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Life Cycle Assessment of Poplar Biomass for High Value Products and Energy

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Abstract: The European Union has embarked on a European Green Deal programme that advocates for a transition from fossil fuels to sustainable production. Attempts are being made to identify biomass sources and bioproducts (pharmaceuticals, cosmetics, or biofuels) that do not compete significantly with food production and have a low environmental impact. Therefore, the aim of this study was to determine the environmental impact of the supercritical CO_2 extraction of poplar biomass in a life cycle assessment (LCA). The production system was examined in a cradle-to-gate approach. In the analysed system, poplar biomass was extracted, and residual biomass was converted to pellets which were used to generate process heat. The functional unit was 1 kg of packaged extract. The results showed that the step of biomass extraction using S-CO_2 (in subsystem II) made the greatest contribution to all but two impact categories, with contribution from 25.3% to 93.8% for land use and global warming categories, respectively. In contrast, the whole subsystem I (biomass production and logistics) had a low environmental impact. Heat generation from residual biomass led to a minor decrease in the system's environmental impact. Greenhouse gases emission reached 440 kg of CO_2 equivalents per 1 kg of the extract, and they were associated with high electricity consumption and steam production. Despite the application of residual biomass for heat generation, the overall environmental impacts, especially in terms of human health and ecosystem damage, remain significant, indicating the need for further optimisation and mitigation strategies in the production process. Moreover, the share of renewables in the energy mix supplied to biorefineries should mitigate the environmental impact of the extraction process.

Keywords: bioeconomy; sustainable production; supercritical extraction; life cycle assessment; lignocellulosic biomass; bioactive compounds

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1. Introduction

The European Union's Bioeconomy Strategy promotes the use of renewable biological resources in the production process and their conversion to bioproducts and bioenergy. This strategy was implemented to address rapid population growth, resource depletion, the adverse effects of anthropogenic pressure on the environment, and climate change. To achieve sustainable and smart production, the EU Commission implemented the European Green Deal, which is a set of policy initiatives aiming to transform the EU into a modern, resource-efficient, and competitive economy [1]. Agricultural support schemes and the introduction of new plant cultivars to agricultural practice can contribute to the development

of bioeconomy. Plant and animal resources are used in the production of food, chemicals, pharmaceuticals, and solid, liquid, and gaseous fuels [2,3].

According to the IPCC WGII Sixth Assessment Report, it is highly probable that global warming will reach or surpass 1.5 °C soon, even in the case of the very low greenhouse gas emissions scenario [4]. This will negatively influence agriculture, decrease crop yields, increase crop prices, and reduce biodiversity. These adverse processes will also reverse some of the improvements in food security, thus decreasing food and feed supply in the future. The adverse impacts of climate change can be expected to be aggravated over the years [5,6]. In addition, the COVID-19 pandemic has disrupted the global food supply chain and increased food prices. The global GDP growth rate decreased by more than 7% between 2019 and 2020, and the number of undernourished people increased to 132 million in 2020 [7].

These challenges necessitate the search for biomass sources and industrial products that do not compete with food and feed production. The production and consumption of bioproducts should be characterised by lower GHG emissions than products derived from fossil fuels. Perennial industrial crops (PIC) grown on marginal agricultural land are an alternative resource for the chemical industry and the energy sector. These lignocellulosic crops can be divided into three groups: woody crops (such as willow, poplar, and black locust), herbaceous perennial crops, such as cup plant, Virginia mallow, and willowleaf sunflower, and grasses, such as miscanthus, giant reed, and prairie cordgrass [8]. One of the greatest advantages of PIC is that they can be produced in low-input farming systems, and that they do not compete with food crop cultivation since they are grown on inferior and marginal soils [9]. In the traditional approach, PIC are cultivated for energy generation. However, these plants are also abundant in biologically active phenolic compounds that can be used in pharmaceutical, cosmetic, and food processing sectors. Phenolic compounds can be extracted in small quantities (around 1% on dry basis) from biomass [10] whose major part can be used for biofuel production and energy generation, for example, in the form of pellets [11]. Bioactive compounds can be extracted from PIC with various methods with water and organic solvents (e.g., methanol, ethanol, hexane) [12]. In recent years, supercritical CO_2 extraction has emerged as a more sustainable method of separating valuable biological components from plants. One of the most important advantages of supercritical CO_2 extraction, compared with solvent extraction, is that it is non-toxic, it does not leave harmful residues in the final product, and it does not contribute to atmospheric pollution. Moreover, supercritical CO_2 extraction can yield highly pure extracts. This is especially advantageous for applications in the food, pharmaceutical, and cosmetic industries where purity is crucial [13]. However, this process requires a high energy input due to the need for maintaining high pressures and temperatures [12]. Therefore, this can lead to high operational costs and energy consumption compared to some other extraction methods [14]. In order to better understand the environmental effects of using the supercritical CO_2 extraction of various extracts method, the life cycle assessment (LCA) method can be used. This is a standardised method to examine or compare the effect of a product system throughout its life cycle [15]. Few examples of LCA papers concerning the production of bioactive compounds from plant biomass using both chemical solvents and supercritical CO_2 extraction have been published so far. Nevertheless, the indications are that extraction of biomass typically entails significant costs and processes that demand substantial chemical solvent inputs, leading to a notable environmental footprint [16,17]. Moreover, extraction processes (both solvent and S-CO_2) are characterised by high energy consumption, and its source (fossil, renewable) usually translates into the environmental impact [16,18], as well as the type and method of biomass production [19]. The above studies are examples of the environmental impact of various types of extraction of various types of compounds from few types of plants. However, to our knowledge, no study on the environmental impact of producing bioactive compounds from poplar biomass has been published so far. Our hypothesis states that the bioactive compounds obtained from poplar and the associated by-products will have a low environmental impact. Hence, this study

aimed to assess the environmental impact of poplar biomass extraction through a life cycle assessment (LCA) and pinpointed any production stages with significant environmental consequences in the resulting bioproduct's life cycle.

2. Materials and Methods

2.1. Aim and Scope of the LCA

The aim of this LCA was to determine the environmental impact of the production of dry poplar biomass extract with use of an attributional LCA. The production system includes the associated by-products and their functions. Poplar biomass was extracted in the examined system, and residual biomass was converted to pellets which were burned to generate process heat. The functional unit was 1 kg of packaged dry extract.

The cradle-to-gate boundary conditions were adopted in the assessment. The following production subsystems were analysed within the adopted boundary conditions (Figure 1):

1. Subsystem I: poplar biomass production and logistics, including pre-treatment.
2. Subsystem II: acquisition of bioactive compounds and by-products in a biorefinery.

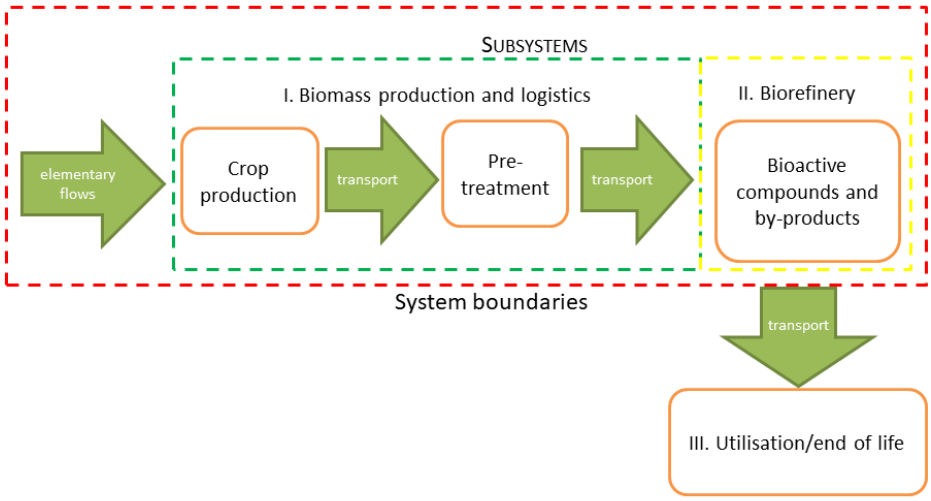


Figure 1. Boundary conditions in the analysed system.

According to ISO 14044, system inputs and outputs should be allocated to specific products based on clearly defined procedures, including the allocation procedure. If allocation cannot be avoided, inputs and outputs should be allocated to different products in a manner that reflects the basic physical dependencies between them. Alternatively, a substitution method can be applied when the inputs and outputs associated with the substitutes for the analysed bioproducts can be identified [20]. This approach was adopted to recycle residual biomass from the extraction process.

The life cycle impact assessment (LCIA) of the analysed production system was assessed with the ReCiPe v. 1.04 method. Impact categories were defined using the ReCiPe midpoint (H) method, and damage categories were defined using the ReCiPe endpoint (H) method. In the midpoint method, environmental impacts were represented by 18 categories: global warming, stratospheric ozone depletion, ionising radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption. Environmental damage was assessed in three categories: human health, ecosystems, and resources. After the classification and characterisation of LCIA results (mandatory elements), a normalisation procedure was performed by bringing characterisation scores expressed in different units to a common reference value. As a

result, the impact of different categories could be compared relative to the reference value. A sensitivity analysis was also performed to answer the following question: would LCIA results change if the Polish energy mix were replaced with the average European energy mix, if only at the stage of supercritical extraction?

2.2. System Description

2.2.1. Subsystem I: Biomass Production and Logistics

The agricultural production stage involved the production and application of fertilisers and herbicides, field management, poplar cultivation, single-stage harvest, and biomass transport from the field to the farm (Figure 2). It was assumed that the plantation life cycle would be 20 years and that poplars would be grown in annual harvest cycles. The fresh matter yield of poplar (*Populus nigra* × *P. maximowiczii*) biomass was determined at 22.2 Mg ha^{-1} year^{-1} (8.75 Mg ha^{-1} year^{-1} dry matter) in a field experiment conducted in 2017–2019 at the Educational and Research Station in Bałdy (operated by the University of Warmia and Mazury in Olsztyn) in north-eastern Poland (53°35′42.5″ N, 20°36′22.9″ E) (unpublished results). It was assumed that biomass would be transported from the farm to a pre-treatment plant (drying and grinding) over 50 km, and from the pre-treatment plant to the processing plant, over 50 km (total of 100 km). Field operations and logistics processes, including biomass drying, associated with the production of poplar biomass in twenty annual harvest cycles are presented in Table 1.

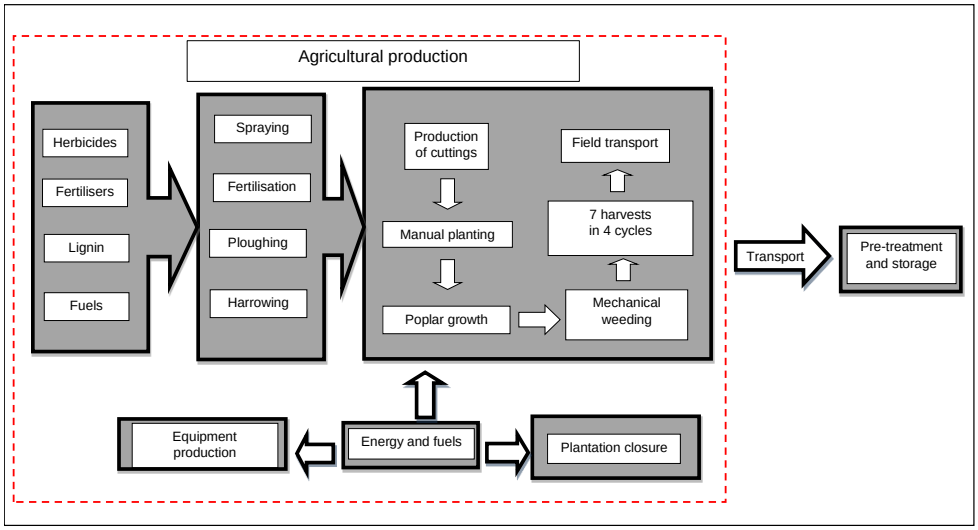


Figure 2. Boundaries of subsystem I. The red dashed line identifies the system being analysed.

Table 1. Analysis of inputs and outputs in poplar production and logistics in twenty annual harvest cycles.

Process	Diesel Oil (kg ha^{-1})	Quantity in the Plantation Life Cycle	Materials and Comments
Production of cuttings	1.26	1	20,000 cuttings, data from Ecoinvent 3
Spraying	2.04	1	Roundup 360 SL, 5 L ha^{-1}
Ploughing	29.30	1	5-ridge plough, ploughing depth—30 cm
Harrowing	11.20	1	2 operations
Marking planting locations	24.44	1	
Mechanical weeding	21.09	1	3 operations
Fertilisation	13.24	20	Ammonium nitrate, triple superphosphate, potash salt: N—90; P_2O_5—30; K_2O—60 kg ha^{-1}
Plantation closure	117.21	1	Rootstock grinding with a rototiller
Harvest	57.22	20	Self-propelled chip harvester, biomass yield: 22.2 Mg ha^{-1} year^{-1} f.m.
Field transport	-	20	Yield multiplied by distance (7 km): the functional unit for this input is 1 tonne-kilometre for a tractor with a trailer (Ecoinvent 3)
Drying	-	20	958 MJ and 25 kWh Mg^{-1}, wood drying (Ecoinvent 3)
Road transport	-	20	Yield multiplied by distance (100 km) for a semi-trailer truck (Euro 4) (Ecoinvent 3)

Greenhouse gas emissions associated with the transformation of organic carbon (OC) and mineral nitrogen in soil were considered in the analysis. Nitrogen and phosphorus leaching, as well as NH_3, NO_x, volatile organic compounds (VOCs), and dust emissions to the atmosphere, were also considered. Greenhouse gas emissions were calculated as the total loss of soil organic carbon (SOC), CH_4 emissions from soil (from anaerobic transformation of SOC), and N_2O emissions caused by nitrification and denitrification. Methane emissions were adopted at zero because poplars were grown on mineral soils that were not waterlogged [21]. Soil organic carbon was determined as the difference between OC supplied to the soil by the cultivated plant (Crop) and the reference plant (Ref). The reference plant was spring barley. Spring barley straw was not harvested and was left in the field [22–24]. Plant-available OC was derived from crop residues deposited above and below the soil surface (C_{above}, C_{below}). The net C input (kg ha^{-1} C) was calculated with the following formula:

$$\text{Net C input} = C_{above_Crop} + C_{below_Crop} - C_{above_Ref} - C_{below_Ref}$$

Organic carbon from crop residues was calculated in the C-TOOL model [25] with the following formulas:

$$C_{above} = (1/\alpha - 1)\varepsilon Y$$

$$C_{below} = [\beta/((1 - \beta)\alpha)]\varepsilon Y$$

Parameters α an β were calculated based on biomass yield, leaf litter mass, C content, and the root:shoot ratio. The C content of plant biomass (ε) and leaf litter was determined with the ELTRA CHS 500 analyser (ELTRA GmbH, Haan, Germany). The analysis was conducted on the assumption that only 9.7% of net C input was sequestered [26].

In addition to changes in SOC, direct and indirect N_2O emissions were also considered in the analysis of GHG emissions. Indirect N_2O emissions were associated with nitrate leaching, as well as NH_3 and NO_x emissions. In the natural environment, around 0.75–1% of NH_3 and NO_x is converted to N_2O. Nitrous oxide emissions were calculated by the method recommended by the Intergovernmental Panel on Climate Change (IPCC) [21].

Nitrate leaching was calculated with the field N-balance method based on the N rate supplied with fertilisers, atmospheric N deposition, annual net N mineralisation in soil based on the amount of humus lost through mineralisation, N content of the harvested biomass, and gas emissions from soil (NH_3, NO_x, N_2O, N_2) [23,24,27]. Nitrogen (N_2) emissions from soil were calculated with the SimDen model [28]. Ammonia, NO_x, PM10, PM2.5, and NMVOC emissions were determined using the indicator method recommended

by the European Environment Agency [29], whereas phosphate leaching from fertilisers was calculated as described by Iriarte [30]. The calculated field emissions are presented in Table 2.

Table 2. Field emissions during poplar production in twenty annual harvest cycles.

Source	Unit of Measure	Quantity	Emission Type
CO_2 from soil organic carbon	kg ha^{-1} $year^{-1}$	−862	sequestration
N_2O	kg ha^{-1} $year^{-1}$	1.58	to air
NH_3	kg ha^{-1} $year^{-1}$	4.79	
NO_x	kg NO_2 ha^{-1} $year^{-1}$	3.6	
PM_{10}	kg ha^{-1} $year^{-1}$	0.90	
$PM_{2.5}$	kg ha^{-1} $year^{-1}$	0.048	
NMVOC	kg ha^{-1} $year^{-1}$	0.86	
PO_4^{3-}	kg ha^{-1} $year^{-1}$	0.30	to water

2.2.2. Subsystem II: Production of Bioactive Substances from Poplar Biomass, and Conversion of Residual Biomass to Pellets

In subsystem II (acquisition of bioactive compounds and by-products in a biorefinery), a mass and energy flow diagram was developed for the extraction process and the conversion of residual biomass to pellets that were burned to generate process heat.

The extraction process involved the following operations: biomass grinding, biomass hydration, extraction, extract unloading during the extraction process, extract unloading from the separator at the end of the extraction process, unloading of residual biomass, extract dehydration, and extract packaging. A diagram of the extraction system is presented in Figure 3 (slanted arrows denote heat exchangers). The extraction process requires increasing the CO pressure and temperature to supercritical values: 7.38 MPa and 31.1 °C. The process starts with the condenser (C), where the liquefied carbon dioxide returns after receiving the extract in the S1 and S2 separators. The gas is cooled in the HE1 exchanger and condensed in C. Liquefied CO_2 is collected in the storage tank (T). From there, it is directed to the pump (P) through the HE2 exchanger, where the liquid CO_2 is cooled to a temperature below zero. The supercritical CO_2 state is achieved using the HE3 heat exchanger, which heats the CO_2 to the operating temperature. The extractor (Ex) has built in heat exchanger, which allows to maintain the extraction temperature inside the apparatus. During the extraction process, a mixture of extract and CO_2 appears at the extractor outlet (Ex). To collect the extract, the pressure in the S1 separator is reduced, then the solution becomes supersaturated and the extract condenses. If the pressures in S1 and S2 are different, the extract mixture will be separated according to the equilibrium conditions in the separators. The extraction process was described in detail by Olba-Zięty et al. [14].

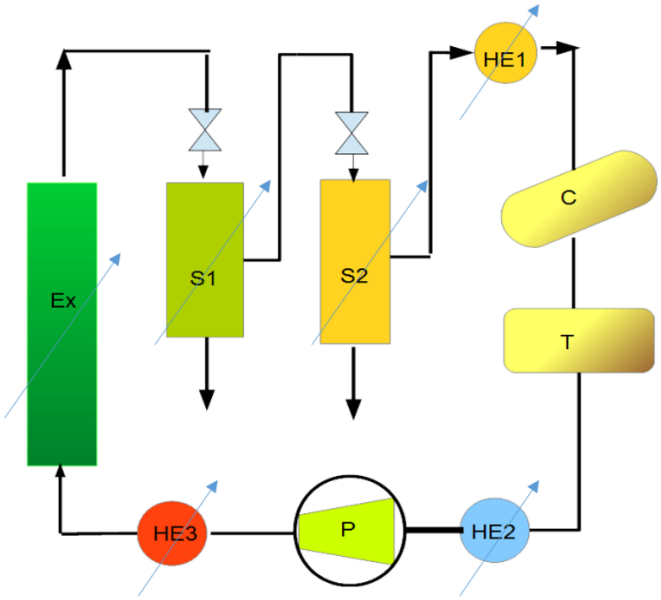


Figure 3. Diagram of supercritical extraction of poplar biomass, where: C—CO_2 condenser; T—CO_2 tank; HE1—heat exchanger cooled with propylene glycol; HE2—heat exchanger cooled with propylene glycol; HE3—steam-to-water supercritical CO_2 heat exchanger; Ex—steam-to-water extractor; S1, S2—steam-to-water separators, P—pump.

The inputs and outputs in the extraction system with the accompanying comments are presented in Table 3. Data for the extraction process were obtained from an existing system for extracting bioactive substances from poplar biomass. Extraction efficiency reached 1.5%, i.e., 3.75 kg of dried extract and 246 kg of pellets were produced in each run. Data for pellet production and heat generation were obtained from the EcoInvent 3 database. Higher heating value and lower heating value of obtained pellets were 19.56 MJ kg^{-1} d.m. and 18.42 MJ kg^{-1}, respectively.

Table 3. Inputs and outputs in the supercritical extraction of poplar biomass.

Input/Output	Input (I)/Output (O)	Type	Quantity	Unit of Measure	Type/Source	Utilisation/Disposal	Comments
			Grinding				
Poplar biomass (chips)	I	biomass	251.25	kg	chip production		
Grinding	I	electricity	10	kWh	360 V		
Ground poplar biomass	O	biomass	1.25	kg	chip production	waste	grinding loss
Ground poplar biomass	O	biomass	250.0	kg		hydration	
			Hydration				
Ground poplar biomass	I	biomass	250.0	kg	biomass processing plant		
Water	I	distilled water	107.0	kg	distilling unit and mains water		
Stirrer	I	electricity	3.00	kWh	230 V		
Hydrated biomass	O	biomass	357.0	kg		extraction	
			Extraction				
Hydrated biomass	I	biomass	357.0	kg	hydration		
Coolant (HE1, HE2)	I	propylene glycol; total in circulation—5000 kg	2.42	kg			1000 kg per 5 years
Heat exchangers (HE1 and HE2)	I	electricity = HE1 = 270 kW; HE2 = 205 kW	656.6	kWh			
CO_2 tank (T)	I	carbon dioxide	125.0	kg			
Pump (P)	I	electricity	175.9	kWh			
Heat exchanger (HE3)	I	steam	437.0	kWh	combined heat and power plant or energy from industrial heat exchangers		
Extractor (Ex)	I	steam	113.3	kWh			
Separator (S1)	I	steam	232.7	kWh			
Separator (S2)	I	steam	438.7	kWh			
Raw extract	O	biomass extract	110.75	kg		unloading/cleaning	
Residual biomass	O	biomass	246.25	kg		unloading/cleaning	
			Unloading/cleaning				
Raw extract	I	biomass extract	110.75	kg	extraction process		
Residual biomass	I	biomass	246.25	kg	extraction process		
Detergent	I	kitchen detergent	10.0	g		sewer	
Ethanol	I	96% ethanol v/v	0.197	kg		reagent disposal	
Water	I	demineralised water	10.0	kg		sewer	
Residual biomass	O	biomass	246.25	kg		pellet production	
Raw extract	O	biomass extract	110.75	kg		drying	

Table 3. *Cont.*

Input/Output	Input (I)/Output (O)	Type	Quantity	Unit of Measure	Type/Source	Utilisation/Disposal	Comments
			Dehydration				
Raw extract	I		110.75	kg	unloading/cleaning		
Evaporator	I	electricity	17.80	kWh			
Freeze-dryer	I	electricity	17.83	kWh			
Water	O	water from the drying process	107.00	kg	unloading/cleaning—water from the extract	sewer	
Dry extract	O		3.75	kg		packaging	
			Packaging				
Dry extract	I		3.75	kg	packaging process		
Bulk packaging	I		0.4	kg	5 dm^3 metal cans with a seal		Ecoinvent 3 database (materials: steel, zinc, rubber)
Packaged extract	O	extract	4.15	kg			
			Pellet production				
Residual biomass	I	biomass	246.25	kg			
Pellets produced from residual biomass	O	biomass	246.25	kg		heat generation	inputs and outputs for pellet production were selected from the Ecoinvent 3 database
			Heat generation				
Pellets produced from residual biomass	I	biomass	246.25	kg	pellet production		
Heat	O	heat	−3987	MJ		avoided burden (heat)	LHV 18.42 MJ kg^{-1}, biomass boiler efficiency—88%

3. Results

3.1. Characterisation Scores at the Midpoint Level

The characterisation scores for the production of 1 kg of packaged dry extract indicate that poplar biomass extraction with supercritical CO_2 made the greatest contribution to all but two (stratospheric ozone depletion and mineral resource scarcity) impact categories in the ReCiPe Midpoint (H) method (ReCiPe 2016), and its contribution ranged from 25.3% to 93.8% for land use and global warming categories, respectively (Figure 4, Table 4). The production of poplar biomass also contributed to stratospheric ozone depletion (61.5%), due to fertilisation and field emissions. The contribution of this process to the remaining impact categories ranged from 0.74% (freshwater eutrophication) to 11.9% (mineral resource scarcity). Packaging, including metal cans (41.7%), made a high contribution to the mineral resource scarcity category. It should be noted that heat generation from residual biomass decreased environmental impacts in all categories, excluding water consumption. The above is clearly visible in land use (−100%), stratospheric ozone depletion (−21.7%), ionising radiation (−23.0%), and terrestrial ecotoxicity (−24.7%) categories.

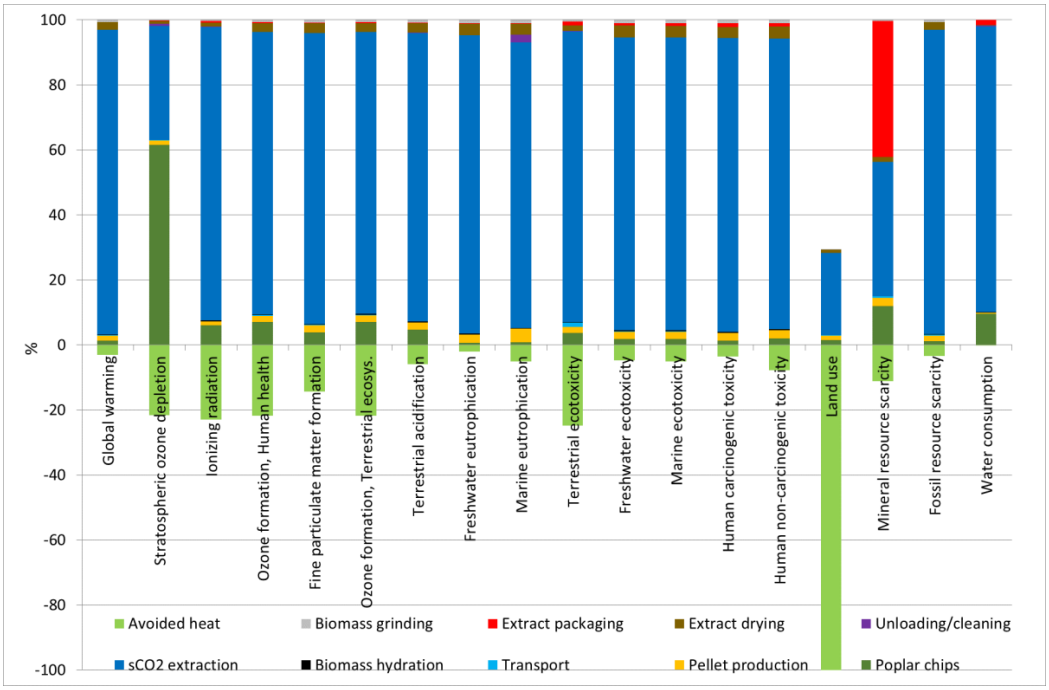


Figure 4. Characterisation scores for poplar biomass extraction with supercritical CO_2.

Table 4. Characterisation scores in the ReCiPe Midpoint H method per 1 kg of dry extract.

Impact Category	Unit	Total	Poplar Chips	Biomass Grinding	Transport	Biomass Hydration	sCO_2 Extraction	Unloading/Cleaning	Extract Drying	Extract Packaging	Pellet Production	Avoided Heat
Global warming	kg CO_2 eq	440	5.71	2.84	1.11	0.87	425	0.121	10.1	0.53	7.24	−13.8
Stratospheric ozone depletion	kg CFC11 eq	2.07×10^{-4}	1.62×10^{-4}	6.48×10^{-7}	8.36×10^{-7}	2.14×10^{-7}	9.25×10^{-5}	1.71×10^{-6}	2.30×10^{-6}	2.05×10^{-7}	3.65×10^{-6}	-5.72×10^{-5}
Ionizing radiation	kBq Co-60 eq	12.8	1.010	0.061	0.026	0.038	15.05	0.019	0.218	0.068	0.187	−3.834
Ozone formation, Human health	kg NO_x eq	0.59	0.052	0.006	0.004	0.002	0.649	3.31×10^{-4}	0.020	0.002	0.015	−0.163
Fine particulate matter formation	kg PM2.5 eq	0.51	0.023	0.005	0.001	0.002	0.533	2.12×10^{-4}	0.018	0.001	0.013	−0.085
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.59	0.053	0.006	0.004	0.002	0.657	3.40×10^{-4}	0.020	0.002	0.015	−0.165
Terrestrial acidification	kg SO_2 eq	1.65	0.081	0.015	0.003	0.004	1.558	0.001	0.052	0.002	0.038	−0.103
Freshwater eutrophication	kg P eq	0.35	0.003	0.004	8.14×10^{-5}	0.001	0.324	2.90×10^{-5}	0.013	3.52×10^{-4}	0.008	−0.007
Marine eutrophication	kg N eq	0.02	1.99×10^{-4}	2.24×10^{-4}	6.99×10^{-6}	6.82×10^{-5}	0.021	0.001	0.001	3.66×10^{-5}	9.68×10^{-4}	−0.001
Terrestrial ecotoxicity	kg 1,4-DCB	601	29.6	3.85	19.78	1.21	703.1	0.86	13.7	9.06	14.3	−194
Freshwater ecotoxicity	kg 1,4-DCB	17.5	0.344	0.191	0.026	0.057	16.52	0.003	0.679	0.132	0.409	−0.883
Marine ecotoxicity	kg 1,4-DCB	22.9	0.448	0.249	0.044	0.074	21.75	0.006	0.884	0.184	0.541	−1.243
Human carcinogenic toxicity	kg 1,4-DCB	21.5	0.280	0.218	0.023	0.067	20.17	0.003	0.775	0.260	0.525	−0.811
Human non-carcinogenic toxicity	kg 1,4-DCB	435	9.66	4.79	0.811	1.43	421	0.526	17.0	5.06	11.56	−36.6
Land use	m^2a crop eq	−23.7	0.486	0.086	0.047	0.026	8.51	0.002	0.304	0.019	0.480	−33.6
Mineral resource scarcity	kg Cu eq	0.45	0.060	0.002	0.004	0.001	0.210	0	0.007	0.212	0.013	−0.057
Fossil resource scarcity	kg oil eq	103	1.15	0.704	0.381	0.210	99.3	0	2.50	0.081	1.96	−3.62
Water consumption	m^3	106	10.3	0.084	0.002	0.281	93.5	0.355	0.298	1.50	0.200	−0.194

Greenhouse gas emissions (global warming category) per 1 kg of produced extract reached 440 kg CO_2 eq. (Table 4). A total of 425 kg of CO_2 eq. originated from the supercritical extraction process alone, and these emissions were associated with high electricity consumption and process steam generation (i.e., energy sources that are indispensable in this process). Residual biomass was processed into pellets, and pellets were burned to generate heat, which reduced GHG emissions by 13.8 kg CO_2 eq.

Normalisation results (per capita in Europe) revealed that the production of 1 kg of packaged dry extract exerted the most detrimental impact in the marine ecotoxicity category, followed by freshwater ecotoxicity, human carcinogenic ecotoxicity, and human non-carcinogenic ecotoxicity impact categories (Figure 5). One kilogram of packaged dry extract made a far smaller contribution to the remaining impact categories, which is why the stages of the production process that exert the most adverse impact on toxicity categories should be identified. High energy consumption in the supercritical extraction process was also a major contributor to the environmental impact of the sCO_2 extraction step.

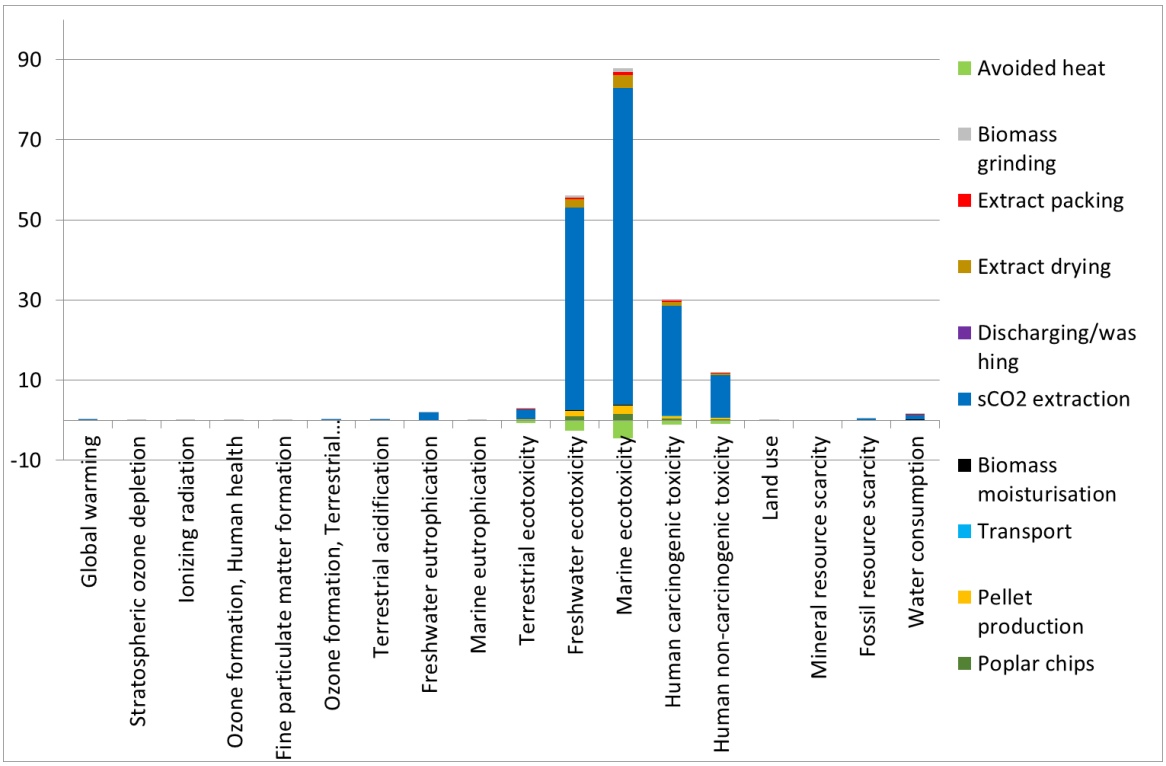


Figure 5. Normalised results for poplar biomass extraction with supercritical CO_2.

3.2. Characterisation Scores at the Endpoint Level

The aggregation of midpoints to three damage categories (human health, ecosystems, and resources) in the ReCiPe Endpoint H method revealed that the supercritical extraction step made the greatest contribution to all three categories, ranging from 90.2% to 94.5% for ecosystems and resources, respectively (Figure 6).

However, avoided heat induced a minor decrease in environmental loads from 5.02% to 11.3% for resources and ecosystems, respectively. The single score indicates that electricity generation from the Polish energy mix exerted the greatest negative impact on the environment (58.2%), followed by the production and utilisation of carbon dioxide (19.9%) and process steam (16.5%) (Figure 7). The use of pelleted residual biomass in heat generation decreased environmental loads by 7.40%.

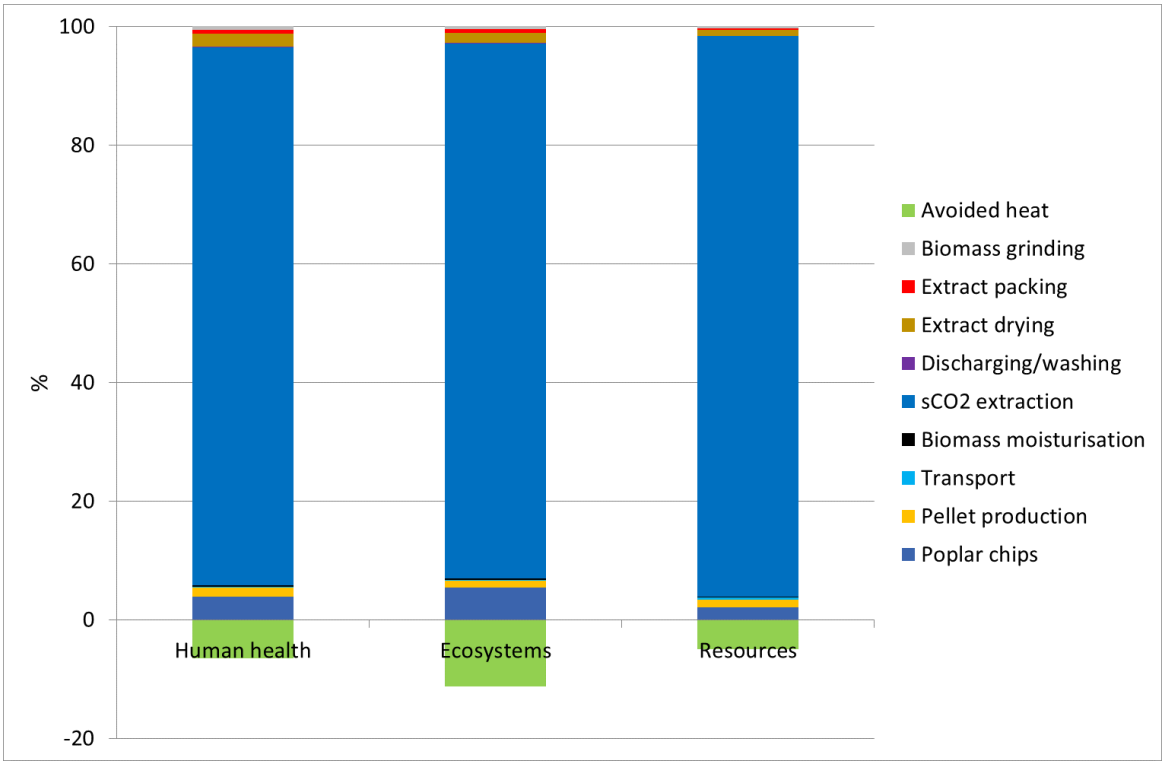


Figure 6. Characterisation scores for poplar biomass extraction with supercritical CO_2 (ReCiPe Endpoint H).

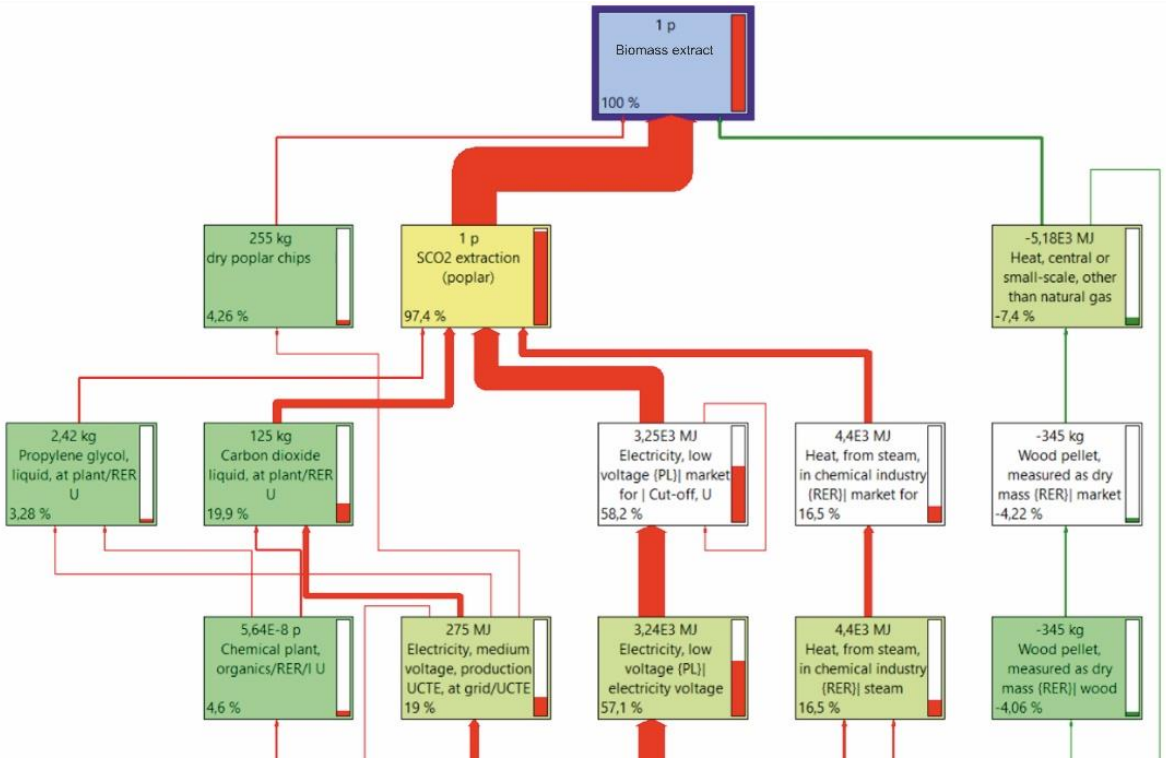


Figure 7. Contribution of different stages of the poplar biomass extraction process to environmental loads expressed as a single score (cut-off value—3%).

Normalised results indicate that dry extract production exerted the greatest damage in the human health category despite the fact that the avoided product (heat generation

from pellets) minimised this impact (Figure 8). The resulting damage to human health was 11- and 69-fold greater than damage to ecosystems and resources, respectively.

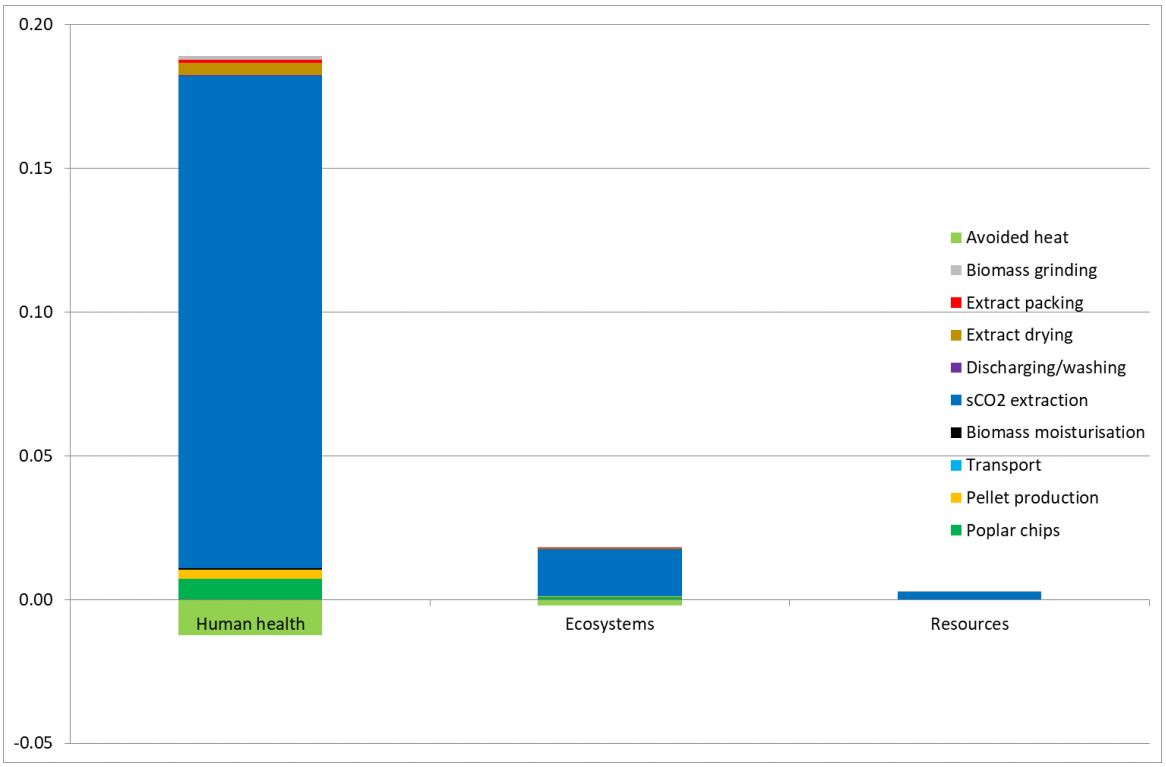


Figure 8. Normalised results (ReCiPe Endpoint) for assessing the impact of poplar biomass extraction with supercritical CO_2.

3.3. Sensitivity Analysis

The study demonstrated that the generation and use of electricity in supercritical CO_2 extraction exerted the greatest negative environmental impact in both methods. Therefore, a sensitivity analysis was performed to answer following question: would LCIA results change if the Polish energy mix were replaced with the European energy mix, if only at the stage of supercritical extraction?

In all but three impact categories in the midpoint method, environmental loads were by 4.99% (water consumption) to 59.5% (freshwater eutrophication) higher for the Polish energy mix (Figure 9). The environmental load in the stratospheric ozone depletion category was nearly identical (0.05% lower for the Polish energy mix), and it was 5.12% lower for the Polish energy mix in the mineral resource scarcity category. The Polish energy mix had the smallest environmental impact in the ionising radiation category (which was 77% lower in comparison with the European energy mix), which could be attributed to the fact that there are no nuclear power plants in Poland. An analysis of environmental loads in the endpoint method revealed that the use of electricity from the Polish energy mix in supercritical extraction caused greater damage in all three categories in comparison with the European energy mix (Figure 10). The observed differences were low in the resources category (1.44%), but much higher in the remaining categories (ecosystems—26.2%, human health—35.0%).

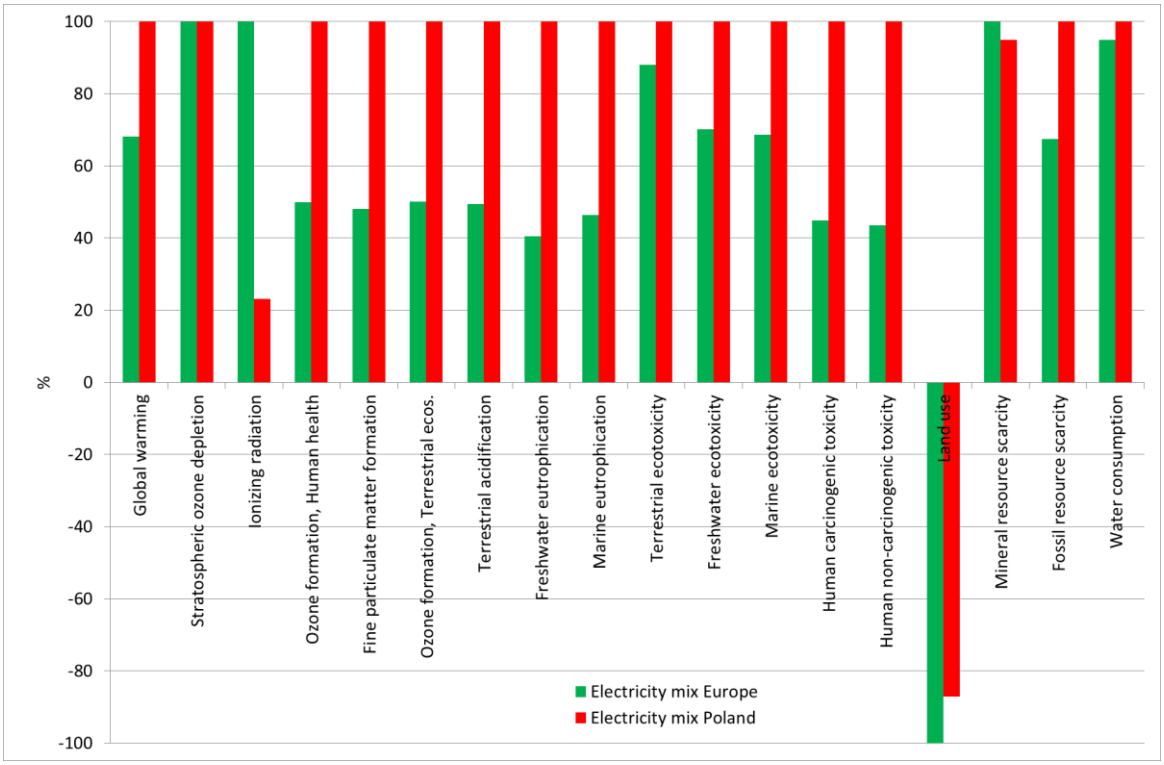


Figure 9. A comparison of the environmental impacts of poplar biomass extraction for the Polish energy mix and the European energy mix (ReCiPe Midpoint H).

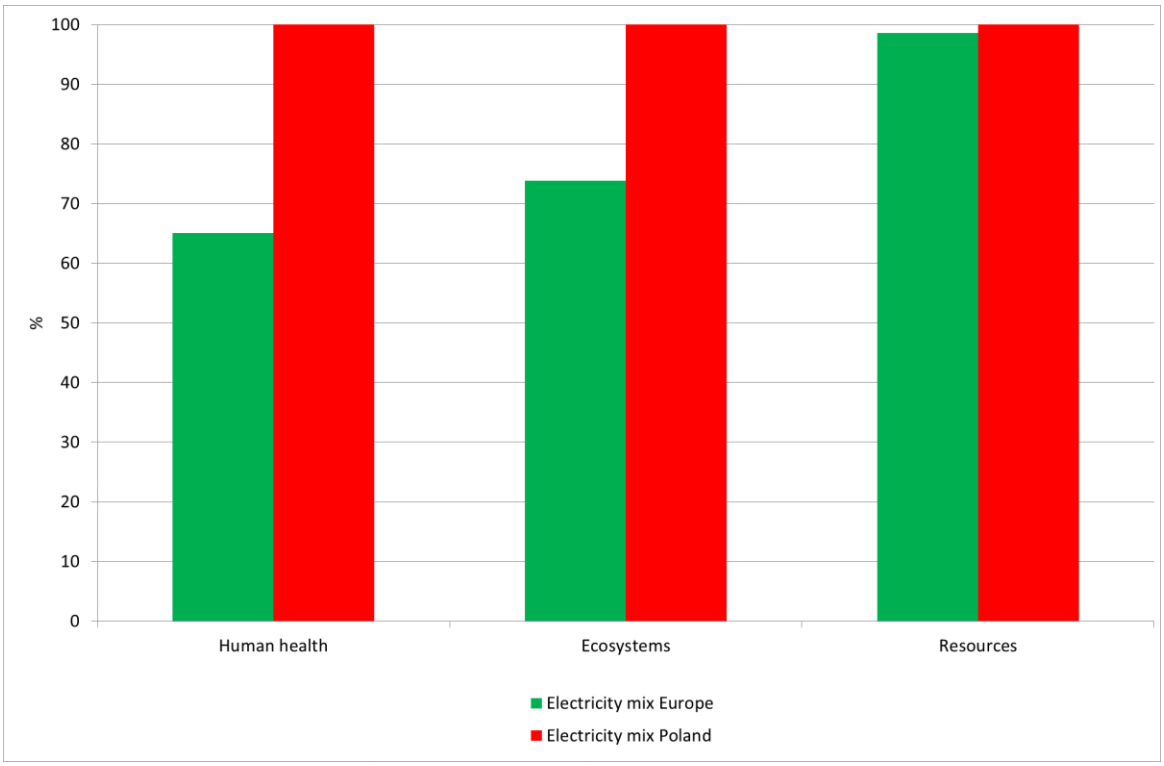


Figure 10. A comparison of the environmental impacts of poplar biomass extraction for the Polish energy mix and the European energy mix (ReCiPe Endpoint H).

4. Discussion

The study demonstrated that the environmental burden associated with poplar biomass production and logistics was low relative to the extraction process. The production of poplar biomass and the biomass of other PIC was less input-intensive and considerably lower than the production of annual crops [31]. In PIC production, lower fertiliser rates are needed to achieve high yields. According to Bacenetti et al. [32], the poplar biomass yield can reach 16.85–17.3 Mg ha^{-1} year^{-1}, depending on the cultivation cycle, which is much higher than in our research. The authors also reported that poplar biomass fixed up to 375 Mg of CO_2 eq. per hectare. At the same time, fertilisation and biomass harvesting are the processes that have the most negative impact on the environment and greenhouse gas emissions. Our other research [33] also confirms that these two processes are mainly responsible for the highest emission intensity of poplar biomass production and their improvement/substitution could further reduce greenhouse gas emissions of the entire biomass production chain. Our research indicates that the environmental impact of biomass production throughout the entire bioactive compound production chain is low, whereas De Marco, Riemma, and Iannone [19] also used sCO_2 extraction for caffeine extraction and observed that crop production made a greater contribution to most environmental impact categories than the extraction process, mainly due to the high consumption of diesel oil and the use of nitrogen and potassium fertilisers. In the climate change category, it was 48% of the total environmental impact. However, it should be noted that the extraction process itself was less energy consuming than in the case of our research, which resulted in a proportional increase in the impact of the coffee bean production step. Moreover, they found that 10 or 20% reduction in fertilisers utilisation would lower the emissions in all the midpoint categories.

Carlqvist, Wallberg, Lidén, and Börjesson [16] analysed the hot water extraction (HWE) of spruce bark and found that bark production was the second most important burden. The environmental burden of biomass extracts obtained by supercritical fluid extraction (SFE) and ultrasound assisted extraction (UAE) did not exceed several percent, with several exceptions. In addition to terrestrial biomass, aquatic biomass can also be used in the extraction process. Similar results on the environmental impact of obtaining spruce bark for the purposes of pressurised hot water extraction were obtained by Ding, et al. [34]. Espada, Pérez-Antolín, Vicente, Bautista, Morales, and Rodríguez [18] obtained β-carotene from solvent-based and supercritical extraction of algae, and found that algal biomass was also characterised by high environmental burden in human toxicity potential and freshwater aquatic ecotoxicity potential categories. Environmental loads were low, but still considerable, in global warming potential and cumulative energy demand categories.

In the present study, the extraction process was characterised by the highest environmental burden in all but two impact categories. This applied also to GHG emissions. High emissions of CO_2 equivalents resulted from high electricity and steam consumption during the supercritical extraction process, in particular due to the high share of lignite and bituminous coal (45.7% and 25.5%, respectively) in the Polish energy mix [35]. The sensitivity analysis revealed that changes in the energy mix would reduce environmental loads, especially when using less carbon intensive fossil fuels or renewable energy sources. De Marco, Riemma, and Iannone [19] made similar observations and found that during the caffeine supercritical extraction step, GHG emissions were associated mainly with the use of fertilisers in agricultural production and electricity. In an alternative scenario (lower fertiliser use and higher share of solar power in the energy mix), the environmental burden decreased from 1.5% to 21.0% for agricultural land occupation and ionising radiation, respectively. In the climate change category, the alternative scenario decreased GHG emissions by 19.0%. Overall, the scenario would reduce overall impact with respect to the base case by 14.6%. A similar reduction could be achieved in the current study, despite the fact that GHG emissions were already low in the production of poplar chips due to the low use of fertilisers and plant protection agents in the poplar plantation. Other researchers also confirmed the high environmental impact of sCO_2 extraction processes. In a study by

Gwee et al. [36], the high demand for electricity in the process of extracting volatile oil from *Aquilaria sinensis* biomass exerted the greatest pressure on the environment. The energy mix in Malaysia, where the study was performed, was comprised of coal natural gas and hydropower with a share of 51%, 45%, and 4%, respectively. In the study by Carlqvist, Wallberg, Lidén, and Börjesson [16] on the HWE of spruce bark, process heat also had the highest environmental impact. However, in the remaining extraction technologies (SFE and UAE), the highest environmental burden was associated with ethanol production and ethanol loss in the recovery process.

When considering circular sustainable production, attention should be paid to greenhouse gas emissions. In the case of our research, GHG emission amounted to 440 kg CO_2 eq. per 1 kg of the obtained sCO_2 extract. In a study by De Marco et al. [32], CO_2 equivalent emissions (per 1 kg of sCO_2 extract) reached 289 kg CO_2 eq. and were 34.3% lower than in the present study. In the β-carotene extraction process, CO_2 equivalent emissions per 1 kg of the obtained extract reached 270 kg CO_2 eq. for sCO_2 extraction but almost doubled (520 kg CO_2 eq.) for solvent extraction. In turn, CO_2 equivalent emissions per 1 kg of volatile oil extracted from *A. sinensis* biomass reached 513.8 kg CO_2 eq., but according to the authors, GHG emissions could be reduced to 58.5 kg CO_2 eq. if the extraction system were rescaled to TRL-9-10 [34]. Greenhouse gas emissions associated with spruce bark extraction were much lower, ranging from 0.68 to 11 kg CO_2 eq. for HWE and UAE technologies, respectively [16]. Considerable differences in the cited results can be attributed to differences in research methodologies, type of extraction, type of extract, biomass type, energy source (renewable vs. non-renewable), maturity of the extraction technology and its scale, as well as the fact that some LCAs relied on generic and modelled data, rather than real-world data from industrial processes. Therefore, it is difficult to clearly compare the results obtained by different authors.

5. Conclusions

The LCA of poplar biomass extraction (cradle-to-gate) with the use of supercritical CO_2 indicates that subsystem I (biomass production and logistics) had a lower share in all midpoint impact categories (from 0.74% to 11%) than subsystem II (production of packaged dry extract) except stratospheric ozone depletion (61.5%), due to fertilisation and field emissions. However, three damage categories (human health, ecosystems, and resources) highlighted that the supercritical extraction process made the greatest contribution to all three categories (from 90.2% to 94.5% for ecosystems and resources, respectively). The environmental burden associated with electricity and steam generation from fossil fuels was analysed in both subsystems. One of the advantages of the presented system is that residual biomass was processed into pellets which can be used for heat generation, for example, in single-family homes. As a result, the system can be credited with an avoided burden (GHG reduction by 13.8 kg CO_2 eq. per 1 kg of obtained extract) because heat was generated from pellets obtained from recycled biomass, rather than pellets produced from fresh wood biomass. This process is consistent with the zero-waste approach. The use of energy generated from fossil fuels was undoubtedly a weak link in the described production system and resulted in high environmental impact per 1 kg of obtained sCO_2 extract (e.g., 440 kg CO_2 eq.). The share of renewables in the energy mix supplied to biorefineries and the share of renewables in the energy generated by biorefineries should be increased to minimise the environmental impact of the extraction process. The energy for the extraction process could be obtained from alternative sources such as solar energy, biogas, and biomass. Process steam could be generated in boilers fired with recycled materials, such as pellets produced from residual biomass after the extraction process. The environmental impact and productivity of alternative systems should be further analysed to validate their feasibility, together with economic analysis and social implications of bioproducts manufacturing.

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and K.T.; data curation, M.K., M.J.S., K.W., E.O.-Z., E.R. and K.T.; writing—original draft preparation, M.K., M.J.S. and K.W.; writing—review and editing, M.J.S., K.W., E.O.-Z., E.R. and K.T.; visualisation, M.K. and E.R.; supervision, M.K. and M.J.S.; project administration, M.J.S. and E.O.-Z.; funding acquisition, M.J.S. All authors have read and agreed to the published version of the manuscript.

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