Grant Agreement number: 101037031

Project acronym: FRONTSH1P

Project title: A FRONTrunner approach to Systemic circular, Holistic & Inclusive solutions for a new Paradigm of territorial circular economy

Type of action: Deployment of systemic solutions with the support of local clusters and the development of regional community-based innovation schemes

Deliverable Number: D4.6

LCA, s-LCA and LCC & main outcomes from CSS2

Delivery type:	**Report**
Lead beneficiary:	**19 - NTUA**
Lead author:	**Antonis Peppas, Chrysa Politi, Konstantinos Baldoukas**
Contributions:	**KFLEX, OPUS, BZURA, NVMT, NTUA, CERTH, LNEG, CARTIF, CSIC**
Contractual delivery date:	**30/04/2025**
Delivery date:	**14/07/2025**
Dissemination level:	**Public**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Partners

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

HISTORY OF CHANGES			
Version	Date	Author/Contributor	Changes
V0.1	14.03.2025	Kostantinos Baldoukas (NTUA)	Draft
V0.2	30.04.2025	Daniele Turati, Lorenzo Quatrale (Novamont)	Review and contribution
V0.3	20.05.2025	Chrysa Politi, Konstantinos Baldoukas, Antonis Peppas (NTUA)	Compile comments and contribution of partners
V0.4	26.06.2025	Vassia Kaperneka, Kostis Atsonios (CERTH)	Compile comments
V0.5	01.07.2025	Daniele Turati, Lorenzo Quatrale (Novamont)	Review and contribution
V0.6	02.07.2025	Chrysa Politi, Konstantinos Baldoukas, Antonis Peppas (NTUA)	Comments compilation, format, review
V0.7	02.07.2025	Vassia Kaperneka, Kostis Atsonios (CERTH)	Comments compilation
V0.8	09.07.2025	Patricia Moura, Cristina Rocha (LNEG)	Review and contribution
V0.9	14.07.2025	Chrysa Politi, Konstantinos Baldoukas, Antonis Peppas (NTUA)	Final Version
V0.10	14.07.2025	Daniele Turati, Lorenzo Quatrale (Novamont)	Final Review

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Disclaimer

Executive Summary

Deliverable D4.6 presents a comprehensive evaluation of the environmental, social, and economic performance of Circular Systemic Solution 2 (CSS2), focusing on food and feed valorisation pathways developed within the FRONTSH1P project. The work builds on pilot-scale results and technological developments reported in previous deliverables (D4.3, D4.4 and D4.5), aiming to assess the environmental benefits and trade-offs of scaling up these processes for industrial implementation in the Łódzkie region of Poland.

Three main scenarios were assessed through Life Cycle Assessment, Life Cycle Costing and Social Life Cycle Assessment:

- **Scenario 2.1**: Conversion of agricultural residues (corn stover) into Free Fatty Acids (FFAs)
- **Scenario 2.2**: Valorisation of organic food waste into biogas and high-quality compost
- **Scenario 2.3**: Cultivation of oil crops on marginal lands for biolubricant and animal feed production

The analyses were carried out in accordance with ISO 14040/44, ISO 21930, and EN15804+A2 methodologies, using both primary data from demonstration plants and secondary data from databases and literature.

The Life Cycle Assessment results indicate that Scenario 2.1, while technically viable and promising in terms of resource valorisation, entails higher impacts in abiotic depletion (mineral and fossil resources) and water use compared to the baseline, due to its energy and chemical intensive processes. In contrast, substantial environmental benefits were observed in categories such as eutrophication, global warming, and photochemical ozone formation, largely driven by the diversion of waste from landfilling and the generation of high-value outputs. From an economic perspective, Life Cycle Costing analysis identified major cost contributors across the CSS2 value chains and highlighted opportunities for cost optimisation and improved economic feasibility through system integration.

Regarding Scenario 2.2, the valorisation of organic food waste through anaerobic digestion and composting demonstrated notable environmental advantages, particularly in the reduction of eutrophication potential and greenhouse gas emissions. The Life Cycle Assessment results showed that converting organic fraction of municipal solid waste into biogas and compost significantly outperforms traditional landfilling approaches by diverting waste from disposal and closing nutrient loops. From an economic standpoint, Life Cycle Costing analysis revealed that despite initial investment costs, the system exhibits promising long-term feasibility due to reduced operational costs, particularly when biogas is utilized for energy generation and compost is valorised as a soil enhancer.

For Scenario 2.3, the cultivation of oil crops on marginal lands for the production of biodegradable biolubricants and animal feed offers a sustainable alternative to fossil-based lubricants, contributing to both land regeneration and resource circularity. The Life Cycle Assessment highlighted environmental benefits in categories such as abiotic depletion and photochemical ozone creation potential, especially when land use and inputs are optimized. Although the scenario entails moderate energy use, its overall ecological footprint remains lower than conventional systems. Life Cycle Costing results suggested that while scalability may be influenced by crop yield variability and market prices, the potential for local economic development and reduced external dependency supports its viability.

The Social Life Cycle Assessment assessed potential social risks and benefits across key stakeholder groups (workers, local community, consumers, and society), showing overall positive contributions in terms of employment, health and safety and social responsibility.

As part of this Deliverable, CERTH had undertaken the design and development of the overall industrial-scale value chains, building upon the findings from the pilot activities carried out in Tasks 4.34.4 and 4.5 (Deliverables 4.3, 4.4 and 4.5). CERTH's role involves the creation of detailed process models using Aspen Plus™, integrating experimental data, literature sources, and input from technology providers to ensure technical consistency and industrial relevance.

For each value chain, the methodology followed included the selection of industrial unit capacity based on information about the feedstock availability in Łódź region/Poland found in the relevant deliverables and literature benchmarks. The process models were then developed in alignment with the laboratory and pilot-scale experiments reported in D4.3, D4.4 and 4.5. In cases where lab- or pilot-scale technologies were found less feasible (from energy or economic perspectives) at an industrial scale, more established industrial processes were selected following discussions with the respective partners.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Model development gave particular attention to feedstock characteristics, including chemical composition and physical properties—especially for components not available in the Aspen Plus databases. Custom component data, reaction development, and suitable thermodynamic models were implemented as required.

Following the simulation runs, heat and mass balances were established, allowing for the calculation of key technical performance indicators for each value chain. These indicators include final product yield (expressed as a ratio), carbon utilization, and specific energy demand. The results demonstrated the technical feasibility of scaling up all three scenarios to an industrial level, supporting their potential implementation within a broader circular economy framework.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Contents

Executive Summary 4

1 Introduction 10

1.1 Purpose of the deliverable 10

1.1.1 Food waste in Europe 11

1.1.2 Food waste in Lodzkie region 13

1.2 Description of CSS2 solutions 14

2 Scenario 2.1 Methodologies 15

2.1 Life Cycle Assessment 15

2.2 Life Cycle Costing 18

2.3 Social Life Cycle Assessment 20

3 LCA analysis for scenario 2.1 24

3.1 Goal and Scope 24

3.1.1 Goal 24

3.1.2 Scope 25

3.1.3 Functions of product system 25

3.1.4 Functional Unit 25

3.1.5 System boundary 26

3.1.6 Impact Assessment Method and Impact Categories Description 26

3.1.7 Assumptions and limitations 27

3.1.8 Data quality 28

3.2 Life Cycle Inventory Analysis of the current study 29

3.3 Life Cycle Impact Assessment and Interpretation 31

3.3.1 Abiotic Depletion 31

3.3.2 Abiotic Depletion - Fossil 33

3.3.3 Acidification Potential 34

3.3.4 Eutrophication Potential 36

3.3.5 Freshwater Aquatic Ecotoxicity Potential 37

3.3.6 Global Warming Potential 39

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

3.3.7 Human Toxicity Potential....40
3.3.8 Ozone Layer Depletion Potential....42
3.3.9 Photochemical Ozone Creation Potential....44
3.3.10 Terrestrial Ecotoxicity Potential....45
3.4 EN15804+A2....47
3.4.1 Resource use indicators....47
3.4.2 Hazardous Wastes....47
3.4.3 Non-hazardous Wastes....48
3.4.4 Use of net fresh water....48
4 LCC methodology for scenario 2.1....49
4.1 Goal and Scope....49
4.1.1 Goal....49
4.1.2 Functions of product system....51
4.1.3 System boundary....51
4.2 Data inventory related to LCC analysis....52
4.3 Life Cycle Interpretation: Results and discussion....52
5 LCA analysis for scenario 2.2....55
5.1 LCA methodology for scenario 2.2....55
5.2 Scenario 2.2: OFMSW collection for biogas and compost production....55
5.3 Life Cycle Impact Assessment and Interpretation for Scenario 2.2....58
6 LCC analysis for scenario 2.2....63
7 LCA analysis for scenario 2.3....65
7.1 LCA methodology for scenario 2.3....65
7.2 Scenario 2.3: marginal lands valorisation....66
7.3 Life Cycle Impact Assessment and Interpretation for Scenario 2.3....67
8 LCC analysis for scenario 2.3....70
9 s-LCA methodology....71
9.1 Goal and Scope....71
9.2 Stakeholders and impact categories....72
9.2.1 Workers....72

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

9.2.2 Consumers 72
9.2.3 Local community 73
9.2.4 Society 73
9.2.5 Supply chain 74
9.3 Performance assessment - Impact assessment 77
9.4 Social LCA results and discussion 80
10 Process simulation and scale up of CSS2 value chains 86
10.1 Scenario 2.1 86
10.1.1 Model description 86
10.1.2 Heat Integration 95
10.1.3 Energy Demands 96
10.1.4 Scenario 2.1 Process simulation results 97
10.2 Scenario 2.2 100
10.2.1 Model description 101
10.2.2 Energy Demands 104
10.2.3 Scenario 2.1 Process simulation results 105
10.3 Scenario 2.3 107
10.3.1 Model description 108
10.3.2 Energy Demands 111
10.3.3 Scenario 2.2 Process simulation results 111
11 Conclusions 114

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

1 Introduction

1.1 Purpose of the deliverable

The present deliverable (D4.6) outlines the activities conducted and results obtained under WP4 (Circular Systemic Solution 2 – Food and Feed), specifically within task 4.6. led by NTUA. The purpose of this deliverable is to determine the key actions that could most effectively enhance the ecological performance of biobased products.

Within the framework of the FRONTSH1P project, three CSS2 scenarios have been strategically developed and implemented. Scenario 2.1 related to Task 4.3 focuses on converting agricultural residue streams into FFAs, which serve as key components in the production of innovative, eco-designed, circular biobased products. Scenario 2.2 related to task 4.4 targets the transformation of food industry waste into compostable bioplastics, supporting the improvement of urban biowaste collection systems and enabling its subsequent valorisation into compost and biomethane. Scenario 2.3 related Task 4.5 explores the cultivation of oil crops on marginal lands as a sustainable source of feedstock for biodegradable biolubricants, tailored for use in agricultural and industrial sectors.

Following the review of current trends in food waste management, the analysis addressed the situation in the Łódzkie region, the CSS2 solutions, the methodologies of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) and the evaluation of the previously outlined scenarios.

The LCA for Scenario 2.1, focused on the production of FFAs, was conducted by NTUA based on data reported by LNEG in accordance with ISO 14040/44, ISO 21930, and other relevant international standards. Meanwhile, the LCA for scenarios 2.2 focused on Organic Fraction of Municipal Solid Waste (OFMSW) collection for biogas and compost production and scenario 2.3 related to marginal lands valorisation was carried out by NVMT in accordance with ISO 14040/44 and ISO 21930 and with the coordination and supervision of NTUA. However, to effectively convey the complexity of the systems under study and support a meaningful interpretation of the results, a discursive and descriptive approach was adopted for Scenarios 2.2 and 2.3. This narrative format allows for a more descriptive presentation of the contextual factors, assumptions, and practical considerations that must be taken into account to ensure the results can lead to actionable improvements and genuine environmental benefits. Furthermore, NTUA performed a s-LCA for the three scenarios in line with ISO 14040/44, ISO 21930, and other applicable international standards.

The LCA and s-LCA focused on CSS2's most value chains were the products, such as compostable bioplastics, biolubricants, fatty acids for insulating foams, oil meal, compost and biomethane, due to the variety of technologies, were involved. Key metrics under consideration included carbon footprint reduction potential and impacts on ecosystems and human health, such as eutrophication potential, ozone depletion and toxicity. A sensitivity analysis helped pinpoint the environmental hotspots within the CSS2 technology pathway and supply chain configuration. Life cycle inventory (LCI) data for the LCA/ S-LCA study was gathered from technology providers (NVMT, LNEG, CIB-CSIC, CARTIF, K-FLEX), demo plant results and process modelling data (CERTH). This data covered raw materials, waste, energy sources and process mass and energy balances. Realistic supply chain scenarios for biomass waste provision were developed in collaboration with NVMT. Additional indicators have been considered for the environmental and social impacts of CSS2 (i.e. Circularity indices ;Linking sustainability indices to SDGs; Indicators for the reduction of littering through biodegradable product adoption; Soil Organic Matter (SOM) dynamics in marginal lands targeted for regeneration)

Furthermore, NTUA and NVMT performed a LCC analysis, gathering data on initial investments, operating and maintenance costs for each CSS2 technology based on demo plant experiences. Additional assumptions addressed decommissioning, replacement, and waste disposal costs.

1.1.1 Food waste in Europe

In 2022 around 132 kg of food waste per inhabitant were generated in the EU. Households generated 54% of food waste, accounting for 72 kg per inhabitant. The remaining 46% was waste generated upwards in the food supply chain. Household food waste is slightly more than twice the amount of food waste arising from the sectors of primary production and manufacture of food products and beverages (10 kg and 25 kg per inhabitant; 8% and 19%, respectively), sectors in which strategies exist for reducing food waste, for instance with the use of discarded parts as by-products. Finally, the sectors restaurants and food services and retail and other distribution of food accounted for 15 kg and 11 kg of food waste per person (11% and 8%, respectively); however, the impact of the end of the COVID-19 lockdowns on these two sectors is still being analysed [1].

[1] Eurostat. (2024, September). Food waste and food waste prevention - estimates. Ec.europa.eu. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

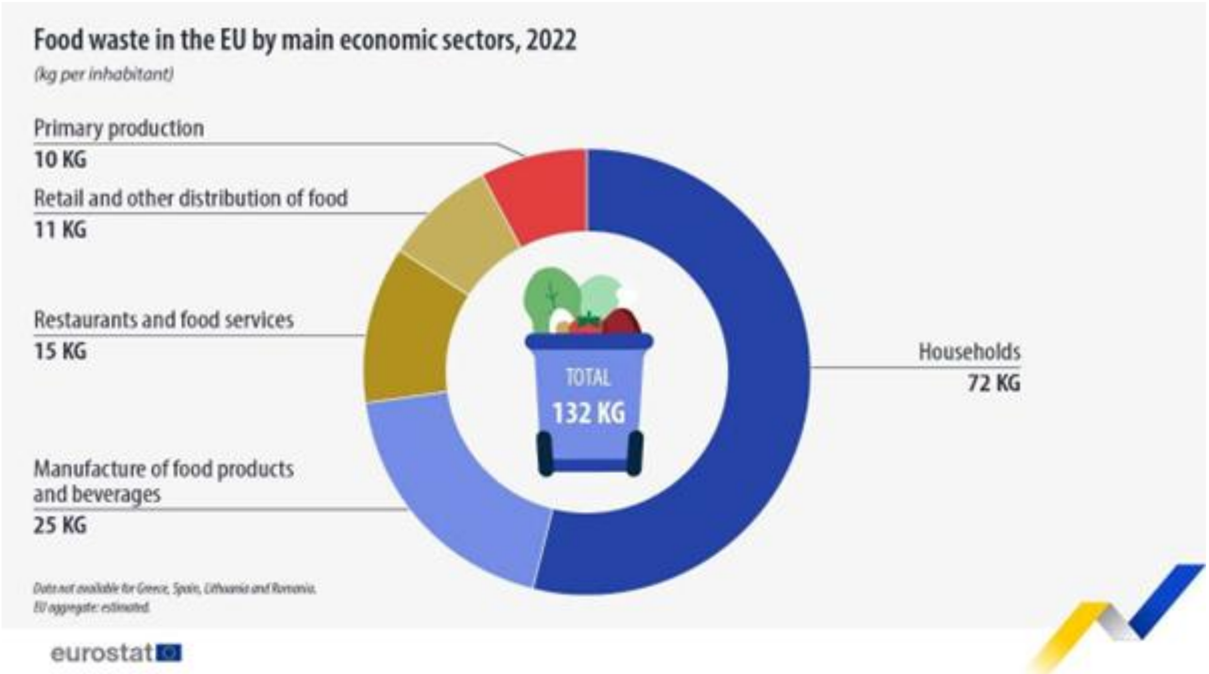


Figure 1 Food waste in the EU by main economic sectors in 2022 [1].

At EU level, the total food waste measured in 2022 was slightly more than 59 million tonnes of fresh mass. Household food waste represented 32 million tonnes of fresh mass, with a 54% share of the total. The second sector in terms of share (19%) was processing and manufacturing, where the amount of measured food waste was slightly more than 11 million tonnes of fresh mass. The remaining share, slightly more than a quarter of the total food waste, was from primary production sector (below 5 million tonnes, 8% share towards the total amount of food waste), restaurants and food services (below 7 million tonnes, 11% share towards the total) and retail and other distribution of food sectors (slightly below 5 million tonnes, 8% share). These amounts are presented in Figure 1.

Table 1 presents the amounts of food waste declared by the countries for reference year 2022, measured in tonnes of fresh mass, by sector of activities.

Table 1 Food waste in the EU by sector of activities in 2022 [1].

Food waste by sector of activities, 2022
(tonnes of fresh mass)

	Total food waste	Primary production	Processing and manufacturing	Retail and other distribution of food	Restaurants and food services	Households
EU	*59 200 000*	*4 600 000*	*11 100 000*	*4 800 000*	*6 600 000*	*32 100 000*
Belgium	1 758 589	33 863	737 026	125 564	111 250	750 886
Bulgaria	614 928	63 904	145 918	38 149	99 792	267 165
Czechia	1 080 608	14 670	165 414	67 296	180 773	652 455
Denmark	1 497 958	116 629	695 475	100 355	75 634	509 865
Germany	10 781 835	177 766	1 564 071	773 598	1 977 549	6 288 851
Estonia	180 747	21 555	39 088	19 681	12 930	87 493
Ireland	749 243	52 837	230 100	89 103	157 045	220 158
Greece (¹) (²)	2 044 324	*362 275*	403 568	*149 911*	*214 559*	914 011
Spain (²) (³)	4 260 845	*845 620*	1 419 257	*348 219*	*213 023*	*1 434 726*
France	9 450 000	*1 179 000*	2 406 000	830 000	1 091 000	*3 944 000*
Croatia	*278 838*	*39 084*	*9 424*	*4 086*	*14 736*	*211 508*
Italy (²)	8 201 419	*652 914*	540 442	*629 154*	474 241	5 904 668
Cyprus	*268 398*	*47 887*	*65 916*	*54 517*	*30 131*	*69 947*
Latvia	232 442	27 226	29 917	15 759	25 183	134 357
Lithuania (¹)	*390 645*	*81 202*	*29 271*	*33 951*	*4 651*	*241 570*
Luxembourg	79 406	7 582	11 430	8 614	9 626	42 154
Hungary	810 600	11 847	139 135	57 862	21 869	579 887
Malta	86 295	555	7 371	4 716	26 934	46 720
Netherlands (²)	2 290 000	322 206	884 373	*152 732*	*83 035*	847 654
Austria	1 184 447	6 226	204 358	83 138	256 040	634 683
Poland	4 545 178	724 875	552 823	474 461	*264 546*	*2 528 473*
Portugal	*1 926 484*	*110 980*	*64 572*	*227 908*	*239 000*	*1 284 025*
Romania	:	:	:	:	:	:
Slovenia	150 839	58	10 587	14 070	55 839	70 285
Slovakia	574 824	36 225	141 776	30 144	11 918	354 760
Finland	607 709	*29 439*	*139 297*	52 828	*81 182*	*304 963*
Sweden	*1 230 000*	*92 000*	*305 000*	*102 000*	*144 000*	*587 000*
Norway	902 731	184 911	142 238	68 105	120 793	386 684
Iceland	60 587	29 065	1 596	1 927	3 856	24 143

(:) not available
Figures in italic are estimates
(¹) 2022 data not reported, 2021 data presented
(²) Definition differs in some figures
(³) 2021 and 2022 data not reported, 2020 data presented.
Source: Eurostat (online data code: env_wasfw)

1.1.2 Food waste in Lodzkie region

In Lodzkie region there are 114 entities generating organic waste i.e. food processing plants (42), then dairies (28), slaughterhouses (21), distilleries (18) and pig farms (5). The largest number of food processing plants is located in the city of Łódź (7). Then dairies in the area of the Tomaszów county (5), Łódź East (4) and Rawa (4). The largest number of dairies is located in the city of Łódź (3) and in the Bełchatów county (3). Most of the slaughterhouses are located in the Piotrków county (6) and most of the distilleries - in the Wieruszów county (4).

In the Lodzkie region, companies producing organic waste are mostly small companies, generating over 50 tonnes of organic waste per year. The main producers

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

of organic waste are slaughterhouses and dairies, which generate waste primarily of animal origin. The most popular way to dispose of waste by companies in the Lodzkie region is waste reception by outside companies or by sending it to individual recipients, such as biogas plants, rendering facilities or composting units. A small number of wastes generating facilities keep waste for their own use. Companies in the Lodzkie region recognize delivering waste to biogas plants as beneficial. Most companies would be willing to hand over waste to biogas plants free of charge, if it existed within a radius of 20-25 km from the place of business conducted, and it would be optimal to use transport provided by the biogas plant. Most companies do not have their own waste tanks, so it would be an advantage to systematically transfer most waste to biogas plants, preferably once a week. Thanks to this, companies would not have to manage additional waste storage space and would not incur additional costs for the disposal of organic waste. The largest amount of waste in the region is generated by companies located in the Piotrków and Łódź. East counties. Waste from animal origin is produced and mainly transferred to outside companies. The facilities of Lodzkie region companies incur quite high costs of waste disposal, which may stimulate them to seek alternative forms of waste disposal. In addition, these entities notice the financial benefits that could lead them to use biogas plants. The potential of organic waste is also apparent in such entities as school, university, hospital cafeterias or the entire catering segment. This would, however, require the development of a special system for segregation and collection of waste from these units [2].

The household is 55% of total food waste. The increase of the OFMSW collection and transformation in biogas and high-quality compost, is an opportunity for the region. Details will be described in paragraph 3.1.5

1.2 Description of CSS2 solutions

The CSS2 focuses on the sustainable management of food and feed through end-of-life disposal, reuse and recycling. This circular approach optimizes resource utilization and minimizes waste through a continuous transformation cycle. It starts with collecting and processing industry, food and agricultural residue to extract valuable sugars and oils. These are then converted into monomers and FFAs, which serve as raw materials for bioplastics suitable for production of biodegradable and compostable bags EN13432 used in OFMSW collection and bio-oils for biodegradable bio lubricants for industries. When these materials reach the end of

[2] S. Aleksandrow and D. Michalak, "Analysis of the potential of the Łódź region in terms of a biogas plant construction," Acta Innovations, vol. 7, pp. 33–47, 2013.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

their life, OFMSW is treated to produce biomethane and compost. The compost could then be reused to enrich soil dedicated for food production and/or applied to marginal lands to support oil crop cultivation (e.g. rapeseed, milk thistles, sunflower). These crops yield seeds that, through crushing by mechanical extraction, produce oilseed cake that could be employed as animal feed and vegetable oil that could be used in the formulation of biodegradable bio-lubricants. At the end of their lifecycle, these materials undergo recycling and reintegration into the cycle, ensuring continuous resource efficiency, waste reduction and the promotion of sustainable industrial processes with both environmental and economic benefits.

The CSS2 Key Innovations are:

i. **Value chain 2.1**: CO_2-assisted pre-treatment of agro-industrial residue, combined with biotechnological processes, to produce FFAs for use in foaming biomaterials.

ii. **Value chain 2.2:** Production of biobased building blocks (diols and dicarboxylic acids) from second-generation feedstocks (regional agro-industrial waste) to create new compostable bioplastics, such as bags for collecting the OFMSW.

iii. **Value chain 2.3:** Development of oil crop genotypes (i.e. Sunflower) for cultivation on marginal lands, aimed at producing biodegradable biolubricant formulations, and oilseed cake meal for that could be employed as animal feed.

2 Scenario 2.1 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.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

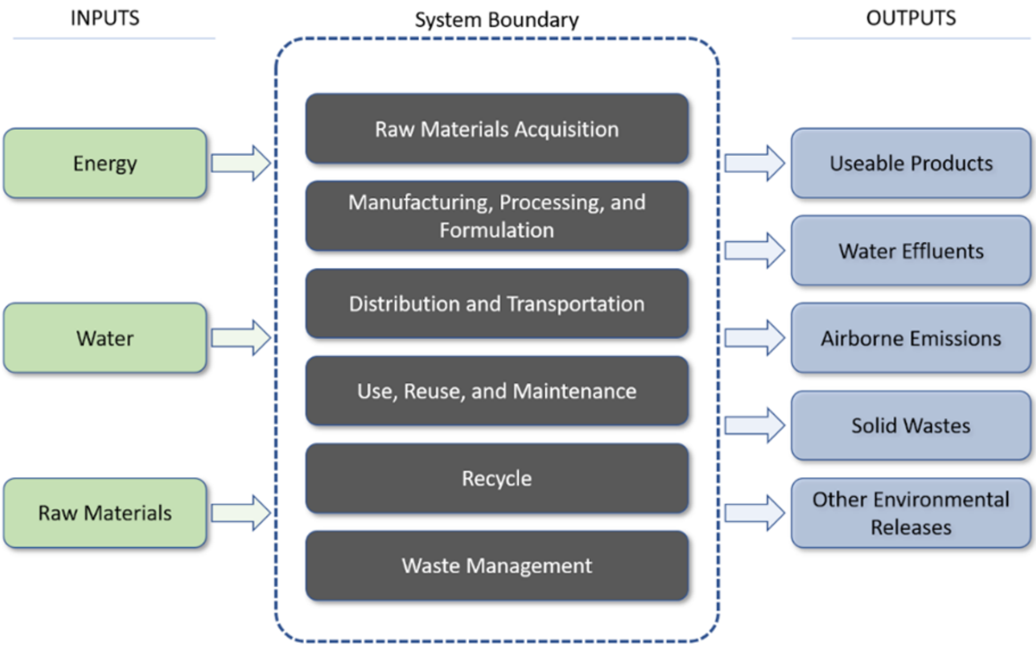


Figure 2 LCA input-output example process.

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.

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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

- **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 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.

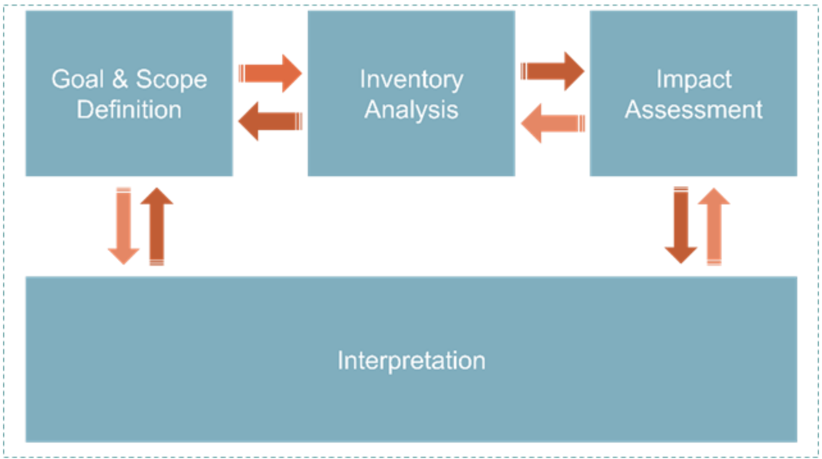


Figure 3 LCA framework.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

2.2 Life Cycle Costing

LCC is one 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 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.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

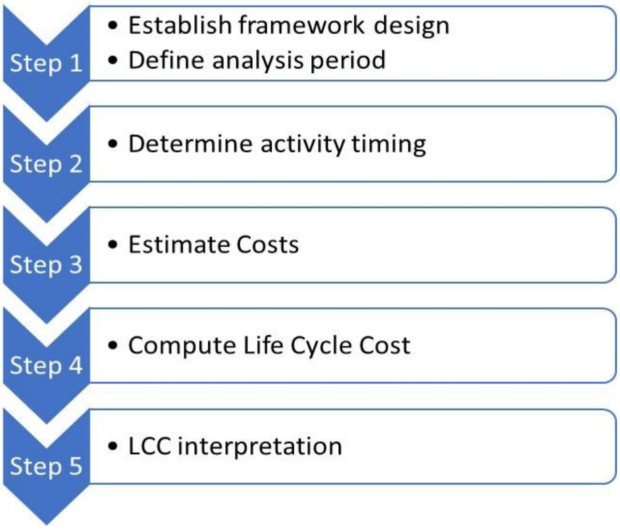


Figure 4 General framework of LCC analysis process.

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.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

2.3 Social 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 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 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'

[5] UNEP, 2020. Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese, G. (eds.). United Nations Environment Programme (UNEP).

[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

[8] EN 15804:2012+A1:2013 "Sustainability of construction works — Environmental product declarations Core rules for the product category of construction products"

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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).

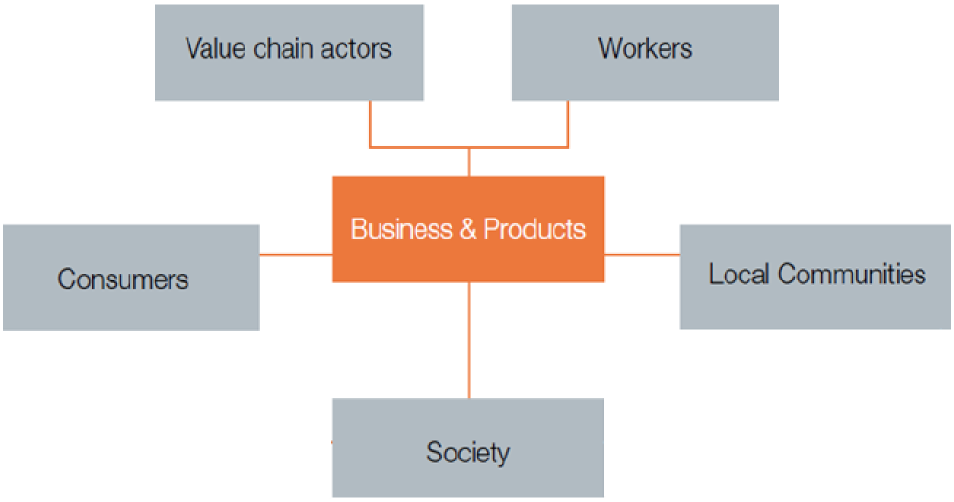


Figure 5 Stakeholders involved in the products life cycle.

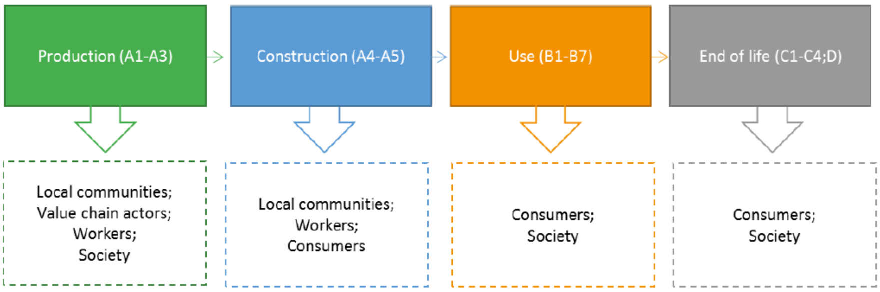


Figure 6 Indicative categories of stakeholders involved in each stage of the product life-cycle.

Specifically, the stakeholders (groups) are:

a) the workers (technicians who maintain and operate the infrastructure, heads and administration)
b) the value chain actors (actors directly involved in value chain activities such as water agencies, engineers, promoters)
c) the local community (community living nearby the area)
d) the consumers (consumers of material/immaterial outputs -natural pigments for food and non-food products and digestate as biofertilizer)
e) the society (society in general terms)

Table 2 Stakeholder groups involved in the lifecycle of food waste.

Stakeholder	Sub-Categories	End of Life
Local Community	Delocalization and Migration	x

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

	Community engagement	x
	Cultural Heritage	x
	Respect of indigenous rights	x
	Local employment	-
	Access to immaterial resources	x
	Access to material resources	x
	Safe and Healthy living conditions	x
	Secure living conditions	x
Value chain actors	Fair competition	x
	Respect of intellectual rights	x
	Supplier relationships	x
	Promoting social responsibility	x
Consumers	Health and safety	x
	Feedback mechanism	x
	Consumer privacy	x
	Transparency	x
	End of life responsibility	x
Workers	Freedom of association & collective bargaining	x
	Child labour	x
	Forced labour	x
	Working hours	x
	Fair salary	x
	Equal opportunities/ discrimination	x
	Health and safety	x
	Social benefits/ social security	x
	Employment relationships	x
Society	Public commitments to sustainable issues	-
	Prevention and mitigation of armed conflicts	x
	Contribution to economic development	x
	Corruption	x
	Technology development	x

3. For every stakeholder, special themes of interest are determined; the purpose of the classification of sub-categories according to stakeholder groups is to make sure that the s-LCA matches the goal and scope and is assessing the bulk of the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

situation. A complete list of sub-categories is reported in agreement with the UNEP/SETAC guidelines [9].

4. Every sub-category is assessed by different indicators. The list of these indicators and the description of their status for the considered processes is the inventory of the s-LCA. Examples of the indicators are reported in the s-LCA methodological sheets [10]. There are three forms of Social LCA data: quantitative, semi-quantitative (yes/no or rating scale responses) and qualitative (descriptive text) and generally these are collected through questionnaires.
5. Once the inventory is concluded, the social impacts can be evaluated by means of the Social Impact Assessment method. The performance of the sectors/companies are assessed, respectively based on the status of the indicators taking into account the performance of the sector/company in relation to the situation in the country or region;

The Social Life Cycle Impact Assessment is the final stage of a Social Life Cycle Assessment. It helps in quantifying the potential social impacts arising from the s-LCA inventory, and it can be performed by firstly doing a performance assessment (PA) and then, by performing an impact assessment (IA). In this study, we will only be doing the PA.

There are many forms of s-LCA data such as rating scales responses, quantitative semi-quantitative (yes/no) or qualitative data (descriptive text) and generally these are collected through s-LCA questionnaires. In order to draw conclusions more efficiently, we have to use one scale for all the indicators, so we rescaled and converted the existing ones to a scale of 1 (least good practice) to 5 (best practice). There are two options for the conversion so we use for every indicator the right equation.

Option 1: the lowest value (x_{min}) is the least good and the highest (x_{max}) is the best

$$y = \left(\frac{4}{(x_{max} - x_{min})}\right)x - \frac{(5x_{min} - x_{max})}{(x_{max} - x_{min})}$$

Option 2: the lowest value (x_{min}) is the best and the highest (x_{max}) is the least good

$$y = \left(\frac{-4}{(x_{max} - x_{min})}\right)x + \frac{5x_{max} - x_{min}}{(x_{max} - x_{min})}$$

[9] UNEP – SETAC – Life Cycle Initiative – Guidelines for Social Life Cycle Assessment of Products, United Nations Environment Programme, 2009

[10] UNEP – SETAC – Life Cycle Initiative – The methodological sheets for sub-categories in Social Life Cycle Assessment (S-LCA), United Nations Environment Programme and SETAC, 2013

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

3 LCA analysis for scenario 2.1

3.1 Goal and Scope

Goal and scope definition is one of the most important steps in any LCA/LCC 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 CSS2 is to evaluate the environmental impacts and costs of processing agricultural residue through the proposed CSS2 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 the impacts of this CSS solution with traditional waste management practices, such as landfilling and fossil fuel-based energy production.

1. **Intended application:**
   - Reduce the use of resources by optimizing waste management and resource recovery processes.
   - Minimize the amount of waste streams generated, focusing on efficient waste handling.
   - Increase recycling rates of the targeted waste streams for sustainable material recovery.
   - Achieve high valorisation of wastes, focusing on converting waste into valuable products.
   - Valorise marginal lands to improve land use and sustainability.
2. **Intended audience:**
   - Citizens, including biogas plant/facility owners, involved in waste-to-energy initiatives.
   - Owners of marginal lands (public or private), aiming to enhance land productivity and sustainability.
   - Farmers, particularly those interested in using byproducts as animal feed or other agricultural applications.
   - Policy makers focused on promoting sustainable waste management practices and climate-conscious policies.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

- Scientific and technical partners involved in environmental research, waste valorisation and industrial processes.
- Replication partners or stakeholders interested in scaling or adapting the technology.

3. Comparative assertions:

The impacts of CSS2 will be compared with current practices such as:

- The treatment of organic waste in the food industry through conventional waste management techniques.
- Current methods of using marginal lands, with the goal of improving land productivity through sustainable practices.

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 agricultural residue at a regional scale (Lodzkie). The scope will cover the collection, processing and valorisation of agricultural residue into biodegradable bio-lubricants, compostable bioplastics, bio-oils, animal feed, lignin compost and biomethane.

3.1.3 Functions of product system

The CSS2 system is designed to process agricultural residue and convert it into valuable by-products such as FFAs, effectively reducing the waste volume sent to landfills.

Functions of the product system include:

- **Fatty acid production (kg):** The system processes agricultural residue to produce fatty acids, which are used in the production of foams.
- **Vegetable oil production (kg):** The system converts agricultural residue into vegetable oils thanks to the valorisation of marginal lands, which are utilized in the manufacturing of lubricants.
- **Bioplastic production:** The system generates bioplastics from second-generation feedstocks (regional agro-industrial waste), which can be used for waste collection bags and other applications.

3.1.4 Functional Unit

The functional unit (FU) for this study is defined as the treatment of 1 ton of agricultural residue through the CSS2 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.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

3.1.5 System boundary

LCA is a complex process that involves several different 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 CSS2 approach to agricultural residue is developed into three scenarios. Outputs of these three scenarios could be considered are final products or intermediate resources for integration with other circular systematic solutions in the FRONTSH1P project.

Scenario 2.1 (CSS2_2.1 FFAs production): This scenario focuses on converting agricultural residue, specifically corn stover, into FFAs through a multi-stage process. The key stages include pre-treatment (steam explosion), washing, enzymatic hydrolysis, solid-liquid separation, fermentation, saponification, liquid extraction, acidification and a final extraction of FFAs using hexane. This process involves inputs like corn stover, water, enzymes and chemicals such as KOH, ethanol and HCl, while producing outputs such as pre-treated biomass, hydrolysates, wastewater and mainly FFAs.

3.1.6 Impact Assessment Method 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 Center of Environmental Science of Leiden University and was published in a guide to the ISO standards in 2001[11]. 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[12]. These indicators collectively provide insights into resource use, emissions and impacts on health and the environment across the assessed system's life cycle.

Table 3 Impact categories included in the method CML.

Method: CML	
Impact category group	**Name of the impact category in the method**

[11] 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

[12] 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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Acidification	AP - 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 Resource use indicators and Human toxicity, along with their subcategories (see Table 4**Error! Reference source not found.**).

Table 4 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) [m^3]
2. Human toxicity
Hazardous waste disposed (HWD) [kg]
Non-hazardous waste disposed (NHWD) [kg]

3.1.7 Assumptions and limitations

This study specifically excludes the collection and transportation of food and agricultural residues to the processing facilities from the system boundaries. This decision was made to narrow the focus of the analysis to the core conversion processes, including the production of FFAs, vegetable oils from marginal lands and compostable bioplastics. The environmental impacts related to logistics (e.g. transportation emissions and fuel consumption) are therefore not accounted for in this assessment. Future LCA updates could incorporate these factors to provide a more

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

holistic view of the CSS2 system's environmental footprint, particularly in terms of regional supply chain performance and distribution logistics.

3.1.8 Data quality

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 implemented in the CSS2 system, including agricultural residue pre-treatment, biotechnological conversion to FFAs, oil crop valorisation, and bioplastic synthesis. These data were derived from real process modelling, experimental activities, and demo-scale operations conducted by partners such as LNEG, CERTH and NVMT. As such, the data reflects the technologies in their current form and captures operational performance under project-specific conditions.

2. Consistency

The data used in this study is consistent with international standards and methodologies, notably the ISO 14040/44 guidelines for conducting LCA. Data was collected and processed using industry-standard software tools and harmonized with ILCD-compliant datasets. All modelling activities followed uniform procedures to ensure comparability across value chains and scenarios within CSS2.

3. Completeness

The data collected for the LCI and LCA analysis is comprehensive within the defined system boundaries. All major inputs and outputs related to the core processing stages, including raw materials, energy consumption, emissions and coproduct flows. However, as noted above, the exclusion of upstream waste collection and transportation limits the completeness of the environmental picture, particularly for scenarios involving distributed supply networks.

4. Representativeness

The data used in this study is representative of the CSS2 systems as deployed in the project's pilot and demo environments. The data captures performance over the operational period of the facilities and reflects the specific configurations tested. Nevertheless, since industrial upscaling is assumed in the modelling, certain assumptions about process efficiencies and product yields may not fully reflect future full-scale deployments.

5. Location specificity

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

The study acknowledges that the data used in the LCA analysis reflects the operational contexts of partner facilities located in various European regions, including Greece, Italy, Portugal and Poland. To ensure regional relevance, Polish (PL) and European (RER) datasets were used in the Sphera model for background systems such as energy, water and fuels.

3.2 Life Cycle Inventory Analysis of the current study

1. CSS2-S2.1 FFAs production

Description of Scenario 1

The main goal of Scenario 2.1 is to transform corn stover into FFAs. This process occurs through 3 main stages which are 1) Pretreatment and Enzymatic hydrolysis, 2) Fermentation and 3) Saponification.

Main stages included in the scenario

The system of converting agricultural residue into FFAs involves three main stages, which are described as follows:

Stage 1: Pre-treatment and Enzymatic hydrolysis

The first stage involves pre-treating the corn stover using a steam explosion. To obtain the cleanest biomass, the pretreated corn stover is washed with an equal amount of water. Corn stover is the main input at this stage, with steam and electricity aiding the steam explosion process. After water washing, the outputs of this process are the pretreated biomass and wastewater. During enzymatic hydrolysis, enzymes are added to convert the biomass into hydrolysate.

Stage 2: Fermentation

Afterwards, the hydrolysate, which is now a sugar solution, is separated from the solid part of the pretreated biomass. During the fermentation process, yeast cells produce microbial lipids from corn stover (CS) hydrolysates. Various supplements are added to the fermentation medium.

Stage 3: Saponification

In this stage, ethanol and potassium hydroxide (KOH) are used to convert the saponifiable lipids (essentially triacylglycerols) into their soap form. The liquid extraction step is used to separate the saponifiable from the unsaponifiable fraction. After that, hydrochloric acid (HCl) is added to the saponifiable fraction to promote the FFA production from the soaps, finally extracting the desired FFAs using hexane.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

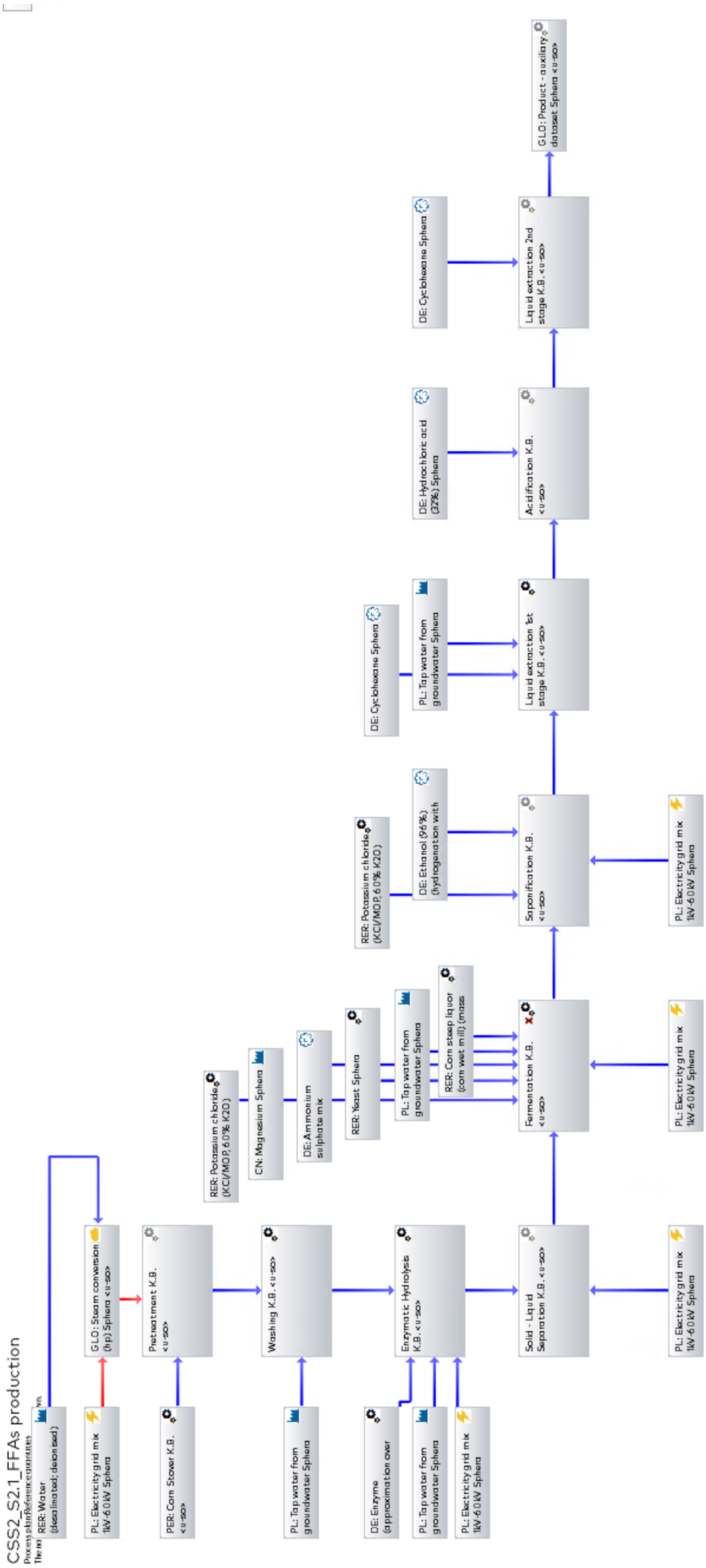


Figure 7 Flowsheet of the CSS2-S2.1 FFAs production.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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 measured in kilograms of antimony equivalent (kg Sb eq.), with antimony (Sb) being used as the benchmark element to indicate total abiotic resource depletion.

As illustrated in Figure 8, the ADP for Scenario 1 is significantly higher than that of the Baseline, reaching approximately 8.19×10^{-6} kg Sb eq., compared to just 1.62×10^{-6} kg Sb eq. in the Baseline. This corresponds to a fourfold increase in abiotic resource consumption. The elevated impact in Scenario 1 is mainly driven by the intensive use of chemicals such as ethanol, hexane and potassium hydroxide, as well as high electricity consumption during enzymatic hydrolysis and freeze drying. Figure 9 shows that the most impactful processes contributing to ADP are lyophilization, saponification, and liquid extraction, which collectively account for the majority of the total burden. In contrast, the Baseline scenario, landfilling without resource recovery, exhibits minimal impact due to the absence of such processing inputs. Although Scenario 1 supports circularity through the valorisation of agricultural residue into high-value FFAs, the results indicate a trade-off with greater depletion of non-renewable mineral resources, highlighting the need for process optimisation and substitution of critical inputs.

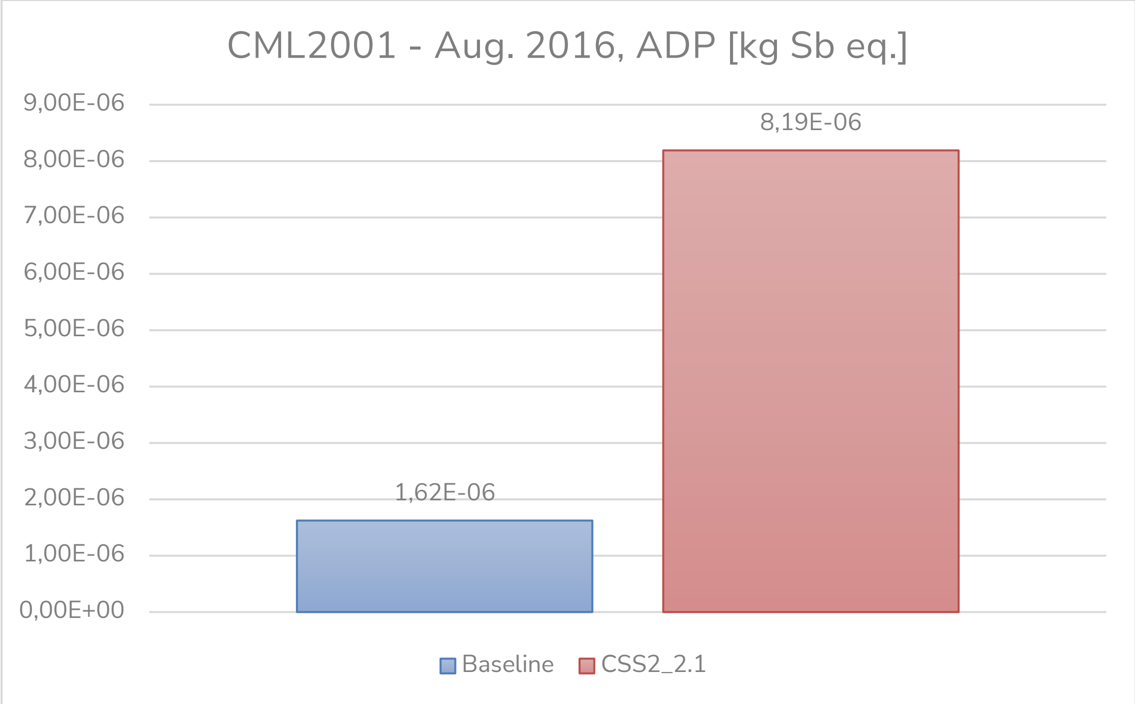


Figure 8 ADP [kg Sb eq.] for each scenario.

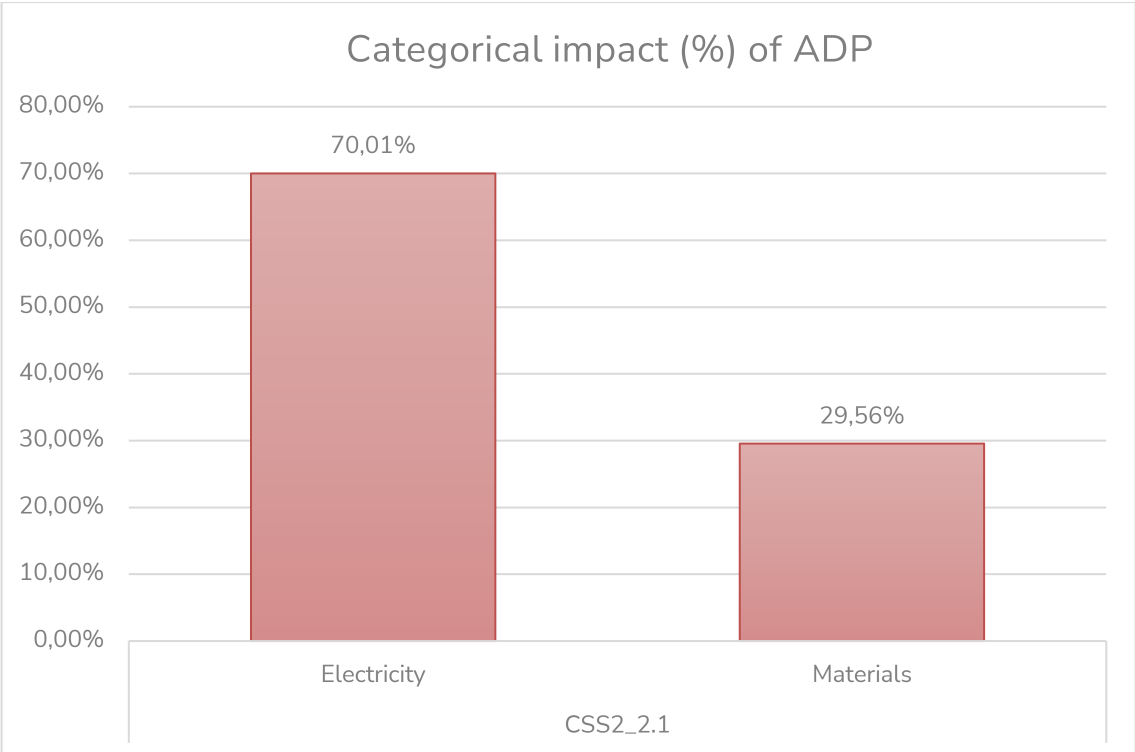


Figure 9 Categorical impact of ADP for each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

3.3.2 Abiotic Depletion - Fossil

The consumption of non-renewable fossil fuels is measured by the ADP 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.

As shown in Figure 10, the ADP-fossil in Scenario 1 is substantially higher than that of the Baseline, reaching approximately 1.23×10^3 MJ, compared to 4.52×10^2 MJ in the Baseline. The increased impact is mainly attributed to the high electricity demand of several processing steps, including enzymatic hydrolysis, freeze drying, and chemical synthesis, all of which rely heavily on fossil-based energy inputs. Additionally, in Figure 11, the upstream production of solvents such as ethanol and hexane further contributes to fossil fuel depletion. In contrast, the Baseline scenario, which is based on landfilling, involves minimal energy input and therefore a lower fossil resource burden. These results underscore the importance of integrating renewable energy sources and improving process efficiency to mitigate fossil fuel dependency in future implementations of CSS2.

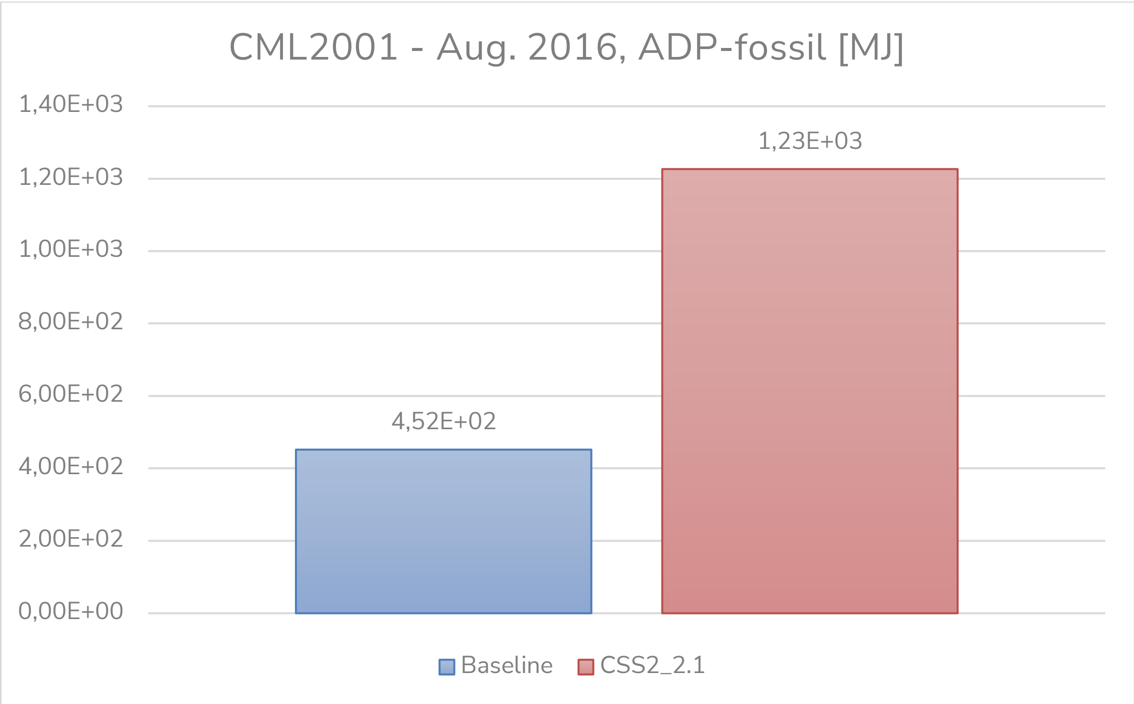


Figure 10 ADP [MJ] impact for each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

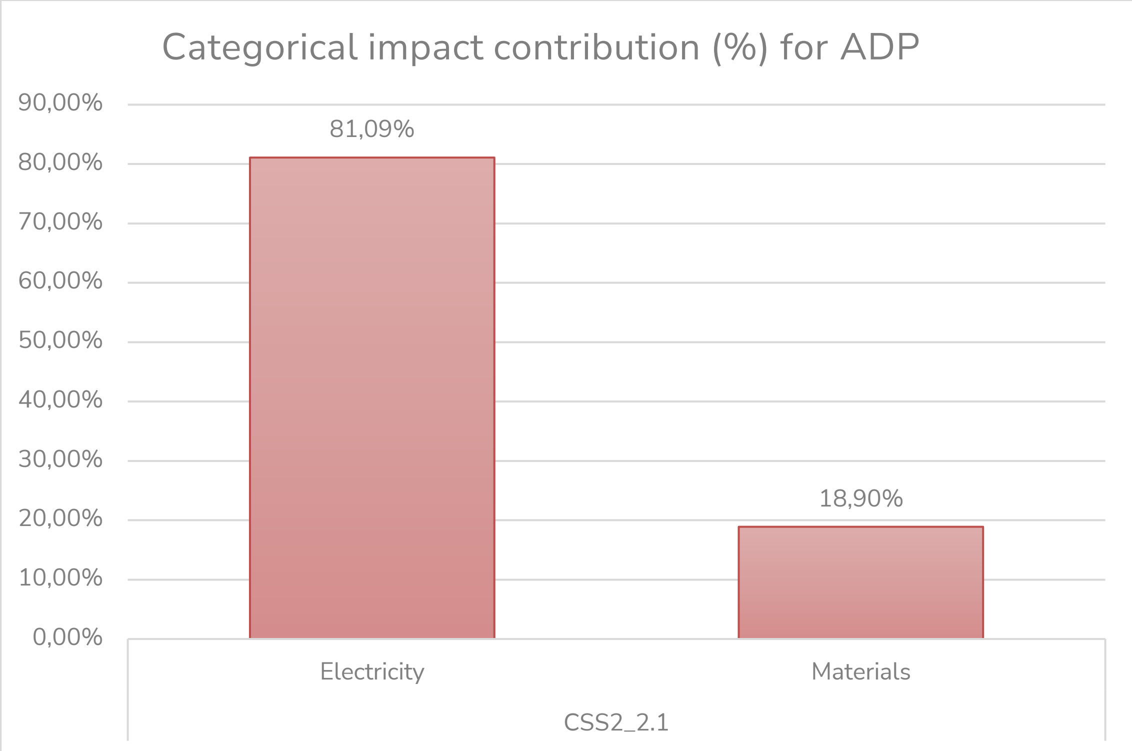


Figure 11 Categorical impact contribution (%) for ADP of each scenario.

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 Acidification Potential (AP), which is expressed in terms of kilograms of SO_2-equivalents.

As illustrated in Figure 12, the AP for Scenario 1 is slightly lower than that of the Baseline, with values of 1.61×10^{-1} kg SO_2 eq. and 1.63×10^{-1} kg SO_2 eq., respectively. In Figure 13, the lower impact in Scenario 1 is likely due to the absence of uncontrolled leachate emissions and better containment of acidifying substances such as ammonia and sulphur oxides, which are typically released during landfilling operations. Although Scenario 1 includes multiple stages involving chemical inputs and energy consumption, the system design allows for greater emission control,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

resulting in a net benefit in this category. These results indicate that the transition to a controlled, closed-loop valorisation process may contribute to reduced acidification impacts compared to traditional waste disposal methods.

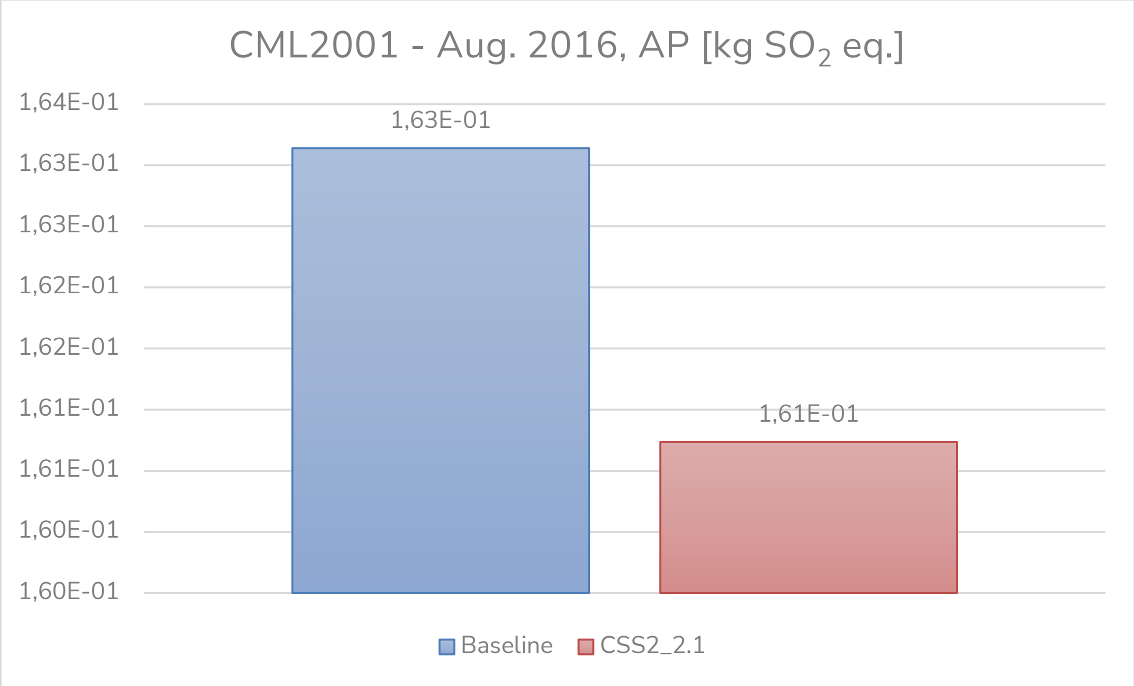


Figure 12 AP [kg SO_2 eq.] impact for each scenario.

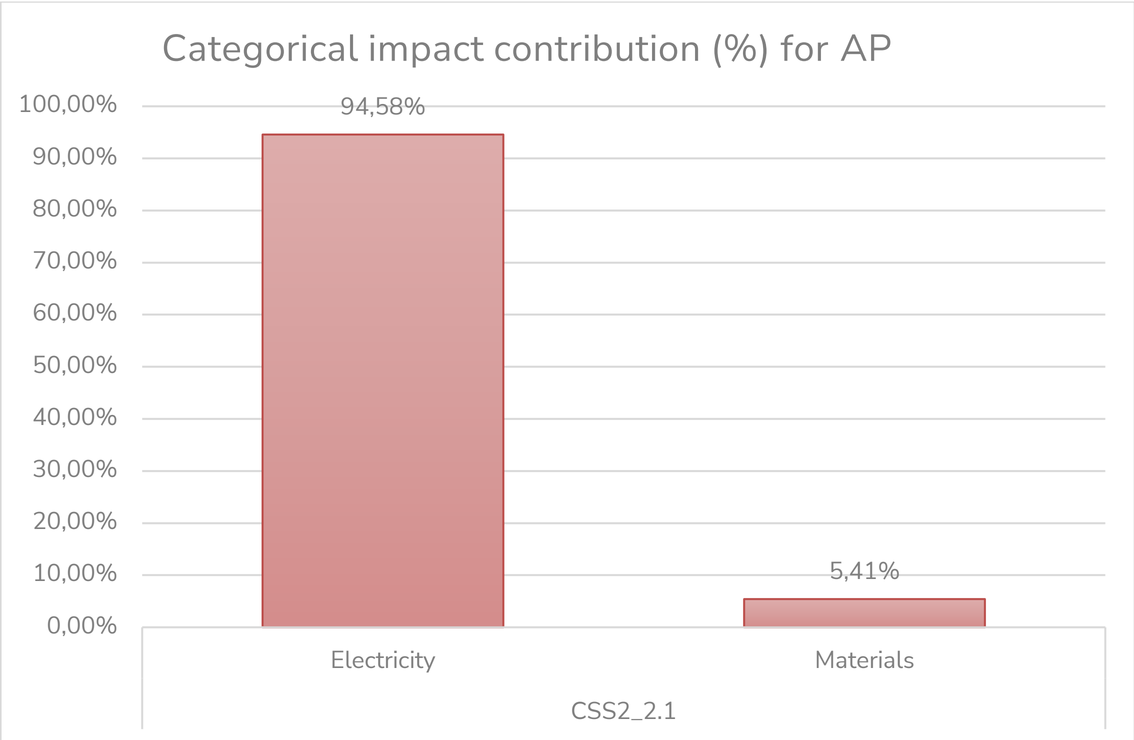


Figure 13 Categorical impact contribution (%) for AP of each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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_x) and oxygen (O_2) equivalents can also serve as interchangeable metrics.

As shown in Figure 14, the EP for Scenario 1 is significantly lower than that of the Baseline, with values of 1.95×10^{-2} kg PO_4 eq. and 8.09×10^{-1} kg PO_4 eq., respectively. The substantial improvement in Scenario 1 is mainly due to the elimination of nutrient leaching and runoff emissions associated with the landfilling of organic waste. In the Baseline scenario, the degradation of agricultural residue in anaerobic conditions leads to the release of nitrogen and phosphorus compounds, which contribute heavily to eutrophication. In contrast, the controlled conversion of waste into FFAs in Scenario 1 prevents uncontrolled discharges and significantly limits nutrient emissions. These results confirm the effectiveness of biochemical valorisation strategies in mitigating eutrophication impacts.

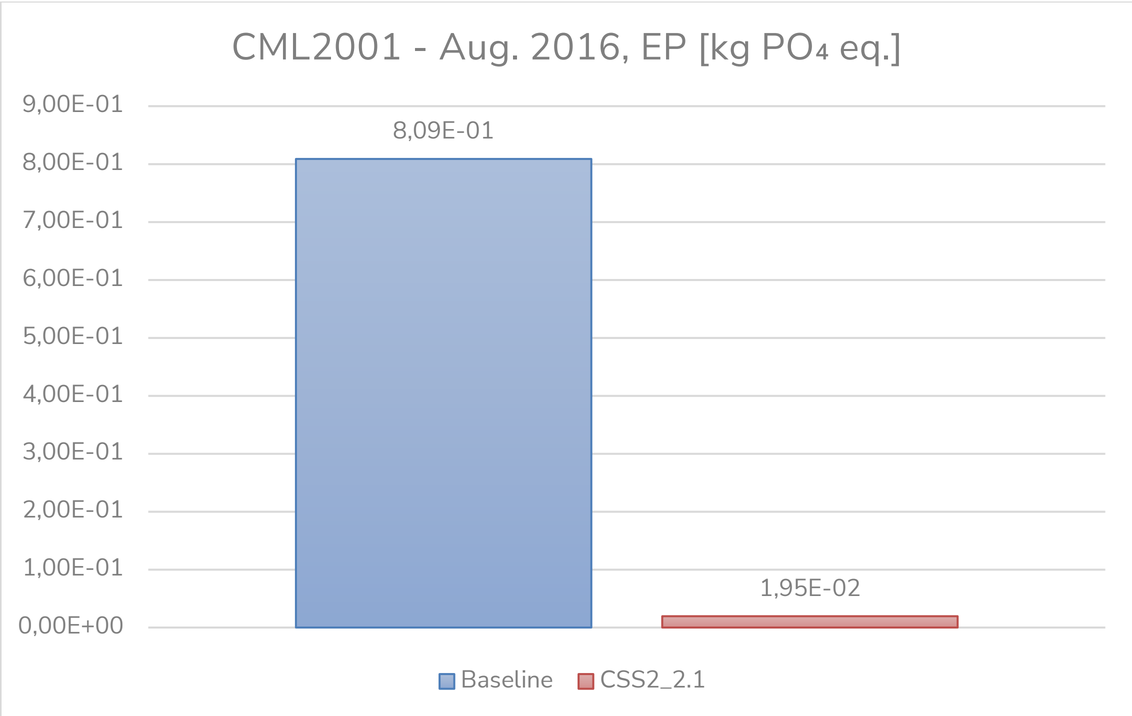


Figure 14 EP [kg PO_4 eq.] impact for each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

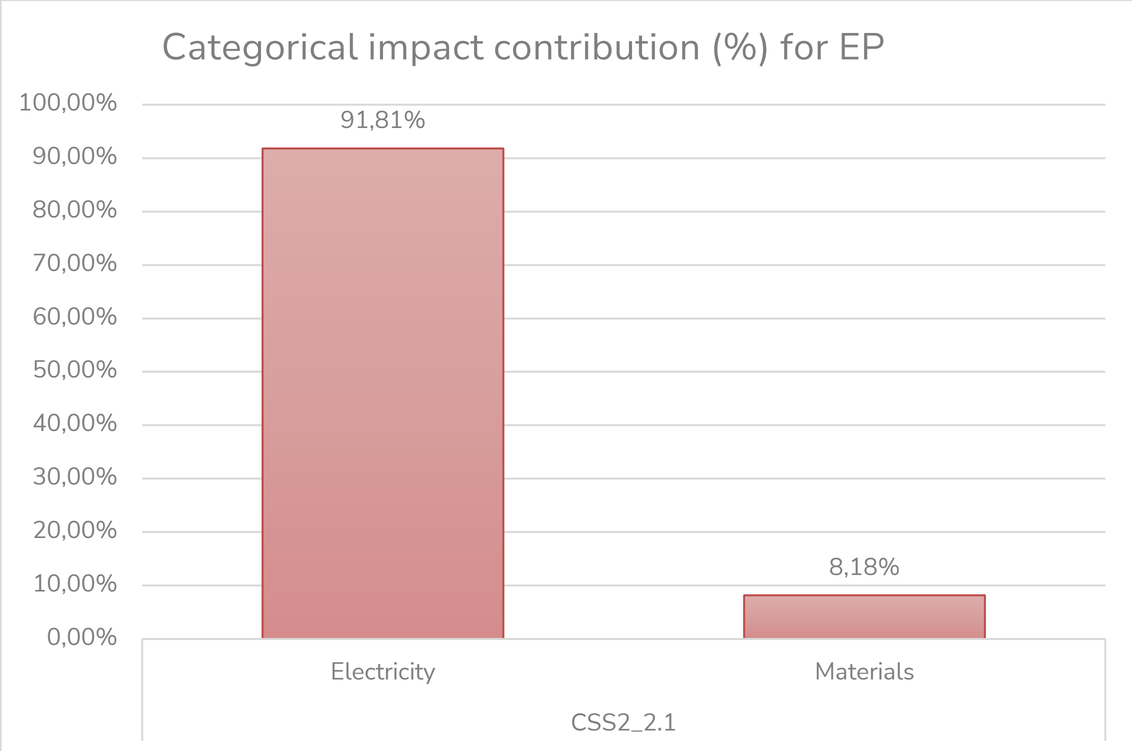


Figure 15 Categorical impact contribution (%) for EP of each scenario.

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.

As presented in Figure 16, the FAETP for Scenario 1 is considerably lower than that of the Baseline, with values of 1.72×10^{-1} kg DCB eq. and 4.87×10^{-1} kg DCB eq., respectively. The significant decrease is primarily due to the avoidance of uncontrolled emissions into water bodies that occur during landfilling, such as leachates containing heavy metals or persistent organic pollutants. In Scenario 1, while several process chemicals are used, their emissions are managed within a closed and contained production environment, limiting their release to freshwater

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

systems. The results indicate that the controlled processing of organic waste into FFAs can lead to substantial improvements in the ecotoxicological profile of the system.

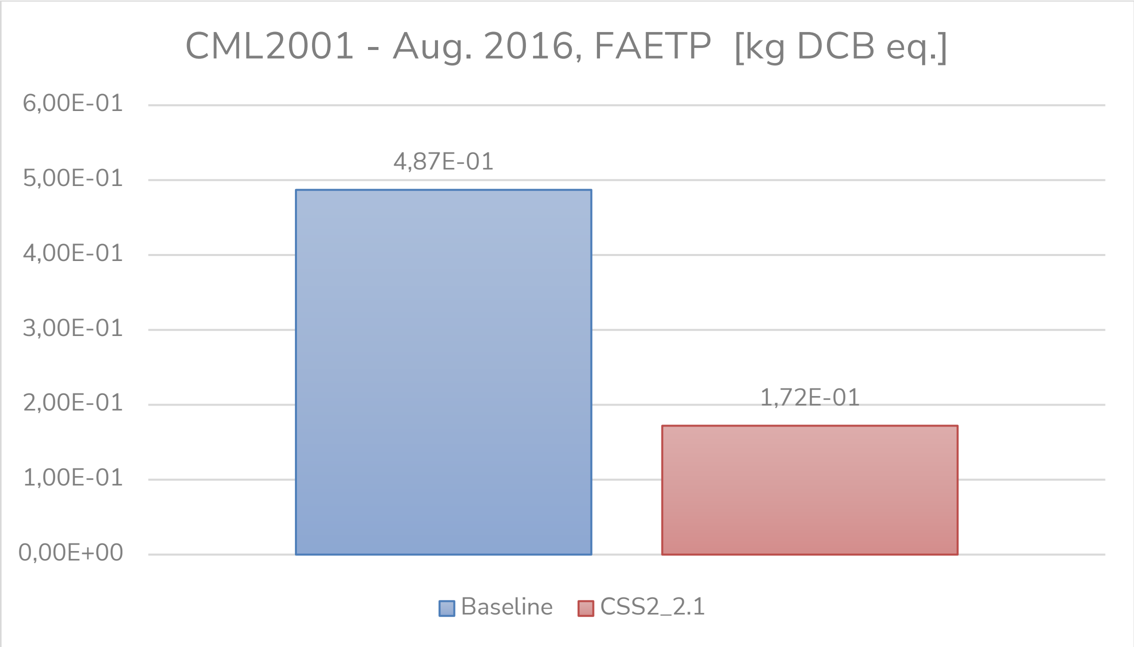


Figure 16 FAETP. [kg DCB eq.] impact for each scenario.

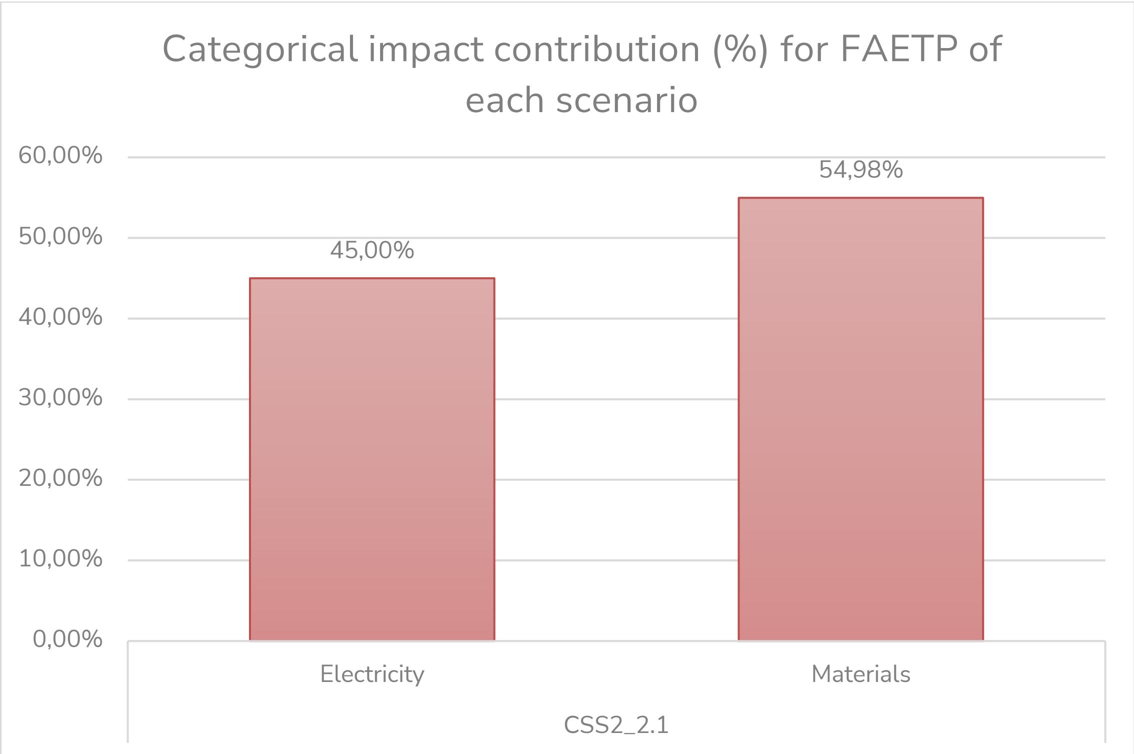


Figure 17 Categorical impact contribution (%) for FAETP of each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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. GWP used for these purposes.

As illustrated in Figure 18, the GWP for Scenario 1 is significantly lower than that of the Baseline, with values of 1.12×10^2 kg CO_2 eq. and 6.75×10^2 kg CO_2 eq., respectively. Based on the Figure 19, the substantial benefit in Scenario 1 is largely attributed to the avoidance of methane emissions from agricultural residue decomposition in landfills, which is a major contributor to GWP in the Baseline scenario. Instead, the valorisation pathway diverts agricultural residue to a controlled production process, where emissions are primarily linked to electricity and chemical inputs, which have a lower global warming. These findings highlight the climate change mitigation potential of converting agricultural residue into high-value products through circular bioeconomy approaches.

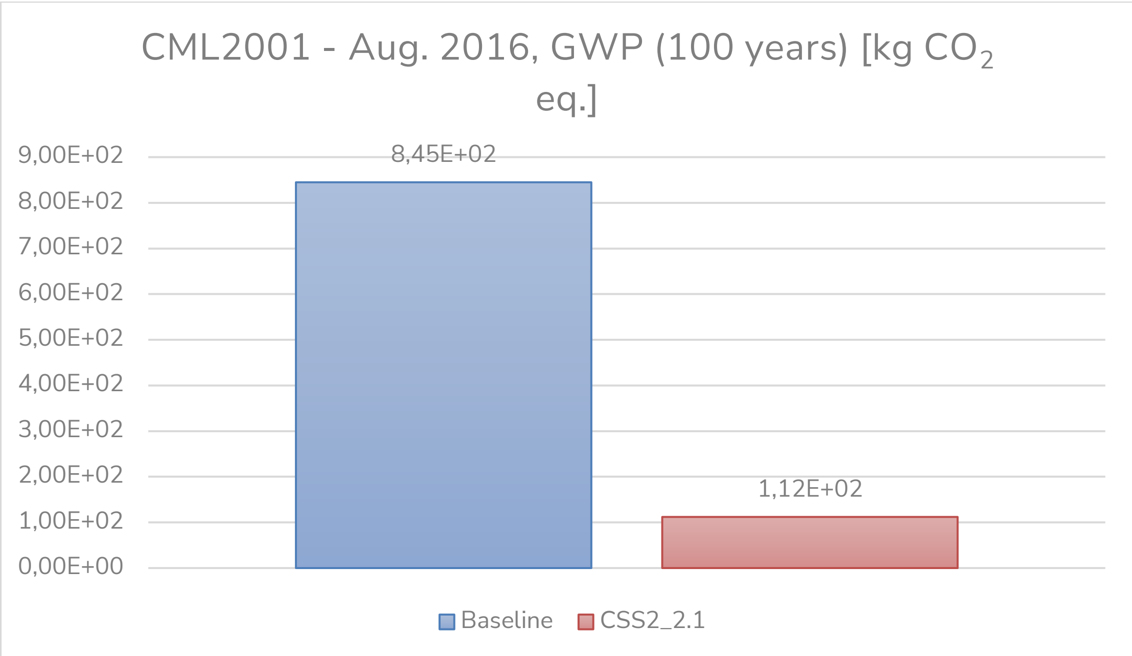


Figure 18 GWP [kg CO_2 eq.] impacts for each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

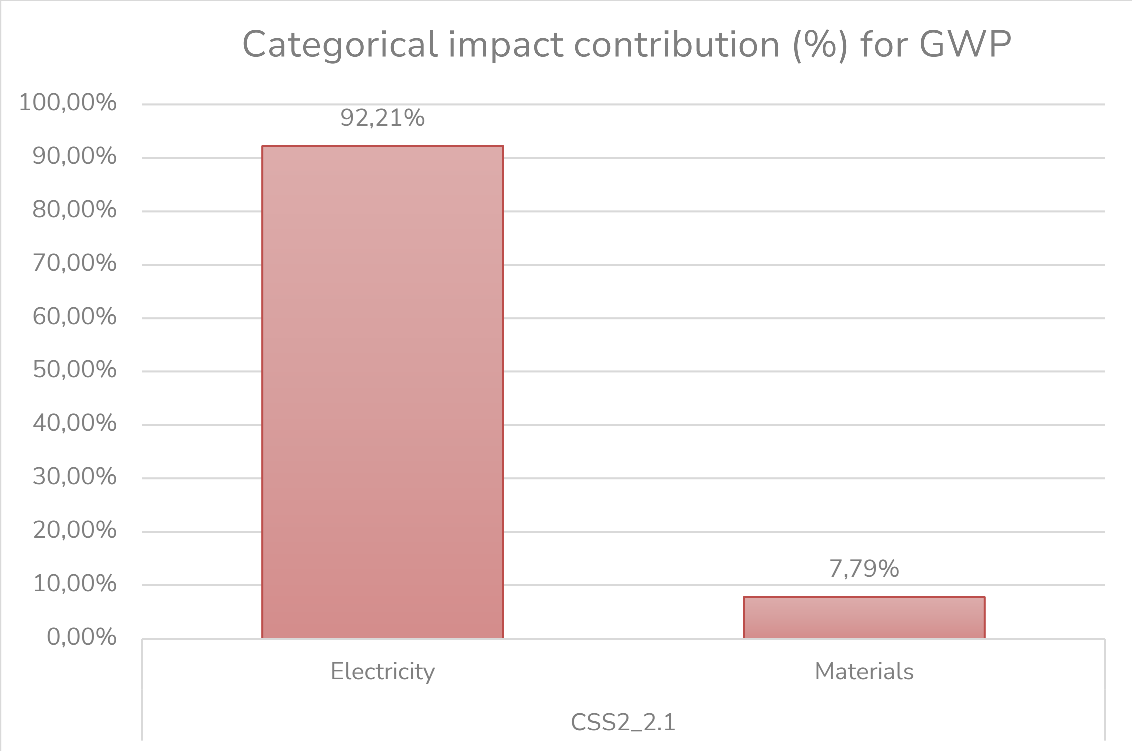


Figure 19 Categorical impact contribution (%) for GWP of each scenario.

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.

As shown in Figure 20, the HTP for Scenario 1 is slightly higher than that of the Baseline, with values of 3.30 kg DCB eq. and 2.93 kg DCB eq., respectively. This corresponds to an increase of approximately 11%. The higher impact in Scenario 1 is mainly associated with the production and use of chemical solvents such as ethanol, hexane, and potassium hydroxide, which contribute to human toxicity through upstream emissions during manufacturing and potential exposure risks during processing. While the Baseline scenario involves fewer industrial chemicals, the landfill pathway still generates toxic substances, though at a lower overall level in this category. These results suggest that further improvements in chemical substitution or process design could help reduce the human toxicity burden of circular valorisation systems.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

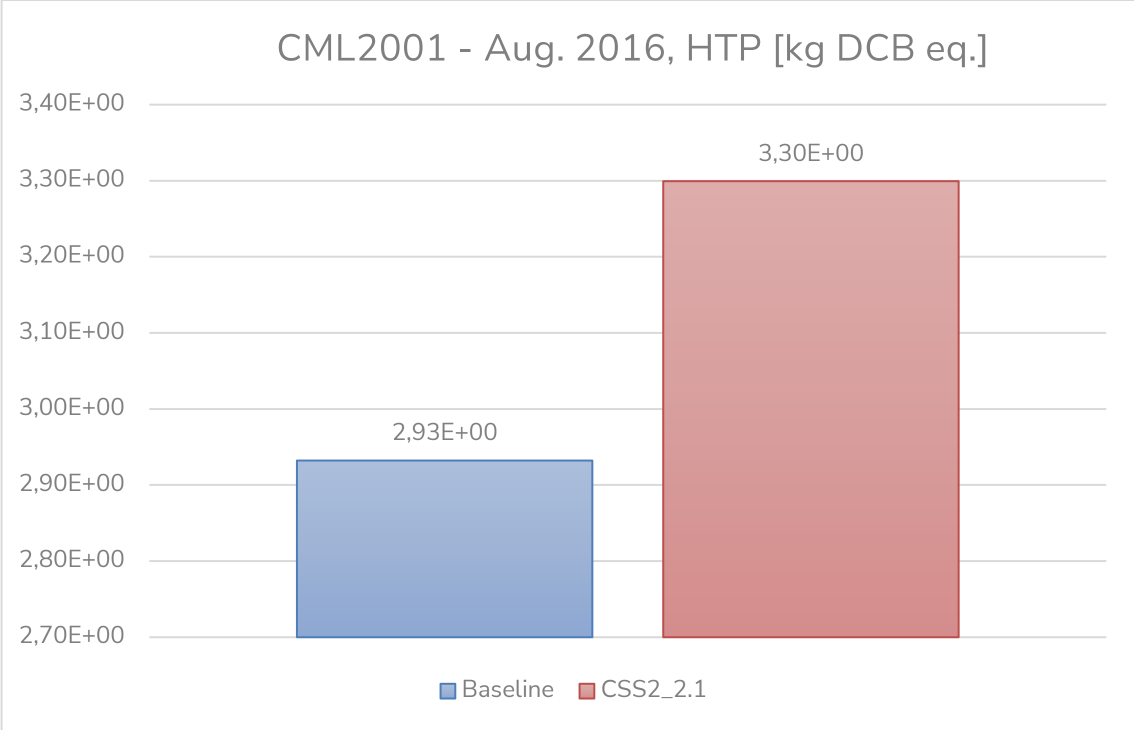


Figure 20 HTP [kg DCB eq.] impact for each scenario.

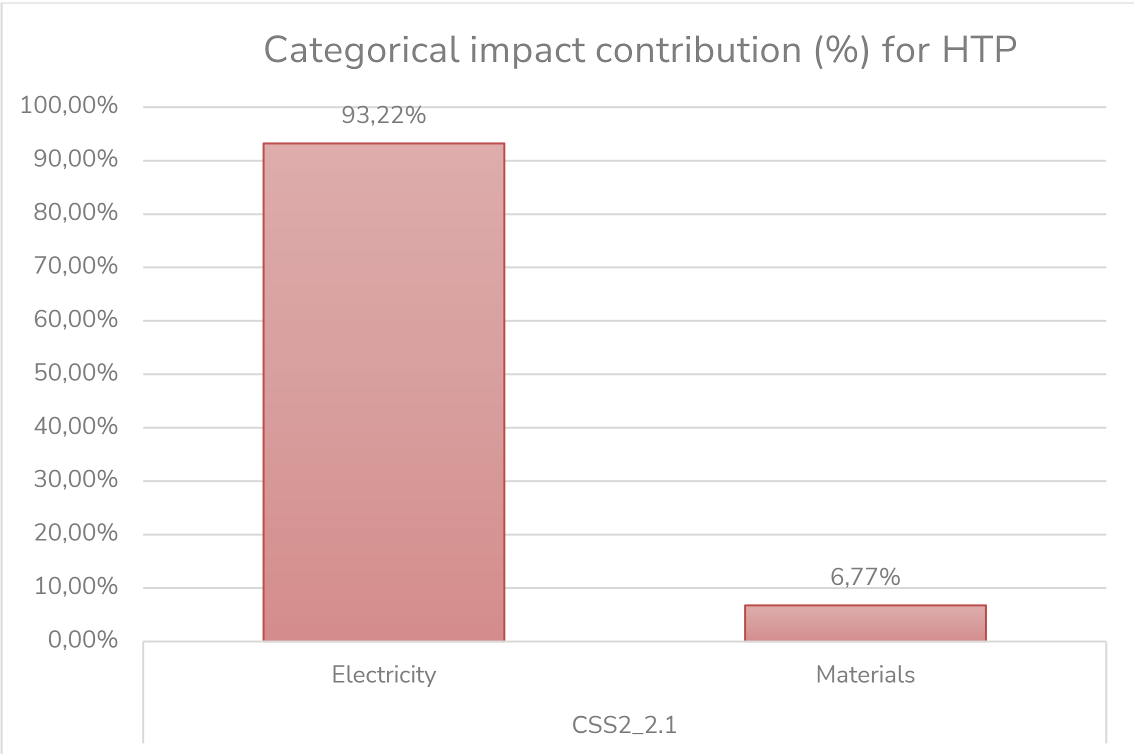


Figure 21 Categorical impact contribution (%) for HTP of each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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.

As illustrated in Figure 22, the Ozone Layer Depletion Potential (ODP) for Scenario 1 is 5.48×10^{-10} kg R11 eq., while the Baseline scenario shows a slightly negative value of -5.28×10^{-10} kg R11 eq. This indicates a net increase in ozone-depleting emissions in Scenario 1, although both values remain extremely low in absolute terms. The result for Scenario 1 is likely linked to the upstream production of certain process inputs, such as solvents or cooling agents, that may involve substances with trace ozone-depleting potentials. Despite the increase, the overall magnitude of the impact remains negligible, suggesting that ozone depletion is not a key differentiator between the two scenarios in this study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

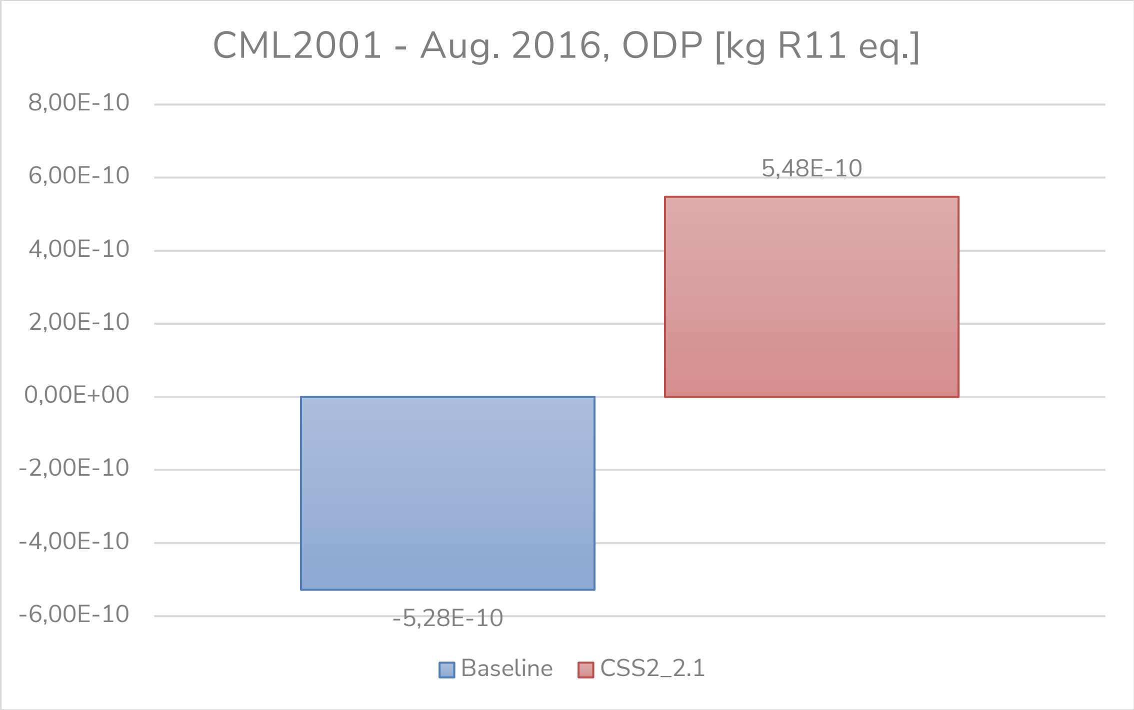


Figure 22 ODP [kg R11 eq.] impact for each scenario.

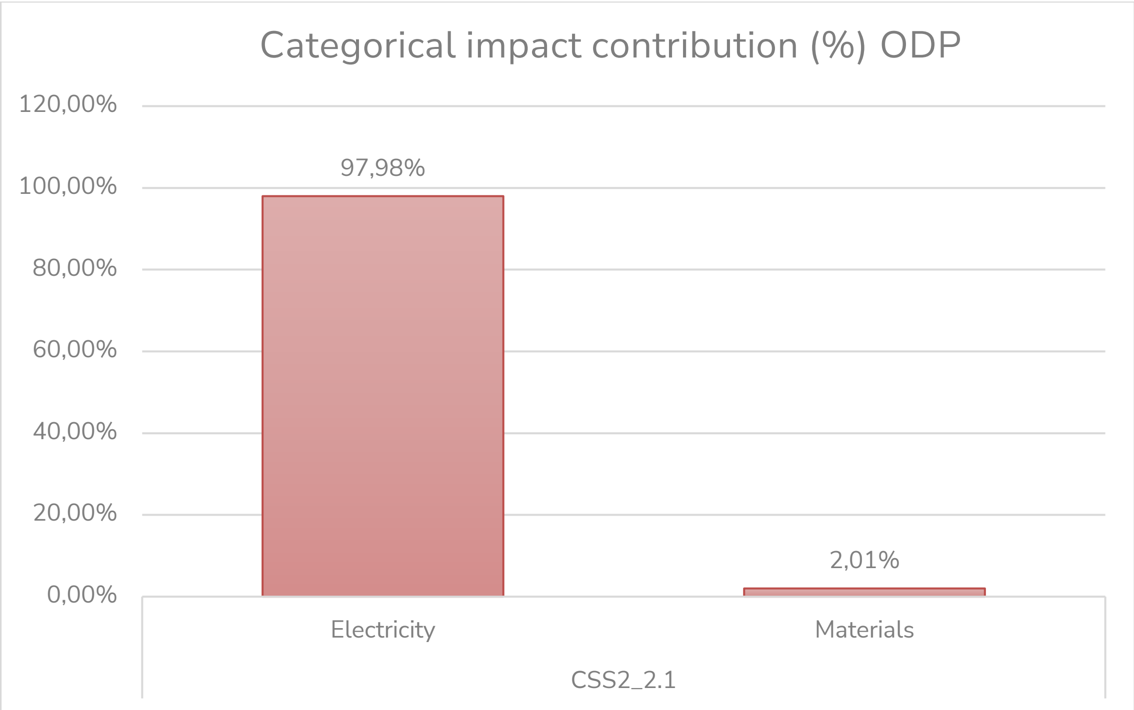


Figure 23 Categorical impact contribution (%) for ODP of each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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.

As presented in Figure 24, the POCP for Scenario 1 is 1.25×10^{-2} kg C_2H_4 eq., which is significantly lower than the Baseline value of 1.96×10^{-1} kg C_2H_4 eq. This corresponds to a reduction of approximately 93.6%. The substantial difference is primarily due to the avoidance of volatile organic compound (VOC) and NO_x emissions typically associated with landfill gas formation in the Baseline scenario. In contrast, the controlled processing environment in Scenario 1 minimizes the formation of photochemical smog precursors. These results confirm that biochemical valorisation pathways can strongly reduce impacts related to ground-level ozone formation and urban air quality degradation.

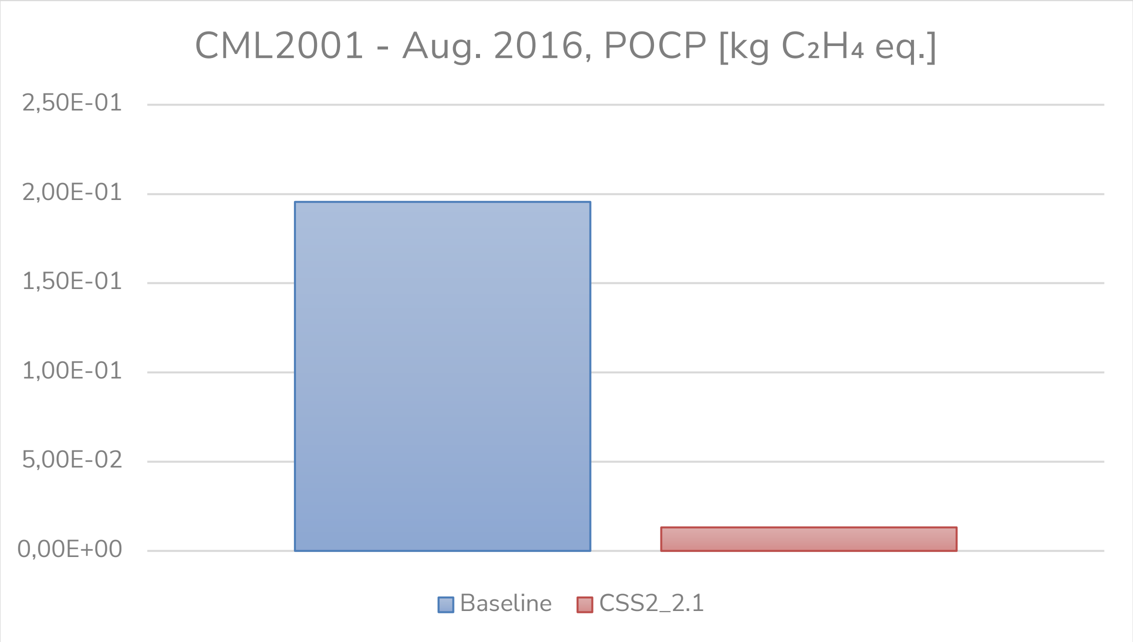


Figure 24 POCP [kg Ethene eq.] for each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

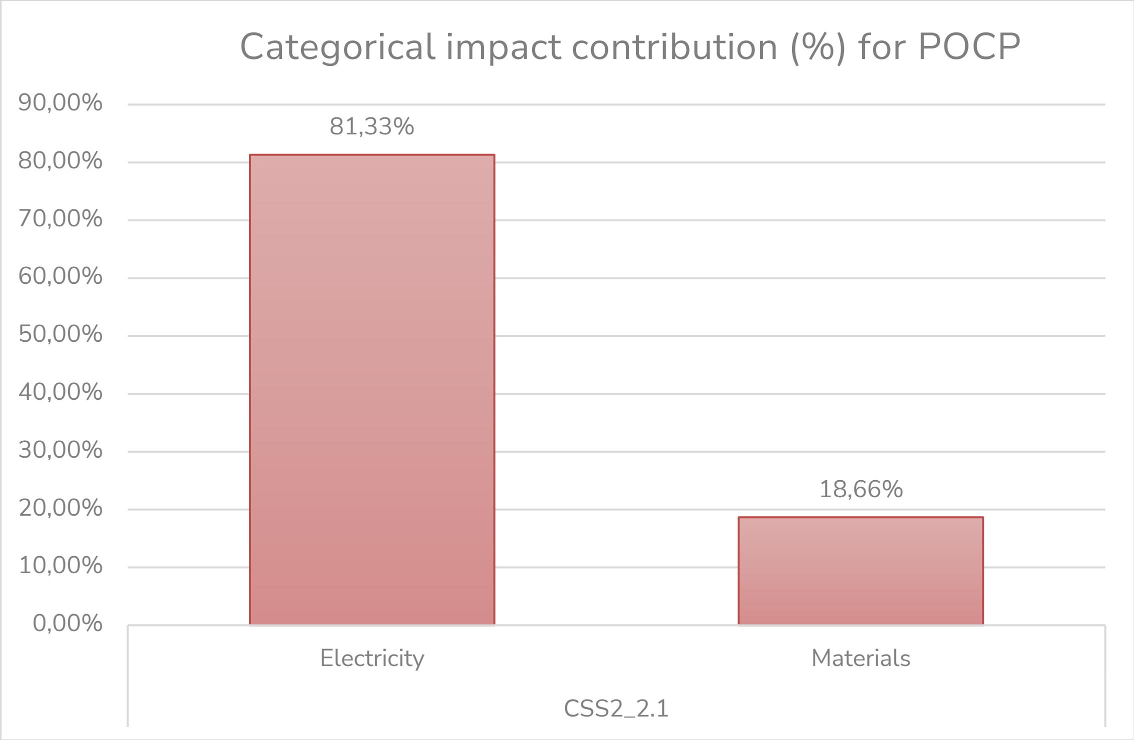


Figure 25 Categorical impact contribution (%) for POCP of each scenario.

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- DCB eq. kg are typically used as the unit of measurement for TETP.

As shown in Figure 26, the TETP for Scenario 1 is 8.02×10^{-2} kg DCB eq., while the Baseline records a substantially higher value of 8.51×10^{-1} kg DCB eq. This represents an 89% reduction in ecotoxicity impact to terrestrial environments. The elevated burden in the Baseline is primarily linked to leachate emissions from landfilling, which may contain heavy metals and persistent organic pollutants that affect soil quality. Scenario 1, on the other hand, benefits from a closed-loop processing system with reduced direct emissions to land, despite the use of chemical inputs. These results highlight the potential of valorisation systems to significantly mitigate toxic impacts on soil ecosystems when compared to traditional landfill disposal.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

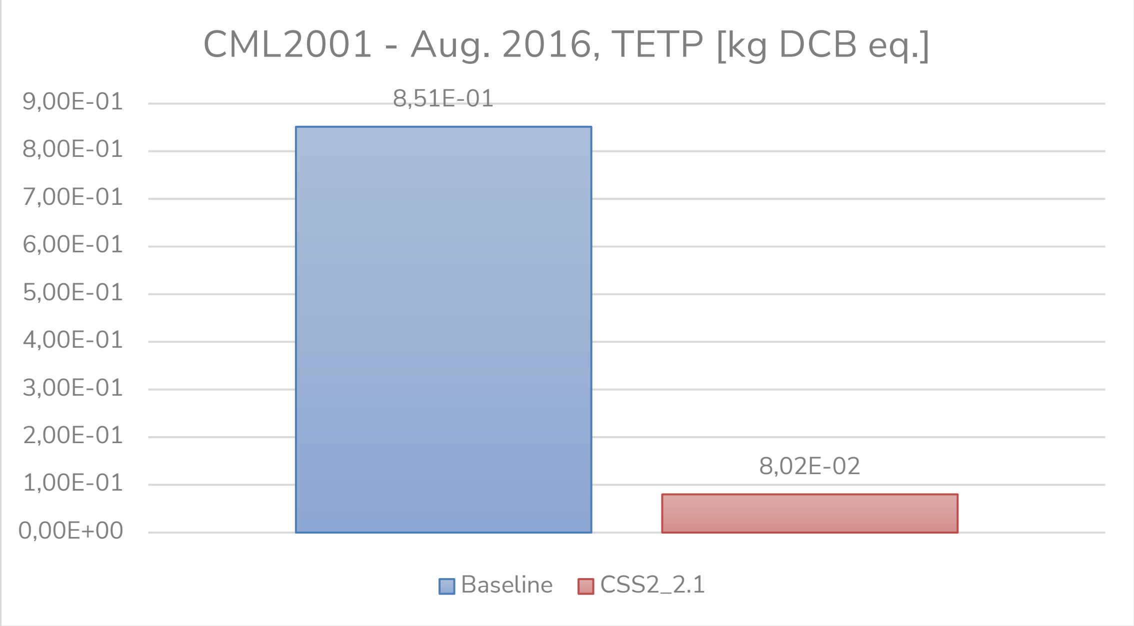


Figure 26 TETP [kg DCB eq.] for each scenario.

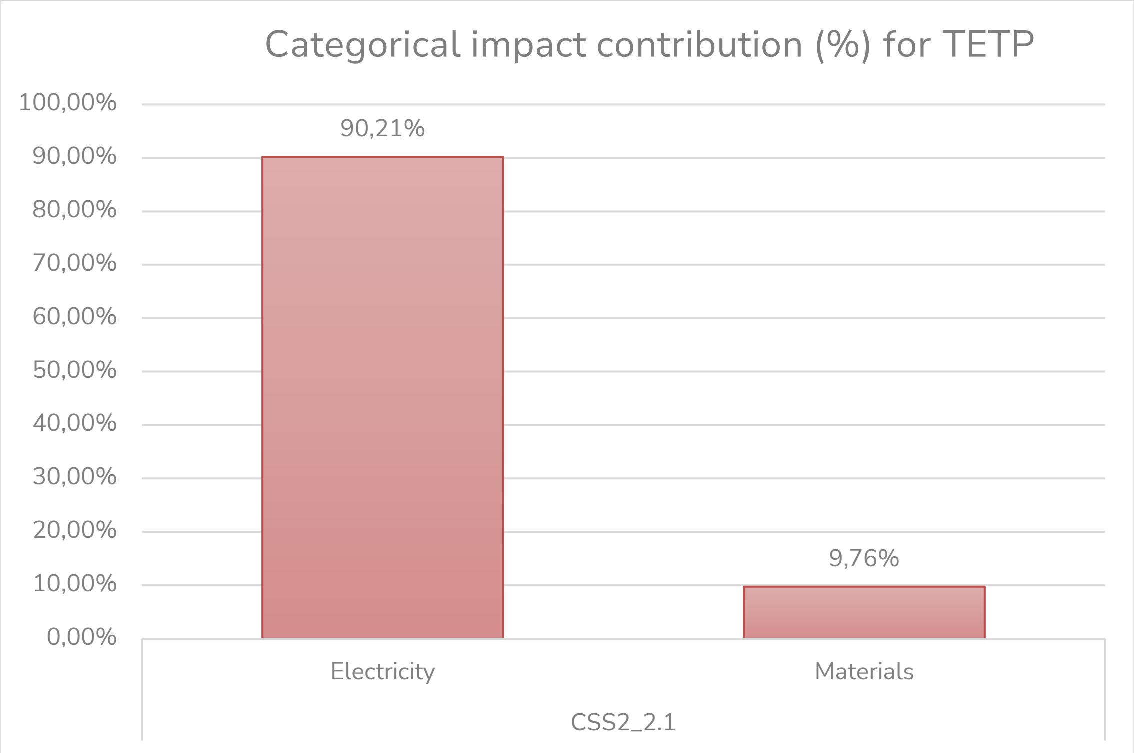


Figure 27 Categorical impact contribution (%) for TETP of each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

3.4 EN15804+A2

3.4.1 Resource use indicators

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.

As shown in Figure 28, the amount of HWD in Scenario 1 is 7.00×10^{-7} kg, whereas the Baseline scenario yields a slightly negative value of $–6.00 \times 10^{-7}$ kg, likely due to system credits from avoided burdens. Although the absolute values are very low, this represents a net increase in hazardous waste generation in Scenario 1, primarily due to chemical usage and upstream impacts from material processing. While not a dominant factor, this result suggests further attention should be given to hazardous waste minimisation in future process optimisation.

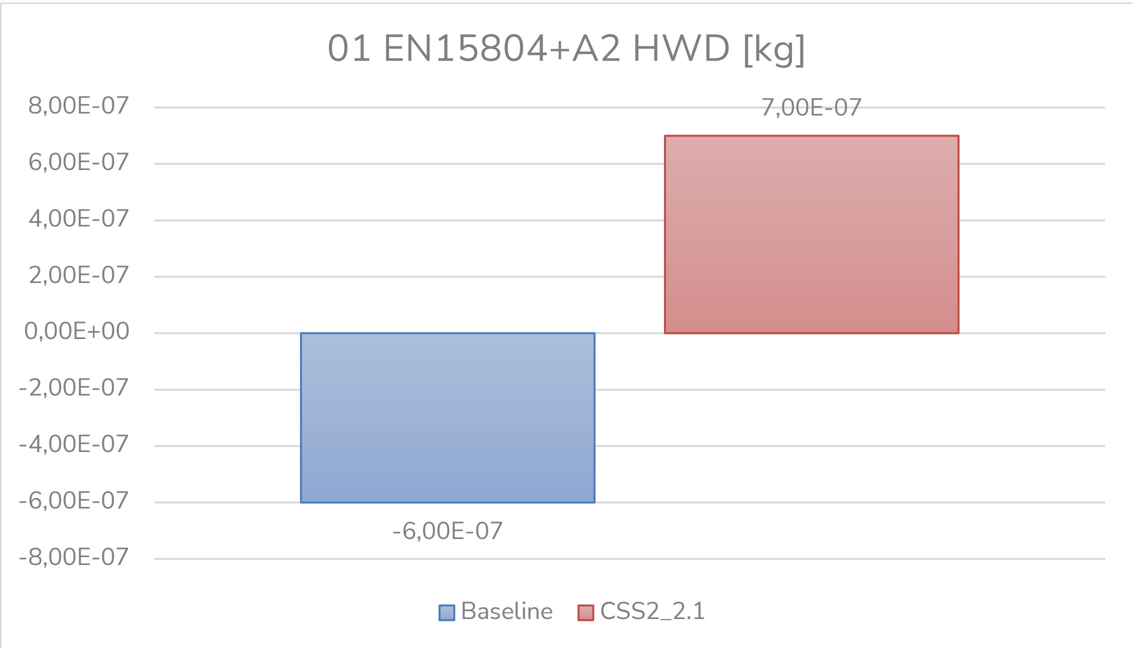


Figure 28 HWD [kg] for each scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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. As illustrated in Figure 29, non-hazardous waste disposal in Scenario 1 is 6.55×10^{-1} kg, compared to a substantially higher value of 8.08×10^{2} kg in the Baseline. This corresponds to a reduction of over 99.9%, demonstrating a major environmental benefit. The drastic difference is due to the avoidance of landfilling, which dominates the non-hazardous waste profile in the Baseline, while Scenario 1 redirects agricultural residue into productive valorisation pathways with minimal residuals. This result clearly supports the waste minimization goals of circular economy principles.

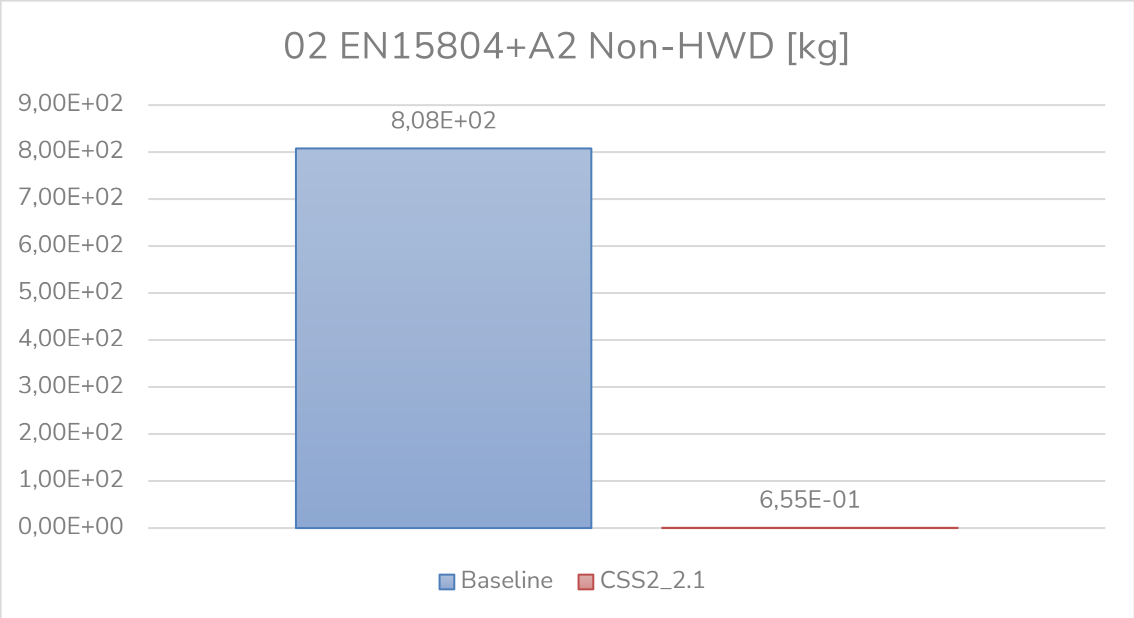


Figure 29 Non- HWD [kg] for each scenario.

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 (m^3), providing a quantifiable indicator of freshwater use.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Figure 30 shows that net freshwater use in Scenario 1 is 3.00 × 10^{-1} m^3, while the Baseline exhibits a negative value of –1.69 × 10^{-1} m^3, likely reflecting credit from avoided water-intensive activities. This indicates a net increase in freshwater demand in Scenario 1, primarily due to water consumption in cleaning, hydrolysis, and extraction processes. Despite other environmental benefits, this result points to a water-use trade-off in the valorisation process, highlighting the need for water recycling and optimisation strategies in future system designs.

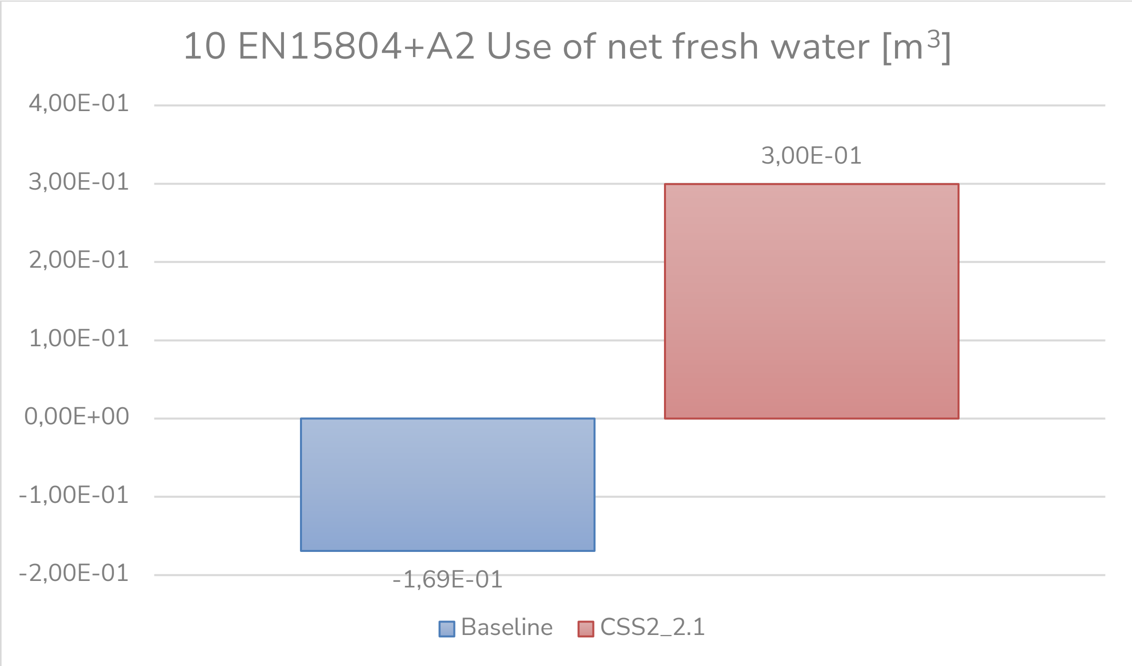


Figure 30 Use of net fresh water [m^3].

4 LCC methodology for scenario 2.1

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 CSS2 technology in respect with the sustainable management of agricultural residue. All necessary data to investigate and evaluate the life cycle cost of FRONTSH1P technologies are collected in close collaboration with NVMT. 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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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 31 and corresponded to initial capital expenditure (CAPEX) as well as recurring costs i.e. operation and maintenance expenditure (OPEX).

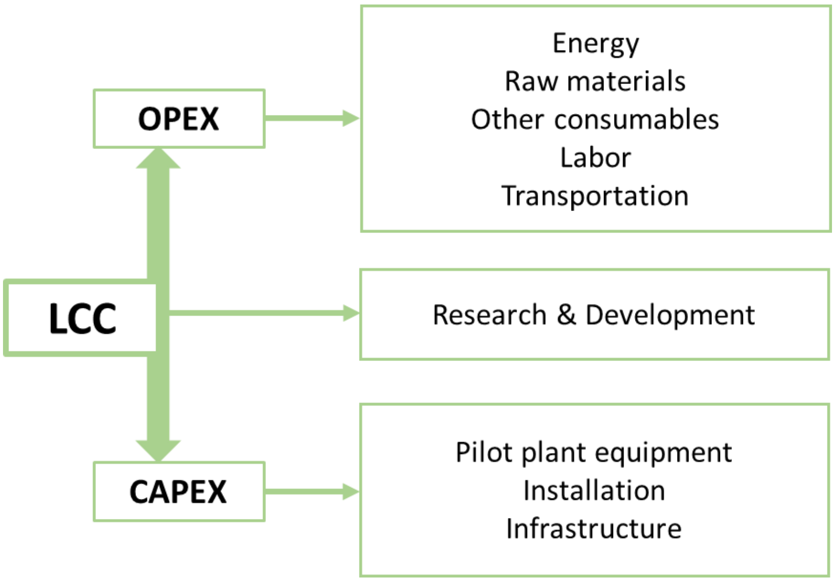


Figure 31 Life Cycle Cost distribution.

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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

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:

Climate change externalities [€] = Total impacts [kg CO_2 eq.] · f [€/ (kg CO_2 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 CSS2 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 2 LCC inventory of Baseline.

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

Table 3 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
1.7	OPEX	Materials	5,024,250	hexane

4.3 Life Cycle Interpretation: Results and discussion

A total of 3,500,000 tonnes of agricultural residue was subjected to landfilling (Baseline) or FFAs production (Scenario 1). The results are presented in the following figure. Based on the costing graph of each scenario, the Baseline exhibits the lowest LCC result (912,262,350 €), followed by Scenario 1 with an increase (817,091,608 €)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

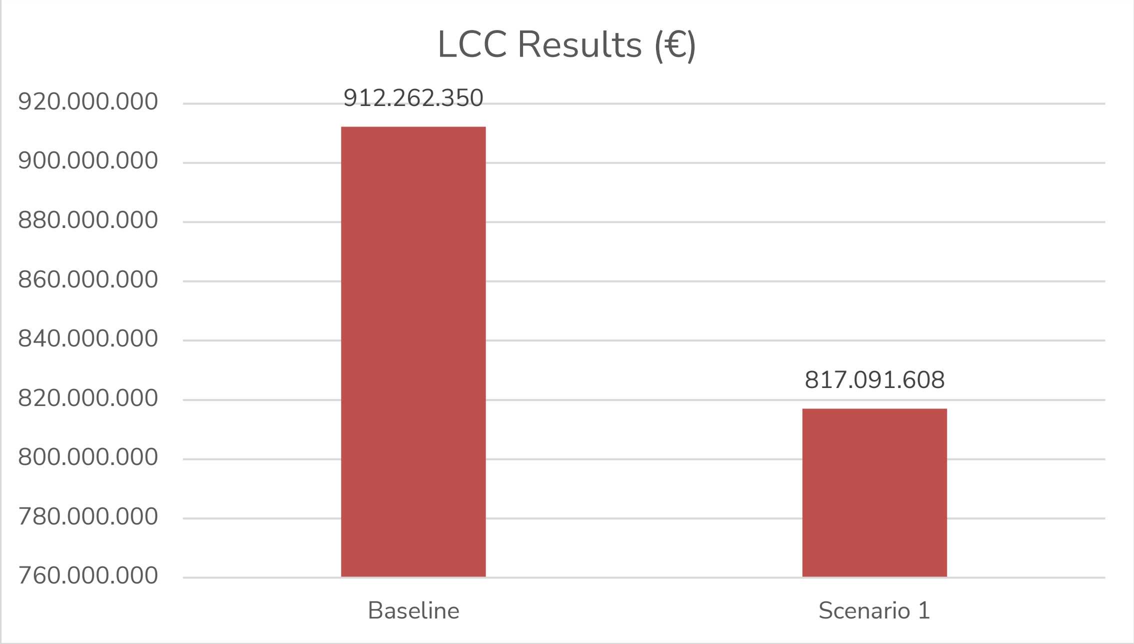


Figure 32 LCC results of each scenario.

Results are further supported by the Figure 33, which presents the undiscounted total sensitivity cost for the 1st year. OPEX costs have the highest contribution across all scenarios. In the Baseline, climate change externalities significantly increase the LCC result. Conversely, contribute to a reduction in the total cost of each scenario. This is due to the fact that energy recovery can lower energy expenses for factories or generate revenue through sales to suppliers.

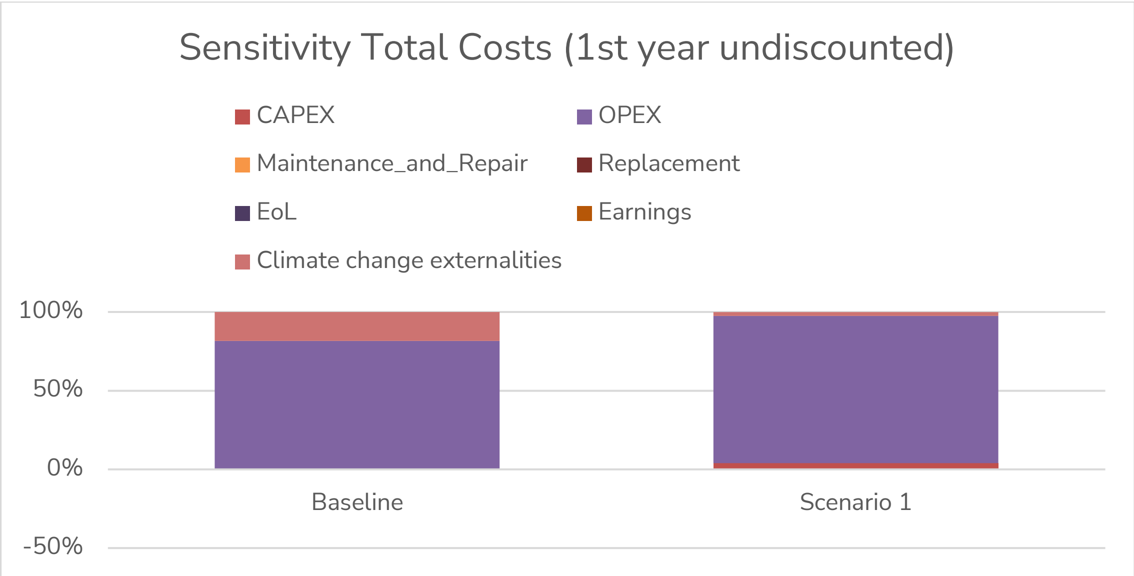


Figure 33 Sensitivity analysis of total costs (1st year undiscounted) for each scenario.

For a horizon of 20 years, the CAPEX of Scenarios 1 will remain unchanged due to maintenance. According to the Figure 34, the cost curves of these scenarios exhibit a

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

decreasing trend, while the net present values progressively decline over time as earnings increase.

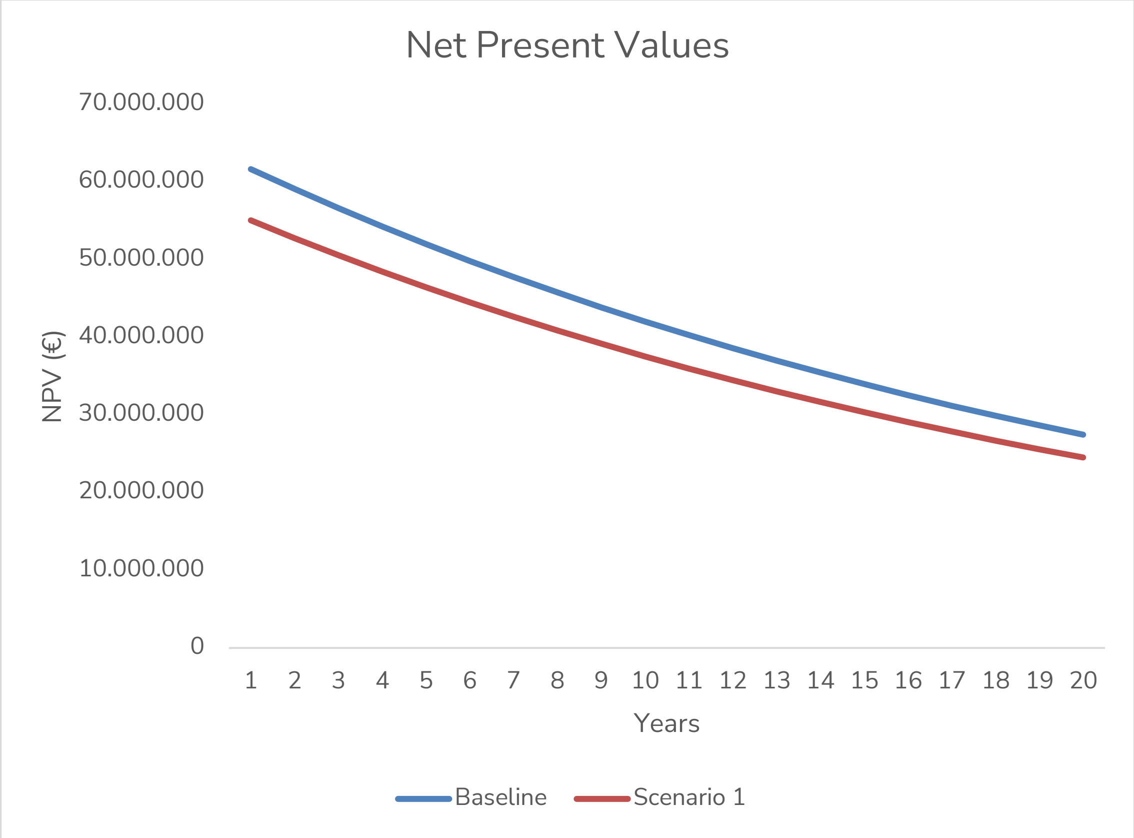


Figure 34 Net present values of each scenario for 20 years horizon.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

5 LCA analysis for scenario 2.2

This section presents the LCA of Scenario 2.2, conducted by Novamont in coordination with NTUA. The analysis examines the environmental performance of Scenario 2.2 across its life cycle. Key assumptions, data considerations, and the resulting environmental impacts are outlined in the following subsections.

5.1 LCA methodology for scenario 2.2

Within Scenario 2.2 a "what-if" (WI) analysis has been performed. WI involves exploring hypothetical scenarios to understand how changes in variables or assumptions might affect the environmental impacts of a product or system determined LCA.

This approach deviates a little bit from the other case studies nevertheless it has been considered the most appropriate one to catch the potentialities of bio-based and compostable products in the management of food waste.

In the context of waste management systems, modern treatment processes often handle various types of waste simultaneously and produce multiple outputs, such as secondary materials (compost) and energy (biogas). This multifunctionality introduces challenges related to allocation, the process of assigning environmental burdens to different outputs.

Within this analysis a System Expansion approach has been followed: this approach involves expanding the system boundaries to include additional functions, thereby avoiding the need to allocate burdens between them.

Avoided Burdens: here, the environmental impacts of avoided processes (e.g., compost instead of producing new fertilizers or biogas instead of producing methane) are subtracted from the total impacts.

To conclude the incorporating of WI analyses into LCA has resulted particular useful in strategic planning and decision-making processes compared to future conditions.

5.2 Scenario 2.2: OFMSW collection for biogas and compost production

As introduced in **Section 1.2**, expanding the collection of the OFMSW for biogas and composting presents a significant opportunity. To fully realize this potential, improved management and utilization of bio-waste are essential.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Bio-waste (i.e. food waste and yard waste) constitute a critical fraction of Municipal Solid Waste (MSW) due to two main factors:

- it is the largest fraction, on average ranging from 30 to 40% of MSW across Europe.
- it poses challenges in management due to odours and leachate production.

Proper EoL treatment of bio-waste is essential for sustainable waste management, as landfilling emits methane, a well-known greenhouse gas, and incineration is inefficient due to the high moisture content, which hinders energy recovery. Therefore, composting and anaerobic digestion should be considered. Specifically, composting and anaerobic digestion are both biological processes that break down organic waste, with composting using oxygen to produce nutrient-rich soil and anaerobic digestion occurring without oxygen to generate biogas and digestate.

Recognizing the impact of the aforementioned EoL treatments, the Waste Framework Directive (WFD) has made the separate collection of the OFMSW, including both wet and green waste, mandatory for all EU Member States as of 1 January 2024.[13] Despite this, to date, approximately 75% of the bio-waste produced ends up in landfill or is incinerated.

More specifically, in the EU27+ the current capture of food waste is 15 million of tonnes per year, while the theoretical maximum potential is estimated to be 60 million of tonnes.[14]

To meet WFD targets and reduce environmental impacts, many local authorities have prioritized separate bio-waste collection. In countries like Poland, it remains significant room for improvement because only slightly more than 10% of food waste is currently biologically recycled (Table 4).

Table 4 Comparison of theoretical potential food waste, operational potential (operational potential, 85% of theoretical potential), current capture and shortfall. (source: extracted from Table 11 "Bio-waste generation in the EU: Current capture levels and future potential" BIC report 2024 here the link https://biconsortium.eu/media/europe-missing-out-potential-bio-waste-almost-75-ending-landfills-or-incinerated. The table has been integrated with the A/B figures by the authors of this case study)

THEORETICAL FOOD WASTE GENERATION PER CAPITA	THEORETICAL POTENTIAL (TONNES)	POTENTIAL CAPTURE WITH OPTIMISED COLLECTION SCHEMES	CURRENT CAPTURE (TONNES) (A)	SHORTFALL (TONNES)	A/B

[13] (Europe Missing Out on the Potential of Bio-waste With Almost 75% Ending up in Landfills or Incinerated, 2024)

[14]Europe missing out on the potential of bio-waste with almost 75% ending up in landfills or incinerated. (2024, November 5). Bio-Based Industries Consortium. https://biconsortium.eu/media/europe-missing-out-potential-bio-waste-almost-75-ending-landfills-or-incinerated

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

			(TONNES) (B)			
EU 27		52,157,348	44,333,745	13,578,084	30,755,661	31 %
EU 27+	116.7	60,034,680.8	51,029,479	15,112,788	35,916,692	30 %
FRANCE	122.3	8,313,315	7,066,318	1,413,507	5,652,811	18 %
GERMANY	94.4	7,834,000	6,658,900	2,480,466	4,178,434	37 %
ITALY	127.7	7,537,688	6,407,034	5,456,950	950,084	85 %
SPAIN	144.0	6,830,337	5,805,786	996,091	4,809,695	17 %
POLAND	112.0	4,216,206	3,583,775	391,604	3,192,171	11 %

As shown in the table, Italy stands out as a model example in terms of current capture over the potential capture with an optimized collection. Italy's success in organic waste management is closely tied to its strategic use of certified biodegradable and compostable plastics (according to EN13432), particularly within door-to-door collection systems. This approach has not only enhanced the efficiency of waste collection but also significantly improved the quality of compost produced, while mitigating environmental concerns such as microplastic contamination.

The success is two main factors, one of which is that the Italian municipalities have systematically implemented the use of compostable bags for collecting organic waste, especially food scraps. This transition to the use of compostable bags was supported by legislation and became mandatory in 2011,[15] aiming to prevent contamination from conventional plastics in composting facilities. The adoption of compostable liners has facilitated hygienic and convenient participation from households, leading to higher compliance rates and cleaner organic waste streams. As a result, the amount of non-compostable materials in collected organic waste has significantly decreased, enabling the production of high-quality compost (defined as containing less than 0.5% non-compostable material by dry matter weight).[16,17]

The second main factor is the door-to-door collection system that has been pivotal in Italy's waste management strategy: by collecting organic waste directly from

[15] Miller, R. A. (2012, August 15). Plastic bag ban and residential SSO diversion | BioCycle. BioCycle. https://www.biocycle.net/plastic-bag-ban-and-residential-sso-diversion/

[16] Wade. (2024, August 6). Italy's experience with compostable plastics in organics recycling | BioCycle. BioCycle. https://www.biocycle.net/italy-compostable-plastics/

[17] *EUR-Lex - 32019R1009 - EN - EUR-Lex.* (2019, June 5). Eur-Lex.europa.eu. https://eur-lex.europa.eu/eli/reg/2019/1009/oj

households, municipalities have achieved higher separation efficiency and reduced further the contamination levels. This method ensures that organic waste is collected promptly, minimizing odour issues and the potential for leachate production. Moreover, it encourages residents to participate actively in waste separation, knowing that their efforts lead to tangible environmental benefits. Furthermore, using compostable bags for bio-waste collection encourages better waste segregation, making it easier to properly dispose of organic waste, reducing the chances of improper disposal and littering

It is important to highlight the importance of reducing contamination from conventional plastics, particularly in relation to the issue of microplastics, which pose a significant environmental concern, especially in composting, where microplastics often originate from non-compostable plastic bags used for organic waste collection. The microplastics can persist in the compost and, when applied to soil, may have detrimental effects on soil health and the broader ecosystem. Studies have shown that compost from facilities utilizing door-to-door collection with compostable bags contains significantly fewer microplastics compared to systems using conventional plastic bags.[18]

Italy's integrated approach, combining regulatory measures, public participation, and infrastructure development, serves as a model for other countries aiming to improve their organic waste management systems. By adopting similar strategies, other nations can achieve comparable sustainable waste management practices.

5.3 Life Cycle Impact Assessment and Interpretation for Scenario 2.2

To quantify the potential benefits associated with increasing the biological recovery rate of food waste and the use of high-quality compost (aided by biodegradable and compostable bin liners), an analysis of compost production and compost utilization has been conducted. To conduct the analysis, a "what if" scenario was considered, comparing Poland's current food waste collection rate of 11% (see Table 22) with a more ambitious, yet achievable, 50% collection rate. This target is realistically attainable, as demonstrated by Italy's success in reaching over 80% collection through compostable bag-based systems implemented over the past 15 years.

[18] Edo, C., Fernández-Piñas, F., & Rosal, R. (2021). Microplastics identification and quantification in the composted Organic Fraction of Municipal Solid Waste. *The Science of the Total Environment*, *813*, 151902. https://doi.org/10.1016/j.scitotenv.2021.151902

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

In absolute terms, this would mean increasing food waste collection in Poland from 391,604 metric tonnes to approximately 1.792 million metric tonnes (a delta of around 1.4 million tonnes annually).

Recovered bio-waste is typically treated through composting or anaerobic digestion (AD) followed by composting. More in detail, compost serves as a soil improver by supplying nutrients, adding humic carbon, and enhancing soil quality. [19] While some of these benefits can be assessed using LCA, others remain beyond the current capabilities of the methodology, such addition of humic carbon e enhancement of soil quality.

The data reported in Table 5 indicate that properly collected and biologically treated food waste (via composting or AD) leads to substantial environmental benefits. According to the US-EPA's Waste Reduction Model (WARM), [20] diverting 1 kg of organic waste from landfill to composting can prevent up to 1.7 kg CO_2 eq. emissions (range reported in the table: -0.198 to -1.533 kg CO_2 eq. /kg food waste).

In Table 5 the EPA emissions factors for different food waste end of life treatments are shown.

Table 5 Emissions factors for different food waste end of life treatments.

	Emission factors (MT CO2e/MT food waste)
Composting	-0,198
Dry Anaerobic Digestion Emission Factors for Food Waste with Digestate Curing	-0,044
Dry Anaerobic Digestion Emission Factors for Food Waste with Direct Land Application	-0,110
Wet Anaerobic Digestion Emission Factors for Food Waste with Digestate Curing	-0,066
Wet Anaerobic Digestion Emission Factors for Food Waste with Direct Land Application	-0,154
Landfills without LFG recovery	1,533
Landfills with LFG recovery and Flaring	0,595
Landfills with LFG Recovery and Electricity Generation	0,463
Combustion with electricity recovery	-0,143

[19] Pascual, J. A., García, C., Hernández, T., & Moreno, J. L. (2010). Long-term effects of organic amendments on soil fertility: A review. In E. Lichtfouse (Ed.), *Genetic engineering, biofertilisation, soil quality and organic farming* (pp. 187–195). *Springer. https://link.springer.com/chapter/10.1007/978-94-007-0394-0_34*

[20] Waste Reduction Model | US EPA. (2025, May 15). US EPA. https://www.epa.gov/waste-reduction-model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

For the purpose of this analysis, we assume a representative GHG emission factor of 1 kg CO_2e/kg for food waste sent to landfill, based on the average of the best and worst-case scenarios presented in Table 23. Meanwhile, we consider the data reported in the table for the GHG emission factors of incineration and composting (respectively, -0.143 kg CO_2e/kg and -0.198 kg CO_2e/kg). Assuming the EU average for undifferentiated disposal of unsorted food waste is 43% to landfill and 57% to incineration, diverting this waste to composting can avoid approximately 0.56 kg CO_2e/kg of food waste,

Meanwhile, for AD, emission reductions vary between -0.154 kg CO_2e/kg (wet digestion) and -0.044 kg CO_2e/kg (dry digestion), therefore diverting food waste to AD results in an avoidance of approximately 0.5-0.6 kg CO_2e/kg of food waste.

As previously discussed, compostable and biodegradable waste bags enhance the efficiency of waste collection and significantly improve the quality of the compost produced. Consequently, their impact on GHG should be included in a comprehensive analysis. Considering that a compostable and biodegradable waste bag has a 'cradle to gate' carbon footprint of 0.05 kg CO_2e per bag, [21] and that each bag is used to collect around 1 kg of food waste, the bag's contribution to the overall carbon footprint of the waste collection and treatment process is less than 3%.

Another factor to consider is that reusing compostable bags, such as those provided for carrying groceries or fruit-and-vegetable bags, for food waste collection is a widespread and environmentally beneficial practice and it is commonly done in Italy. These bags are also legally required to be certified according to the EN13432 standard and are designed to be biodegradable and compostable, making them suitable for organic waste disposal. By repurposing these bags, citizens effectively reduce the demand for new materials, thereby minimizing the environmental impact associated with the production and distribution of additional waste bags.

Building on the contextualization of metrics and assumptions, we can now calculate the "what if" scenario in absolute terms. Increasing Poland's food waste collection rate to 50 percent of its potential, which corresponds to approximately 1.4 million tonnes of food waste, could result in an estimated annual reduction of around 800,000 tonnes of CO_2e.

Furthermore, considering the specific EoL treatment of undifferentiated bio-waste in Poland (36% incineration and 64% landfill) the estimated 1.4 million tonnes of food waste redirected to appropriate composting could result in an annual reduction of approximately 1.1 million tonnes of CO_2e.

[21] (2024, July 25). Environmental Product Declaration [Review of Environmental Product Declaration]. Https://Www.environdec.com/Home; BioBag International AS. https://api.environdec.com/api/v1/EPDLibrary/Files/5118ee11-d32d-4b93-b970-08dca749c5b7/Data

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Using a similar approach, we can extend the analysis to the EU 27+. By implementing optimized food waste collection schemes capable of capturing the full potential (Table 22 column "shortfall"), estimated at approximately 36 million metric tonnes, the overall expected benefit is a reduction of around 20 million tonnes of CO_2e. This corresponds to the annual greenhouse gas emissions of approximately 2 million EU citizens (bases on an average of 10,7 tonnes of CO_2e per capita per year).[22]

Furthermore, the LCA was extended beyond GHG emissions to include additional impact categories assessed using the CML method. To ensure a comprehensive assessment, the foreground data, in terms of mass balance of the composting process included air and water emissions, were derived from Progetto GERLA.[23] Additionally, the composition of food waste was modelled using average values, providing the foundation for calculating inventory data for both the composting process and the undifferentiated end-of-life treatment options. The latter was assessed using the Calculation tool for waste disposal in MSW, developed by Gabor Doka (version 2.1, 2008 Ecoinvent). Specifically, this tool facilitated the analysis of waste sent to landfill and incineration, thereby enabling a direct comparison between the two treatment pathways.

Two distinct scenarios were defined for this comparative analysis:

1. Current scenario where 1,4 million tonnes of food waste per year (delta in the "what if" scenario) are not separately collected ending in the undifferentiated stream represented by 36% incineration and 64% landfill.
2. Future scenario where the same amount of food waste (1,4 Ml tonnnes) is sent to industrial composting. According to the methodological approach followed in the WARM tool (US EPA) the credits coming from energy production (from incineration) and fertilizer replacement (by compost) were included in the system boundaries.

Figure 35 presents the comparative normalized results, while Table 24 reports the absolute LCIA results for the treatment of 1.4 million tonnes of food waste under the analysed scenarios (comparative analysis scenario 1 and 2).

---

[22]Eurostat. (2025, February 19). EU greenhouse gas footprint: 10.7 tonnes per capita. *Eurostat*. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250219-1

[23] "*Supporto tecnico-scientifico in materia di valutazione del ciclo di vita (LCA) applicata a sistemi di gestione di rifiuti urbani in Regione Lombardia*" Progetto GERLA- Grosso M., Rigamonti L., Brambilla V., Luglietti R., Falbo A. (Politecnico di Milano)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

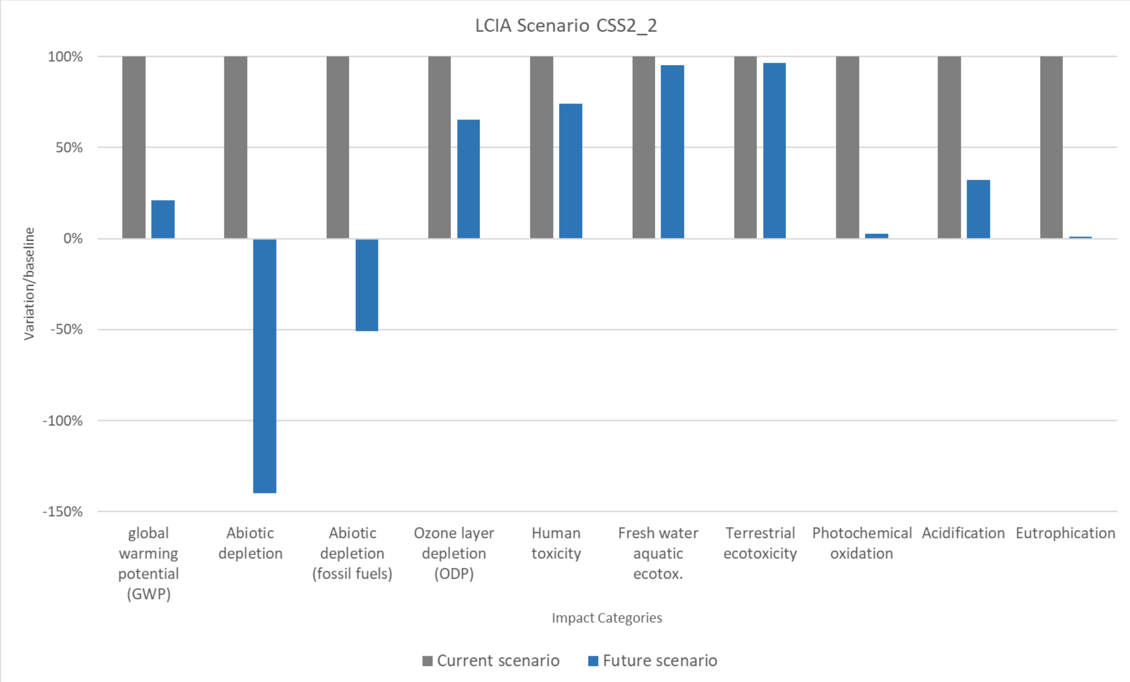


Figure 35 comparative LCIA results of current scenario and future scenario (values normalized to the highest). Method: CML-IA baseline v 3.10

Table 4 absolute LCIA results for 1,4 Ml tonnes of food waste act category

	Unit	Current scenario	Future scenario	Saving Future scenario vs current
GWP	Ton CO_2e	1.400.000	300.000	-79%
Abiotic depletion	kg Sb eq	185	-259	-240%
Abiotic depletion (fossil fuels)	MJ	2,65E+08	-1,35E+08	-151%
ODP	kg CFC-11 eq	1,13	0,74	-35%
Human toxicity	kg 1,4-DB eq	1,51E+08	1,12E+08	-26%
Fresh water aquatic ecotox.	kg 1,4-DB eq	8,64E+06	8,24E+06	-5%
Terrestrial ecotoxicity	kg 1,4-DB eq	1,02E+06	9,83E+05	-4%
Photochemical oxidation	kg C2H4 eq	2,41E+05	5,96E+03	-98%
Acidification	kg SO2 eq	3,00E+05	9,69E+04	-68%

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Eutrophication	kg PO4---eq	2,36E+06	2,55E+04	-99%

According to the results, the environmental benefits of diverting food waste to composting, as compared to current disposal practices, range from 4 percent to 240 percent across the evaluated impact categories. In particular, negative values were recorded for abiotic depletion and fossil fuel depletion, indicating that the environmental credits from fertilizer substitution exceeded the burdens associated with the collection and composting processes.

6 LCC analysis for scenario 2.2

For Scenario 2.2, given that the EoL treatments are already implemented at an industrial scale, a LCC analysis was conducted for a composting facility to be located in Europe, with an annual processing capacity ranging from 40,000 to 100,000 tonnes.

However, the economic parameters of such facilities can vary significantly across different EU countries due to local regulatory frameworks, labour costs, land prices, and financial incentives. Therefore, country-specific assessments are essential to obtain accurate and relevant cost estimates.

This analysis integrates internal data obtained from expert consultations with a prominent stakeholder in the composting sector, focusing on the Italian context. The findings indicate that CAPEX varies significantly, ranging from €300 to €670 per ton of total capacity. This fluctuation is primarily driven by facility size and the level of automation employed: larger, less automated plants tend to have lower per-ton costs. Similarly, that operative expenditure (OPEX), encompassing maintenance, repairs, cleaning, energy consumption, salaries, and other associated costs, typically ranges between €30 and €60 per ton of input, showing a decrease with increased facility size and automation.

As illustrated in Figure 36 and Figure 37, the distribution of these costs across various components is visually represented, providing further insight into their respective estimated contributions.[24]

[24]Costs for Municipal Waste Management in the EU. (n.d.). https://ec.europa.eu/environment/pdf/waste/studies/euwastemanagement_annexes.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

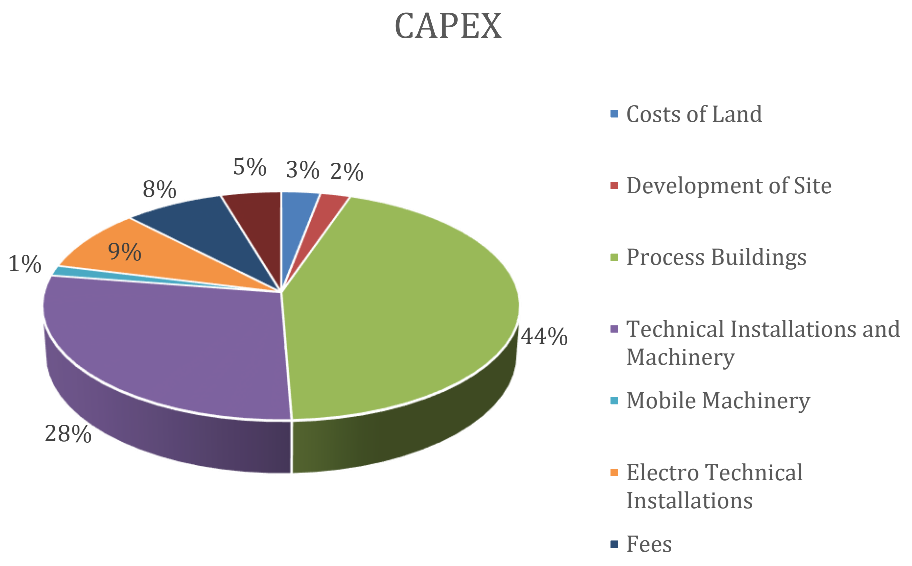


Figure 36 CAPEX estimated for the composting plant.

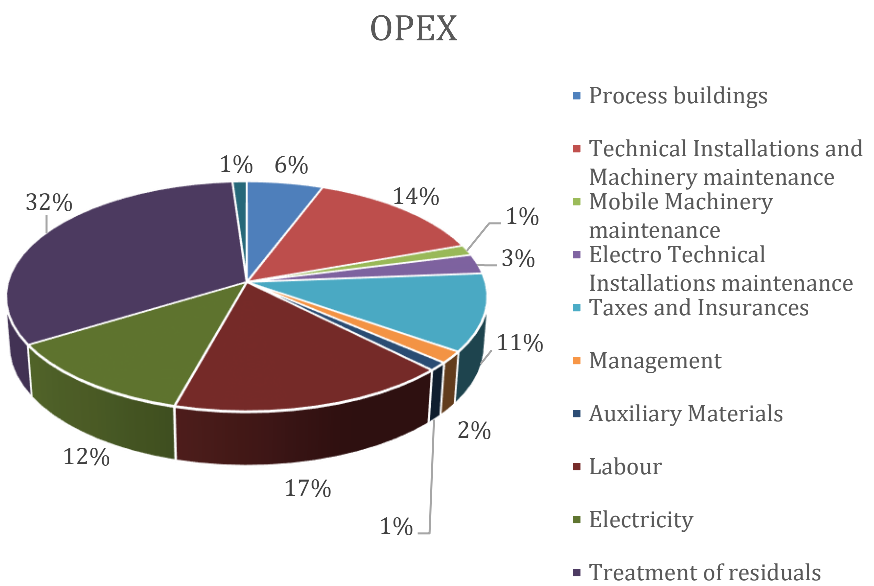


Figure 37 OPEX estimated for the composting plant.

Therefore, depending on size and efficiency, estimated composting facilities may incur CAPEX ranging from €12 million to €67 million, and OPEX between €1.2 million and €6 million, with smaller, less efficient plants being significantly more expensive per ton processed. Based on these estimates, the CAPEX for composting facilities in the WI scenario, projected to treat 1.4 million tonnes of bio-waste, is approximately 1 billion euros. Given the scale and financial implications of such investments, securing adequate funding becomes a critical component of successful implementation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

In Europe, composting facilities can be financed through a combination of EU funds, national government initiatives, private sector investments, and environmental finance. The EU plays a pivotal role in funding large-scale composting projects, [25] such as in Greece,[26] while national governments offer specific support tailored to local needs. Furthermore, the private sector, in collaboration with public entities, contributes significantly to the development of modern, automated composting facilities.

7 LCA analysis for scenario 2.3

As for Scenario 2.2, the LCA of Scenario 2.3 was carried out by Novamont, with methodological details presented in a descriptive format to contextualize better the framework and to explain the calculations throughout the description.

7.1 LCA methodology for scenario 2.3

Within this case study the assessment was focused on the impacts associated to the use of high-quality compost in agriculture land from a carbon management and greenhouse gas emission balance perspective. To this regard, within Frontsh1p, a significant activity carried out within scenario 2.3 has regarded an update and implementation of a crop-specific provisional model for assessing SOM dynamics associated to the sunflower production.

More in details, SOM plays a critical role in maintaining soil health and ecosystem functionality, with approximately 60% of SOM being composed of carbon (C). As the primary indicator of soil quality, SOM provides several essential ecosystem services that are vital for both agricultural productivity and environmental sustainability. Firstly, SOM contributes to resistance to soil erosion by improving soil structure and binding soil particles together, which prevents loss of topsoil from wind or water erosion. Secondly, SOM significantly enhances soil water retention, especially in sandy soils, by increasing the soil's ability to hold water, thereby ensuring a more reliable water supply for plants during dry periods. Furthermore, SOM supports soil fertility by acting as a reservoir for essential plant nutrients, promoting beneficial microbial activity that helps mineralize nutrients into plant-available forms. Lastly,

[25] Reconstructing areas affected by conflicts: the role of the bio-based solutions - KETMarket Open Innovation Ecosystem. (2024, December 10). https://ketmarket.eu/funding/harmonizing-and-optimising-composting-plants-performances-in-europe//

[26] Inforegio - Over €65 million in EU funds for new waste management facilities in Greece's Peloponnese region. (2021). Europa.eu. https://ec.europa.eu/regional_policy/whats-new/newsroom/25-04-2025-over-eur65-million-in-eu-funds-for-new-waste-management-facilities-in-greece-s-peloponnese-region_en

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

SOM supports soil biodiversity, creating a favourable environment for a diverse range of soil organisms, such as microbes, earthworms, and insects, that contribute to nutrient cycling, disease suppression, and overall soil health.

The amount and quality of SOM are crucial not only for soil fertility and biodiversity but also for global environmental processes. Even small changes in the soil carbon pool can have profound effects on agricultural yield and the global greenhouse gas (GHG) cycle. Maintaining soils rich in organic carbon, restoring degraded agricultural lands, and adopting soil management practices that increase SOM content can significantly contribute to food security by enhancing agricultural productivity and mitigating anthropogenic GHG emissions. By restoring and protecting organic carbon-rich soils, we not only improve soil health but also help mitigate climate change, offering a win-win solution for both food production and environmental sustainability.

7.2 Scenario 2.3: marginal lands valorisation

Novamont drew on its experience in Italy to promote the sustainable valorisation of marginal lands in Poland through a regenerative agriculture approach that includes local farmers. (as reported in Deliverable D4.5). This approach builds on the success of the First2Run project,[27] which, during 2015-2019, has demonstrated an innovative agro-industrial value chain. The project focused on cultivating low-input oil crops, specifically cardoon, on marginal and stony lands in Southern Mediterranean regions of Italy (primarily Sardinia) for the production of biobased and biodegradable plastics, cosmetics, and biolubricants.

As part of First2Run, Novamont successfully developed and implemented:

i. Large-scale cardoon cultivation.
ii. An optimized low-input cultivation protocol, transferred to farmers through dedicated training sessions.
iii. Satellite and drone-based monitoring techniques to assess field conditions and crop health.
iv. New harvesting prototypes designed to separately collect seeds and biomass, suitable for Sardinia's stony marginal lands.
v. Improved cardoon hybrids with enhanced yield and quality.
vi. Strategies for improving SOM.

In economic terms, marginal lands are areas where agricultural production is not economically viable with conventional farming practices because lands have low

[27] FIRST2RUN | Circular Bio-based Europe Joint Undertaking (CBE JU). (2025, July 4). https://www.cbe.europa.eu/projects/first2run

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

productivity and, without intervention, may not generate sufficient yields to justify conventional investments in agriculture.

By implementing sustainable, low-input agricultural models, such as those demonstrated by First2Run, marginal lands can be converted back into biobased value chains, creating new economic opportunities and maintaining environmental benefits.

The benefits of this development model for farmers can be summarized as:

- New opportunities to diversify and improve the income associated with agricultural activities.
- Direct involvement in the production of organic-based products guaranteeing them a key role in the first transformation of the raw materials produced.

The implementation of this model is possible thanks to the collaboration between different actors, covering different roles: farmers associations, farmers and cooperatives, agro-industry, biorefineries.

7.3 Life Cycle Impact Assessment and Interpretation for Scenario 2.3

The specific SOM model was developed and applied within the Frontsh1p project to estimate site-specific SOM dynamics following sunflower cultivation on marginal lands. It considers both pedoclimatic conditions and agricultural practices, including the application of high-quality compost. More in details, the model takes into account the main soil characteristics, annual mean temperature, and management of cropping systems and in particular organic fertilizers and crop residues.

In the model, a typical 3-year crop rotation cycle has been implemented to optimize soil health, nutrient cycling, and long-term sustainability of the cropping system.

- Year 1: Sunflower - As the main crop, sunflowers are sown after proper soil preparation.
- Year 2: Legumes (field beans) - Legumes are excellent for the soil as they fix atmospheric nitrogen,[28] improving soil fertility for the next crop. This helps balance the nutrient consumption of the sunflowers.
- Year 3: Cereals (wheat) - Cereals, such as corn, are good for alternating with sunflowers, as they do not excessively compete for the same nutrients and allow for different resources use in the soil.

[28] Soil improvements with legumes | Soils, fertility and nutrients | Government of Saskatchewan. (n.d.). Government of Saskatchewan. https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/soils-fertility-and-nutrients/soil-improvements-with-legumes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

As known crop rotation with sunflowers[29] is particularly useful to avoid the disadvantages of monoculture, which can deplete the soil, increase susceptibility to diseases and pests, and reduce biodiversity.

The model implements the Hénin-Dupuis equation to describe the dynamics of organic matter (OM) in a complex cropping system. This equation incorporates two distinct kinetic constants, k1 and k2, which respectively represent two different processes of OM transformation over the course of a year: humification and mineralization.

The equation reported hereby:

$$\Delta SOM = k1*M-k2*SOM \quad (1)$$

Where:

- M (in Mg/ha) represents the dry matter, which includes raw OM, exogenous OM, and crop residues.
- k1 (% w/w) is the humification constant, which represents the proportion of OM that is converted into humus.
- k2 (% w/w) is the mineralization constant, which indicates how much of the humus is broken down into CO_2.

k1 represent the new SOM formed from the fresh OM input in Δ timeframe. It is not a fixed parameter but varies depending on OM characteristics. In particular, k1 is correlated with the Biological Stability Index (BSI, % w/w), which is determined through laboratory analysis of the biochemical fractions of the OM. Before calculating k1, the OM input is corrected for its ash content to isolate the actual organic fraction. This corrected OM value is then related to the total input M, allowing the estimation of k_1 using the following formula:

$$k_1 = BSI*OM/M \quad (2)$$

In contrast, the coefficient k_2 represents the proportion of existing SOM that is lost in Δ timeframe. While soil type has a limited direct influence on the mineralization rate of fresh organic inputs, k_2 is more broadly affected by site-specific conditions. A gross estimation of the mineralization constant k_2 can be made based on several factors, including agricultural management practices (i.e. tillage frequency and depth, irrigation, and the use of crop residues or organic fertilizers) comprehended in 1200 constant, clay content (A, g/kg), total carbonates ($CaCO_3$, g/kg), and the site's mean annual air temperature (T, °C):

[29] Kussul, N., Deininger, K., Shumilo, L., Lavreniuk, M., Ali, D. A., & Nivievskyi, O. (2022). Biophysical impact of sunflower crop rotation on agricultural fields. *Sustainability, 14*(7), 3965. https://doi.org/10.3390/su14073965

$$k_2 = \frac{1200*0.2*(T-5)}{(200+A)*(200*0.3*CaCO_3)} \qquad (3)$$

To implement the model for scenario 2.3, the following average values for Poland have been considered:

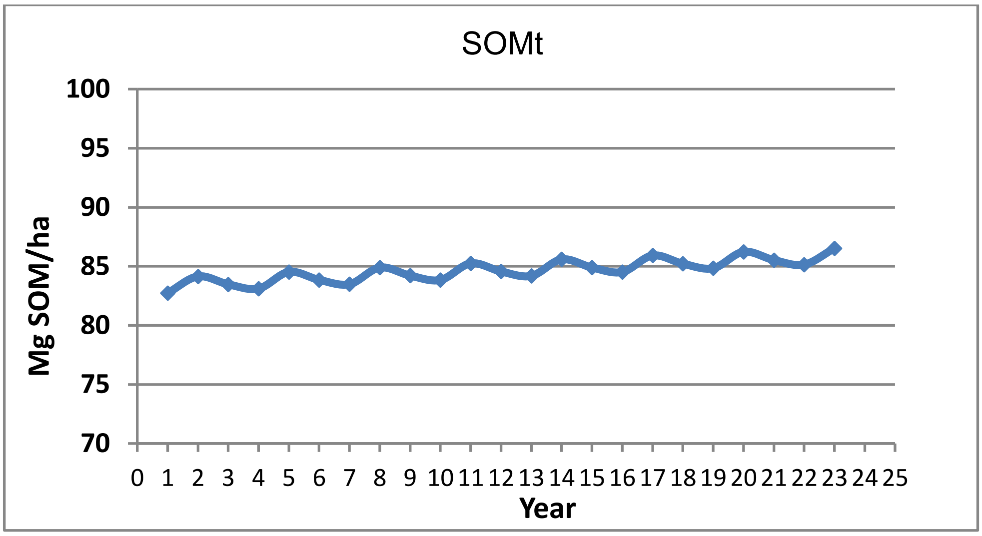
- T: 8°C [30]
- Clay: 25%
- $CaCO_3$: from 10% up to 15%
- $SOMt_0$: 2,5% [31]

As shown in equation (2) the k_2 is multiplied for SOM term, that takes into account basic soil parameters, such as: specific residual biomass and agricultural practices, such as harvesting practices, depth and organic fertilizer (such as compost) application. Therefore, the SOM stock in the top 30 cm of soil was estimated by considering several factors: soil organic carbon (SOC, % w/w), C in SOM (58%), bulk density (BD, Mg/m^3), and coarse materials (CM, % v/v):

$$SOM = \frac{SOC}{0.58} * BD * (1 - CM) * h \qquad (4)$$

For scenario 2.3, the model considers applying 20 Mg/ha of high-quality compost every three years before sunflower sowing, with a total timeframe of 22 years. The compost used has 50% dry matter (w/w), 1.8% nitrogen content (w/w dry matter), 48% organic carbon (w/w dry matter), and a humification coefficient k1 of 0.2, indicating that 20% of the compost's organic carbon will be converted into stable SOM.

In Figure 38, the SOM outlook is presented for a system applying 20 Mg of compost every three years.



[30] TRADING ECONOMICS. (n.d.). Temperatura media in Polonia | 1901-2023 dati | 2024-2025 previsione. https://it.tradingeconomics.com/poland/temperature

[31] Average values for Poland are based on the National Institute of Earth Sciences and FAO

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Figure 38: SOM outlook applying 20 Mg of compost every three years (crop rotation: 1° year sunflower, 2° year field beans and 3° year wheat)

The presented results show that by the end of the 22nd year, the SOM increase amounts to 3.8 Mg/ha, with 2.21 Mg of SOC/ha (58% of SOM is SOC). This translates to an atmospheric CO_2 uptake of 8.1 metric tonnes, or an average of 0.37 Mg CO_2/ha per year, due to the SOM increase.

To evaluate the benefits associated with the long-term increase in SOM, a literature review on sunflower production was conducted. Due to the unavailability of specific data for sunflower production in Poland, secondary data from Ecoinvent 3.10 for Romania were used, as the geographic conditions and yields were similar: Romania's sunflower yield was 2,450 kg/ha, compared to Poland's 2,260 kg/ha. This led to a calculated CFP (cradle to farm gate) of 2.46 metric tonnes CO_2/ha.

Based on the SOM model analysis conducted within Frontsh1p, the oil cropping system (sunflower) on marginal lands with compost application (one application every three years) resulted in an increase of 3.8 Mg/ha after 22 years. This increase in SOM corresponds to approximately 0.37 tonnes CO_2e/ha in CO_2 uptake. Consequently, the compost application is estimated to reduce the CFP emissions by about 15%.

These results highlight that incorporating high-quality compost into the cultivation protocol enhances the sustainability of sunflower production. Additionally, this approach supports the development of the high-quality compost market, reinforcing the synergies between biowaste recycling and agriculture, and contributing to the advancement of a circular bioeconomy.

8 LCC analysis for scenario 2.3

As previously described, Scenario 2.3 focused on the cultivation of sunflower on marginal lands. As these lands required no major preparatory works or infrastructural development, the project incurred virtually no CAPEX.

Implementation was carried out in close cooperation with local farmers, who utilized existing agricultural machinery and seed treatment facilities already available in the area. No new equipment or dedicated infrastructure was needed, and cultivation activities were embedded within traditional farming systems. The operational model relied on decentralized, low-input practices, resulting in minimal financial flows and limiting the feasibility and added value of conducting a comprehensive life cycle cost analysis.

For this reason, the great value of this scenario lies in its ability to create synergies with local farmers and businesses in the surrounding area. By leveraging existing assets and fostering collaborative production models, the project contributes to optimizing economic, social, and environmental returns for local communities, particularly in underutilized rural areas where sustainable development opportunities are most needed.

9 s-LCA methodology

9.1 Goal and Scope

This study focuses on food/organic waste in Europe and specifically in the Łódzkie region of Poland, where organic waste production is high. It is expected that the food waste disposal generated by these industries may result in various social and sociological impacts throughout its lifecycle.

The goal of this s-LCA is to evaluate and quantify the social impacts resulting from the new waste management solutions and technologies throughout the lifecycle of these industries for the 3 scenarios: i) 2.1 (production of FFAs ii) 2.2 OFMSW collection for biogas and compost production and iii) 2.3 (marginal lands valorisation for production of bio-lubricant and animal feed). The aim is to determine whether the outcomes indicate improvements in sustainability and efficiency. The social and sociological effects of food waste management will be further analysed through impact subcategories for each stakeholder group.

In this study, the CSS2 is applied as the alternative food waste management approach, focusing on the sustainable management of food and feed through end-of-life, disposal, reuse and recycling.

For the analysis, two case studies were conducted: one by an institute in Portugal and the other by a company in Italy, both of which implemented the CSS2. 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 newly developed solution. The social LCA of all the scenarios of the CSS2 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 food waste with the use of quantitative-semi quantitative-qualitative data that were collected from the s-LCA questionnaire.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

9.2 Stakeholders and impact categories

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

9.2.1 Workers

In this study, the term "workers" refers to those individuals responsible for operating and maintaining the systems within the facility, including technicians, supervisors and administrative staff. Workers are assessed across various indicators, with two key categories being particularly significant: i) Health and Safety and ii) Working Conditions.

For the Health and Safety category, the focus was on the availability of safety measures and the rate of fatal accidents in the workplace. Specifically, we examined the presence of safety protocols, preventive measures, emergency plans and initiatives designed to promote healthy workplace practices. Data for this category was collected both quantitatively (fatal accident rates) and qualitatively (presence of safety measures), mainly through the s-LCA questionnaire.

In the case of Working Conditions, the assessment was split into two subcategories: fair salary and working hours. Although we were unable to obtain specific data on the minimum wage, we evaluated the pay disparities between male and female workers at the facility, using qualitative data from the questionnaire. For working hours, we analysed the likelihood of workers needing to work overtime, based on their responses to the questionnaire.

Additional indicators for this stakeholder group included: Freedom of Association, Collective bargaining Child Labor, Forced Labor, Equal Opportunity/Discrimination, Social Security/Benefits and Employment Relationships. These were also evaluated using a combination of qualitative and quantitative data gathered through the questionnaire.

9.2.2 Consumers

Consumers are defined as individuals who "consume" the outputs, both material and immaterial, of the system. Two key impact categories for this stakeholder group are Health and Safety, which were assessed quantitatively through public health spending and end-of-life responsibility, which refers to the presence of systems within the organization that provide consumers with information about product end-of-life options. This was measured through the recycling rate, indicating the percentage of materials recycled or recovered from waste, as well as the safety of

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

handling products at the end of their life. Additionally, the feedback mechanism was evaluated using the press freedom scale, while consumer privacy was assessed based on the rule of law scale. Finally, transparency was measured using the corruption percentage index.

9.2.3 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 CSS2 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.

9.2.4 Society

This stakeholder category was assessed using five different impact categories, with two of them being especially significant, public commitment to sustainability and technological development.

For public commitment to sustainability, values were determined based on the proportion of resources dedicated to sustainability and social activities that govern the processes involved, as well as the use of critical raw materials. Another important indicator was the per capita ecological footprint, which was evaluated quantitatively.

Regarding technological development, R&D expenditure was analysed to assess whether the innovative technological systems had a positive impact on the organization, as well as the involvement in technology transfer projects.
Other factors considered for society included economic development, the mitigation of armed conflict, poverty alleviation and corruption.

9.2.5 Supply chain

Finally, for the value chain actors, the primary impact categories identified included fair competition, promoting 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 are two impact categories that were examined using various indicators.
For the supplier relationships category, factors such as the identification of significant actual and potential negative social impacts were considered, as well as the nature of the relationship between the organization and its suppliers on specific themes. On the other hand, the category of suppliers of raw materials and technology was assessed based on raw material traceability, the protection of human rights among employees of suppliers, and the integration of ethical, social, environmental and gender equality criteria.
In addition, fair competition was evaluated based on regulatory quality, the promotion of social responsibility was measured using the Good Country Index and the 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	Women's share of work force [%] QN-P
	(6)1 Equal opportunity	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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

	(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 spends 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 organization/ 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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

	(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)3 Community engagement	Collaboration with local centres of higher education (YES - 100, NO - 0) QL-P
	(20)4 Community engagement	Presence of organizational reports disclosed to local community (YES-100, NO-0) QL-P
	(20)5 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
	(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
	(29) Fair competition	Regulatory quality [0 (lowest) to 100 (highest)] QN-P

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Value chain actors	(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
	(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

9.3 Performance assessment - Impact assessment

Table 7 indicates the methodology we used to perform the PA of this analysis.

Table 7 s-LCA PA of WP4.

Stakeholders	Indicators	Reference Study	Case Study
Workers	(1) Freedom of association	5,00	5,00
	(1) Collective bargaining	5,00	5,00
	(2) Child labour	4,80	5,00
	(3) Forced labour	4,98	5,00
	(4) Fair salary	1,14	1,56
	(4)1 Fair salary	1,00	1,00

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

	(5) Working hours	2,78	3,89
	(6) Equal opportunity/ Discrimination	2,80	2,85
	(6)1 Equal opportunity/ Discrimination	5,00	5,00
	(7) Health and safety	4,99	5,00
	(7)1 Health and safety	5,00	5,00
	(7)2 Health and safety	5,00	5,00
	(7)3 Health and safety	1,01	1,00
	(8) Social Security/Benefits	2,08	2,07
	(8)1 Social Security/Benefits	1,00	5,00
	(9) Employment relationships	5,00	5,00
	(9)1 Employment relationships	5,00	5,00
Consumers	(10) Health & Safety	1,42	1,40
	(11) Feedback Mechanism	4,03	4,11
	(12) Consumer Privacy	3,8	3,68
	(13) Transparency	3,44	3,22
	(14) End of life responsibility	5,00	5,00
	(14)1End of life responsibility	1,00	5,00
	Description of final product	5,00	5,00
Local community	(15) Access to material resources	2,34	1,95
	(16) Access to immaterial resources	4,95	4,96
	(16)1 Access to immaterial resources	1,19	1,18
	(17) Delocalization and Migration	3,6	3,47
	(17)1 Delocalization and Migration	3,92	3,46
	(18) Safe & healthy living conditions	1,40	1,38

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

	(18)1 Safe & healthy living conditions	5,00	5,00
	(18)2 Safe & healthy living conditions	5,00	5,00
	(19) Respect of indigenous rights	4,33	4,05
	(20) Community engagement	3,92	4,48
	(20)1 Community engagement	1,00	5,00
	(20)2 Community engagement	5,00	5,00
	(20)3 Community engagement	5,00	5,00
	(20)4 Community engagement	5,00	5,00
	(21) Local employment	4,75	4,74
	(21)1 Local employment	3,30	3,30
	(21)2 Local employment	4,10	-
	(21)3Local employment	5,00	1,00
	(22) Secure living conditions	1,00	1,00
	(22)1 Secure living conditions	3,32	3,71
Society	(23) Commitment to sustainability	3,90	3,98
	(23)1 Commitment to sustainability	-	-
	(23)2 Commitment to sustainability	1,00	5,00
	(24) Economic development	4,49	4,52
	(25) Technology development	1,09	1,10
	(25)1 Technology development	3,00	5,00
	(26) Mitigation of armed conflict	4,34	4,47
	(27) Poverty alleviation	5,00	1,00

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

	(27) Corruption	3,82	3,84
Value chain actors	(28) Fair competition	3,97	3,96
	(29) Promoting social responsibility	4,40	4,30
	(29)1 Promoting social responsibility	-	1,70
	(30) Supplier relationships	3,90	3,90
	(30)1 Supplier relationships	1,00	5,00
	(30)2 Supplier relationships	5,00	5,00
	(30)3 Supplier relationships	5,00	5,00
	(31) Suppliers of raw materials and technology	5,00	5,00
	(31)1 Suppliers of raw materials and technology	5,00	5,00
	(31)2 Suppliers of raw materials and technology	1,00	5,00
	(32) Respect of intellectual property rights	3,50	3,70

9.4 Social LCA results and discussion

In this section, the outcomes for each stakeholder group and impact category, as outlined previously, are discussed. The goal is to determine which indicators played a role in the observed improvements of the new solution, contributing to enhanced lifecycle sustainability in the region. Furthermore, a final comparison between the two cases is included to emphasize the differences and assess the overall effect of the new solution.

Table 8 Average results for the five stakeholder groups.

	Reference Study Average	Case Study 1 Average	Case Study 2 Average	Case Study 3 Average
Workers	3,62	4,31	3,52	3,92
Consumer	3,384	3,66	3,98	3,82
Local Community	3,66	3,85	2,81	3,33

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Society	3,33	3,39	3,63	3,51
Supply chain	3,78	4,33	4,01	4,17

Figure 39 Average results for each stakeholder group in the two cases.

According to Figure 39, we observe that there was an improvement in the case study for all the stakeholder groups, except for the local community, where a slight decline is noted compared to the reference study. The results, therefore, are quite satisfactory. A further analysis of each group will be provided bellow.

In Figure 40, a comparison is made between the overall results of the reference and the case study in this analysis. Following this, the individual graphs offer a more in-depth analysis of each stakeholder group (Figure 41-Figure 45).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

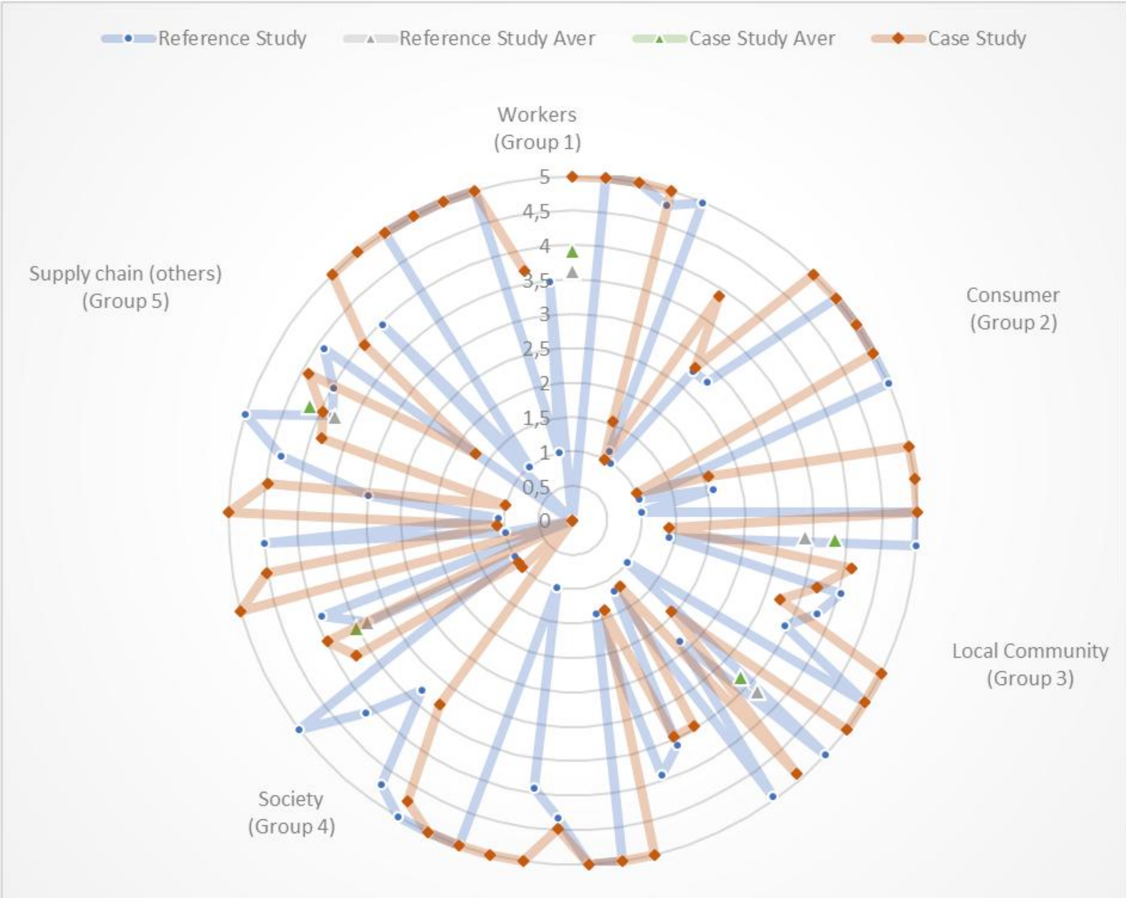


Figure 40 Results for each stakeholder group in the two cases.

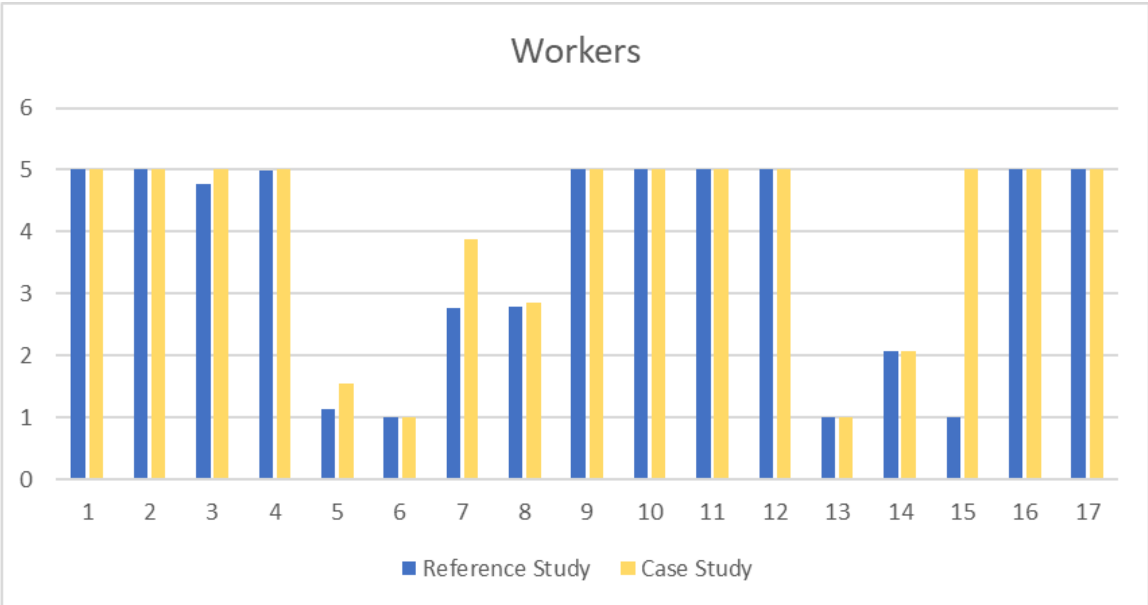


Figure 41 Workers' results between the two scenarios.

As shown in Figure 41, there is much improvement in the case study compared to the reference study. Specifically, the main positive results are that there were no incidents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

of child or forced labour, 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. There was also a slight improvement in the women's share of the workforce, as well as in the minimum wage of workers.

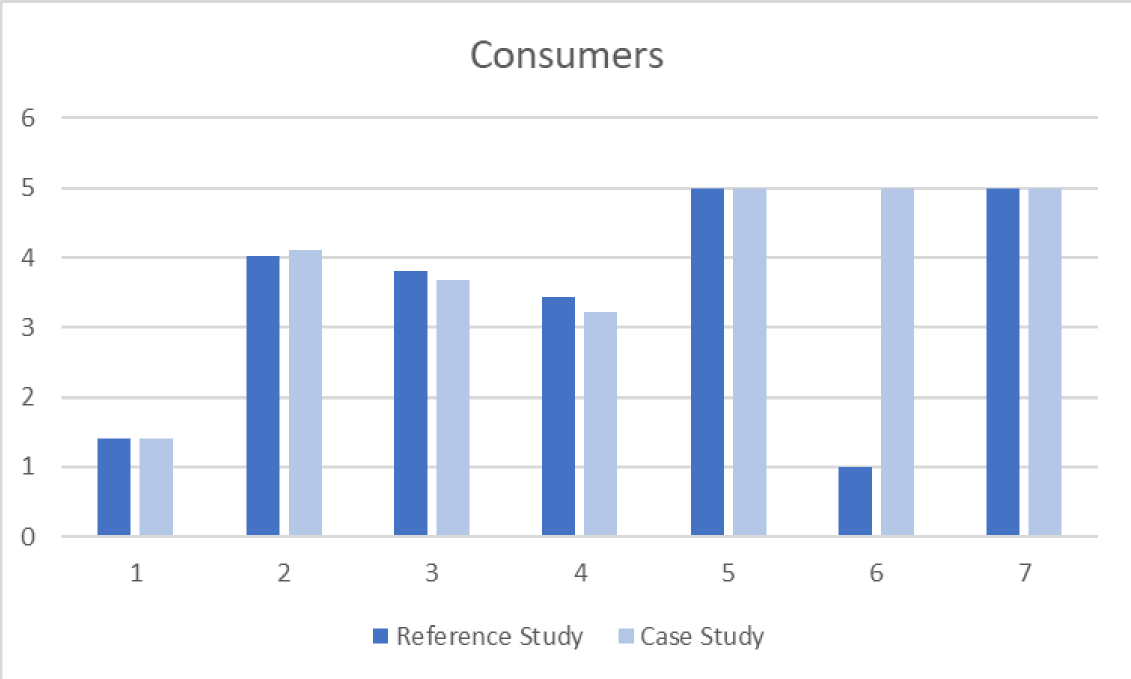


Figure 42 Consumers' results for the two cases.

In Figure 42, we observe that the new management solution was highly effective because it helped handle the end of life with safety and harmlessness. An improvement was also identified in the feedback mechanism category. On the other hand, two impact categories (rule of law and transparency) were slightly declined without affecting the overall outcome of this stakeholder group.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Figure 43 Local community's results for the two cases.

According to Figure 43, 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. Although there are some negative outcomes, they do not affect the overall goal of the management solution. For example, the support for resettlement employees is a primary concern, 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, which led to this result, do not undermine the objective of the management solution.

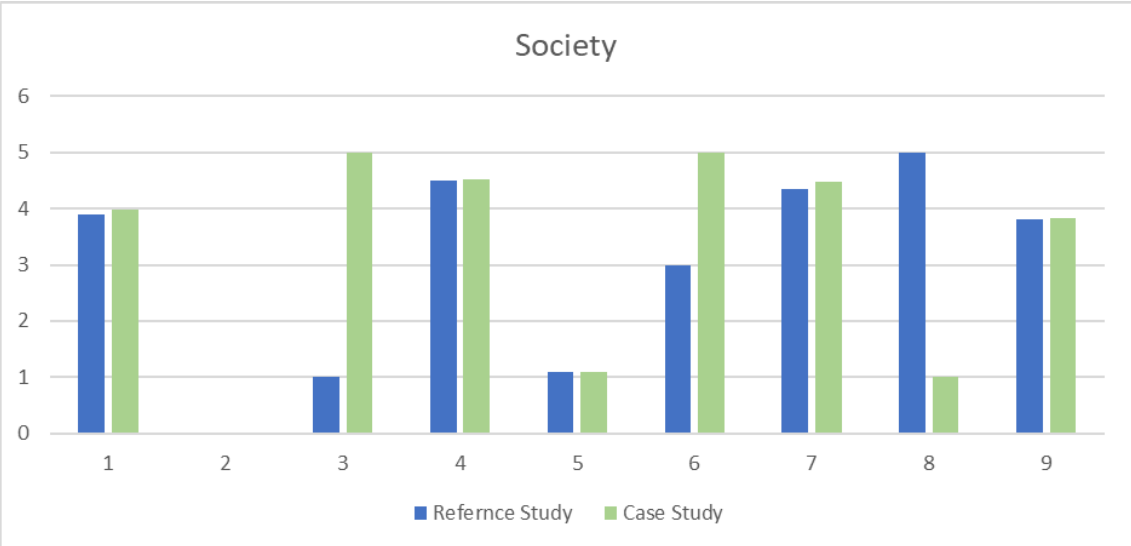


Figure 44 Society's results for the two cases.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

For society, we observe in Figure 44that there is mainly an improvement in the case study due to the non-use of critical raw materials and the high involvement in technology transfer projects. In addition, some other indicators in which there was a slight improvement are the commitment to sustainability, the economic development, the limited mitigation of armed conflict and the control of corruption. The only disadvantage was that there wasn't a formalized commitment to reducing poverty. However, this new solution does not focus on poverty alleviation and therefore does not impact its objective.

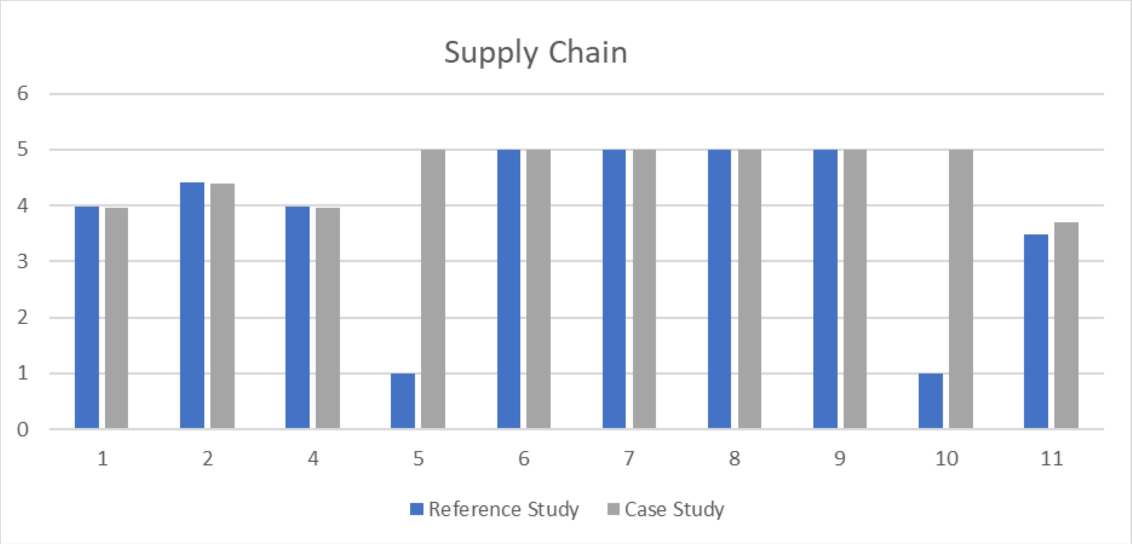


Figure 45 Supply chain's results between the two cases.

Finally, in Figure 45, there is a clear improvement, as no suppliers were identified with significant actual or potential negative social impacts. Additionally, there was a positive impact on raw material traceability and respect for intellectual property rights.

In conclusion, the s-LCA primarily focuses on the social parts of the study and specifically assesses the significant improvements resulting from the implementation of the new food waste management solution. The findings indicate that the scenario utilizing the alternative CSS2 solution (case study) delivered the most favourable outcomes across various stakeholders (except the local community) and impact categories. The case study demonstrated significant progress in areas such as workplace safety and working conditions, environmental management (end-of-life handling), local development and technological engagement. While there were some negative aspects regarding the local community, the overall developments suggest the effectiveness of the new management solution in promoting sustainable practices across multiple sectors.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

10 Process simulation and scale up of CSS2 value chains

CERTH performed the design of the value chains at industrial scale by developing house-built models in the dedicated process software Aspen Plus. Through the process simulation runs and the heat & mass balance calculations, technical performance indicators such as final product yield, carbon utilization and total specific power consumptions were estimated.

10.1 Scenario 2.1

The primary objective of this chapter is to scale up the CSS2 1st value chain by developing a process simulation at commercial scale. The simulation will generate heat and mass balances, enabling the assessment of key technical performance indicators, including final product yield, carbon utilization efficiency, and total specific power consumption. These models are based on experimental and pilot-scale results from the Deliverable 4.3, using CS sourced from the Łódź region in Poland.

10.1.1 Model description

The process models were developed using the commercial software Aspen Plus™. Simulation results were validated against experimental data provided by LNEG. While these simulations offer valuable insights into process performance, uncertainties may arise due to variations in experimental conditions and inherent model assumptions.

Considering logistical constraints such as biomass losses, transportation limitations, and operational inefficiencies, this study assumes a scaled-up unit with a feedstock capacity of 700,000 tonnes of CS per year for process modelling. This capacity represents the upper range of existing facilities while accounting for realistic limitations in biomass collection and utilization.

The primary specifications of the feedstock are presented in Table 9. This composition is based on laboratory and pilot-scale analyses of CS collected during the experiments, in D4.3. The CS, as received, had a moisture content of 19% (w/w). After pretreatment—specifically, steam explosion followed by washing—the solid fraction exhibited a moisture content of 74% (w/w). The pre-treatment stage enables the recovery of 95% (dry weight basis) of the initial biomass.

Table 9 Composition of CS feedstock, expressed as mass percentage of oven-dried weight and total weight (including 19% w/w moisture).

CS ***composition***	***% of dry weight***	***% of total weight (with moisture)***
cellulose	40.0%	32.4%
hemicellulose	*28.3%*	*22.9%*
xylan	24.0%	19.4%
arabinan	2.7%	2.2%
acetyl groups	1.6%	1.3%
lignin	15.4%	12.5%
ash	3.1%	2.5%
extractives	*13.2%*	*10.7%*
dichloromethane	1.1%	0.9%
ethanol	7.0%	5.7%
water	5.1%	4.1%
humidity		19.0%

In the model, the feedstock was considered as a mixture of conventional solids (lignin, cellulose, xylan, arabinan, ash) and liquids (water, extractives). The chemical formula, as well as the physical property data (such as molecular weight, density, heat capacities, enthalpy of formation, acentric factor, critical temperature, pressure and volume) for the biomass components, enzymes and yeast were extracted from NREL (National Renewable Energy Laboratory) Aspen Plus database for biofuel components [32].

In lignocellulosic hydrolysates, the presence of aliphatic acids is common. The hydrolysis of hemicellulose acetyl groups generates acetic acid (AA), while the thermochemical degradation of polysaccharides leads to the formation of formic and levulinic acids [33], as well as furans. Characterization of both raw and pretreated CS revealed only trace amounts of furfural in both samples, with no detectable hydroxymethylfurfural (HMF). Thus, for simplicity, acetyl groups are represented as AA in the model.

The standard cubic equation of state Peng-Robinson was selected as the property method for all models. To compensate for the poor job that equations of state generally do at predicting liquid density, the Peng-Robinson (PENG-ROB) property method in Aspen Plus™ uses the American Petroleum Institute (API) method for pseudocomponents and the Rackett model for real components to calculate liquid molar volume. The PENG-ROB model has also been extended to handle polar components and non-ideal chemical systems. For biological processes like fermentation, the NRTL (Non-Random Two-Liquid) method is used due to the

[32] R. J. Wooley and V. Putsche, "Development of an ASPEN PLUS Physical Property Database for Biofuels Components," pp. 1–32, 1996.

33 L. J. Jönsson, B. Alriksson, and N. O. Nilvebrant, "Bioconversion of lignocellulose: Inhibitors and detoxification," Biotechnol. Biofuels, vol. 6, no. 1, pp. 1–10, Jan. 2013, doi: 10.1186/1754-6834-6-16/FIGURES/3.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

prevalence of oxygenated and polar molecules. This method works well under the mild temperature and pressure conditions typical of these operations. Across all models, the compressors' isentropic efficiency was set at 85%, while the pumps' efficiency at 70%. The terms lipid, fatty acid (FA) and triglycerides are used with the same meaning for describing intracellular lipids

The following paragraphs provide a detailed description of the models' sub-processes. The reactions and main conditions, as well as the input parameters for these processes are summarized in Table 11 and Table 12.

10.1.1.1 Biomass pretreatment and enzymatic hydrolysis

The modelling of the feedstock processing consists of two main stages: the steam explosion pre-treatment of CS and the enzymatic hydrolysis of the pre-treated biomass. All the processes are modelled as stoichiometric reactors (RStoic) with specific reaction stoichiometry. Although the processes are mostly batch, for the scale-up scenario they are represented as continuous, given that we care about the annual numbers (input/output). For modelling purposes, starch, cellulose and hemicellulose (xylan, arabinan) polymers are represented by their monomers. The steam explosion pre-treatment is carried out using a proprietary non-catalysed technology that employs only high-pressure steam without acid addition. The raw CS is exposed to saturated steam at 180°C (13 bar). For the compression of the steam a multi-compressor system with three stages is used in the simulation environment. This step disrupts the lignocellulosic structure, facilitating enzymatic hydrolysis. The pre-treated biomass is then washed with water at a 1:1 (w/w) ratio to remove solubilized impurities, such as extractives (ethanol, dichloromethane) generating wastewater as a byproduct.

After washing, an intermediate pre-hydrolysis step is performed at 50°C, using the Cellic® CTec3 enzyme cocktail (represented in the model as the enzyme cellulase, with the chemical formula $CH_{1.57}N_{0.29}O_{0.31}S_{0.007}$), to promote a pre-liquefaction effect to enhance subsequent enzymatic saccharification.

In the enzymatic hydrolysis stage, the pre-hydrolyzed biomass is mixed with water and additional Cellic® CTec3 at a dosage of 3% (w/w oven-dried solids). The hydrolysis reaction occurs at 50°C and pH 5. The solids concentration in the reaction is set to 250 g/L, leading to high sugar yields. The enzymatic conversion yields are set to reach 85.4% for cellulose and 100% for xylan.

Following hydrolysis, a solid-liquid separation step is performed to recover the sugar-rich hydrolyzate and remove residual cellolignin. The sugar solution undergoes an evaporation-based concentration process, yielding a final concentrated sugar solution (~100 g/L monosaccharides), while excess water is removed as vapor. This

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

process achieves high enzymatic hydrolysis efficiency while minimizing enzyme consumption, making it suitable for large-scale bioconversion applications. The solid/liquid separation and concentration process were modeled using a simple splitter block, where the target concentration of the sugar solution is attained.

10.1.1.2 Yeast fermentation to FFAs

The second stage of the process involves fermenting the sugar solution derived from enzymatic hydrolysis to produce FFAs and yeast biomass, using the recombinant oleaginous yeast *Yarrowia lipolytica* DGA1 xylreductase. The yeast biomass is presented in the model with the molecular formula $C_4H_{6.5}O_{1.9}N_{0.7}$. The fermentation is simulated in a stoichiometric reactor, where the temperature is maintained at 28°C and the pH is controlled at 7.3 using 2.5 M HCl and 2.5 M NaOH solutions. The yeast inoculum is introduced at a concentration of 10% (v/v), ensuring complete substrate conversion. The feed rate is carefully controlled to keep residual sugar concentrations below 20 g/L, preventing substrate inhibition.

The primary metabolic products of fermentation consist of 7 g/L of lipids and 27 g/L of yeast biomass. At the end of the process, the FA profile is predominantly oleic acid (18:1ω9) at 43.03%, followed by palmitic acid (16:0) at 21.25%. Smaller proportions of linoleic acid (18:2ω6), stearic acid (18:0), and palmitoleic acid (16:1ω9) are also present at 13.17%, 9.19%, and 8.42%, respectively. Trace amounts of lignoceric acid (24:0), behenic acid (22:0), and arachidic acid were detected at concentrations below 5%. However, for simplicity, the yeast fermentation reactions leading to their production were not included in the model. Instead, their final concentrations were incorporated into the linoleic acid fraction, as it is the primary FA produced.

The stoichiometric reactions in this phase account for biomass formation and the intracellular accumulation of triacylglycerols (TAGs). In the next stage, these TAGs undergo saponification to yield the FFAs listed above. A triglyceride is composed of three FA molecules bonded to a glycerol ($C_3H_8O_3$) backbone. The corresponding triglycerides for each FA are shown in Table 10.

Table 10 Corresponding Triglycerides for Each Fatty Acid.

Fatty Acid	***Chemical Formula***	***Triglyceride Name***	***Triglyceride Formula***
Oleic acid	$C_{18}H_{34}O_2$	Triolein	$C_{57}H_{104}O_6$
Palmitic acid	$C_{16}H_{32}O_2$	Tripalmitin	$C_{51}H_{98}O_6$
Linoleic acid	$C_{18}H_{32}O_2$	Trilinoein	$C_{57}H_{102}O_6$
Stearic acid	$C_{18}H_{36}O_2$	Tristearin	$C_{57}H_{110}O_6$
Palmitoleic acid	$C_{16}H_{30}O_2$	Tripalmitolein	$C_{51}H_{94}O_6$

The reactions and stoichiometric relationships are based on [34],[35]. The conversion rates were carefully calculated to ensure that the subsequent TAG decomposition and FFA release accurately simulate both lipid content and FA distribution, as observed in the FRONTSH1P experiments mentioned earlier. Lysine is added to the reactor to support the growth phase, along with oxygen, as the process occurs under aerobic conditions. A Python script was implemented to compute the conversion rates:

```
import numpy as np

# -------------------------------
# Stoichiometric Conversion Calculation
# -------------------------------

# Molecular weights (g/mol)
MW = {
    'glucose': 180.16,
    'xylose': 150.13,
    'triolein': 885.4,
    'tripalmitin': 807.3,
    'trilinolein': 879.3,
    'tristearin': 891.5,
    'tripalmitolein': 807.3,
    'biomass': 94.8  # MW of C4H6.5O1.9N0.7 (approx. g/mol)
}

# Reaction stoichiometries: moles of sugar per mole of product
stoich = {
    'G_triolein': 13.5,
    'G_tripalmitin': 12.5,
    'G_trilinolein': 13.5,
    'G_tristearin': 14.0,
    'G_tripalmitolein': 12.0,
    'X_triolein': 17.0,
    'X_tripalmitin': 15.0,
    'X_trilinolein': 16.0,
    'X_tristearin': 16.5,
    'X_tripalmitolein': 15.0,
    'G_biomass': 1.0,  # mol glucose to mol biomass
    'X_biomass': 1.0   # mol xylose to mol biomass
```

[34] A. Tanimura et al., "Lipid production via simultaneous conversion of glucose and xylose by a novel yeast, Cystobasidium iriomotense," PLoS One, vol. 13, no. 9, 2018, doi: 10.1371/journal.pone.0202164.
35 M. Gallego-García, A. Susmozas, A. D. Moreno, and M. J. Negro, "Evaluation and Identification of Key Economic Bottlenecks for Cost-Effective Microbial Oil Production from Fruit and Vegetable Residues," Ferment. 2022, Vol. 8, Page 334, vol. 8, no. 7, p. 334, Jul. 2022, doi: 10.3390/FERMENTATION8070334.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

```
}

# Compute weight yields: g product per g sugar
yields = {}
for key, n in stoich.items():
    sugar_code, product = key.split('_')
    sugar = 'glucose' if sugar_code == 'G' else 'xylose'
    prod_key = 'biomass' if product == 'biomass' else product
    yields[key] = MW[prod_key] / (n * MW[sugar])

# Target lipid distribution and fraction
total_lipid_fraction = 0.135
lipid_profile = {
    'triolein': 0.4303,
    'tripalmitin': 0.2125,
    'trilinolein': 0.1317,
    'tristearin': 0.0919,
    'tripalmitolein': 0.0842
}

# Build system A * x = b
A = np.zeros((7, len(yields)))
b = np.zeros(7)

keys = list(yields.keys())

# Equation 0: total lipid mass fraction
for i, key in enumerate(keys):
    if not key.endswith('biomass'):
        A[0, i] = yields[key]
b[0] = total_lipid_fraction

# Equations 1-5: each lipid
for eq_idx, (lipid, frac) in enumerate(lipid_profile.items(), start=1):
    b[eq_idx] = frac * total_lipid_fraction
    for i, key in enumerate(keys):
        if key.endswith(lipid):
            A[eq_idx, i] = yields[key]

# Equation 6: biomass formation (rest of mass)
b[6] = 1 - total_lipid_fraction
for i, key in enumerate(keys):
    if key.endswith('biomass'):
        A[6, i] = yields[key]

# Solve via least squares
x, *_ = np.linalg.lstsq(A, b, rcond=None)
```

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

```
# Print conversions
print("Conversion fractions (fraction of sugar consumed):")
for key, val in zip(keys, x):
    print(f"  {key}: {val:.6f}")

# Sum conversions by sugar type
sum_G = sum(val for key, val in zip(keys, x) if key.startswith('G_'))
sum_X = sum(val for key, val in zip(keys, x) if key.startswith('X_'))
print(f"\nTotal glucose conversion: {sum_G:.6f}")
print(f"Total xylose conversion: {sum_X:.6f}")
print(f"Unreacted glucose: {1 - sum_G:.6f}")
print(f"Unreacted xylose: {1 - sum_X:.6f}")

# Calculate final lipid content reconstructed
reconstructed_lipid_fraction = np.dot(A[0], x)
print(f"\nReconstructed lipid fraction: {reconstructed_lipid_fraction:.6f} ({reconstructed_lipid_fraction*100:.2f}% w/w)")
```

After fermentation, yeast biomass is separated from the broth using a centrifuge, modelled as a solid-liquid separator with a 99% biomass recovery rate. In the experimental phase, lyophilization was employed to dry the recovered yeast biomass. This technique, which involves freezing the biomass and applying a vacuum to sublimate water directly from ice to vapor, ensures the preservation of sensitive compounds such as fatty acids, minimizing degradation. As a result, lyophilization led to optimal lipid retention, with the final dried biomass containing 16.7% (w/w) fatty acids, primarily within the C16–C18 range, with oleic acid as the dominant product. However, lyophilization is not commonly applied at industrial scale due to its batch-mode operation, high capital and energy costs, and limited throughput. Therefore, for process scale-up, more conventional and continuous drying methods such as spray drying are considered [36],[37]. While these techniques can achieve low final moisture contents (typically around 5–8%), they are generally associated with a reduction in FA content. Comparative tests with oven drying at 40°C, 50°C, and 60°C revealed decreases in FA content of 19.3%, 20.5%, and 30.6%, respectively, relative to the lyophilized biomass. Consequently, although spray drying was not directly tested, it is expected to result in similar or slightly improved outcomes relative to oven drying and is deemed suitable for scale-up. For the purpose of process simulation, drying is modelled as a material separator that removes 95% of the initial moisture, resulting in a final biomass moisture content of approximately 5%, which aligns with the

[36] M. Bordiga et al., “A Comprehensive Review of the Latest Trends in Spray Freeze Drying and Comparative Insights with Conventional Technologies,” Pharm. 2024, Vol. 16, Page 1533, vol. 16, no. 12, p. 1533, Nov. 2024, doi: 10.3390/PHARMACEUTICS16121533.

[37] S. A. Desobry, F. M. Netto, and T. P. Labuza, “Comparison of Spray-drying, Drum-drying and Freeze-drying for β-Carotene Encapsulation and Preservation,” J. Food Sci., vol. 62, no. 6, pp. 1158–1162, Nov. 1997, doi: 10.1111/J.1365-2621.1997.TB12235.X.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101037031

acceptable moisture levels for saponification [38]. In the scale-up scenario, drying at 40°C is considered a feasible approach, as it maintains a balance between energy efficiency and lipid preservation. Based on experimental comparisons, drying at 40°C led to a reduction in FA content of approximately 19.3% relative to lyophilized biomass. Accordingly, the final FA content in the dried biomass is estimated at approximately 13.5%. The FA profile remains predominantly in the C16–C18 range, with oleic acid as the major component. This adjusted lipid content is reflected in the scaled-up process model to ensure realistic yield projections.

10.1.1.3 Production of FFAs – Downstream Processing

The third stage of the process involves the extraction of FFAs from the dried yeast biomass through a saponification and solvent-based recovery process. This stage is modelled in Aspen Plus using a combination of stoichiometric reactors, liquid-liquid extractors, and phase separators to simulate the conversion and separation steps.

The process begins with saponification, where the freeze-dried yeast biomass is reacted with a 0.37 M KOH solution in absolute ethanol at room temperature. This reaction is modelled using a stoichiometric reactor to convert the lipid content of the biomass into FA soaps.

Following saponification, the reaction mixture undergoes a liquid-liquid extraction using hexane to separate the unsaponifiable matter. This step is modelled using a liquid-liquid extractor, where the organic phase containing non-saponifiable compounds is removed, while the hydroalcoholic phase, containing the FA soaps, is retained. A simple splitter is used to separate the two phases, discarding the organic phase.

Next, the hydroalcoholic phase is acidified with HCl to convert the FA soaps into FFAs. This acidification reaction is modelled using a stoichiometric reactor, where the addition of HCl facilitates the conversion of soaps into FFAs.

To recover the FFAs, a second liquid-liquid extraction is performed using hexane. This step is modelled using another liquid-liquid extractor, where the FFAs preferentially partition into the upper organic phase. The separation of the organic (hexanic) and aqueous (hydroalcoholic) phases is modelled using a phase separator.

The process achieves an overall FFA recovery efficiency of 88%. The FFAs are collected from the organic phase, and the final concentrated product is removed using a material splitter to isolate the purified fatty acids.

Table 11 Reactions' names, conditions and conversions, for the Scenario 2.1.

[38] I. Chanakaewsomboon and A. Moollakorn, "Soap formation in biodiesel production: effect of water content on saponification reaction," Int. J. Chem. Environ. Sci., vol. 2, no. 2, pp. 28–36, Apr. 2021, doi: 10.15864/IJCAES.2203.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Reaction name	T (°C) / p (bar)	Stoichiometric Reaction	No	Conversion
Biomass steam explosion	180/13	$C_6H_{10}O_5(cellulose) + H_2O \rightarrow C_6H_{12}O_6(glucose)$	(1)	0.065
		$C_5H_8O_4(xylan) + H_2O \rightarrow C_5H_{10}O_5(xylose)$	(2)	0.7
		$C_5H_8O_4\,(arabinan) + H_2O \rightarrow C_5H_{10}O_5(arabinose)$	(3)	0.7
Enzymatic hydrolysis	50/1	$C_6H_{10}O_5(cellulose) + H_2O \rightarrow C_6H_{12}O_6(glucose)$	(4)	0.854
		$C_5H_8O_4(xylan) + H_2O \rightarrow C_5H_{10}O_5(xylose)$	(5)	0.99
		$C_5H_8O_4\,(arabinan) + H_2O \rightarrow C_5H_{10}O_5(arabinose)$	(6)	0.90
Glucose and xylose fermentation to lipids	28/1	$C_6H_{12}O_6 + 4.3\,O_2 + 0.35\,C_6H_{14}O_2N_2(lysine) \rightarrow C_4H_{6.5}O_{1.9}N_{0.7}\,(yeast) + 4.1\,CO_2 + 5.2\,H_2O$	(7)	0.673697
		$C_5H_{10}O_5 + 3.3\,O_2 + 0.35\,C_6H_{14}O_2N_2 \rightarrow C_4H_{6.5}O_{1.9}N_{0.7} + 3.1\,CO_2 + 4.2\,H_2O$	(8)	0.808455
		$13.5\,C_6H_{12}O_6 + O_2 \rightarrow C_{57}H_{104}O_6\,(triolein) + 24\,CO_2 + 29\,H_2O$	(9)	0.085227
		$12.5\,C_6H_{12}O_6 + 2.5\,O_2 \rightarrow C_{51}H_{98}O_6\,(tripalmitin) + 24\,CO_2 + 26\,H_2O$	(10)	0.041562
		$13.5\,C_6H_{12}O_6 + 2.5\,O_2 \rightarrow C_{57}H_{98}O_6\,(trilinolein) + 24\,CO_2 + 32\,H_2O$	(11)	0.025801
		$14\,C_6H_{12}O_6 + 2.5\,O_2 \rightarrow C_{57}H_{110}O_6\,(tristearin) + 27\,CO_2 + 29\,H_2O$	(12)	0.018778
		$12\,C_6H_{12}O_6 + 0.5\,O_2 \rightarrow C_{51}H_{92}O_6\,(tripalmitolein) + 21\,CO_2 + 25\,H_2O$	(13)	0.01739
		$17\,C_5H_{10}O_5 + 5\,O_2 \rightarrow C_{57}H_{104}O_6 + 28\,CO_2 + 33\,H_2O$	(14)	0.081219
		$15\,C_5H_{10}O_5 + 2.5\,O_2 \rightarrow C_{51}H_{98}O_6 + 24\,CO_2 + 26\,H_2O$	(15)	0.041563
		$16\,C_5H_{10}O_5 + 1.5\,O_2 \rightarrow C_{57}H_{98}O_6 + 23\,CO_2 + 31\,H_2O$	(16)	0.026124
		$16.5\,C_5H_{10}O_5 + O_2 \rightarrow C_{57}H_{110}O_6 + 25.5\,CO_2 + 27.5\,H_2O$	(17)	0.01912
		$14.5\,C_5H_{10}O_5 + O_2 \rightarrow C_{51}H_{92}O_6 + 21.5\,CO_2 + 25.5\,H_2O$	(18)	0.016695
Saponification of lipids	75/1	$C_{57}H_{104}O_6 + 3\,KOH\,(potassium\ hydroxide) \rightarrow 3\,C_{18}H_{33}O_2K\,(potassium\ oleate) + C_3H_8O_3\,(glycerol)$	(19)	0.95
		$C_{51}H_{98}O_6 + 3\,KOH \rightarrow 3\,C_{16}H_{31}O_2K\,(potassium\ palmitate) + C_3H_8O_3$	(20)	0.95
		$C_{57}H_{98}O_6 + 3\,KOH \rightarrow 3\,C_{18}H_{31}O_2K\,(potassium\ linoleate) + C_3H_8O_3$	(21)	0.95
		$C_{57}H_{110}O_6 + 3\,KOH \rightarrow 3\,C_{18}H_{35}O_2K\,(potassium\ stearate) + C_3H_8O_3$	(22)	0.95
		$C_{51}H_{92}O_6 + 3\,KOH \rightarrow 3\,C_{16}H_{29}O_2K\,(potassium\ palmitoleate) + C_3H_8O_3$	(23)	0.95
Acidification of FA Soaps to FFAs	40/1	$C_{18}H_{33}O_2K + HCl\,(hydrochloric\ acid) \rightarrow C_{18}H_{34}O_2\,(oleic\ acid) + KCl\,(potassium\ chloride)$	(24)	0.98
		$C_{16}H_{31}O_2K + HCl \rightarrow C_{16}H_{32}O_2\,(palmitic\ acid) + KCl$	(25)	0.98
		$C_{18}H_{31}O_2K + HCl \rightarrow C_{18}H_{32}O_2\,(linoleic\ acid) + KCl$	(26)	0.98
		$C_{18}H_{35}O_2K + HCl \rightarrow C_{18}H_{36}O_2\,(stearic\ acid) + KCl$	(27)	0.98
		$C_{16}H_{29}O_2K + HCl \rightarrow C_{16}H_{30}O_2\,(palmitoleic\ acid) + KCl$	(28)	0.98

Table 12. Parameter values, for the Scenario 2.1.

Unit	Parameter	Input
Steam explosion	Vapour-to-biomass ratio (w/w)	1
Washing	Water-to-biomass ratio (w/w)	1
	Pressure (atm) / Temperature (°C)	1 / 50
Enzymatic hydrolysis	Enzyme concentration (% w/w oven-dried solids)	3
	Solid separation efficiency (%)	100
	Liquid separation efficiency (%)	99.5
	Evaporation-based concentration Pressure (bar) / Temperature (°C)	0.5 / 60
	Sugars concentration after concentration (% m/v)	10
Glucose fermentation to TAGs	Lysine-to-sugars ratio	0.2
	Inoculum concentration (% vol.)	1
Centrifugation	Biomass (including lipids) separation efficiency (%)	99
	Biomass moisture mass fraction after centrifugation	0.7

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Spray drying	Drying Pressure (bar) / Temperature (°C) Total moisture removal (%)	1 / 40 95
Saponification of dried yeast biomass	KOH-to-lipids ratio (mol/mol) KOH concentration in ethanol (g/L)	3 21
Liquid-liquid extraction of unsaponifiable matter	Hexane-to-reaction mixture ratio (v/v) Hexane-to-water ratio (v/v) FA soaps recovery (%) Pressure (atm) / Temperature (°C)	2 1 95 1 / 25
Acidification of FA soaps to FFAs	HCl-to-soap ratio (mol/mol) H2O-to-reaction mixture (w/w)	1 2
Liquid-liquid extraction of FFAs with hexane	Pressure (atm) / Temperature (°C) Hexane-to-aqueous phase (v/v) FFAs recovery (%)	1 / 25 3 93

10.1.2 Heat Integration

In order to optimize the processes in terms of energy consumption a specific strategy is adopted regarding the way that heat and cooling demands at each process are fulfilled. At first, the characteristics of the hot water and steam utilities that are employed to cover the heat demands at the endothermic processes through steam condensation are determined the same for all cases (Table 13). Moreover, cooling water is used for the unexploited heat.

Table 13 Utilities specifications.

Utility name	Specifications	Use
Cooling water	water, T_{in}/T_{out}: 20/25 °C	Cooling
Hot water	water, T_{in}/T_{out}: 95/85 °C	Heating
Low P steam	saturated steam/condensate, 130 °C	Heating
Medium P steam	saturated steam/condensate, 205 °C	Heating

Heat integration in this process modelling study was conducted to optimize energy efficiency by minimizing the need for external heating and cooling utilities. The methodology involved identifying all relevant hot and cold process streams based on simulation data, followed by performing pinch analysis to determine energy targets and locate the pinch point. Composite and Grand Composite Curves were developed to visualize heat recovery opportunities. A Heat Exchanger Network (HEN) was then designed using pinch-based principles to match heat sources and sinks effectively while respecting the minimum temperature approach (ΔTmin). The proposed network was simulated using Aspen Plus™, allowing for validation of heat duties, utility savings, and overall system performance. The results were evaluated to ensure technical feasibility and economic viability, with adjustments made as necessary to optimize heat recovery under realistic operating constraints.

10.1.3 Energy Demands

The energy consumption of the entire process was calculated through a combination of Aspen Plus™ integrated models' results and literature data. From the literature, the energy consumption of water evaporator, spray dryer, and centrifuge separator were obtained.

More specifically, a decanter centrifuge was selected as a separator as it is commonly used in wastewater treatment, and it has an energy consumption of 1.5-2 kWh/m^3 of slurry treated [39]. As water evaporator, a single-stage evaporator was selected with an energy consumption of 700 kWh/m^3 of water evaporated [40]. Even though a multi-stage evaporator would significantly lower the energy consumption to 50-70 kWh/kg, this unit is extremely hard to operate in transient conditions, as each stage operates in different conditions. However, it is a solution that should be investigated [41]. Lastly, regarding the spray drying in industrial scale it consumes around 3-20 GJ/t evaporated, with the average being 1.33 MWh/kg [42].

The results for each main process and the total for the simulation are summarized in Table 14.

Table 14 Specific energy input in MWh/kg product (FFAs) for each step of the process and for the whole process, for the Scenario 2.1.

Process Step	***Specific Heat Input (kWh_{th}/kg FFAs)***	***Specific Power Input (kWh_e/kg FFAs)***
Pretreatment	19.68	0.02
Hydrolysis	51.77	0.43
Fermentation	5.76	0.12
DSP	3.10	0

[39] A. Leone, C. Perone, A. Berardi, and A. Tamborrino, "Energy analysis and numerical evaluation of the decanter centrifuge for wastewater management to allow a sustainable energy planning of the process," Energy Convers. Manag. X, vol. 22, p. 100596, Apr. 2024, doi: 10.1016/J.ECMX.2024.100596.

[40] "Multi-stage evaporation process – Low energy costs for leachate treatment," Environmental Science & Engineering Magazine. Accessed: Jun. 11, 2025. [Online]. Available: https://esemag.com/archives/multi-stage-evaporation-process-low-energy-costs-for-leachate-treatment/

[41] A. Leone, C. Perone, A. Berardi, and A. Tamborrino, "Energy analysis and numerical evaluation of the decanter centrifuge for wastewater management to allow a sustainable energy planning of the process," *Energy Convers. Manag. X*, vol. 22, p. 100596, Apr. 2024, doi: 10.1016/J.ECMX.2024.100596.

[42] C. G. J. Baker and K. A. McKenzie, "Energy Consumption of Industrial Spray Dryers," *Dry. Technol.*, vol. 23, no. 1-2 SPEC. ISS., pp. 365–386, 2005, doi: 10.1081/DRT-200047665.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Total	*80.30*	*0.57*

10.1.4 Scenario 2.1 Process simulation results

Figure 46 presents the block flow diagram of the system, the main process steps and the main streams, the characteristics of which are shown below in Table 15. In Table 16 Key results calculated from the mass and heat balances retrieved from the simulation runs, for the Scenario 2.1.Table 16 the key results calculated from the mass and heat balances retrieved from the simulation runs are presented. Carbon Utilization is defined as the ratio of the carbon content in the final product to the carbon content in the input feedstock. It represents the efficiency of carbon conversion and is typically expressed as a percentage. Mass Yield refers to the ratio of the mass flow rate of the final product to the mass flow rate of the feedstock. It indicates the overall material conversion efficiency of the process. Specific Energy Demand is defined as the amount of energy required (in kilowatt-hours, kWh) to produce one kilogram of the final product. It provides a measure of the process's energy intensity.

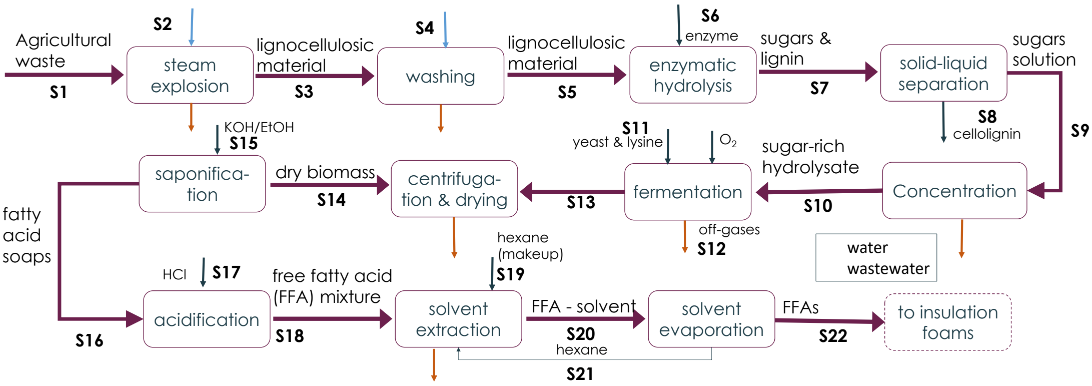


Figure 46 Block chain diagram of the Scenario 2.1 process, showing the main streams (S).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Table 15 Characteristics, mass & volume flows and mass fractions of the main process streams (S1-S22) as they appear in Figure 46, for the Scenario 2.1.

	Stream																					
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22
Temperature, °C	25.00	180.00	50.00	25.00	37.51	25.00	50.00	50.00	50.00	60.00	25.00	28.00	28.00	28.00	25.00	75.00	26.23	75.00	25.00	25.00	115.00	115.00
Pressure, bar	1.00	13.00	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mass Vapor Fraction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.03	0.00	0.01	0.00	0.00	1.00	0.00
Mass Liquid Fraction	0.00	1.00	0.74	1.00	0.59	1.00	0.98	0.67	1.00	1.00	1.00	0.00	0.91	0.14	1.00	0.18	1.00	0.99	1.00	1.00	0.00	1.00
Mass Solid Fraction	1.00	0.00	0.26	0.00	0.41	0.00	0.02	0.33	0.00	0.00	0.00	0.00	0.09	0.86	0.00	0.79	0.00	0.00	0.00	0.00	0.00	0.00
Average MW	51.30	18.02	27.12	18.02	35.52	18.02	19.67	26.30	19.29	19.67	146.10	31.50	20.25	106.39	48.86	97.44	18.21	21.61	86.18	43.25	86.09	230.96
Mass Flow, ktonne/y	700	700	1395	1033	847	4450	5297	388	4909	3855	78	102285	1649	169	14	184	127	189	4	569	376	20
Mass Fractions																						
O2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.976	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H2O	0.231	1.000	0.605	1.000	0.439	0.998	0.903	0.617	0.926	0.906	0.000	0.022	0.869	0.003	0.000	0.003	0.979	0.797	0.000	0.265	0.000	0.000
CO2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
XYLOSE	0.000	0.000	0.078	0.000	0.121	0.000	0.028	0.019	0.029	0.037	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GLUCOSE	0.000	0.000	0.012	0.000	0.018	0.000	0.041	0.028	0.042	0.053	0.000	0.000	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ARABINOSE	0.000	0.000	0.009	0.000	0.014	0.000	0.003	0.002	0.003	0.004	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CELLULOSE	0.324	0.000	0.152	0.000	0.250	0.000	0.006	0.080	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
XYLAN	0.194	0.000	0.029	0.000	0.048	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ARABINAN	0.022	0.000	0.003	0.000	0.005	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ASH	0.025	0.000	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
YEAST	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.088	0.859	0.000	0.792	0.000	0.000	0.000	0.000	0.000	0.000
BIOMASS	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CELLULASE	0.000	0.000	0.000	0.000	0.000	0.002	0.002	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LIGNIN	0.125	0.000	0.063	0.000	0.103	0.000	0.016	0.225	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ETHANOL	0.057	0.000	0.028	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.680	0.053	0.000	0.046	0.000	0.015	0.001	0.000
DICHLMET	0.009	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ACETIC ACID	0.013	0.000	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PALMITOLEIC ACID	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.003	0.000	0.085
PALMITIC ACID	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.000	0.008	0.000	0.202
STEARIC ACID	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.003	0.000	0.092
OLEIC ACID	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.047	0.000	0.015	0.000	0.408
LINOLEIC ACID	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.000	0.005	0.000	0.129
LYSINE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.999	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TRIPALMITIN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.031	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
TRIOLEIN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.061	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000
TRILINOLEIN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.019	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

TRISTEARIN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.014	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
TRIPALMITOLEIN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.013	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
KOH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.320	0.001	0.000	0.001	0.000	0.000	0.000	0.000
HCL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.021	0.000	0.000	0.000	0.000	0.000
POTASSIUM OLEATE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.058	0.000	0.001	0.000	0.000	0.000	0.000
POTASSIUM PALMITATE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.029	0.000	0.001	0.000	0.000	0.000	0.000
POTASSIUM LINOLEATE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.000	0.000	0.000	0.000	0.000	0.000
POTASSIUM STEARATE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.013	0.000	0.000	0.000	0.000	0.000	0.000
POTASSIUM PALMITOLEATE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.000	0.000	0.000	0.000	0.000	0.000
GLYCEROL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.013	0.000	0.012	0.000	0.004	0.000	0.000
KCL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.028	0.000	0.009	0.000	0.000
HEXANE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	1.000	0.670	0.999	0.085
Volume Flow, m^3/d	569	2316	3720	2844	1642	12247	14450	907	13543	10677	226	$222\cdot10^6$	4351	185	45	2966	349	2685	1581	1993	386009	69

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Table 16 Key results calculated from the mass and heat balances retrieved from the simulation runs, for the Scenario 2.1.

Key Result	***Value***
Feedstock mass flow (tn/year)	700480
Product mass flow (tn/year)	20019
Process water demand (tn/year)	1733000
FFAs purity (%)	92
Carbon utilization (%)	7
Mass yield (%)	4
Specific electrical demand (kWh_e/kg FFAs)	0.57
Specific heat demand (kWh/kg FFAs)	73.1
Specific cooling demand (kWh/kg FFAs)	5.4

The simulation results indicate that 40g per kg of inlet feedstock is finally converted into FFA and there is a huge potential for valorisation of the remaining biogenic components such as the lignin and cellulose and the compounds found at the water effluent streams. The great flow rate of the process water reveals the significance of the wastewater treatment for the effective cleaning and reuse of the water. The total heat demands are 152.8 MW which is 38% of the feedstock heat input. Although a heat integration strategy has been performed, there is further room for waste heat management and reduction of the heating needs. These heating demands can be covered from the combustion of biogas produced from AD after the wastewater treatment.

10.2 Scenario 2.2

The CSS2 2nd value chain of the FRONTSH1P project focuses on establishing a circular bioeconomy by converting the OFMSW and compostable bags into renewable energy (in the form of methane-rich biogas) and high-quality compost. This compost will then be utilized for crop cultivation in marginal lands, as part of Value Chain 3.

To demonstrate the feasibility of this concept, a pilot facility was established in the municipality of Parzęczew, coordinated by the BZURA Inter-Municipal Association. The facility is designed for the treatment of OFMSW and the production of biogas, serving as a practical demonstration of waste valorisation. It plays a central role in showcasing the potential for renewable energy generation and organic fertilizer production through biowaste conversion technologies.

Now fully operational, the pilot plant functions as a testing ground for evaluating AD processes. It has been designed to handle approximately 150 kg of organic waste per day, composed of 79% kitchen waste, 5% green waste, and 16% contaminants (mainly packaging materials). The core of the system is a single fermentation tank with a total volume of 4 m^3 and a working volume of 3.5 m^3. The process operates at a thermophilic temperature of 55°C,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

with a retention time of at least 21 days. However, during testing, the majority of the organic material was converted into biogas within just 12 days.

Due to the high methane yield potential of the kitchen waste feedstock, the AD process has proven to be highly efficient. The system achieves up to 476.8 m^3 of methane (CH_4) and 836.9 m^3 of total biogas per megagram (Mg) of organic dry matter.

The primary objective of this report is to scale up the CSS2 value chain by developing a process simulation in Aspen Plus™, reflecting the broader OFMSW and biodegradable bag waste streams generated across the Łódzkie region. The simulation will generate comprehensive mass and energy balances, supporting the evaluation of critical technical performance indicators such as final product yield, carbon utilization efficiency and total specific power consumption.

The simulation models are based on a combination of experimental data obtained from the pilot facility—detailed in Deliverable 4.4—and additional data provided by NOVAMONT on biodegradable bags, following direct communication. These data sources are complemented by relevant literature to ensure a robust and comprehensive modelling foundation. This integrated approach supports the development of scalable and sustainable solutions for regional bioenergy and compost production, aligning with the circular economy objectives of the FRONTSH1P project.

10.2.1 Model description

The process models were developed using the commercial software Aspen Plus™. Simulation results were validated against experimental data provided by relevant FRONTSH1P partners. While these simulations offer valuable insights into process performance, uncertainties may arise due to variations in experimental conditions and inherent model assumptions.

For the scaled-up scenario, Italy's state-of-the-art OFMSW treatment system located in the municipality of Busto Arsizio, and operated at the Legnano facility, was selected as a benchmark. Busto Arsizio, with a population of approximately 83,000, was chosen due to its similarities with the Łódzkie region in terms of municipal structure and population density, making it a relevant analogue for the region's waste management challenges.

Project partners were introduced to the complete OFMSW management system in Busto Arsizio, including the waste collection methods, transport logistics to the Legnano treatment plant, and the full-scale treatment process. This visit provided valuable insights into the integration and efficiency of a mature, high-performing biowaste valorisation system. Key characteristics of the Busto Arsizio and Legnano system include:

- Waste Collection Efficiency: Busto Arsizio collects approximately 119 kg of OFMSW per capita annually, amounting to 9.8 thousand tons per year, which represents 39% of the total municipal waste collected by weight.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

- Treatment Capacity: The Legnano facility processes more than 40,000 tons of OFMSW and 12400 tons of green waste each year.
- Output: The plant produces approximately 14,000 tons of high-quality compost and 4 million cubic meters of methane-rich biogas annually.

Regarding the biodegradable bags, it is considered a ratio of 1kg of OFMSW / bag, resulting in 17900 ton/year of bioplastics. Considering Legnano unit's capacity, this study assumes a scaled-up unit in Łódzkie region with a feedstock capacity of about 58.700 tonnes of OFMSW and biodegradable bags mixture per year for process modelling. The primary specifications of the feedstock are presented in Table 17. This composition is based on laboratory and pilot-scale analyses of OFMSW and biodegradable bags collected during the FRONTSH1P project experiments, as presented in D4.4, as well as on literature data for typical OFMSW and biodegradable bags' composition [43],[44],[45],[46]. In the model, the feedstock was defined as a nonconventional solids and water mixture with the above-mentioned characteristics.

Table 17 Composition of feedstock (OFMSW and biodegradable bags mixture).

OFMSW & biodegradable bags mixture mass fractions composition	
H2O	0.15
BIOMASS	0.85
Biomass proximate analysis in weight % in dry basis except moisture	
MOISTURE	50
FC (fixed carbon)	55
VM (volatile matter)	40
ASH	5
Biomass ultimate analysis in weight % in dry basis except moisture	
ASH	18
CARBON	42
HYDROGEN	6
NITROGEN	2
CHLORINE	0.2
SULFUR	0.2
OXYGEN	31.6

[43] D. Saha, A. Sinha, S. Pattanayak, and B. Roy, "Pyrolysis kinetics and thermodynamic parameters of plastic grocery bag based on thermogravimetric data using iso-conversional methods," *Int. J. Environ. Sci. Technol.*, vol. 19, no. 1, pp. 391–406, Jan. 2022, doi: 10.1007/S13762-020-03106-Z.

[44] R. Naghavi, M. A. Abdoli, A. Karbasi, and M. Adl, "Improving the quantity and quality of biogas production in tehran anaerobic digestion power plant by application of materials recirculation technique," *Int. J. Renew. Energy Dev.*, vol. 9, no. 2, pp. 167–175, Jul. 2020, doi: 10.14710/IJRED.9.2.167-175.

[45] R. K. Singh and B. Ruj, "Plasticwaste management and disposal techniques - Indian scenario," *Int. J. Plast. Technol.*, vol. 19, no. 2, pp. 211–226, Dec. 2015, doi: 10.1007/S12588-015-9120-5.

[46] C. E. Gómez-Camacho, L. Giansante, and B. Ruggeri, "Closing the loop: A sustainable strategy for MSW management with zero residues and energy production," *Chem. Eng. Trans.*, vol. 86, pp. 1351–1356, 2021, doi: 10.3303/CET2186226.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

The NRTL- RK (Non-Random Two-Liquid - Redlich-Kwong) was selected as the property method for all models. For biological processes like fermentation, the NRTL method is used due to the prevalence of oxygenated and polar molecules. This method works well under the mild temperature and pressure conditions typical of these operations. The NRTL-RK property method uses the NRTL activity coefficient model for the liquid phase, the Redlich-Kwong equation of state for the vapor phase, the Rackett model for liquid molar volume and Henry's law for supercritical components.
The following paragraphs provide a detailed description of the models' sub-processes. The process modelling and scale-up analysis presented in this report are based on a representative feedstock composition derived from a combination of experimental results and literature data, as abovementioned. The feedstock, comprising the OFMSW and biodegradable bags, is inherently variable due to factors such as seasonal composition changes, collection practices, contamination levels, and preprocessing methods. Given the conceptual nature of this study and the variability of the selected feedstock, the results should be interpreted as indicative estimates. For this stage of conceptual development and with this type of feedstock, a deviation of up to ±20-30 % can be expected in key parameters due to uncertainties in feedstock composition and process performance.

10.2.1.1 Feedstock pretreatment

The biological solid feedstock first undergoes mechanical shredding to achieve a uniform particle size, facilitating its subsequent use in AD. A drying step follows, aimed at reducing the biomass moisture content by 20% to improve digestion efficiency. Drying is performed at 200 °C and atmospheric pressure and simulated using a stoichiometric reactor.

10.2.1.2 Anaerobic digestion

In the second stage, the pretreated biomass is subjected to AD to produce biogas and compost. For process modelling, an RYIELD reactor is used to simulate the non-stoichiometric breakdown of biomass based on known product yield distributions. This is followed by an RGIBBS reactor, which rigorously determines the equilibrium (phase and chemical) of the products by minimizing Gibbs free energy across multiple phases. RYIELD reactor operates at 40 °C and 1 atm and the yields inserted in the model are presented in Table 18. RGIBBS reactor is set to operate at 45 °C and 1 atm, performing the phase and chemical equilibrium calculations.

Table 18 Mass yield of each component in the RYIELD reactor.

Component	***Basis Yield (mass)***
H2O	0.61
C	0.2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

H2	0.02
N2	0.09
CL2	0.02
S	0.04
O2	0.6
ASH	0.2

The decomposition of biomass is assumed to generate the following products:
H_2O, C, CH_4, CO_2, CO, H_2, H_2S, HCl, Cl_2, NH_3, N_2, ASH.
These are categorized into two output streams:

- Biogas: CH_4, CO_2, H_2, H_2S, NH_3 (70% of total NH_3), CO, and N_2 - assumed to account for 70% of the products by phase distribution.
- Compost (Solid Residue): ASH, H_2O, residual NH_3 (30%), trace sulphur compounds, and undigested solids.

The two phases are finally separated and stored in a biogas and digestate tank accordingly.

10.2.2 Energy Demands

The energy consumption of the entire process was calculated through a combination of Aspen Plus™ results and literature data [47],[48],[49],[50],[51],[52],[53],[54]. The energy demand range for each process is presented in Table 19.

Table 19 Energy demand in kWh/ton wet feedstock and energy type for each process step, for the Scenario 2.2.

Process Step	Energy Demand (kWh/ton wet feedstock)	Energy Type

[47] Y. Van Fan, J. J. Klemeš, C. T. Lee, and S. Perry, "Anaerobic digestion of municipal solid waste: Energy and carbon emission footprint," *J. Environ. Manage.*, vol. 223, pp. 888–897, Oct. 2018, doi: 10.1016/J.JENVMAN.2018.07.005.
[48] G. Newsom, "Enabling Anaerobic Digestion Deployment to Convert Municipal Solid Waste to Energy ," 2020. Accessed: Jun. 17, 2025. [Online]. Available: https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-011.pdf
[49] G. Gadaleta, S. De Gisi, and M. Notarnicola, "Feasibility Analysis on the Adoption of Decentralized Anaerobic Co-Digestion for the Treatment of Municipal Organic Waste with Energy Recovery in Urban Districts of Metropolitan Areas," *Int. J. Environ. Res. Public Heal. 2021, Vol. 18, Page 1820*, vol. 18, no. 4, p. 1820, Feb. 2021, doi: 10.3390/IJERPH18041820.
[50] J. Bacenetti, M. Negri, M. Fiala, and S. González-García, "Anaerobic digestion of different feedstocks: Impact on energetic and environmental balances of biogas process," Sci. Total Environ., vol. 463–464, pp. 541–551, Oct. 2013, doi: 10.1016/J.SCITOTENV.2013.06.058.
[51] P. Seruga, M. Krzywonos, A. Seruga, Ł. Nied´zwiecki, H. Pawlak-Kruczek, and A. Urbanowska, "Anaerobic Digestion Performance: Separate Collected vs. Mechanical Segregated Organic Fractions of Municipal Solid Waste as Feedstock," Energies 2020, Vol. 13, Page 3768, vol. 13, no. 15, p. 3768, Jul. 2020, doi: 10.3390/EN13153768.
[52] A. H. Bhatt and L. Tao, "Economic Perspectives of Biogas Production via Anaerobic Digestion," Bioeng. 2020, Vol. 7, Page 74, vol. 7, no. 3, p. 74, Jul. 2020, doi: 10.3390/BIOENGINEERING7030074.
[53] O. Anaya-Reza et al., "Wet anaerobic digestion of organic fraction of municipal solid waste: experience with long-term pilot plant operation and industrial scale-up," Bioprocess Biosyst. Eng., vol. 47, no. 2, p. 235, Feb. 2024, doi: 10.1007/S00449-023-02958-2.
[54] E. Lindkvist, M. Karlsson, and J. Ivner, "System Analysis of Biogas Production—Part II Application in Food Industry Systems," *Energies 2019, Vol. 12, Page 412*, vol. 12, no. 3, p. 412, Jan. 2019, doi: 10.3390/EN12030412.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

1. Shredding / Pre-treatment	2–10	Electricity
2. Conveying / Pumping	1–3	Electricity
3. Buffer Tank / Homogenization	1–5	Electricity
4. Digester Heating	30–80	Thermal (heat)
5. Digester Mixing	3–10	Electricity
6. Biogas Handling	2–8	Electricity
7. Digestate Treatment	2–5	Electricity
8. Control Systems & Ancillaries	1–5	Electricity

In total, the AD process consumes approximately 90 kWh per ton of feedstock (30 kWh/ton electricity and 60 kWh/ton thermal energy), resulting in a total annual energy demand of 5.29 million kWh, considering around 58700 ton of feedstock per year. This equates to around 208 kWh per ton of total product, 246 kWh per ton of compost, and approximately 1.08 kWh/m^3 of biogas produced.

10.2.3 Scenario 2.1 Process simulation results

Figure 47 presents the block flow diagram of the system, the main process steps and the main streams, the characteristics of which are shown below in Table 20. In Table 16 Key results calculated from the mass and heat balances retrieved from the simulation runs, for the Scenario 2.1.Table 21 the key results calculated from the mass and heat balances retrieved from the simulation runs are presented. Carbon Utilization is defined as the ratio of the carbon content in the final product to the carbon content in the input feedstock. It represents the efficiency of carbon conversion and is typically expressed as a percentage. Mass Yield refers to the ratio of the mass flow rate of the final product to the mass flow rate of the feedstock. It indicates the overall material conversion efficiency of the process. Specific Energy Demand is defined as the amount of energy required (in kilowatt-hours, kWh) to produce one kilogram of the final product. It provides a measure of the process's energy intensity.

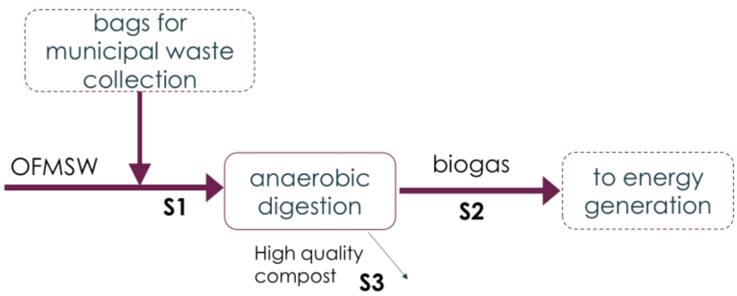


Figure 47 Block chain diagram of the Scenario 2.2 process, showing the main streams (S)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Table 20 Characteristics, mass & volume flows and mass fractions of the main process streams (S1-S3) as they appear in Figure 47, for the Scenario 2.2.

	Stream		
	S1	S2	S3
Temperature, °C	20	45	45
Pressure, atm	1.00	1.00	1.00
Mass Vapor Fraction	0.00	1.00	0.00
Mass Liquid Fraction	0.15	0.00	0.39
Mass Solid Fraction	0.85	0.00	0.61
Mass Flows, tonne/year	58732	3737	21499
Mass Fractions			
H_2O	0.15	0.09	0.38
C	0.00	0.00	0.40
CH_4	0.00	0.58	0.00
CO_2	0.00	0.18	0.00
CO	0.00	0.00	0.00
H_2	0.00	0.00	0.00
H_2S	0.00	0.01	0.00
HCL	0.00	0.01	0.00
CL_2	0.00	0.00	0.00
NH_3	0.00	0.00	0.00
N_2	0.00	0.13	0.00
S	0.00	0.00	0.00
O_2	0.00	0.00	0.00
BIOMASS	0.85	0.00	0.00
ASH	0.00	0.00	0.21
Volume Flow, m^3/year	45783	4.90E+06	13850

Table 21 Key results calculated from the mass and heat balances retrieved from the simulation runs, for the Scenario 2.2.

Key Result	***Value***
Feedstock mass flow (tn/year)	58732
Products	
Compost mass flow (tn/year)	18000
Biogas volume flow (Nm^3/year)	4.90E+06
Carbon utilization	
Biogas	8.6%
Compost	41.4%
Total	50.0%
Mass yield	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Biogas	6.4%
Compost	36.6%
Total	43.0%
Specific energy demand (kWh/tn product)	209
Specific energy demand (kWh/tn compost)	246
Energy demand (kWh/cum biogas)	1.08

10.3 Scenario 2.3

The CSS2 3rd value chain of the FRONTSH1P project focuses on establishing a circular bioeconomy by converting the sunflower seeds collected from sunflowers grown in marginal lands for the production of biodegradable biolubricants for industrial applications. As byproduct, oilseed cake is also produced which can be utilised as animal feed. For the cultivation of the sunflowers, compost produced as by-product of the second value chain of CSS2 is used.

The project specifically investigates sunflower as a primary feedstock due to its favourable agronomic characteristics, regional familiarity among farmers, and the relatively low presence of undesirable compounds such as glucosinolates and erucic acid. Cultivated on a 5.2-hectare test plot in Parzęczew municipality, sunflower seeds were harvested and mechanically processed through cold pressing. This method ensures a gentle extraction of crude vegetable oil and oilseed cake without solvent use, preserving both the oil's FA profile and the nutritional quality of the cake.

Subsequent analytical characterizations revealed that the oil predominantly contains linoleic acid (≈63%), followed by oleic acid (≈24%), along with minor contributions from saturated fatty acids such as palmitic and stearic acids. The oilseed cake was evaluated for its suitability as an animal feed component. Beyond extraction, the crude sunflower oil was further processed into biodegradable biolubricants, targeting industrial applications such as hydraulic fluids. Given the inherent limitations of vegetable oils—namely their sensitivity to oxidation, thermal degradation, and poor cold-flow properties—carefully selected additives were incorporated into the base oil. These included antioxidants, anti-wear agents, viscosity modifiers, and in some cases, advanced nanomaterials such as halloysite nanotubes to enhance tribological performance.

The primary objective of this report is to scale up the CSS2 value chain by developing a process simulation in Aspen Plus™, reflecting the maximum capacities of sunflower seeds that can be produced across the Łódzkie region's marginal lands. The simulation will generate comprehensive mass and energy balances, supporting the evaluation of critical technical performance indicators such as: final product yield, carbon utilization efficiency and total specific power consumption.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

The simulation models are built upon both experimental data from the pilot facility (as presented in Deliverable 4.5) and supporting literature. This approach will guide the development of scalable, sustainable solutions for regional bioenergy and compost production within the circular economy framework of the FRONTSH1P project.

10.3.1 Model description

The process models were developed using the commercial software Aspen Plus™. Simulation results were validated against experimental data provided by relevant FRONTSH1P partners. While these simulations offer valuable insights into process performance, uncertainties may arise due to variations in experimental conditions and inherent model assumptions.

Considering agronomic, logistical, and operational constraints—including yield variability, post-harvest losses, and limitations in field accessibility—this study assumes a scaled-up processing model based on the utilization of 7,554.9 hectares of marginal lands in the Łódzkie region, as established in the FRONTSH1P project. This area reflects a realistic yet ambitious implementation scenario that aligns with the regional availability of unutilized land and local farming capacity.

To simulate the feedstock in Aspen Plus, a reverse-engineering (end-to-start) approach was applied. Specifically, the known outputs from D4.5—FFAs and oilseed cake—were used to reconstruct the composition of the original sunflower seed feedstock. The oilseed cake was approximated as a mixture of cellulose and residual oil, representing the fibrous, protein-rich matrix left after oil extraction. The FFAs included in the model were the five primary fatty acids identified during experimental characterization (refer to Table 22), namely myristic, palmitic, stearic, oleic, and linoleic acids. Fatty acids present in concentrations below 1% were excluded for simplification, and the remaining five were normalized to represent 100% of the oil-derived fraction.

Table 22 The five primary fatty acids produced from mechanical extraction and their mass distribution in the oil mixture

Fatty Acid	Formula	MW	Mass % (experiments)	Mass % (normalised)
Myristic acid	$C_{14}H_{28}O_2$	228.37	0.90	0.91
Palmitic acid	$C_{16}H_{32}O_2$	256.42	6.17	6.26
Stearic acid	$C_{18}H_{36}O_2$	284.48	4.98	5.05
Oleic acid	$C_{18}H_{34}O_2$	282.46	23.73	24.07
Linoleic acid	$C_{18}H_{32}O_2$	280.45	62.82	63.71
Total			98.6	100

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Mechanical extraction of the seeds produces two distinct fractions: (i) a liquid fraction—the crude oil—comprising approximately 35–40% of the seed mass, and (ii) a solid fraction—the oilseed cake—making up 60–65% (as derived from D4.5). For modelling purposes, the oil content of the seeds was set at 40 wt.%, while 5 wt.% of each individual FFA was assumed to remain entrained in the oilseed cake along with cellulose. This assumption ensures that trace oil content within the solid matrix is accounted for.

The molar composition of the products generated from this mechanical extraction (Table 23) was then used to derive an empirical molecular formula for the sunflower seed pseudo-component, calculated to be $C_{33}H_{58}O_{15}$. The physical property data (such as density, heat capacities, enthalpy of formation, acentric factor, critical temperature, pressure and volume) for the sunflower seeds, as well as the oilseed cake, were extracted from NREL (National Renewable Energy Laboratory) Aspen Plus database for biofuel components, using the data provided for biomass and cellulose [55].

Table 23 Molecular formula, molecular weight and mol distribution of each component of mechanical extraction products.

Component	Formula	MW	Mass % (relative to seed)	Moles / 100g seeds	Mol %	Mol % (normalised)
Myristic acid	$C_{14}H_{28}O_2$	228.37	0.37	0.002	0.004	0.011
Palmitic acid	$C_{16}H_{32}O_2$	256.42	2.50	0.010	0.027	0.068
Stearic acid	$C_{18}H_{36}O_2$	284.48	2.02	0.007	0.020	0.050
Oleic acid	$C_{18}H_{34}O_2$	282.46	9.63	0.034	0.095	0.238
Linoleic acid	$C_{18}H_{32}O_2$	280.45	25.48	0.091	0.253	0.634
Oilseed cake	$C_6H_{10}O_5$	162.14	60.00	0.370	1.032	2.580

The following paragraphs provide a detailed description of the models' sub-processes. The process modelling and scale-up analysis presented in this report are based on a representative feedstock composition derived from experimental data derived from Deliverable 4.5. In this case, the selected feedstock consists of sunflower seeds cultivated on marginal lands. It is important to note that feedstock grown under such conditions may exhibit variability in oil content, moisture, and impurities due to suboptimal soil quality, climatic stresses, and agricultural practices. Given the conceptual stage of this study and the specific characteristics of the feedstock, the data and performance estimates should be considered indicative. For this level of analysis, a deviation of up to ±15–25% can be expected due to variability in feedstock properties, processing efficiency, and model assumptions.

[55] R. J. Wooley and V. Putsche, "Development of an ASPEN PLUS Physical Property Database for Biofuels Components," pp. 1–32, 1996.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

10.3.1.1 Mechanical extraction

The mechanical extraction process was modelled in Aspen Plus to simulate the physical separation of sunflower seeds into two primary product streams: crude vegetable oil and oilseed cake. This process, which mimics cold pressing at temperatures below 50 °C (45 °C was assumed as the process temperature), was represented using a stoichiometric reactor (RStoic). The stoichiometric reaction assumed to take place, representing the breakdown of sunflower seeds during mechanical extraction is as follows:

$$C_{33}H_{58}O_{15}\ (sunflower\ seeds)$$
$$\rightarrow\ 0.0111479\ C_{14}H_{28}O_2\ (myristic\ acid)$$
$$+\ 0.0680647\ C_{16}H_{32}O_2\ (palmitic\ acid)\ +\ 0.0495184\ C_{18}H_{36}O_2\ (stearic\ acid)$$
$$+\ 0.237645\ C_{18}H_{34}O_2\ (oleic\ acid)\ +\ 0.633624\ C_{18}H_{32}O_2\ (linoleic\ acid)$$
$$+\ 3.19463\ C_6H_{10}O_5\ (oilseed\ cake)$$

This reaction is formulated on a molar basis and reflects the experimental FA composition obtained from cold-pressed sunflower oil, as well as the cellulose-rich residue constituting the oilseed cake. It assumes complete oil extraction and hydrolysis of triglycerides into FFAs, with a small fraction of FFAs retained in the solid phase.

10.3.1.2 Biolubricants' synthesis

To simulate the formulation of biolubricants in Aspen Plus, a representative set of performance-enhancing additives was selected, based on both the project findings and established lubricant formulation practices. These additives are incorporated into the FFA base stream to improve oxidative stability, viscosity control, anti-wear performance, corrosion resistance, and tribological behaviour. In Aspen Plus, each additive is modelled as either a conventional component (when available in the Aspen component database), a user-defined pseudo-component, or a non-conventional solid (for inert nanoparticles). A mixing unit (MIXER block) is used to simulate the blending process on a mass flow basis. The final biolubricant stream reflects the combined properties of the FFAs and additives, which are input at low concentrations (typically 0.5–2.0 wt.%) to reflect real-world formulations. Table 24 shows the additives considered in the simulation.

Table 24 Additives added in the fatty acids' mixture for the synthesis of biolubricants and their characteristics

Additive Function	Aspen Plus Representation	Concentration in biolubricant as used in the model (wt%)
Antioxidant	Conventional component	0.5
Anti-wear Agent	Conventional or pseudo-component	1.0
Viscosity Modifier	User-defined pseudo-component (MW ≈ 1500 g/mol)	2.0
Friction Modifier	Non-conventional solid	1.5

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

10.3.2 Energy Demands

To estimate the energy demands across the value chain, a combination of literature data and Aspen Plus simulation outputs was utilized [56],[57],[58],[59],[60]. The results for each energy consuming process are presented in Table 25.

Table 25 Energy consumption for each process step, for the Scenario 2.3.

Process Step	Energy Type	Value	Specific Energy Demand (MWh/tn biolubricants)
Mechanical Extraction	Electricity	0.05-0.08 kWh/kg seed (0.18-0.29 MJ/kg)	0.03
Oil Production	Electricity	0.1325 kWh/kg oil (0.48 MJ/kg)	0.13
	Heat (steam)	0.78 kWh/kg oil (2.8 MJ/kg)	0.77
Blending Formulation	Mixing & heating	~0.04–0.27 MJ/kg product	0.03

The mechanical extraction of sunflower seeds, modelled as a cold pressing process, requires a relatively low amount of energy, typically around 0.18–0.29 MJ per kilogram of feedstock. This accounts for the electricity used in pressing operations under controlled temperatures of 45–50 °C. Additional energy is required for crude oil handling and blending with additives, with up to 3.3 MJ/kg of oil needed for heating, pumping, and mixing operations. These values reflect realistic industrial conditions and ensure the energy demand estimates align with the process scales and assumptions used in the FRONTSH1P project.

10.3.3 Scenario 2.2 Process simulation results

Figure 48 presents the block flow diagram of the system, the main process steps and the main streams, the characteristics of which are shown below in Table 26. In Table 27 the key results calculated from the mass and heat balances retrieved from the simulation runs are presented. Carbon Utilization is defined as the ratio of the carbon content in the final product

[56] V. Havrysh, A. Kalinichenko, P. Pysarenko, and M. Samojlik, "Sunflower Residues-Based Biorefinery: Circular Economy Indicators," Process. 2023, Vol. 11, Page 630, vol. 11, no. 2, p. 630, Feb. 2023, doi: 10.3390/PR11020630.

[57] E. Le Clef and T. Kemper, "Sunflower Seed Preparation and Oil Extraction," Sunflower Chem. Prod. Process. Util., pp. 187–226, Jan. 2015, doi: 10.1016/B978-1-893997-94-3.50014-3.

[58] A. Suardi, I. Bravo, C. Beni, P. Papetti, and R. Leonardo Rana, "Carbon footprint of hemp and sunflower oil in southern Italy: A case study," Ecol. Indic., vol. 160, p. 111786, Mar. 2024, doi: 10.1016/J.ECOLIND.2024.111786.

[59] A. Quinsac, P. Carré, and F. Fine, "Combining pelletizing to cold pressing in the rapeseed crushing process improves energy balance and the meal and oil quality," Eur. J. Lipid Sci. Technol., vol. 118, no. 9, pp. 1326–1335, Sep. 2016, doi: 10.1002/EJLT.201400495; CTYPE: STRING: JOURNAL.

[60] V. Havrysh, A. Kalinichenko, G. Mentel, U. Mentel, and D. G. Vasbieva, "Husk Energy Supply Systems for Sunflower Oil Mills," Energies 2020, Vol. 13, Page 361, vol. 13, no. 2, p. 361, Jan. 2020, doi: 10.3390/EN13020361.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

to the carbon content in the input feedstock. It represents the efficiency of carbon conversion and is typically expressed as a percentage. Mass Yield refers to the ratio of the mass flow rate of the final product to the mass flow rate of the feedstock. It indicates the overall material conversion efficiency of the process. Specific Energy Demand is defined as the amount of energy required (in kilowatt-hours, kWh) to produce one kilogram of the final product. It provides a measure of the process's energy intensity.

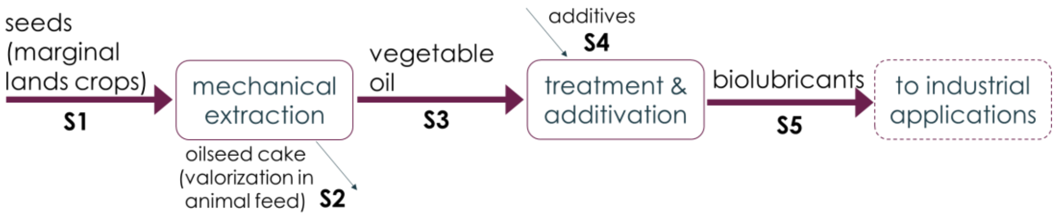


Figure 48 Block chain diagram of the Scenario 2.3 process, showing the main streams (S).

Table 26 Characteristics, mass & volume flows and mass fractions of the main process streams (S1-S5) as they appear in Figure 48, for the Scenario 2.3.

	Stream				
	S1	**S2**	**S3**	**S4**	**S5**
Temperature, °C	25	45	45	25	25
Pressure, atm	1	1	1	1	1
Mass Vapor Fraction	0.00	0.00	0.00	0.00	0.00
Mass Liquid Fraction	0.00	0.03	1.00	0.70	0.99
Mass Solid Fraction	1.00	0.97	0.00	0.30	0.01
Average MW	796.90	163.94	278.91	439.78	284.11
Mole Fractions					
Mass Flows, tonne/year	3626	2420	1206	63	1269
Mass Fractions					
SEEDS	1.000	0.000	0.000	0.000	0.000
OILSEED	0.000	0.974	0.000	0.000	0.000
MYRISTIC	0.000	0.000	0.009	0.000	0.009
PALMITIC	0.000	0.002	0.063	0.000	0.059
STEARIC	0.000	0.001	0.051	0.000	0.048
OLEIC	0.000	0.006	0.241	0.000	0.229
LINOLEIC	0.000	0.017	0.637	0.000	0.605
ANTIOXIDANT	0.000	0.000	0.000	0.100	0.005
ANTI-WEAR AGENT	0.000	0.000	0.000	0.400	0.020
VISCOSITY MODIFIER	0.000	0.000	0.000	0.200	0.010
FRICTION MODIFIER	0.000	0.000	0.000	0.300	0.015
Volume Flow, m^3/year	485	465	1370	58	1435

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

Table 27 Key results calculated from the mass and heat balances retrieved from the simulation runs, for the Scenario 2.3.

Key Result	***Value***
Feedstock mass flow (tn/year)	3626
Products	
Oilseed cake (tn/year)	2420
Biolubricants (m^3/year)	1435
Carbon utilization	
Oilseed cake	53.6%
Biolubricants	24.8%
Total	78.4%
Mass yield	
Oilseed cake	66.8%
Biolubricants	35.0%
Total (including additives)	101.7%
Specific energy demand (MWh/tn biolubricant)	0.96

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

11 Conclusions

The analysis of CSS2_2.1, focused on the biochemical valorisation of agricultural waste into FFAs, reveals a mixed sustainability profile. Significant environmental benefits are achieved in key categories, including Global Warming Potential, Eutrophication Potential, POCP and Terrestrial Ecotoxicity Potential, primarily due to the diversion of food waste from landfill and its transformation into high-value outputs. However, trade-offs are observed in impact categories such as Abiotic Depletion, Fossil Resource Depletion and Freshwater Use, which are linked to the high energy and chemical input requirements of the process, particularly during hydrolysis, extraction and drying. These findings underline the need for process optimisation, especially regarding energy efficiency, chemical substitution and water reuse strategies, in order to enhance the environmental performance of industrial-scale implementations.

The LCC analysis of Scenario 1 identifies capital and operating costs associated with chemical inputs and energy use as the dominant economic burdens. The production of FFAs from food waste, while environmentally beneficial in some categories, currently involves high processing costs, particularly due to the need for enzymes, solvents and temperature-controlled operations. While economies of scale and potential revenue from high-value products may improve economic viability in the long term, the current results point to the necessity of exploring cost-saving opportunities, such as process integration, resource recovery and valorisation of co-products, to improve financial sustainability.

The s-LCA of Scenario 1 reveals positive social performance across several stakeholder categories. The implementation of the CSS2_2.1 value chain promotes job creation, worker health and safety, and technology innovation in the Łódzkie region. The shift from landfill disposal to controlled biochemical conversion processes reduces potential exposure to pollutants for both workers and surrounding communities. However, upstream supply chains for chemical inputs may introduce social risks in categories such as fair wages or working conditions, depending on sourcing practices. These results suggest that while the local social benefits of CSS2_2.1 are evident, responsible sourcing policies and transparent supplier engagement are essential to maintain a high overall social sustainability profile.

Scenario 2.2, analysed within the framework of the European WFD and the current waste management context, enabled a comparative evaluation between Italy's successful practices and the present situation in Poland and Europe. Key factors contributing to Italy's achievements, such as supportive legislation, active municipal and citizen participation, and door-to-door waste collection, were examined in detail. Furthermore, using compostable bags for bio-waste collection encourages better waste segregation, making it easier to properly dispose of organic waste, reducing the chances of improper disposal and littering

A "what if" scenario assuming a 50% bio-waste collection rate in Poland vs current 11% current collection rate was used to assess potential benefits in terms of GHG savings and

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031

other environmental impact categories, based on the CML method. This analysis highlighted best practices, the positive outcomes that could be replicated and underlined the importance of civilian engagement. Additionally, the project activities were contextualized within this broader framework to support strategic insights and compost facility CAPEX and OPEX were outlined.

Scenario 2.3 explored the use of marginal land within a regenerative agriculture model. The foundation of the calculation model was established based on outcomes from previous projects and adapted to the Frontsh1p framework. A detailed analysis of SOM dynamics related to sunflower cultivation was conducted, highlighting the primary environmental benefits. The crop rotation cycle was also defined, and the Hénin-Dupuis equation was descripted and applied to model OM dynamics over a 22-year period within a complex cropping system.

Furthermore, the Polish project context was incorporated to assess the advantages of applying high-quality compost from Scenario 2.2. The resulting CO_2 uptake was calculated, demonstrating an estimated 15% reduction in CFP carbon footprint emissions due to compost application. Finally, all relevant activities related to corresponding project task were contextualized within this framework, further highlighting the benefits of this value chain.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101037031