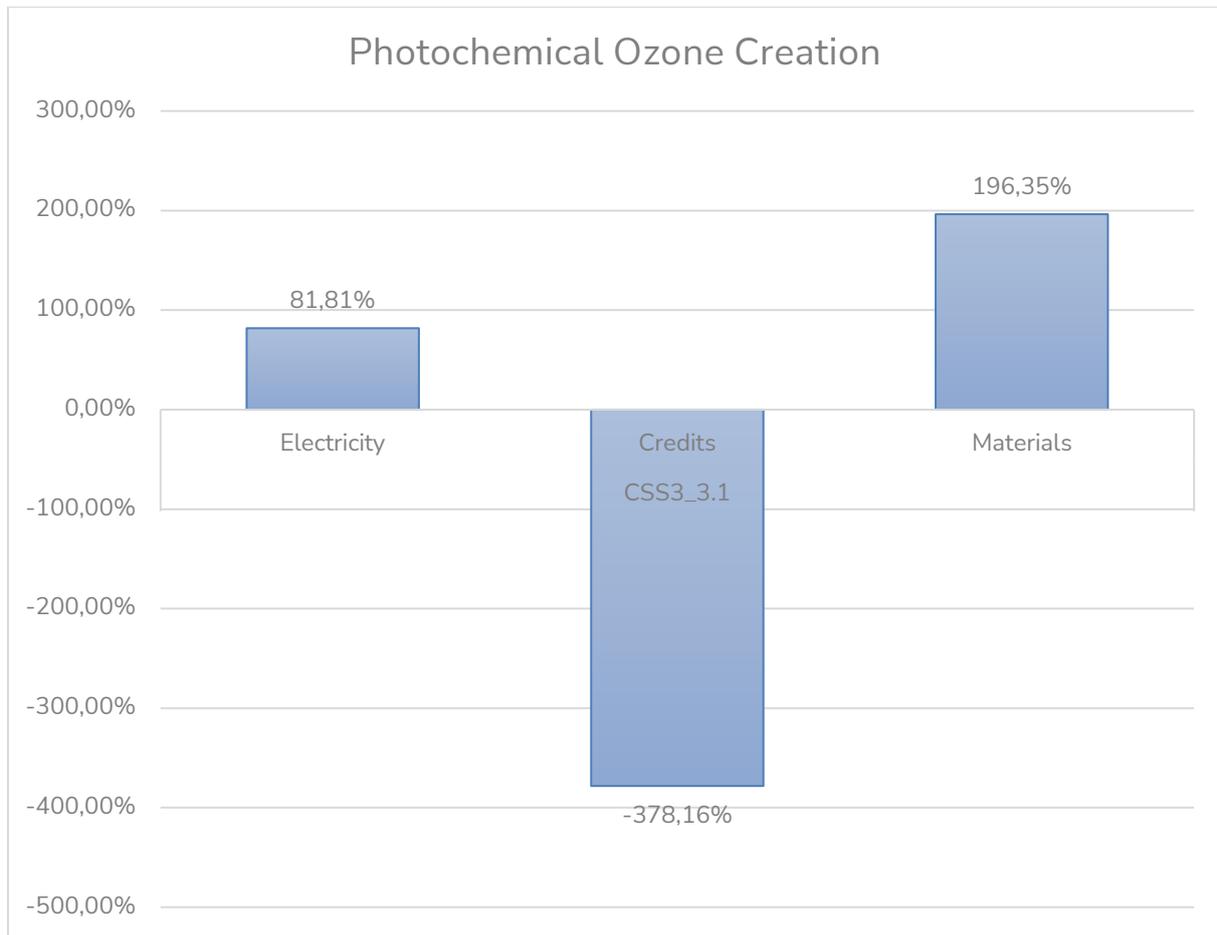
Figure 26 Categorical impact contribution (%) for Photochemical Ozone Creation

3.3.10   Terrestrial Ecotoxicity Potential

Terrestrial Ecotoxicity Potential (TETP) is used as an environmental impact category in LCA to evaluate the potential ecological harm to terrestrial ecosystems, including soil and land organisms, as a result of substances or activities. The potential toxicity of substances and their impact on terrestrial ecosystems over the course of their lifetime is measured by TETP. Kilograms of 1,4-dichlorobenzene (DCB) equivalent (kg DCB eq.) are typically used as the unit of measurement for TETP.

In Figure 27, the Terrestrial Ecotoxicity Potential (TETP) impact across different wastewater treatment scenarios is compared. The Baseline scenario shows a low TETP value of 5.27E-02 kg DCB eq., reflecting the minimal ecological harm during landfilling, where toxic substances are trapped rather than released into the environment. In Scenario 3.1, the TETP increases to 1.39E-03 kg DCB eq., mainly due to the additional fuel consumption. On the other hand, Scenarios 1.2 and 1.3 show negative TETP values (-9.09E-01 and -5.78E-01 kg DCB eq., respectively), indicating beneficial environmental impacts through energy recovery processes like Combined Heat and Power (CHP) and combustion. The categorical impact breakdown (Figure 28) reveals that Electricity contributes 48.27% to the TETP, while

Materials have a significantly higher contribution at 251.94%. Credits provide a negative offset of -200.21%, helping to reduce the overall terrestrial ecotoxicity potential.
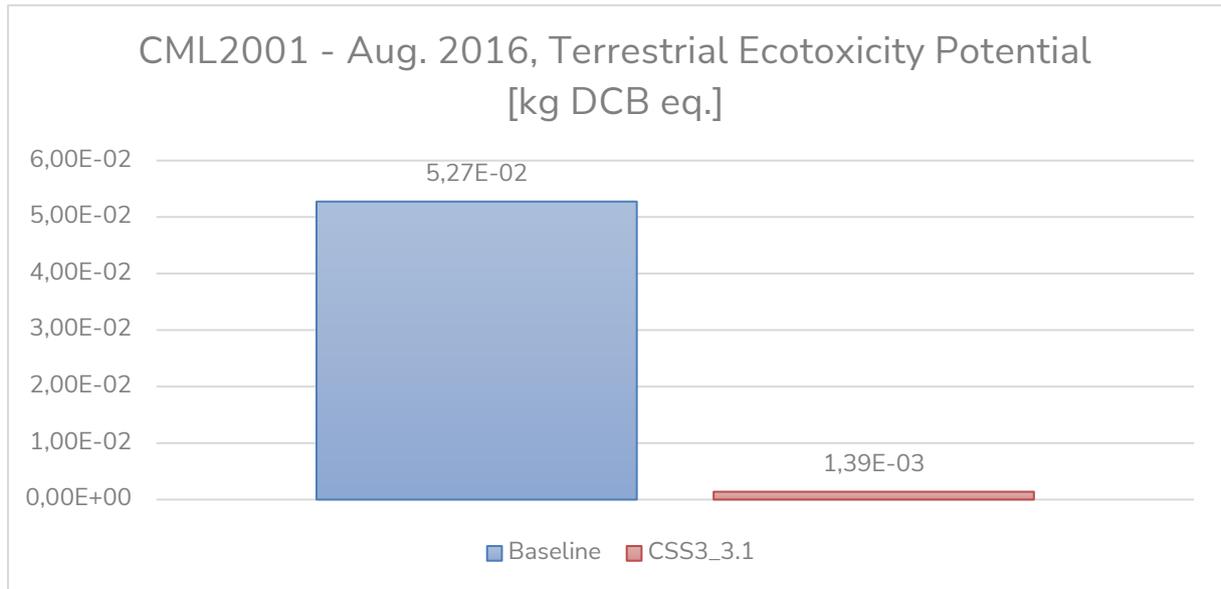

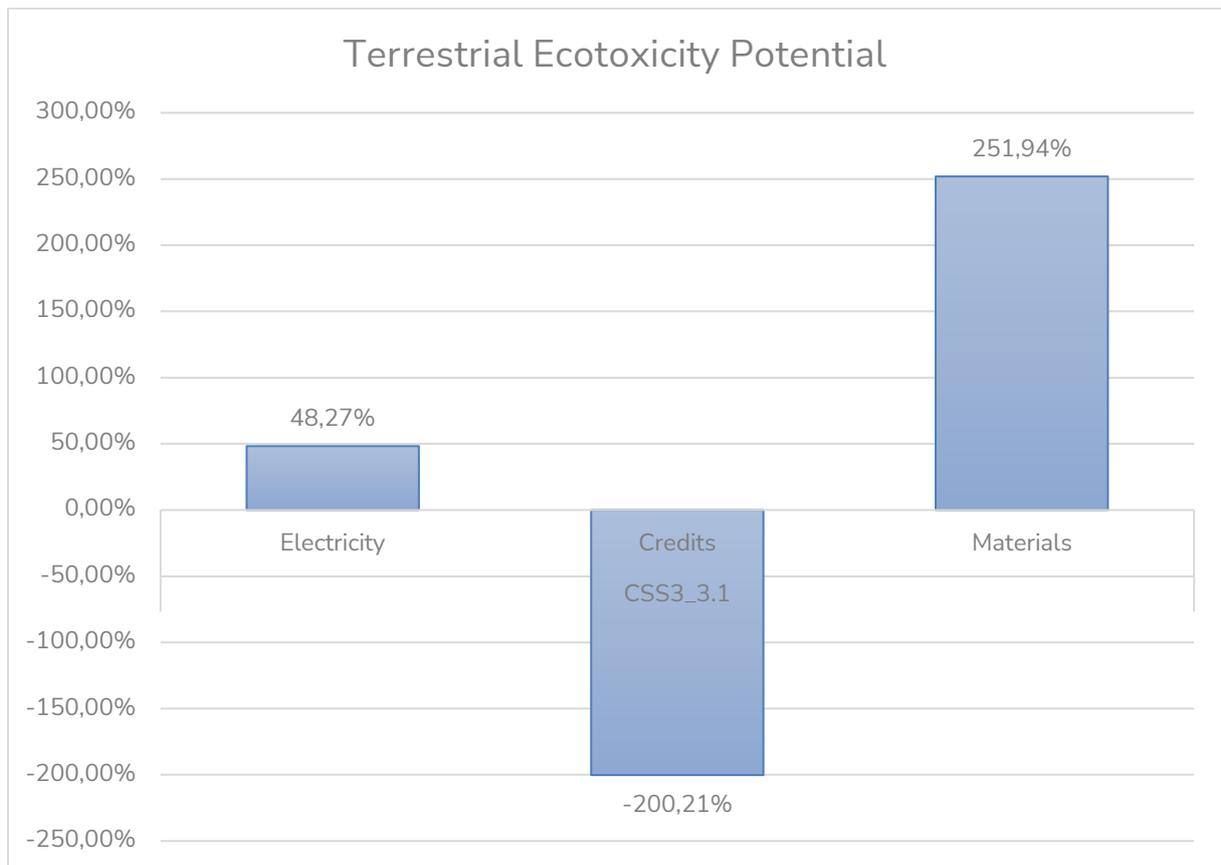*Figure 27 Terrestrial Ecotoxicity Potential [kg DCB eq.].*

Figure 28 Categorical impact contribution (%) for Terrestrial Ecotoxicity Potential.

3.4 EN15804+A2

3.4.1 Resource use indicators

Use of renewable primary energy (PERE) and total use of renewable primary energy resources (PERT) indicators for the Baseline scenario is 2.33E+00 MJ, for CSS3_3.1 is 1.81E+01 MJ. This increase indicates a higher reliance on renewable energy in the CSS3_3.1 scenario compared to the Baseline, suggesting that wastewater treatment in CSS3_3.1 benefits from a substantial improvement in renewable energy utilization.

Use of non-renewable primary energy (PENRE) indicators for the Baseline scenario is 5.32E+00 MJ, while for CSS3_3.1 it shows a negative value of -4.25E+00 MJ. This reduction reflects a net decrease in non-renewable energy use, attributed to energy recovery or substitution processes within the CSS3 scenario, which highlights a shift toward more sustainable energy practices and a minimized dependence on non-renewable resources.

3.4.2 Hazardous Wastes

The hazardous impact category covers various fractions that represent fire, health and environmental hazards posed by substances. These hazards may arise from waste or materials that are dangerous to human, animal and ecosystem. The unit of measurement for hazardous waste disposed (HWD) is typically expressed in kilograms (kg), providing a quantifiable indicator of the potential harmful impact of these materials to health and the environment.

In Figure 29, In Figure 29, the HWD impact values for the Baseline (4.81E-09 kg) and CSS3_3.1 (2.42E-08 kg) scenarios are compared. The CSS3_3.1 scenario shows an increased impact, indicating a higher potential for hazardous waste disposal. This increase is likely due to factors such as elevated energy consumption and increased materials handling, contributing to more waste being disposed of during the wastewater treatment process. Conversely, the Baseline scenario exhibits a lower impact, indicating less hazardous waste generation during traditional waste management.
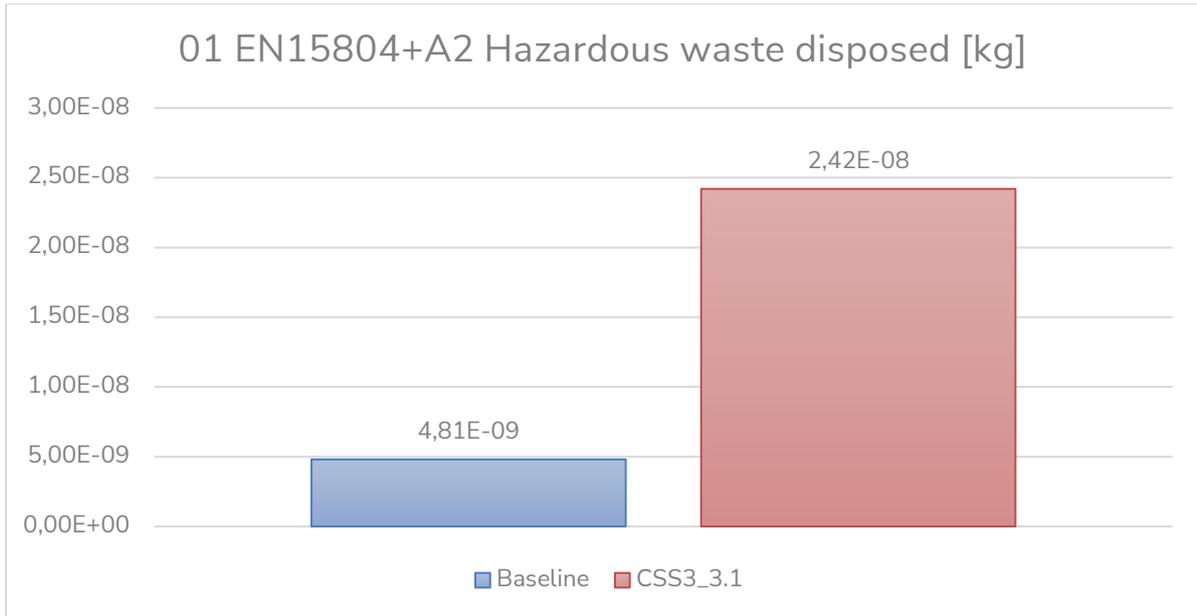
Figure 29 Hazardous waste disposed [kg].

3.4.3 Non-hazardous Wastes

The non-hazardous impact category encompasses waste materials that are not considered dangerous to human health or the environment. This includes household waste and industrial waste similar to household waste. The unit of measurement for NHWD is typically expressed in kilograms (kg), providing a quantifiable indicator of the amount of waste that requires proper disposal to reduce its environmental impact.

In Figure 30, the Baseline scenario, with landfilling, has the highest NHWD value of 9.68E-01 kg, as wood packaging waste does not significantly affect human health or the environment during landfilling. In contrast, the CSS3_3.1 scenario shows a reduction in the NHWD value to 5.63E-01 kg. This decrease is primarily due to the incorporation of wastewater treatment processes in the CSS3 scenario, which help to reduce the amount of non-hazardous waste and improve the overall environmental performance compared to the traditional landfilling approach.
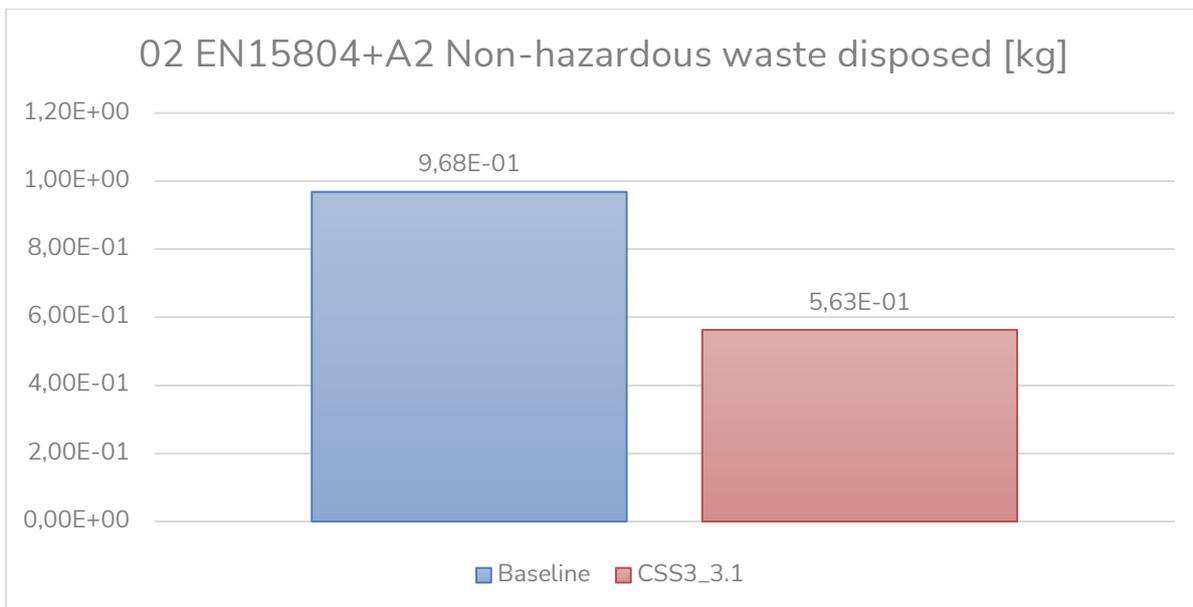
02 EN15804+A2 Non-hazardous waste disposed [kg]

Figure 30 Non-hazardous waste disposed [kg].

3.4.4 Use of net fresh water

The use of net fresh water refers to the calculation of the difference between the inflows of water resources and the outflows of water returned to the freshwater environment, as recorded in the LCI. This metric measures the net consumption of freshwater resources during the lifecycle of a product or activity. The unit of measurement is typically expressed in cubic meters (m³), providing a quantifiable indicator of freshwater use.

In Figure 31, the use of net freshwater is compared across different scenarios. The Baseline scenario shows a value of 5.63E-03 m³, indicating the net consumption of freshwater resources during the standard waste management process. Scenario CSS3_3.1 exhibits a significantly higher value of 1.00E+00 m³, suggesting an increased use of freshwater compared to the Baseline. This difference likely reflects the specific processes and materials involved in CSS3_3.1, which may require more water consumption for treatment or processing of wastewater, highlighting the importance of efficient water management in the wastewater treatment lifecycle.
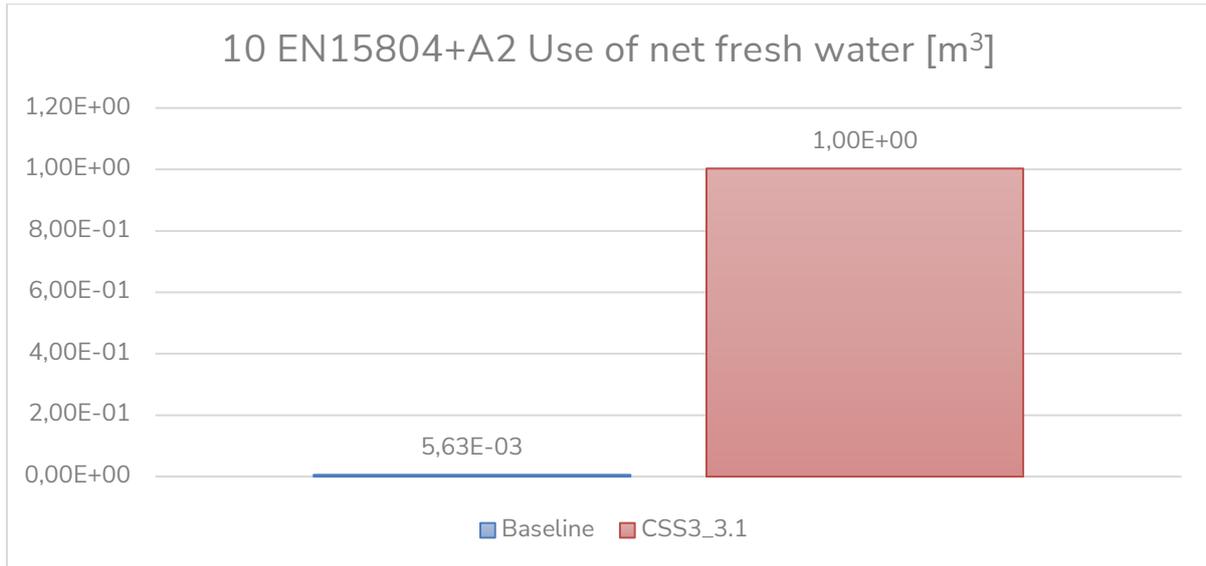
10 EN15804+A2 Use of net fresh water [m³]

Figure 31 Use of net fresh water [m³].

4 LCC methodology

4.1 Goal and Scope

4.1.1 Goal

The methodology of LCC is more straightforward compared to LCA. The goal and scope definitions are stated to understand the overall life cycle cost of the proposed CSS3 technology in respect with the sustainable management of wood packing waste. All necessary data to investigate and evaluate the life cycle cost of FRONTSH1P technologies are collected in close collaboration with LNEG for understanding the procedures followed during the experimental activity and ensuring the interpretation of valuable data as well as avoiding any data loss. The collected data were proper analysed and interpreted in line with the framework of life cycle cost analysis. Based on this analysis, the most viable and cost-effective part of the cost value chain is identified, and critical review is performed.

The relevant LCC parameters that have to be considered in the current analysis are distributed as shown in Figure 32 and corresponded to initial capital expenditure (CAPEX) as well as recurring costs i.e. operation and maintenance expenditure (OPEX).
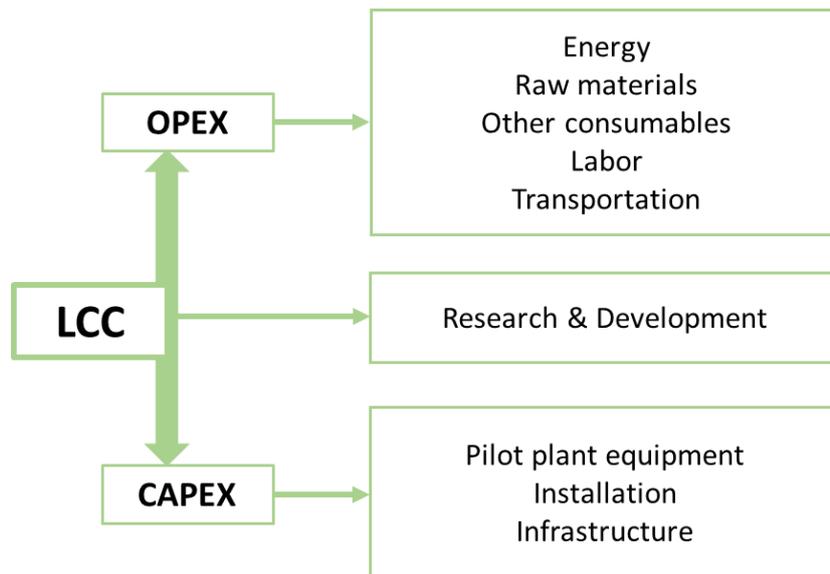
Figure 32 Life Cycle Cost distribution.

More precisely, CAPEX is assumed to be the total cost of the project including the aggregated cost of engineering, civil works, construction, electrical and mechanical components and contingency percentage. Depending on the project scale and expected duration, a contractor may choose to include an inflation rate in a tender application. Considering the plant scale range involved in this study, it is assumed that a plant can be constructed in one year and that the project cost estimation provided by the contractor does not include an inflationary cost factor. Furthermore, in order to finalize the process flow as well as the design of the stabilization pilot plant, laboratory trials were implemented. For this reason, the cost related to the laboratory instruments as well as laboratory consumables and a bench scale equipment before the final scale-up of the whole technology is taken into account in the current analysis. On the other hand, OPEX refers to the ongoing expenses a company incurs to operate its business daily. The operational costs include labour, energy, chemicals and sludge disposal. Smaller expenses generally fall under the operation and maintenance (O&M) category. OPEX is incurred throughout the asset's lifespan, but it is not always charged or paid on a uniform basis.

4.1.2 Functions of product system

For all the scenarios under investigation, it is necessary to consider the total cost of labour, maintenance, repairs and any other auxiliary supplies. It is important to note that throughout the entire lifecycle, energy, materials and labour costs should be included, while transportation is not included.

Calculation of environmental externalities (indirect costs)

The estimation of environmental externalities is based on Climate Change, one of the main externalities mentioned in the EU's 7th Environment Action Programme as key priorities to be addressed in EU and Member States policies. For the evaluation of the Climate Change

externality, it is critical to convert the environmental impact into monetary values. Monetary valuation can be defined as "the practice of converting measures of social and biophysical impacts into monetary units". The scope of monetary valuation is limited to estimating the value of changes in the availability of non-market goods. Changes in availability concern both changes in the amount and in the quality of a good and the service that the good provides to society. The key point to consider in monetary evaluation is that the main aim is assessing the changes in utility as a result of a given cause and effect relation and this can be done quantifying the marginal utility or damage. From this point of view, monetary value can be used as a measure of utility. The following equation is used for the conversion of potential climate change impact into externality:

$$\text{Climate change externalities [€]} = \text{Total impacts [kg } CO_2 \text{ eq.]} \cdot f \text{ [€/ (kg } CO_2 \text{ eq.)]}$$

where f is equal to 0.004 €/ kg CO_2 eq. (or 4 €/ ton CO_2 eq.)

4.1.3 System boundary

The boundary system for the LCC of the current study is selected in accordance with that of the LCA analysis. In this way, it is possible to consider the whole procedure in respect to the proposed CSS3 technology. It is noted that the material cost is included in the feed, while the cost of energy is accounted for at different stages of the process. Additionally, maintenance, repair and labour costs are considered. Finally, transportation cost has not been included in Scenarios 1, as it was not calculated in the LCA analysis.

4.2 Data inventory related to LCC analysis

Table 4 LCC inventory of Baseline.

Baseline		
Life cycle phase	Target activities	Cost (€)
OPEX	Waste disposal	52,500,000

Table 5 LCC inventory of Scenario 1.

Scenario 1				
Process	Life cycle phase	Target activities	Cost (€)	Comment
1.1	OPEX	Energy	1,136	Electricity
1.3	OPEX	Energy	745,465	Electricity
	CAPEX	Equipment Acquisition	1,298	1L-bioreactor
1.4	OPEX	Energy	47,082	Electricity
1.5	OPEX	Energy	49,430,318	Electricity
	CAPEX	Equipment Acquisition	2,349,803	7L-bioreactor
1.6	OPEX	Energy	743,400	Electricity
1.9	OPEX	Materials	5,024,250	Cyclohexane

4.3 Life Cycle Interpretation: Results and discussion

A total of 24,872 tonnes of wastewater were subjected to landfilling (Baseline) and valorisation/treatment (Scenario 1). The results are presented in the following Figure 33 and 36. Based on the cost graph for each scenario, the Baseline exhibits a higher LCC result (€5,517,895), followed by Scenario 1 with a small decrease (€5,311,093).
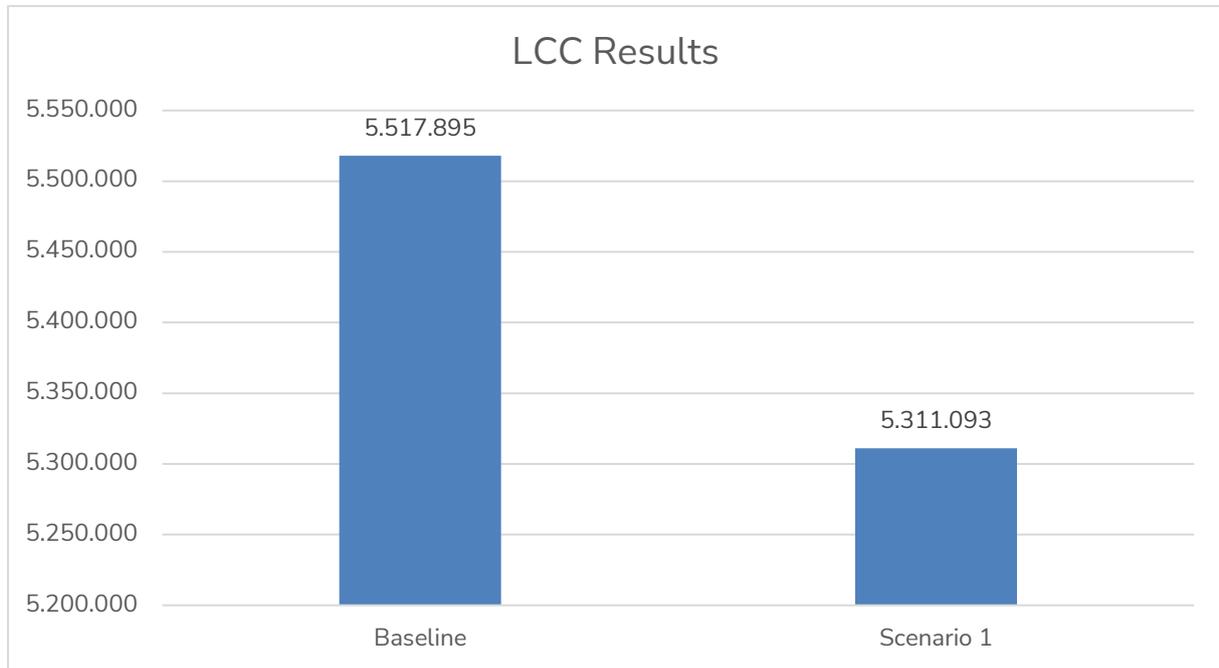
Figure 33 LCC results of each scenario.

The results are further supported by the Figure 34, which presents the undiscounted total sensitivity cost for the first year. OPEX costs make the highest contribution across both the Baseline and Scenario 1. In the Baseline, climate change externalities increase the LCC result. In contrast, in Scenario 1, earnings from microalgae contribute to a reduction in the total cost. This is because the production of bio stimulants, bio-fertilizers and other bio-based products can generate revenue through sales to suppliers.

Figure 34 Sensitivity analysis of total costs (1st year undiscounted) for each scenario.

Over a 20-year horizon, the CAPEX of Scenario 1 will remain unchanged due to maintenance. As shown in Figure 35, the cost curves for these scenarios exhibit a 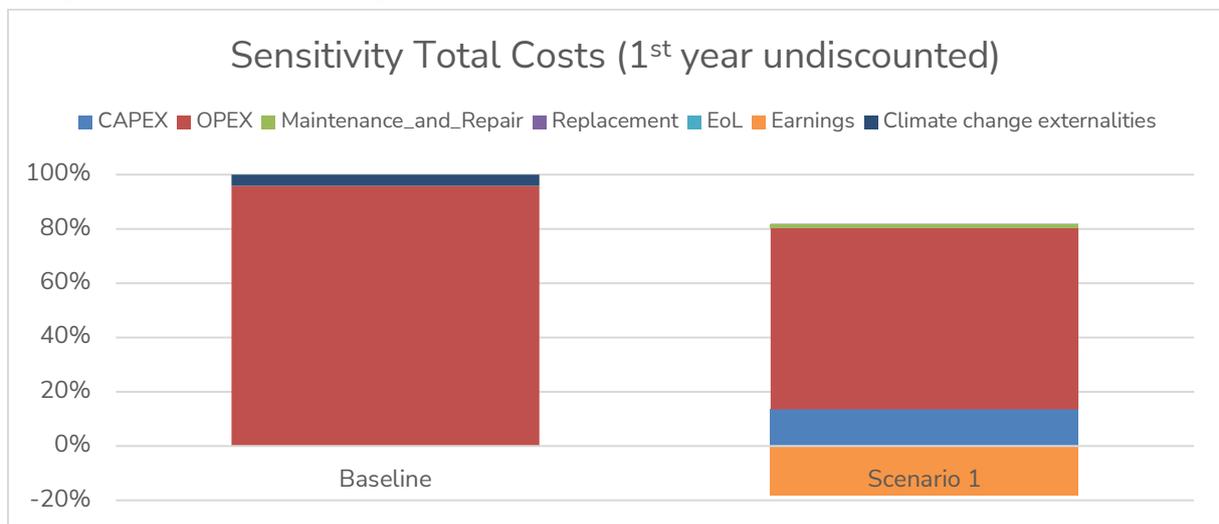decreasing trend, while the net present values progressively decline over time, based on the annual discount factor CF(T).
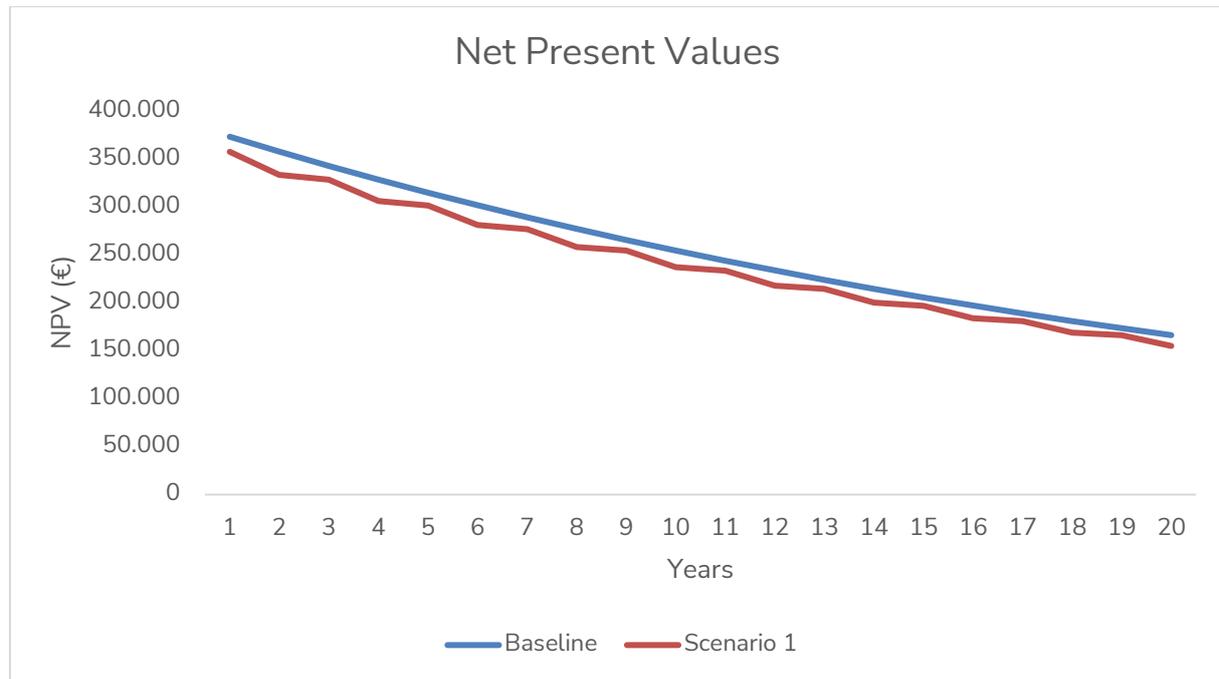

Figure 35 Net present values of each scenario for 20 years horizon.

5 s-LCA Methodology

5.1 Goal and Scope

This study explores ways to enhance wastewater treatment across Europe, particularly in regions experiencing water scarcity issues, with a focus on the Lodzkie region of Poland. Proper management and conservation of water resources are vital for maintaining the climate regulation. An ineffective water waste management can lead to various social, sociological, and environmental consequences throughout its lifecycle.

The goal of this Social Life Cycle Assessment (s-LCA) is to assess and measure the social impacts of new water waste management solutions and technologies across the lifecycle of these regions. In addition, we determine whether the results show improvements in sustainability and efficiency. The social and sociological effects of water waste management will be further examined through impact subcategories for each stakeholder group.

In this study, the Circular Systemic Solution 3 (CSS3) is applied as the new water waste treatment approach, focusing on minimizing waste and continually reusing resources.

For the analysis, two case studies were conducted: one by an institute in Portugal and the other by an organisation in Italy, both of which implemented the Circular Systemic Solution

3. Since the objective is not to directly compare the two case studies, we calculated the average results from both case studies and compared them with the baseline system commonly used in Europe. This approach was used to assess the social risks associated with the new recommended solutions of CSS3 that were mentioned above. The social life cycle assessment of all the options of the CSS3 is performed together given the same organizations are involved into the analysis.

The scope of the s-LCA is to do a cradle to grave analysis including the system boundaries of End of life of water waste with the use of quantitative-semi quantitative-qualitative data that were collected from the s-LCA questionnaire.

5.2 Stakeholders and impact categories

According to the guidelines published by UNEP/SETAC, the stakeholders that can be affected by the life cycle stage of the wastewater management are the following:

5.2.1 Workers

In this study, the term "workers" refers to the individuals who operate and maintain the systems within the facility, including technicians, supervisors, and administrative staff. Workers were assessed across a variety of indicators, with two primary categories standing out: i) Health and Safety, and ii) Working Conditions.

For the Health and Safety category, the emphasis was placed on the availability of safety measures and the frequency of fatal accidents in the workplace. Specifically, we looked at the implementation of safety protocols, preventive actions, emergency plans, and initiatives aimed at fostering a healthy work environment. Data for this category was gathered both quantitatively (fatal accident rates) and qualitatively (presence of safety measures), primarily through the s-LCA questionnaire.

In the Working Conditions category, the evaluation was divided into two subcategories: fair salary and working hours. Specifically, we focused on specific data on the minimum wage as well as the pay disparities between male and female workers, using qualitative data from the questionnaire. For working hours, we assessed the likelihood of overtime based on worker responses.

Additional indicators for this group included Freedom of Association, Collective Bargaining, Child Labour, Forced Labour, Equal Opportunity/Discrimination, Social Security/Benefits, and Employment Relationships. These were also evaluated using both qualitative and quantitative data collected through the questionnaire.

5.2.2 Consumers

Consumers are identified as individuals who "use" the outputs, both material and immaterial produced by the system. Two important impact categories for this stakeholder group are

Health and Safety, which were evaluated quantitatively through public health expenditure, and end-of-life responsibility, regarding the presence of systems in the organization that inform consumers about options for product disposal or recycling. This was measured by the internal management and the safety measures involved in handling products at the end of their life cycle. Additionally, the feedback mechanism was assessed using the press freedom index, while consumer privacy was evaluated based on the rule of law index. Lastly, transparency was measured through the corruption index.

5.2.3 Local community

This group of stakeholders refers to the communities living near the industrial area and other regions where activities related to resource recovery take place. Among the various impact categories, three were particularly important for this group: i) Community engagement, ii) Secure, Safe, and Healthy living conditions, and iii) Local employment.

For community engagement, the organization's contribution to local development was assessed, including the support provided for community initiatives (such as volunteer hours or financial donations) and the collaboration with local centres of higher education. Data for these aspects was collected qualitatively through a questionnaire filled out by members of the local community.

The safety and security of the community are also critical factors. In this context, reducing the use of hazardous substances and materials plays a key role in improving living conditions in these areas. Additionally, the presence or absence of terrorism in these regions was considered. As with other indicators, relevant data was obtained through questionnaire responses.

For local employment, the local unemployment rates and the proportion of local residents employed by the organization were evaluated to determine how much the organization involves local people in its operations, even with the implementation of the new CSS3 solution. Data for these indicators was provided quantitatively.

Other indicators for this stakeholder group included access to material and immaterial resources, delocalization and migration, and the respect for indigenous rights. These were evaluated in a similar way, using the same approach described above.

5.2.4 Society

This stakeholder group was evaluated across five different impact categories, with two key ones standing out: public commitment to sustainability and technological development. For public commitment to sustainability, values were determined based on the percentage of resources allocated to sustainability and social initiatives that influence the processes in place, as well as the usage of critical raw materials. Another important indicator was the per capita ecological footprint, which was assessed quantitatively.

In terms of technological development, R&D spending was examined to determine whether the innovative technological systems had a positive effect on the organization, along with the level of participation in technology transfer projects. Other factors taken into account for society included economic growth, efforts to reduce armed conflict, poverty reduction and corruption.

5.2.5 Supply chain

Lastly, for the value chain actors, the key impact categories identified included fair competition, promotion of social responsibility, supplier relationships, suppliers of raw materials and technology, and respect for intellectual property rights. Supplier relationships and suppliers of raw materials and technology were two categories that were evaluated using various indicators.

For the supplier relationships category, factors such as the identification of significant actual and potential negative social impacts were considered, along with the nature of the relationship between the organization and its suppliers on specific issues. Meanwhile, the suppliers of raw materials and technology category was assessed based on the traceability of raw materials, the protection of human rights among supplier employees, and the integration of ethical, social, environmental, and gender equality criteria.

Regarding the promotion of social responsibility, only the Good Country Index was evaluated, as we were unable to obtain data on the percentage of suppliers assessed for social impacts. Additionally, fair competition was evaluated based on regulatory quality and respect for intellectual property rights was assessed through the Global IP Index.

Table 6 Summary of stakeholders and their indicators.

Stakeholders	Indicators	Data source
Workers	(1) Freedom of association	ITUC Freedom of association [YES (100) - NO (1)] QL-P
	(1) Collective bargaining	Subject to collective bargaining [YES-100, NO-0] QL-P
	(2) Child labour	Child labour [% of children ages 7-14] QN-N
	(3) Forced labour	Forced labour and slavery [% of population] QN-N
	(4) Fair salary	Minimum wage [EUR/month] QN-P
	(4)1 Fair salary	Unequal remuneration [YES-100, NO-0] QL-N
	(5) Working hours	Hours worked per week [hours] QN-N
	(6) Equal opportunity/Discrimination	Women's share of work force [%] QN-P
	(6)1 Equal opportunity/Discrimination	Establishment of a committee/person for matters of discrimination [YES-100, NO-0] QL-P
	(7) Health and safety	Fatal accidents at work [-] QN-N
	(7)1 Health and safety	Presence of preventive measures and emergency protocols (YES-100, NO-0) QL-P

	(7)2 Health and safety	Measures to improve wellbeing and healthy practices in the facilities (YES-100, NO-0) QL-P
	(7)3 Health and safety	Hours of the health and safety training sessions that are usually attended per employee per year? (per level of employment) QN-P
	(8) Social Security/Benefits	Social protection expenditure [% of GDP] QN-P
	(8)1 Social Security/Benefits	Violations of obligations to employees under labour or social security laws [YES-100, NO-0] QL-N
	(9) Employment relationships	Social or training activities planned [YES-100, NO-0] QL-P
	(9)1 Employment relationships	Anonymous procedure for employees to state issues related with working conditions [YES-100, NO-0] QL-P
Consumers	(10) Health & Safety	Public health spend per capita [%] QN-P
	(11) Feedback Mechanism	Press freedom [0, constrained - 100, free] QN-P
	(12) Consumer Privacy	Rule of law [0-100] QN-P
	(13) Transparency	Corruption percentage index [0, highly corrupt - 100, very clean] QN-P
	(14) End of life responsibility	Safe and harmless to handle the end of life [YES-100, NO-0] QL-P
	(14)1 End of life responsibility	Recycle rate (proportion of materials recycled or recovered from waste) QN-P
	Description of final product	Certification/label of organisation/facility [YES-100, NO-0] QL-P
Local community	(15) Access to material resources	GDP per capita [EUR per capita] QN-P
	(16) Access to immaterial resources	Total literacy above 15 years [%] QN-P
	(16)1 Access to immaterial resources	Public expenditure In Education [percent of GDP] QN-P
	(17) Delocalization and Migration	Wellbeing [0-100] QN-P
	(17)1 Delocalization and Migration	Satisfaction with Life Scale (SWLS) [0-100] QN-P
	(18) Safe & healthy living conditions	Public health expenditure per capita [percent of GDP] QN-P
	(18)1 Safe & healthy living conditions	Management effort to minimize use of hazardous substances [YES 100, NO 0] QL-P
	(18)2 Safe & healthy living conditions	Certified environmental management system [YES-100, NO-0] QL-P
	(19) Respect of indigenous rights	Political freedom and Civil rights [1 (complete freedom) to 7 (no freedom)] QN-N
	(20) Community engagement	Voice and accountability [0-100] QN-P
	(20)1 Community engagement	Contribution of the organization to the local development (YES - 100, NO - 0) QL-P
	(20)2 Community engagement	Collaboration with local centres of higher education (YES - 100, NO - 0) QL-P

	(20)3 Community engagement	Presence of organizational reports disclosed to local community (YES-100, NO-0) QL-P
	(20)4 Community engagement	Protection of Indigenous communities in the local community [YES-100, NO-0] QL-P
	(21) Local employment	Unemployment rates [% of population] QN-N
	(21)1 Local employment	Employees originally from the local community (%) QN-P
	(21)2 Local employment	Percentage on spending on locally based suppliers [% of GDP] QN-P
	(21)3 Local employment	Support resettled employees [Yes-100, NO-0] QL-P
	(22) Secure living conditions	Political Stability and Absence of Violence and Terrorism [0, very bad - 100, very good] QN-P
	(22)1 Secure living conditions	Presence of risks in the facility [YES-100, NO-0] QL-N
Society	(23) Commitment to sustainability	Ecological Footprint per capita [global hectares -GHA per capita] QN-N
	(23)1 Commitment to sustainability	Percentage of the resources spend in sustainability and social activities (%) QN-P
	(23)2 Commitment to sustainability	Use of critical raw materials [YES 100, NO 0] QL-N
	(24) Economic development	UN Human Development Index [0-100] QN-P
	(25) Technology development	R&D spend [percent of GDP] QN-P
	(25)1 Technology development	Involvement in technology transfer projects [High-100, Medium -50, Low-0] QL-P
	(26) Mitigation of armed conflict	Global Peace Index [1(very peaceful) to 5 (maximum unrest)] QN-N
	(27) Poverty alleviation	Formalized commitment to reduce poverty [YES-100, NO-0] QN-P
	(28) Corruption	Control of corruption index (WB) [0, very bad - 100, very good] QN-P
Value chain actors	(29) Fair competition	Regulatory quality [0 (lowest) to 100 (highest)] QN-P
	(30) Promoting social responsibility	Good Country Index QN-P
	(30)1 Promoting social responsibility	Percentage of suppliers assessed for social impacts (%) QN-P
	(31) Supplier relationships	Regulatory quality [0 (lowest) to 100 (highest)] QN-P
	(31)1 Supplier relationships	Suppliers identified as having significant actual and potential negative social impacts [YES-100, NO-0] QL-N
	(31)2 Supplier relationships	Organization provides guidance / instructions to customers on how to handle your materials to avoid health and safety issues [YES-100, NO-0] QL-P
	(31)3 Supplier relationships	Organization provides support to suppliers in terms of consciousness-raising and counselling

		concerning social responsibility issues [YES-100, NO-0] QL-P
	(32) Suppliers of raw materials and technology	Integration on ethical, social, environmental, and gender equality criterions in purchasing policy, distribution policy, and contract signatures [YES-100, NO-0] QL-P
	(32)1 Suppliers of raw materials and technology	Presence of a specific explicit code of conduct that protect human rights of employees among suppliers [YES-100, NO-0] QL-P
	(32)2 Suppliers of raw materials and technology	Raw material traceability [YES-100, NO-0] QL-P
	(33) Respect of intellectual property rights	Global IP Index [0 (no IP protection)- 35 (best IP protection)] QN-P

*Note: QL: qualitative indicator. QT: quantitative indicator. P: the higher, the more positive. N: the higher, the more negative

5.3 Performance assessment - Impact assessment

Following the methodology above, we performed the performance assessment of this analysis:

Table 7 s-LCA performance assessment of WP5.

Stakeholders	Indicators	Data source	Performance assessment in Reference Study	Performance assessment in the Average Case Study
Workers	(1) Freedom of association	ITUC Freedom of association	5,00	5,00
	(1) Collective bargaining	Subject to collective bargaining	5,00	1,00
	(2) Child labour	Child labour	4,77	5,00
	(3) Forced labour	Forced labour and slavery	4,98	5,00
	(4) Fair salary	Minimum wage	1,14	1,56
	(4)1 Fair salary	Unequal remuneration	1,00	1,00
	(5) Working hours	Hours worked per week	2,78	3,33
	(6) Equal opportunity/Discrimination	Women's share of work force	2,80	2,78
	(6)1 Equal opportunity/Discrimination	Establishment of a committee/person for matters of discrimination	5,00	5,00

	(7) Health and safety	Fatal accidents at work	4,99	5,00
	(7)1 Health and safety	Presence of preventive measures and emergency protocols	5,00	5,00
	(7)2 Health and safety	Measures to improve wellbeing and healthy practices in the facilities	5,00	5,00
	(7)3 Health and safety	Hours of the health and safety training sessions that are usually attended per employee per year? (per level of employment)	1,01	1,00
	(8) Social Security/Benefits	Social protection expenditure	2,08	2,07
	(8)1 Social Security/Benefits	Violations of obligations to employees under labour or social security laws	1,00	5,00
	(9) Employment relationships	Social or training activities planned	5,00	3,00
	(9)1 Employment relationships	Anonymous procedure for employees to state issues related with working conditions	5,00	5,00
Consumers	(10) Health & Safety	Public health spend per capita	1,42	1,40
	(11) Feedback Mechanism	Press freedom	4,03	4,11
	(12) Consumer Privacy	Rule of law	3,80	3,68
	(13) Transparency	Corruption percentage index	3,44	3,22
	(14) End of life responsibility	Safe and harmless to handle the end of life [YES-100, NO-0]	5,00	5,00

	(14)1 End of life responsibility	Recycle rate (proportion of materials recycled or recovered from waste)	1,00	5,00
	Description of final product	Certification/label of organisation/facility	5,00	5,00
Local community	(15) Access to material resources	GDP per capita	2,34	1,95
	(16) Access to immaterial resources	Total literacy above 15 years	4,95	4,92
	(16)1 Access to immaterial resources	Public expenditure In Education	1,19	1,18
	(17) Delocalization and Migration	Wellbeing	3,60	3,47
	(17)1 Delocalization and Migration	Satisfaction with Life Scale (SWLS)	3,92	3,46
	(18) Safe & healthy living conditions	Public health expenditure per capita	1,40	1,38
	(18)1 Safe & healthy living conditions	Management effort to minimize use of hazardous substances	5,00	1,00
	(18)2 Safe & healthy living conditions	Certified environmental management system	5,00	1,00
	(19) Respect of indigenous rights	Political freedom and Civil rights	4,33	5,00
	(20) Community engagement	Voice and accountability	3,92	4,48
	(20)1 Community engagement	Contribution of the organization to the local development	1,00	5,00
	(20)2 Community engagement	Collaboration with local centres of higher education	5,00	5,00
	(20)3 Community engagement	Presence of organisational reports disclosed to local community	5,00	1,00

	(20)4 Community engagement	Protection of Indigenous communities in the local community	5,00	1,00
	(21) Local employment	Unemployment rates	4,75	4,74
	(21)1 Local employment	Employees originally from the local community	3,30	3,30
	(21)2 Local employment	Percentage on spending on locally based suppliers	4,11	-
	(21)3 Local employment	Support resettled employees	5,00	1,00
	(22) Secure living conditions	Presence of risks in the facility	1,00	3,00
	(22)1 Secure living conditions	Political Stability and Absence of Violence and Terrorism	3,32	3,71
Society	(23) Commitment to sustainability	Ecological Footprint per capita	3,89	3,98
	(23)1 Commitment to sustainability	Percentage of the resources spend in sustainability and social activities	-	-
	(23)2 Commitment to sustainability	Use of critical raw materials	1	-
	(24) Economic development	UN Human Development Index	4,49	4,52
	(25) Technology development	R&D spend	1,09	1,07
	(25)1 Technology development	Involvement in technology transfer projects	3,00	5,00
	(26) Mitigation of armed conflict	Global Peace Index	4,34	4,47
	(27) Poverty alleviation	Formalised commitment to reduce poverty	5,00	1,00
	(28) Corruption	Control of corruption index (WB)	3,82	3,84

Value chain actors	(29) Fair competition	Regulatory quality	3,97	3,96
	(30) Promoting social responsibility	Good Country Index	4,41	4,39
	(30)1 Promoting social responsibility	Percentage of suppliers assessed for social impacts	-	-
	(31) Supplier relationships	Regulatory quality	3,97	3,96
	(31)1 Supplier relationships	Suppliers identified as having significant actual and potential negative social impacts	1,00	-
	(31)2 Supplier relationships	Organisation provides guidance / instructions to customers on how to handle your materials to avoid health and safety issues	5,00	-
	(31) 3 Supplier relationships	Organisation provides support to suppliers in terms of consciousness-raising and counselling concerning social responsibility issues	5,00	-
	(32) Suppliers of raw materials and technology	Integration on ethical, social, environmental, and gender equality criterions in purchasing policy, distribution policy, and contract signatures	5,00	5,00
	(32)1 Suppliers of raw materials and technology	Presence of a specific explicit code of conduct that protect human rights of	5,00	5,00

		employees among suppliers		
	(32) 2 Suppliers of raw materials and technology	Raw material traceability	1	-
	(33) Respect of intellectual property rights	Global IP Index	3,49	3,69

5.4 s-LCA results and discussion

This section discusses the results for each stakeholder group and impact category, as described earlier. The aim is to identify which indicators contributed to the observed improvements in the new solution, leading to better water lifecycle sustainability in the region. Additionally, a final comparison between the two cases is provided to highlight the differences and evaluate the overall impact of the new solution.

Table 8 Average results for the five stakeholder groups.

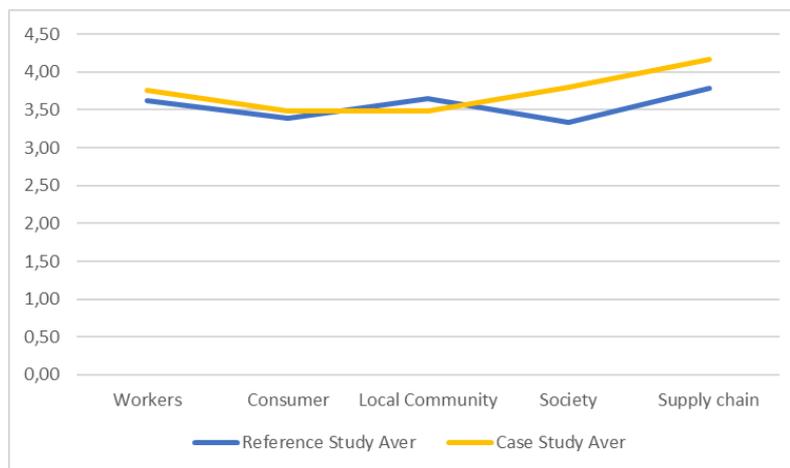|	Reference Study Aver	Case Study 1 Aver	Case Study 2 Aver	Case Study Aver
Workers	3,62	4,00	3,52	3,76
Consumer	3,38	2,99	3,98	3,49
Local Community	3,66	3,81	2,81	3,49
Society	3,33	4,15	3,44	3,80
Supply chain	3,78	4,33	4,01	4,17

Figure 36 Average results for each group in the two cases.

Average results for each stakeholder group in the two cases. Based on the data from Table 8 it is evident that all stakeholder groups showed an improvement in the case study, with the exception of the local community, which experienced a slight decrease compared to the reference study. Overall, the results are positive.

Figure 37 presents a comparison of the overall results between the reference and case study in this analysis. Following that, the individual graphs provide a detailed examination of each stakeholder group. A more detailed analysis of each group will be provided below (Figure 38-42).
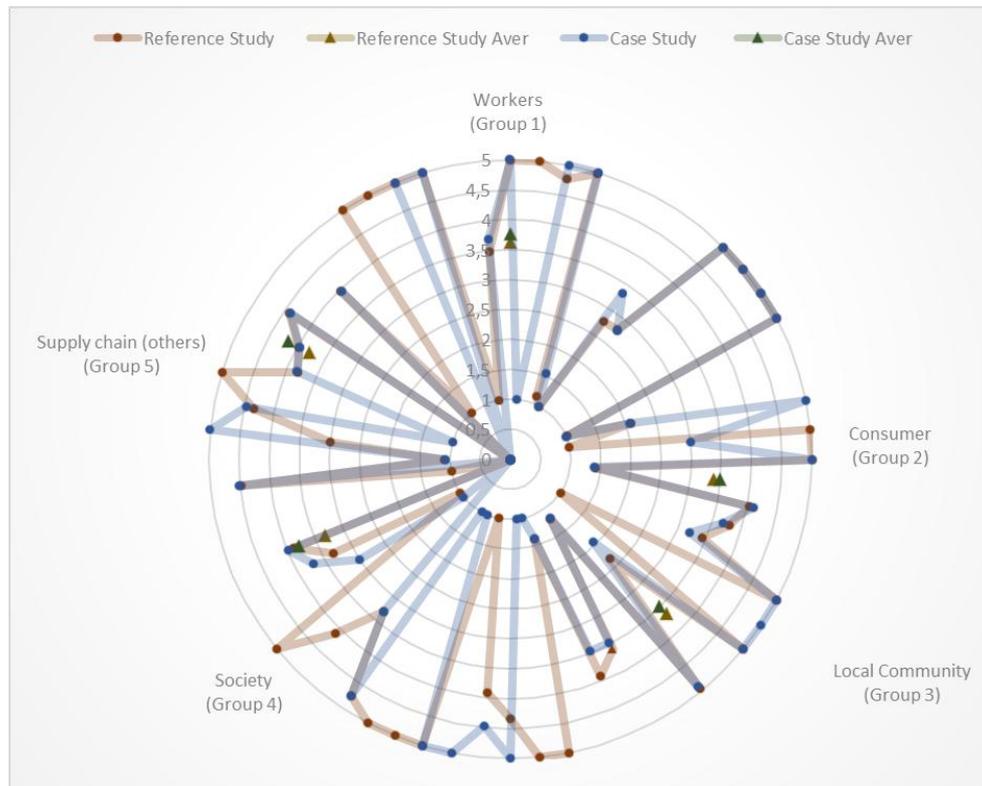

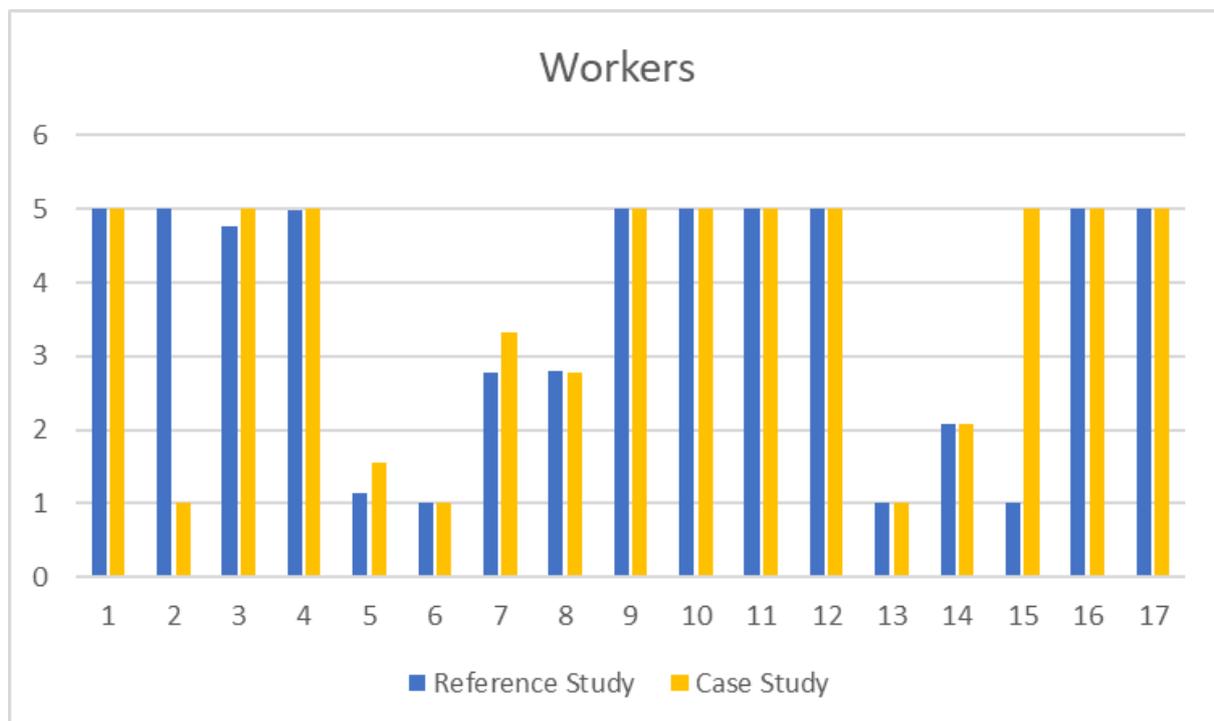*Figure 37 Results for each stakeholder group in the two cases.*

Figure 38 Workers' results for the two cases.

As shown in Figure 38, a small improvement is observed in the case study compared to the reference study. Specifically, the main positive results are that there were no incidents of child or forced labour, the minimum wage and working hours were beneficial for the employees, there were no accidents at all, and there were no violations of hygiene and safety standards or violations of obligations to employees under labour or social security laws. The only negative outcome was the absence of collective bargaining.
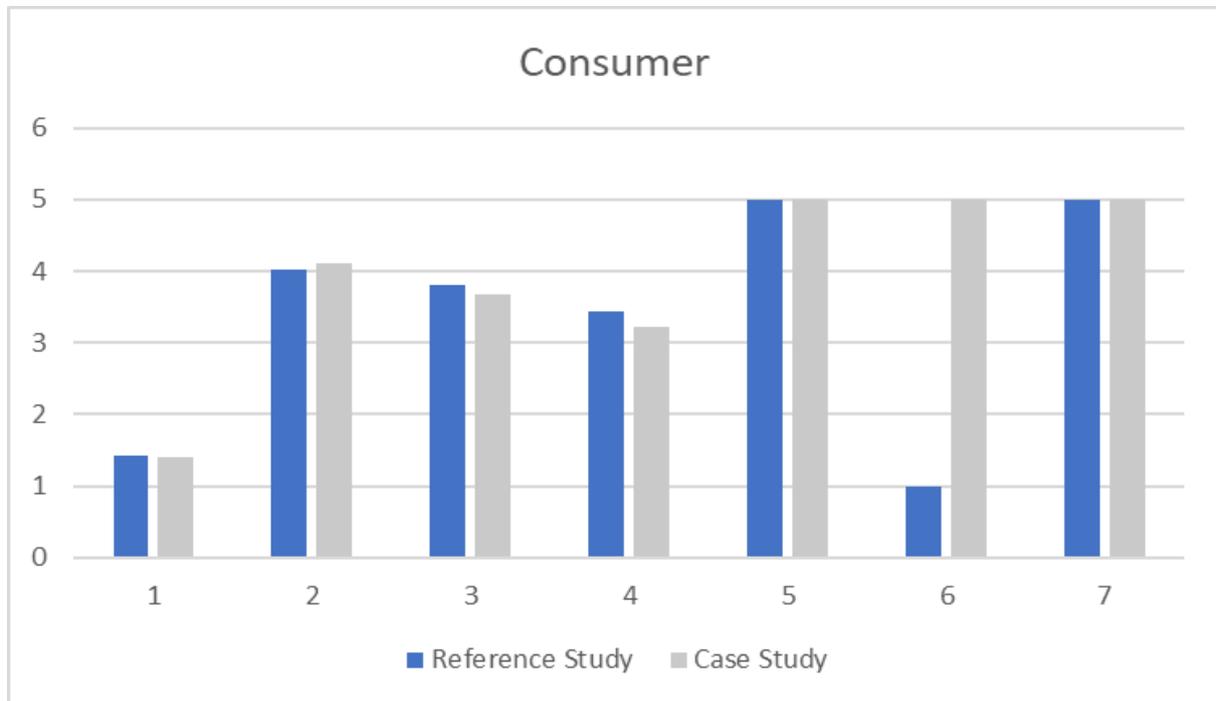

Figure 39 Consumers' results between the two cases.

In Figure 39, it is clear that the new management solution proved to be very effective, as it ensured safe and harmless handling of the end of life. A small improvement was also noted in the feedback mechanism category. However, two impact categories (rule of law and transparency) saw a slight decline, though this did not significantly affect the overall outcome for this stakeholder group.
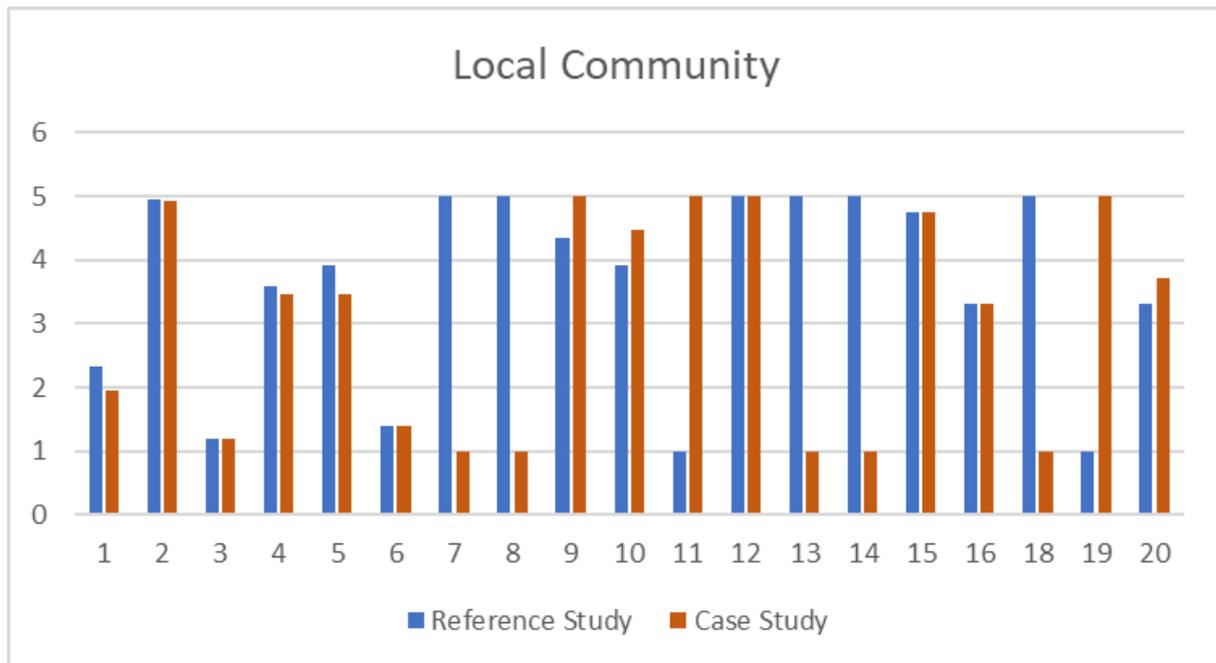
Figure 40 Local community's results for the two cases.

According to Figure 40, there are several differences between the two studies. Firstly, some very important positive outcomes include the organizations' contribution to local development, the assurance of secure living conditions, the respect of indigenous rights and the improvement in voice and accountability in community engagement. However, there are certain drawbacks that arise with this alternative approach. For example, the support for resettlement employees, the management effort to minimize use of hazardous substances, the lack of a certified environmental system and the non-protection of indigenous groups in the local community are some of the primary concerns, while secondary issues include minor differences in the categories of delocalization and migration, as well as access to material and immaterial resources. While the overall outcome for the local community has not improved with the adjustments made in the case study, these negative impacts except the indicator of safe and healthy living conditions, do not undermine the objective of the management solution.
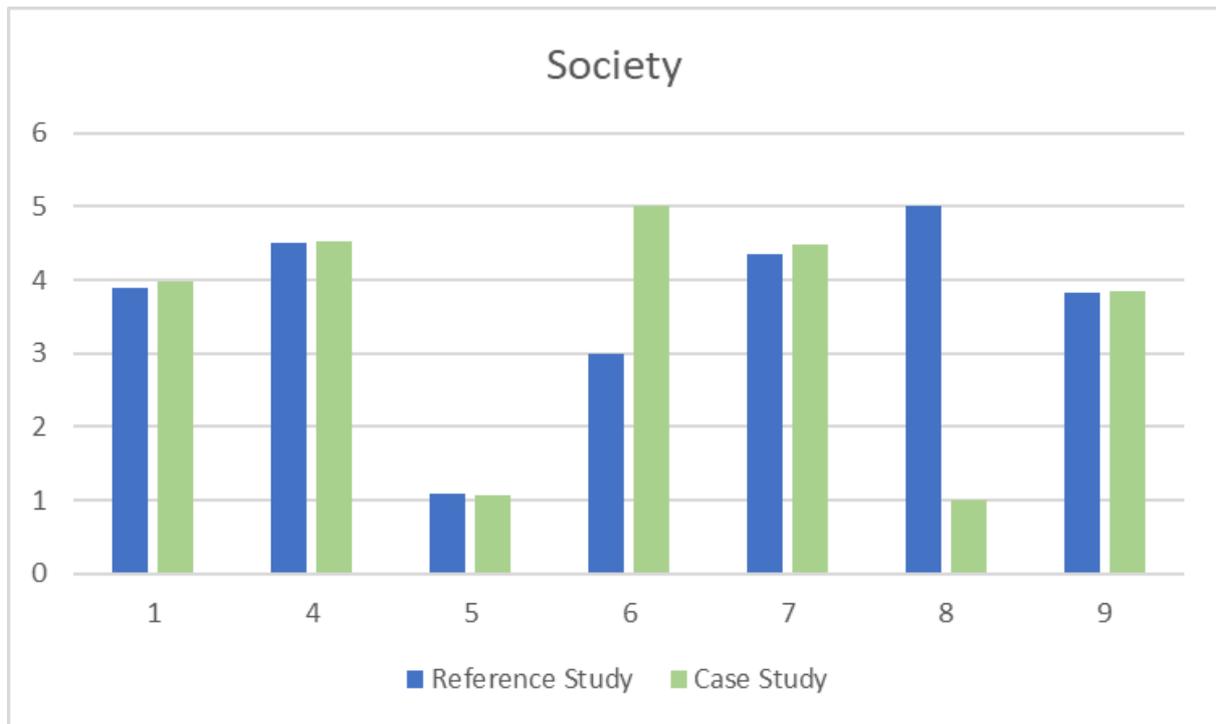
Figure 41 Society's results for the two cases.

In Figure 41, we see that for society, the case study shows a notable improvement, mainly due to the significant involvement in technology transfer projects. Additionally, there were slight improvements in indicators such as commitment to sustainability, economic development, limited mitigation of armed conflict, and corruption control. The only drawback was the absence of a formal commitment to reduce poverty. However, since the new solution does not prioritize poverty alleviation, this does not affect its overall objective.
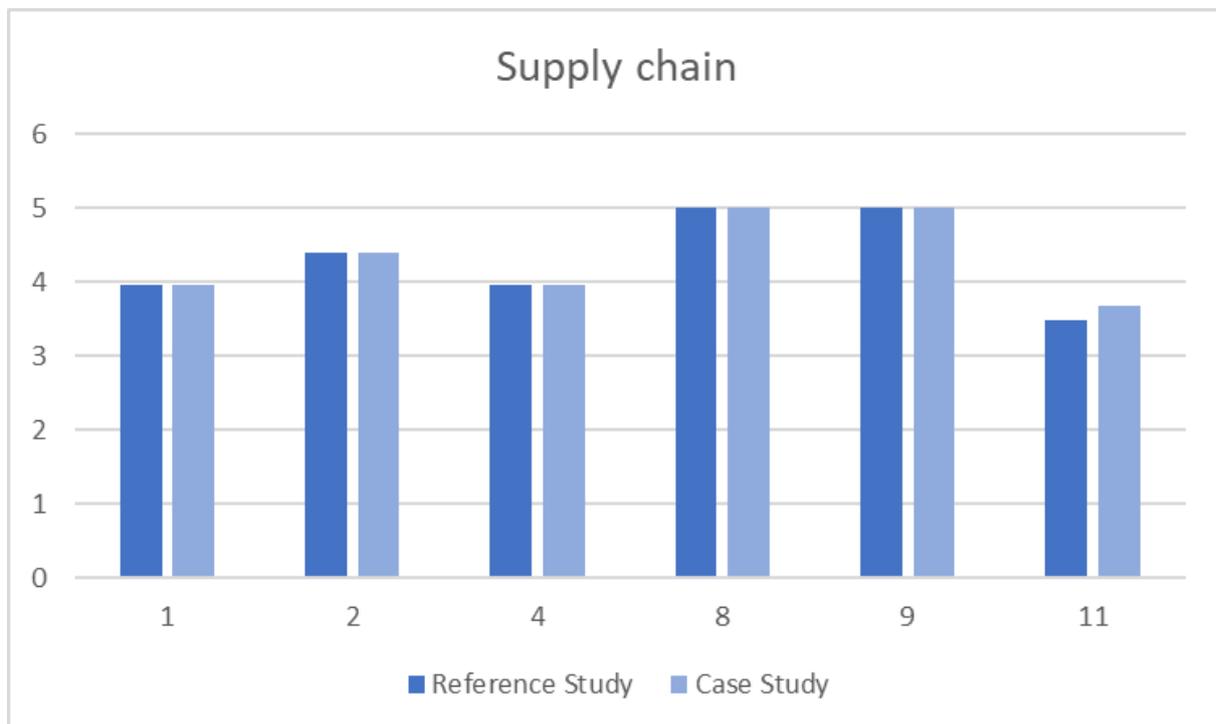

Figure 42 Supply chain's results for the two cases.

Finally, in Figure 42 it is clear that most of the indicators are about the same in both of the cases except for the respect of intellectual property rights where an improvement in the alternative solution is observed.

In conclusion, the s-LCA mainly concentrates on the social aspects of the study, specifically evaluating the notable improvements resulting from the introduction of the new wastewater treatment solution. The results show that the scenario using the alternative CSS3 solution (case study) produced the most positive outcomes across various stakeholder groups (with the exception of the local community) and impact categories. The case study revealed substantial progress in areas such as workplace safety, working conditions, environmental management (end-of-life handling), local development, economic development, commitment to sustainability and technological involvement. Although there wasn't an improvement in the stakeholder group of local community, the overall results highlight the progress of the new management solution in applying sustainable practices across various sectors.

6 Conclusions

This deliverable presented an integrated sustainability assessment of the CSS3 for the treatment and valorisation of wastewater in the Lodzkie region, employing LCA, LCC and s-LCA methodologies. The outcomes of the analysis offer valuable insights into the environmental, economic and social dimensions of implementing circular economy principles at a territorial level.

From an environmental perspective, the comparative LCA analysis of CSS3 Scenario 3.1 (microalgae-based wastewater treatment) against the Baseline (landfilling) demonstrated significant potential for impact reduction across key categories. Scenario 3.1 exhibited a more beneficial environmental profile, including reduced or negative values in categories such as Global Warming Potential (0.33 vs 1.01 kg CO_2 eq.), Abiotic Depletion – Fossil (-4.06 vs 4.08 MJ), Acidification Potential (-3.72E-03 vs 1.01E-03 kg SO_2 eq.) and Eutrophication Potential (-3.34E-05 vs 4.88E-05 kg PO_4 eq.). These results indicate the scenario's effectiveness in mitigating pollutant emissions, lowering dependency on fossil resources and offsetting environmental burdens through energy recovery and bioresource production. Additionally, CSS3 increased the use of renewable primary energy (from 2.33 MJ to 18.1 MJ) while reducing non-renewable energy consumption (from 5.32 MJ to -4.25 MJ), further reinforcing its alignment with climate-neutral objectives.

In economic terms, the LCC analysis revealed that, while the Baseline scenario incurred the lowest immediate costs (€5.52 million), it failed to account for long-term environmental externalities and lacked value recovery potential. In contrast, Scenario 3.1 involved a slightly lower total life cycle cost (€5.31 million), primarily due to the opportunity to generate economic value through the production of biostimulants and biofertilizers. Although capital

and operational expenditures were higher, especially in energy and material use, these were offset by avoided costs associated with environmental impacts and by the prospective revenues from circular bioeconomy markets. Over a 20-year horizon, the Scenario's cost trajectory benefited from technological stability and decreasing net present value trends, supporting its financial viability under realistic discounting scenarios.

The s-LCA further confirmed the positive social implications of CSS3 implementation. Compared to the baseline, the case study scenario improved scores across most stakeholder groups —including workers, consumers, local communities and society— particularly in areas such as occupational health and safety, fair working conditions, community engagement and public investment in sustainability. Notably, the CSS3 solution contributed to increased local employment, reduced pollutant exposure in surrounding areas and promoted knowledge transfer and innovation in water treatment technologies. The only stakeholder group with no significant change was the supply chain, which maintained stable and responsible sourcing and partnership practices throughout the implementation process.

In summary, the combined results of the LCA, LCC and s-LCA assessments underline the multifaceted value of the CSS3 solution in transitioning toward a circular and sustainable regional economy. The environmental gains, while subject to data limitations such as the exclusion of wastewater transport and full downstream treatment, are substantial; the economic analysis supports long-term investment in wastewater valorisation technologies, and the social outcomes highlight strengthened inclusivity, innovation and public well-being. These findings support the scalability and replicability of CSS3, aligning with the broader objectives of the FRONTSH1P project and EU policy goals on circularity, water resilience and climate neutrality.