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Analyzing life cycle assessment using renewable energy in industrial water treatment with a new polymer flocculant

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ABSTRACT

The practical application of life cycle analysis contributes to the creation of more efficient, green technologies, such as the use of renewable energy – photovoltaic panels – in industrial wastewater treatment processes. Life cycle assessment allows for the comparison of CO_2 emissions and renewable energy consumption in wastewater treatment flocculants to identify the most environmentally friendly solutions using polymer flocculant – sodium salt of sulfonic acid derived from phenol-formaldehyde resin waste. The results of the research into the environmental impact of a new generation of polymer flocculant synthesized from phenol-formaldehyde resin waste confirmed that this is the right direction for research, as it is ecologically justified. The aim of the study was to assess the life cycle of a flocculant synthesized from phenol-formaldehyde resin waste (novolak T) using energy obtained from photovoltaic panels. The environmental life cycle assessment was performed using SimaPro Developer v9.4 software, applying the Environmental Footprint (EF) 3.0 method and ecoinvent datasets. The functional unit was 100 kg of sodium salt of the sulfonic derivative of novolak T. The characterization results indicate a climate change impact of 170.1 kg of CO_2 equivalent and an acidification impact of 5.99 mol H^+ equivalent per functional unit. The greatest negative impact on the environment is the production of sulfuric acid and sodium carbonate used to obtain sodium salt of phenol-formaldehyde resin sulfonated derivative. Recycling novolak waste results in negative results in the analyzed impact categories, including resource use and fossil fuels (-5.02×10^3 MJ). Recycling has a positive impact, and the overall results indicate that in the supply chain and reagent consumption in the quarter-technical scale production process, it is the main factor reducing the environmental footprint of the polymer-flocculant derived from waste.

Keywords: life cycle assessment, phenol-formaldehyde resin waste, polymer flocculant production, mine wastewater

INTRODUCTION

The increasing volume of plastic waste, combined with growing environmental and sustainability requirements, creates a pressing need for innovative methods of waste material management [1]. One of the key strategies in this area involves the chemical transformation of polymer waste into high value-added products, while simultaneously reducing their negative impact on the natural environment [2]. A notable example of such an approach is the use of expanded polystyrene and phenol-formaldehyde resin waste as raw materials for synthesizing a new generation of wastewater treatment aids – polyelectrolytes with flocculation properties [3–4]. Polymer-based flocculants are widely used in coagulation-flocculation processes to remove fine suspended solids from water and wastewater [5]. However, their conventional production is associated with high energy consumption, reliance on non-renewable raw materials, and the emission of harmful chemical substances [3]. Moreover, synthetic flocculants are often poorly biodegradable, which can lead to secondary environmental pollution [6]. Consequently, increased attention is being directed towards the development of biodegradable and environmentally friendly alternatives that can be obtained from post-consumer or industrial waste, in line with the principles of a circular economy [7–8]. This paper presents the concept of producing and applying flocculants synthesized via chemical modification of polystyrene and phenol-formaldehyde resin waste. To provide a comprehensive evaluation of the environmental impact of this approach, a life cycle assessment (LCA) was conducted [9], in accordance with ISO 14040 and ISO 14044 standards [10–11]. LCA enables the identification of environmental "hotspots" throughout a product's life cycle and allows for comparison of various production scenarios in terms of emissions, energy demand, and resource consumption. The results of the LCA analysis demonstrated that the integration of renewable energy sources into the flocculant synthesis process, as well as their subsequent application in wastewater treatment, leads to a significant reduction in overall environmental footprint [3]. In particular, the use of electricity generated from photovoltaic installations – instead of fossil fuel-based energy – resulted in a 30-fold decrease in the environmental impact of the flocculant production process, and approximately a 13% reduction in the impact associated with the wastewater treatment stage [3]. This approach significantly enhances the environmental performance of the system and may serve as a model solution for industries aiming to reduce energy consumption and pollutant emissions. This study places special emphasis on the role of renewable energy sources (RES) as a factor that mitigates the environmental impact of polymer waste management [12–14]. The synergy between material recovery and the use of clean energy makes it possible not only to reduce the amount of waste sent to landfills but also to lower the energy intensity of the entire life cycle [15–16]. As a result, the polyelectrolytes obtained in this way demonstrate not only high technological efficiency in water and wastewater treatment processes but also a considerably lower environmental impact [17].

The study was to evaluate the environmental performance of a sulfonated derivative of phenol-formaldehyde resin waste (novolac T) when used as a polymer flocculant in the treatment of industrial wastewater, particularly mine waters. The focus was on assessing the full life cycle of the product, from raw material acquisition to its application in wastewater treatment, with special consideration given to the use of renewable energy sources in the production stage. By quantifying the environmental footprint for different scenarios – including both conventional and RES-powered production – the study sought to identify the most sustainable technological pathway. While numerous studies have addressed the efficiency and performance of polymer-based flocculants [18–20], few have investigated the environmental implications of producing such materials from hazardous phenol-formaldehyde resin waste, particularly when powered by renewable energy sources [13, 15, 17, 21]. Moreover, the integration of LCA methodology into the comparative analysis of conventional versus RES-powered production of flocculants derived from industrial waste remains insufficiently explored in the literature [12,22]. This study addresses that gap by combining waste valorization, renewable energy integration, and comprehensive environmental assessment. The research was based on a cradle-to-cradle LCA model covering the extraction of raw materials, material transportation, chemical synthesis of the flocculant, and its application in industrial wastewater treatment [23]. The functional unit was defined as either the production of 100 kg of flocculant or the treatment of 20,000 m^3 of mine water per day. Environmental impact categories were assessed according to ISO 14040 [11] and ISO 14044 [10], using regional data for Poland and considering both conventional and photovoltaic-powered production processes. The laboratory-scale synthesis was carried out via the amination of aromatic compounds, followed by sulfonation to obtain the final product, which was then tested in coagulation-flocculation processes for mine water treatment. From waste phenol-formaldehyde resins, the first author obtained compounds that were used as flocculants in wastewater treatment processes with good results [24]. With regard to the effectiveness of the new compounds used as flocculants, the environmental analysis of the products was carried out using the LCA method. The aim of the research was to assess the life-cycle assessment of the product – sodium sulphonic salt of a phenol-formaldehyde resin derivative (novolac T) used in the treatment of mine drainage water (in the case of two hard coal mines belonging to the Katowice Coal Holding in Poland. LCA was carried out with particular emphasis on emissions associated with the use of energy obtained from photovoltaic panels for the processes.

RESEARCH METHODOLOGY

LCA is now a widely used and proven method worldwide as a reliable tool for assessing environmental impacts, but its application in systemic waste management is a relatively new area of application with developmental potential. The application of LCA is associated with high requirements for data use, the analysis phase is labor- and time-intensive, as well as resource-intensive. Nevertheless, the authors found the technique to be the most suitable for use in the environmental assessment of new flocculants.

The study of the environmental impact of the new generation of flocculants was carried out based on a quarter-scale technological study of the process of producing sulfonated derivatives of waste phenol-formaldehyde resins. The first author's monograph includes simplified technological diagrams of flocculant production [24]. The development of a technological diagram for flocculant production enabled research and analysis of the environmental impact of the new product using the LCA method, which utilizes data on the amount of materials and energy obtained from photovoltaic panels consumed for the planned production (calculated on the basis of the developed flocculant production technology). For the synthesized sulfonated derivative of novolac T, tests were carried out on their solubility in typical organic solvents and water. The synthesis of the flocculant is presented in the first author's monograph [24]. A sulfonated derivative of phenol-formaldehyde resin waste – novolak T – was obtained through a process of sulfonation with concentrated sulfuric acid (VI). The obtained products were subjected to $CaCO_3$ calcination and precipitation in the form of sodium salts in a reaction with Na_2CO_3.

The product obtained was well soluble at room temperature as well as at the boiling point of the solvent. Subsequently, tests were carried out using the following substrates: metallurgical wastewater, a basic coagulant, and a synthesized sulfonated derivative of novolac T. The basic coagulant was an aluminum sulphate solution $(Al_2SO_4)_3 \cdot 18H_2O$ (pure for analysis), used in the removal of colloidal contaminants in the KWK1 (mine waters – mine 1) and KWK2 (mine waters – mine 2) mine water treatment processes, differing in the parameters of underground water contamination. The study was carried out for two coal mines belonging to Katowice Coal Holding in Poland.

Procedure for purifying mine water from the KWK1 and KWK2 hard coal mines. Studies of the flocculation process using sodium salt of a sulfonated derivative of phenol-formaldehyde resin were conducted by first determining the optimal dose of coagulant – 1% solution of standard coagulant $Al_2(SO_4)_3$, and then flocculant – 0.1% solutions of a new polyelectrolyte. The parameters in the tested mine water were determined after obtaining the optimal doses of coagulant and flocculant. After adding the coagulant and flocculant to a specified amount of the tested mine water, it was mixed on a mechanical stirrer for 1 minute at a speed of 300 rpm and 15 minutes at a speed of 90 rpm, then left to stand for 30 minutes, after which measurements were taken.

The LCA analysis was carried out on the basis of a quarter-technical scale technological study using a manufactured phenol-formaldehyde resin-based polymer (novolac T), according to the assumptions contained in the ISO 14040 standard in four stages: 1) definition of the purpose and scope of the study 2) analysis of the set of inputs and outputs, 3) assessment of the environmental impact of the life cycle, 4) interpretation - conclusions including the verification of the results). The calculations were performed for the territorial scope of the analysis – Poland. The technological scope of the LCA included the analysis performed based on the project data. The unit of analysis was adopted - production of 100 kg of a given flocculent.

In order to conduct the LCA analysis, the system boundaries were established [Diagram 1]. The system boundaries were defined in the publications of the first author. Diagram showing the system boundaries [24]. The system boundaries include: polymer waste collection, flocculant production, and the use of a new generation of flocculant in wastewater treatment. The reagents and materials used are taken into account from the extraction of natural resources to their use in production.

The analysis did not include infrastructure and materials related to the maintenance of the installation. Electricity production data were modelled using data from the Ecoinvent database as an average for Poland: Electricity, low voltage {PL} market for | Cut-off, U and Transport of purchased raw materials: distance 200 km, payload 20 t, EURO5 standard. The research was carried out using software: SimaPro Developer v. 9.4.0.2. Characterization charts were produced using the EF 3.0v.1.03 method, and weighting for a weighting factor of '1' for each impact category. Once the set of inputs and outputs (LCI) analysis was produced, an environmental footprint assessment was performed to calculate the environmental footprint of the product using all categories and environmental footprint impact models according to the selected method. The analysis was performed using the EF 3.0 method using SimaPro software. A database implementation – Ecoinvent – was performed. The EF 3.0 method is an impact assessment method adopted by the European Commission (EC). In the study, it takes into account the normalization factors and weights published in November 2019 by the EC.

RESULTS AND DISCUSSION

For the new type of flocculant produced – sodium salt of the sulfonated derivative of novolac T – an assessment was made of the

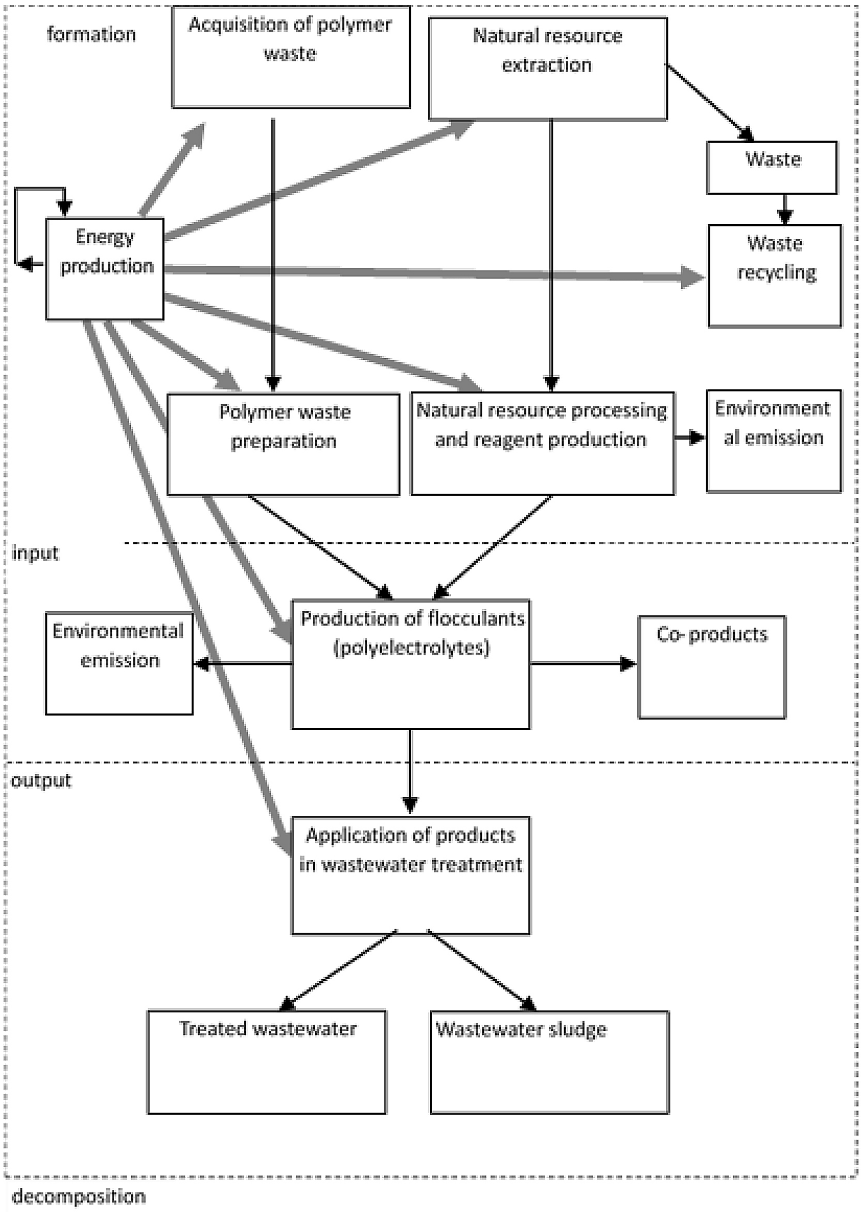

Diagram 1. Life cycle of a flocculant synthesized from phenol-formaldehyde resin polymer waste [24]

potential impact of the flocculant used in the treatment of mine water from the two mines KWK1 and KWK2, taking into account the production process. 100 kg of sodium salt of the sulfonated derivative of novolac T was taken as the functional unit in the production step. This was assumed to be the daily production volume. Having created the summary of the inputs and outputs of the flocculant treatment processes, raw material and process trees were developed using the chosen method. The magnitude of individual impacts on the polymer flocculant (sodium salt of the sulfone derivative of novolac T waste) mine water treatment process is visualized by the thickness and color of the lines connecting the individual processes, where red represents a negative impact on the environment and green represents a positive impact.

LCA of mine water treatment process KWK1

Table 1 contains the composition of the treated mine water (in relation to 1 liter as a functional unit) and the inventory table of the treatment process in relation to 1m^3. The treated mine water comes from coal mines.

Loads in the treated groundwater were calculated from the reduction difference – e.g. if the chloride content in the contaminated groundwater was 1670.4 mg/dm^3 and in the treated water 18.1 mg/dm^3, this means that it was reduced by 1652.3 mg/dm^3, and this calculated value is entered into the inventory table in the SimaPro software. The RES symbol indicates the method of obtaining energy from photovoltaic panels. In the acidification category, the main source of loading is flocculant, the contribution of which almost completely shapes the result; other factors, including batch water and electricity, are of marginal importance (Table 2).

For climate change, flocculant remains the dominant factor, with a smaller but noticeable contribution from bore water; the other elements have no significant impact. In ecotoxicity, freshwater, strong opposing impacts are observed, with the key reduction contribution coming from treatment (negative value), while effluent and to a lesser extent make-up water is responsible for the positive end result. In the particulate matter category, almost all impact was attributed to the flocculant, with the other factors contributing very little. For eutrophication, the marine total score is shaped by the negative influence of flocculant, with a small positive contribution from make-water and electricity. Similarly, for eutrophication, freshwater, where the flocculant is the main source of loading, and earning water and electricity are of negligible importance. In the category eutrophication, terrestrial, the flocculant is the largest contributor, supplemented by make-water; electricity plays no significant role. In the area of human toxicity, cancer, the reducing effect of the flocculant predominates, with a marginal positive contribution from earning water. By contrast, in human toxicity, non-cancer the flocculant makes the largest contribution, with batch water as a complementary factor. In the ionizing radiation category, there is a significant negative contribution from the flocculant, partly offset by a positive contribution from batch water. For land use, the result is shaped solely by the flocculant, with the other factors being negligible. In ozone depletion, the total result is due to the negative contribution of the flocculant and the positive contribution of earning water, while electricity is negligible. The situation is similar in photochemical ozone formation, where the negative contribution of the flocculant plays a dominant role, with a small contribution from earning water. In the category of resource use, fossils, the reducing effect of the flocculant predominates, while batch water contributes positively to the environment. For resource use, minerals and metals, the total result is almost entirely shaped by the flocculant. In the last category, water use, the main factor is make-up water. In all the impact categories analysed, sulphuric acid is the dominant load, while electricity shows a marginal contribution (Figure 1).

Table 1. Pollution loads of mine water KWK1

Emission to water	Unit	Amount	Emission to water	Unit	Amount
BOD_5 (Biological oxygen demand)	mg/L	3.4	Sulfate	mg/L	1480.5
COD (Chemical oxygen demand)	mg/L	38.7	Chloride	mg/L	1670.4
Ammonia as N	mg/L	0.69	Suspended substances, unspecified	mg/L	47.5

Table 2. Results after the characterisation step for the KWK1 mine water treatment process with the sulfonated derivative of novolac T-OZE in relation to the functional unit

Impact category	Unit	Total	Treatment	Flocculant	Baking water	Energy	Wastewater
Acidification	mol H+ eq	1.282379	0	1.272585	0.009793	6.77E-07	0
Climate change	kg CO2 eq	45.65323	0	44.55341	1.099703	0.000126	0
Ecotoxicity, freshwater	CTUe	109142.1	-9961386	-225.214	246.0171	0.02416	10070508
Particulate matter	disease inc.	6.88E-06	0	6.81E-06	6.85E-08	4.30E-12	0
Eutrophication, marine	kg N eq	-0.00382	0	-0.00465	0.000825	4.41E-06	0
Eutrophication, freshwater	kg P eq	0.001684	0	0.001676	7.75E-06	4.31E-07	0
Eutrophication, terrestrial	mol N eq	0.063774	0	0.054774	0.008998	1.69E-06	0
Human toxicity, cancer	CTUh	-1.85E-07	0	-1.86E-07	1.17E-09	1.22E-13	0
Human toxicity, non-cancer	CTUh	2.49E-07	0	1.52E-07	9.76E-08	1.67E-11	0
Ionizing radiation	kBq U-235 eq	-0.07343	0	-0.33125	0.257803	1.47E-05	0
Land use	Pt	120.125	0	120.1246	0	0.000373	0
Ozone depletion	kg CFC11 eq	6.58E-07	0	-3.94E-07	1.05E-06	2.39E-12	0
Photochemical ozone formation	kg NMVOC eq	-0.0263	0	-0.02957	0.003269	3.66E-07	0
Resource use, fossils	MJ	-863.256	0	-886.505	23.24675	0.001933	0
Resource use, minerals and metals	kg Sb eq	4.86E-06	0	4.86E-06	1.93E-10	3.35E-10	0
Water use	m3 depriv.	455.613	0	65.50098	390.1143	-0.00233	0

Note: OZE – energy from photovoltaic panels.

In many cases, a significant reduction effect is observed for novolac T waste, which contributes to lowering the total impact, especially in categories such as freshwater ecotoxicity, resource use, fossils and photochemical ozone formation. In the categories related to toxicity (both human toxicity, cancer and non-cancer), sulphuric acid is the main factor, while the other components are of lesser importance. In contrast, in the case of eutrophication (marine, freshwater, terrestrial), sodium carbonate is the dominant component having a negative effect, with a compensatory effect of novolac waste. In other categories, such as ionising radiation, ozone depletion or resource use, there is also a predominance of sulphuric acid in the generation of environmental impacts and a noticeable reducing effect from novolac waste. The analysis of the weighted results shows that the highest environmental burden is in the acidification category, where the dominant factor is wastewater, when a reduction effect comes from the treatment stage (Table 3).

A very similar result was achieved in the category of particulate matter, also most influenced by wastewater, with a strong reduction effect from the treatment process. In the third place, there is the category of climate change, for which the main burden is the flocculant, and the other components are of marginal importance. Relatively high values are also recorded in the ecotoxicity, freshwater and eutrophication, marine categories, where again the flocculant is the largest contributor, while the contribution of tailings water remains small. Significant, albeit lower, contributions to total loads also appear in the categories – eutrophication, terrestrial and ionizing radiation, both of which are mainly shaped by the flocculant (with the addition of make-water). A similar relationship occurs in the categories – human toxicity, cancer and ozone depletion, where the flocculant is the dominant source. The lowest values were obtained in the categories with negative results, such as resource use, minerals and metals, human toxicity, non-cancer and resource use, fossils. In all cases, the flocculant plays a key role in reducing environmental burdens. Small negative values also emerged in the land use and photochemical ozone formation categories, where the compensatory effect of the flocculant dominated, while the contribution of the make-up

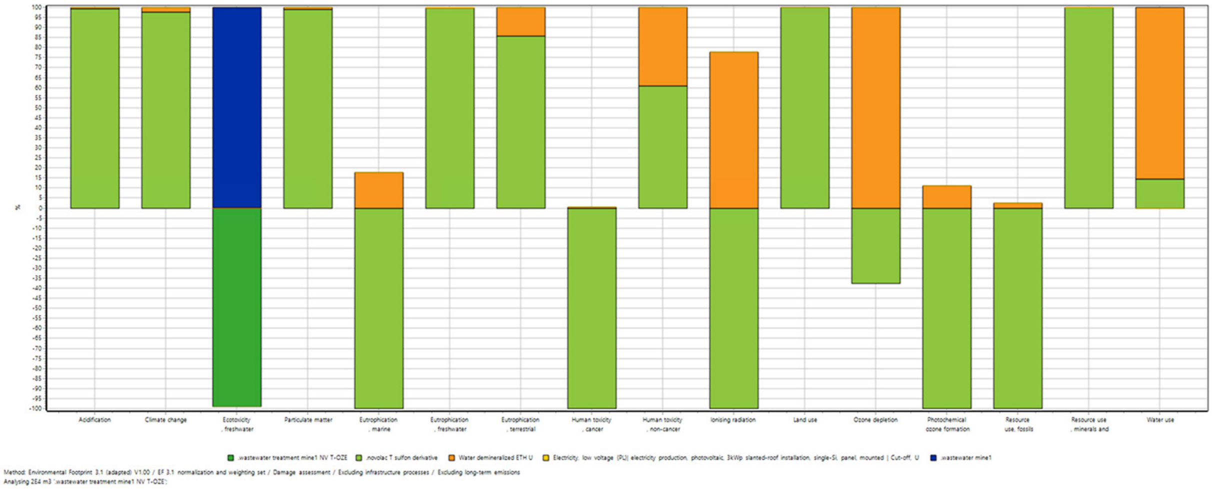

Figure 1. Results after the characterization step for the KWK1 mine water treatment process with the sulfonated derivative of novolac T-OZE in relation to the functional unit

Table 3. Post-weighting results for the KWK1 mine water treatment process with the sulfonated derivative of novolac T-OZE in relation to the functional unit [Pt]

Impact category	Total	Treatment	Flocculant	Baking water	Energy	Wastewater
Acidification	0.042793	-3.37218	0.002766	0.003086	1.64E-08	3.409122
Climate change	0.001431	0	0.00142	1.09E-05	7.55E-10	0
Ecotoxicity, freshwater	0.001273	0	0.001242	3.07E-05	3.53E-09	0
Particulate matter	0.036947	-3.37218	-7.62E-05	8.33E-05	8.18E-09	3.409122
Eutrophication, marine	0.001035	0	0.001025	1.03E-05	6.47E-10	0
Eutrophication, freshwater	-5.79E-06	0	-7.05E-06	1.25E-06	6.69E-09	0
Eutrophication, terrestrial	2.93E-05	0	2.92E-05	1.35E-07	7.52E-09	0
Human toxicity, cancer	1.34E-05	0	1.15E-05	1.89E-06	3.55E-10	0
Human toxicity, non-cancer	-0.00023	0	-0.00023	1.44E-06	1.51E-10	0
Ionizing radiation	3.57E-05	0	2.17E-05	1.40E-05	2.38E-09	0
Land use	-8.72E-07	0	-3.93E-06	3.06E-06	1.75E-10	0
Ozone depletion	1.16E-05	0	1.16E-05	0	3.62E-11	0
Photochemical ozone formation	7.93E-07	0	-4.75E-07	1.27E-06	2.89E-12	0
Resource use, fossils	-3.08E-05	0	-3.46E-05	3.82E-06	4.28E-10	0
Resource use, minerals and metals	-0.0011	0	-0.00113	2.98E-05	2.47E-09	0
Water use	5.77E-06	0	5.77E-06	2.29E-10	3.98E-10	0

water was minimal. In categories with positive but relatively low values – such as water use, photochemical ozone formation and land use – the flocculant showed the greatest impact, while electricity remained insignificant in all categories. In summary, the main sources of environmental burden in the weighted analysis are wastewater (especially in acidification and particulate matter) and the flocculant (in all other positive categories). The analysis of the weighted results for the treatment process of mine water with the sulfonated derivative of novolac T (RES) clearly shows the dominant influence of the ecotoxicity category, freshwater, where the environmental burden is clearly the highest (Figure 2).

The effluent prior to the treatment process is mainly responsible for this high result, while the treatment process itself generates a significant reduction effect, which is evident in the negative contribution. The other categories show trace values, close to zero, with no clear positive or negative deviations. This means that in the categories such as acidification, climate change, eutrophication (marine, freshwater, terrestrial) as

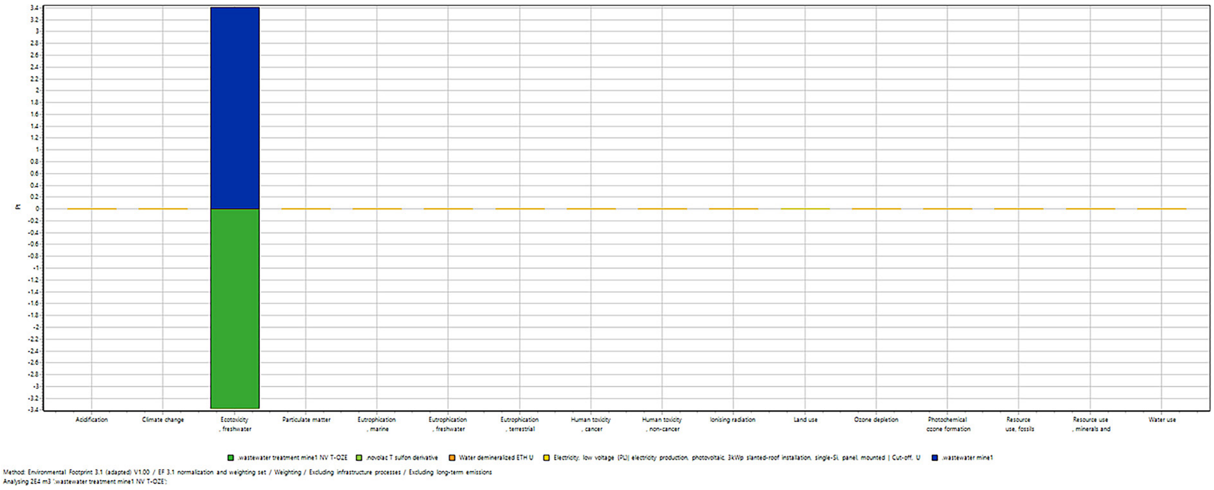

Figure 2. Post-weighting results for the KWK1 mine water treatment process with the sulfonated derivative of the T-OZE novolac in relation to the functional unit

well as human toxicity, ionizing radiation, land use, ozone depletion, resource use, water use and others – the impact of the analyzed process is negligible or neutral from the point of view of environmental footprint. In summary, the key area of environmental impact in the analyzed treatment process is freshwater ecotoxicity, with the net effect suggesting a significant improvement in environmental quality resulting from wastewater treatment. Figure 3 shows a "process tree" of the KWK1 underground water treatment using the sulfonated derivative novolac T.

The main input streams include 93.5 kg of sulphuric acid, which generates an environmental impact of 0.000159 Pt, and 63.6 MJ of electricity, which contributes the most to the environmental load of the inputs (0.000462 Pt). Novolac waste is also an important component of the system (13.6 kg), the presence of which reduces the total environmental impact by -0.000103 Pt, which may be due to its further use or material recovery. The end result of the process is the treatment of 20,000 m³ of pit water, which is associated with the largest individual environmental impact of 0.00127 Pt. Despite partial offsetting of the impact by novolac waste, the total environmental impact for the functional unit analyzed is 0.00124 Pt. This means that the key environmental impact factors in this system are mainly the wastewater treatment process and electricity consumption.

LCA of mine water treatment process KWK2

Table 4 contains the composition of the treated mine water (in relation to 1 liter), and the inventory table of the treatment process is referred to in the same way as for the KWK1 mine water to 1m3. The treated underground water also comes from the KWK2 coal mine with the parameters listed in Table 4.

The analysis of the characterized results shows that in the category of climate change [kg CO_2 eq], the main source of the environmental burden is the flocculant, which accounts for almost all the CO_2-equivalent emissions, while the contribution of make-water remains marginal, and electricity is not significant (Table 5).

A similar pattern is observed in the ozone depletion [kg CFC11 eq] category, where the flocculant is the dominant factor and make-up water makes a complementary contribution. In the category of ionizing radiation [kBq U-235 eq], wastewater is the dominant load and accounts for the highest emissions, while the treatment process shows a clear reduction effect. The flocculant and tailings water are of secondary importance in this case. Also, in the category of photochemical ozone formation [kg NMVOC eq], the flocculant remains the main factor, while batch water has only a minor contribution and electricity remains insignificant. Some categories show negative values, indicating a compensatory effect. This is the case of particulate matter [disease incidence], where the reducing effect of the flocculant outweighs the positive effect of batch water, and the acidification [mol H^+ eq] category, where the flocculant plays the main reducing role. A similar phenomenon is observed in the categories of eutrophication, marine [kg N eq], land use [Pt] and water use [m³ depriv.], where the reducing effect of the flocculant significantly

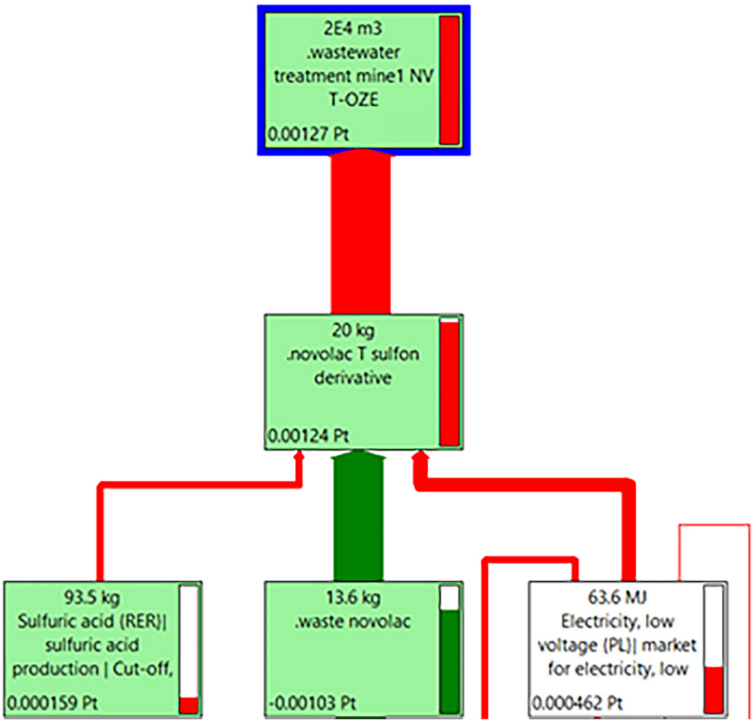

Figure 3. Environmental footprint for the KWK1 mine water treatment process with the sulfonated derivative of novolac T - process network in relation to the functional unit

Table 4. Pollutant loads of pit water from the KWK2 mine

Emission to water	Unit	Amount	Emission to water	Unit	Amount
BOD_5 (Biological oxygen demand)	mg/L	4.4	Chloride	mg/L	4620.7
COD (Chemical oxygen demand)	mg/L	49.0	Iron	mg/L	0
Detergent, anionic	mg/L	0	Manganese	mg/L	0
Ammonia as N	mg/L	0.85	Suspended substances, unspecified	mg/L	30.7
Sulfate	mg/L	487.3		mg/L	

reduces the total values, with a partial compensating contribution from make-up water. In the other categories, positive loads are mainly shaped by the flocculant. In the case of human toxicity, non-cancer [CTUh] and human toxicity, cancer [CTUh], almost the entire result is attributed to this component, with a significant contribution in the case of carcinogenic toxicity also by batch water. In the categories of eutrophication, freshwater [kg P eq] and eutrophication, terrestrial [mol N eq], the flocculant is primarily responsible for the loadings, although in freshwater eutrophication the contribution of make-up water is also significant. An interesting relationship was noted in the ecotoxicity category, freshwater [CTUe], where the flocculant has a reducing effect, while make-up water introduces a load, resulting in a low positive total value. In the category of resource use, fossils [MJ], the flocculant is the only significant factor, while in resource use, minerals and metals [kg Sb eq], batch water plays a dominant role, with a complementary but lesser influence of the flocculant. In summary, in most categories, the flocculant is the most significant and is responsible for the dominant environmental loadings, while in selected categories (acidification, particulate matter, land use, water use, marine eutrophication) it acts as a reducing factor, leading to negative values. Wastewater significantly shapes the result only in the category of ionizing radiation, while wastewater shows a noticeable impact in selected cases, especially in the use of mineral resources and metals. Electricity remains insignificant in all categories. In all the impact categories analyzed, the wastewater treatment mine KWK2 -OZE process has the largest share in shaping the results (Figure 4).

Table 5. Results after the characterization step for the KWK2 mine water treatment process with the sulfonated derivative of novolac T-OZE in relation to the functional unit

Impact category	Unit	Total	Treatment	Flocculant	Baking water	Energy	Wastewater
Climate change	kg CO$_2$ eq	2.564757	0	2.545169	0.019587	6.77E-07	0
Ozone depletion	kg CFC11 eq	91.30634	0	89.10681	2.199406	0.000126	0
Ionizing radiation	kBq U-235 eq	12346421	-1.6E+07	-450.427	492.0343	0.02416	27857276
Photochemical ozone formation	kg NMVOC eq	1.38E-05	0	1.36E-05	1.37E-07	4.30E-12	0
Particulate matter	disease inc.	-0.00765	0	-0.00931	0.00165	4.41E-06	0
Human toxicity, non-cancer	CTUh	0.003368	0	0.003352	1.55E-05	4.31E-07	0
Human toxicity, cancer	CTUh	0.127546	0	0.109547	0.017997	1.69E-06	0
Acidification	mol H+ eq	-3.71E-07	0	-3.73E-07	2.33E-09	1.22E-13	0
Eutrophication, freshwater	kg P eq	4.99E-07	0	3.04E-07	1.95E-07	1.67E-11	0
Eutrophication, marine	kg N eq	-0.14687	0	-0.66249	0.515605	1.47E-05	0
Eutrophication, terrestrial	mol N eq	240.2495	0	240.2492	0	0.000373	0
Ecotoxicity, freshwater	CTUe	1.32E-06	0	-7.89E-07	2.10E-06	2.39E-12	0
Land use	Pt	-0.05259	0	-0.05913	0.006539	3.66E-07	0
Water use	m^3 depriv.	-1726.51	0	-1773.01	46.4935	0.001933	0
Resource use, fossils	MJ	9.73E-06	0	9.73E-06	3.86E-10	3.35E-10	0
Resource use, minerals and metals	kg Sb eq	911.2283	0	131.002	780.2286	-0.00233	0

In all the impact categories analyzed, the wastewater treatment mine KWK2 -OZE process has the largest share in shaping the results. In many cases, its reduction effect is visible, especially in the categories such as freshwater ecotoxicity, marine eutrophication, ionizing radiation, ozone depletion or resource use, fossils, where environmental burdens are significantly reduced. A noticeable positive contribution of demineralized water is also observed in several categories, especially in eutrophication marine, ionizing radiation, ozone depletion and water use. Electricity tends to have a complementary role, with a more significant contribution only in the categories of human toxicity non-cancer and photochemical ozone formation. The analysis of the weighted results shows that the highest environmental burden is in the ionizing radiation category, where wastewater is the dominant factor, while the treatment process has a compensatory effect, reducing the total score (Table 6).

In the second place, there is the category of resource use, minerals and metals, where the largest contribution comes from wastewater and, to a lesser extent, the flocculant. Relatively high values were also obtained in the categories of climate change, ozone depletion and photochemical ozone formation, in which the flocculant is the main source of loading, with a minimal contribution from earning water. Lower but positive values were recorded in the categories of human toxicity, non-cancer, human toxicity, cancer, eutrophication, freshwater, eutrophication, terrestrial, ecotoxicity, freshwater and resource use, fossils. In all cases, the dominant factor is the flocculant, while in the case of freshwater eutrophication, eutrophication also has a significant contribution. The lowest values were obtained in the categories with negative results, such as acidification, water use, land use, particulate matter or eutrophication, marine. In each of these categories, the reduction effect is mainly due to the presence of the flocculant and is partly compensated by the contribution of bore water. The main sources of environmental loading in the weighted analysis are effluent (particularly in the ionizing radiation category), the flocculant (dominant in most of the positive categories) and tailings water (key in the use of mineral resources and metals and in some of the eutrophication categories). The treatment process has a compensatory role, significantly reducing loads in selected cases. On the basis of the presented graph, it can be concluded that in all the impact categories, the underground water treatment process plays a key role (Figure 5).

In many cases, its effect is reductive, especially with regard to the categories such as freshwater

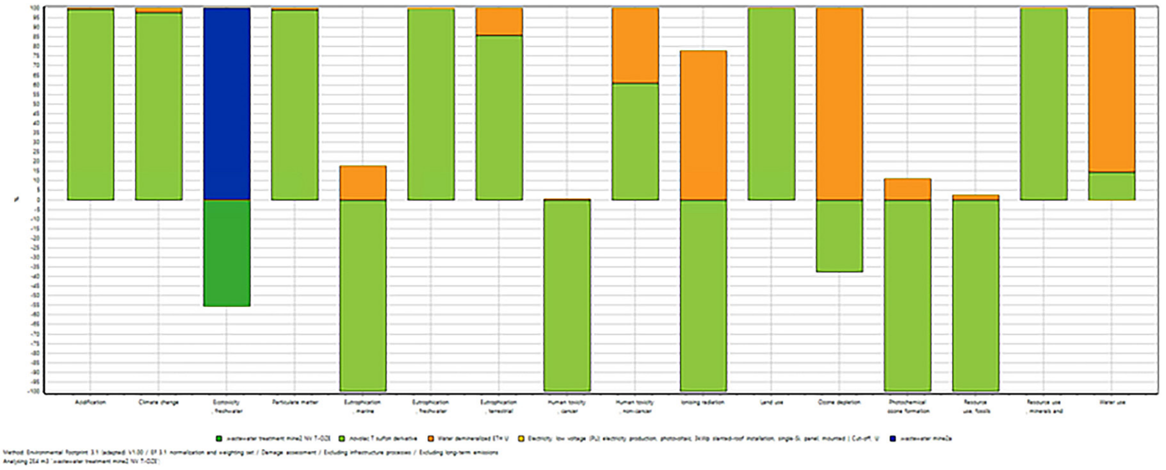

Figure 4. Post-stage characterization results for the KWK2 mine water treatment process with the sulfonated derivative of novolac T-OZE in relation to the functional unit

Table 6. Post-weighting results for the KWK2 mine water treatment process with the sulfonated derivative of T-OZE novolac in relation to the functional unit [Pt]

Impact category	Total	Treatment	Flocculant	Baking water	Energy	Wastewater
Climate change	0.002862	0	0.00284	2.19E-05	7.55E-10	0
Ozone depletion	0.002546	0	0.002485	6.13E-05	3.53E-09	0
Ionizing radiation	4.179576	-5.25083	-0.00015	0.000167	8.18E-09	9.430393
Photochemical ozone formation	0.002071	0	0.00205	2.06E-05	6.47E-10	0
Particulate matter	-1.16E-05	0	-1.41E-05	2.50E-06	6.69E-09	0
Human toxicity, non-cancer	5.87E-05	0	5.84E-05	2.70E-07	7.52E-09	0
Human toxicity, cancer	2.68E-05	0	2.30E-05	3.78E-06	3.55E-10	0
Acidification	-0.00046	0	-0.00046	2.88E-06	1.51E-10	0
Eutrophication, freshwater	7.13E-05	0	4.34E-05	2.79E-05	2.38E-09	0
Eutrophication, marine	-1.74E-06	0	-7.86E-06	6.12E-06	1.75E-10	0
Eutrophication, terrestrial	2.33E-05	0	2.33E-05	0	3.62E-11	0
Ecotoxicity, freshwater	1.59E-06	0	-9.51E-07	2.54E-06	2.89E-12	0
Land use	-6.15E-05	0	-6.92E-05	7.65E-06	4.28E-10	0
Water use	-0.00221	0	-0.00227	5.95E-05	2.47E-09	0
Resource use, fossils	1.15E-05	0	1.15E-05	4.58E-10	3.98E-10	0
Resource use, minerals and metals	0.006761	0	0.000972	0.005789	-1.73E-08	0

ecotoxicity. Figure 6 shows a “process tree” of the KWK2 underground water treatment using the sulfonated derivative novolac T.

Wastewater treatment mine KWK2 -OZE using the flocculant of the sulfonated derivative of novolac T generates a load of 0.00255 Pt, which is largely dependent on the production and use of 40 kg sulfonated derivative of novolac (0.00248 Pt). The associated processes also influence the value of this indicator. The production of sulphuric acid (187 kg) is particularly important, accounting for 0.000318 Pt, as well as electricity consumption (127 MJ), which generates 0.000923 Pt. In contrast, the recycling or management of waste novolac (27.2 kg) has an offsetting effect, reducing the total burden by -0.00207 Pt. Thus, the processes associated with the synthesis and use of the novolac derivative, as well as the energy and sulphuric acid requirements, have the greatest impact on the total environmental footprint. At the same time, the recovery of novolac waste plays a key reduction role, partially offsetting the burdens created.

The increasing volume of plastic waste, combined with growing environmental and sustainability requirements, creates a pressing need for

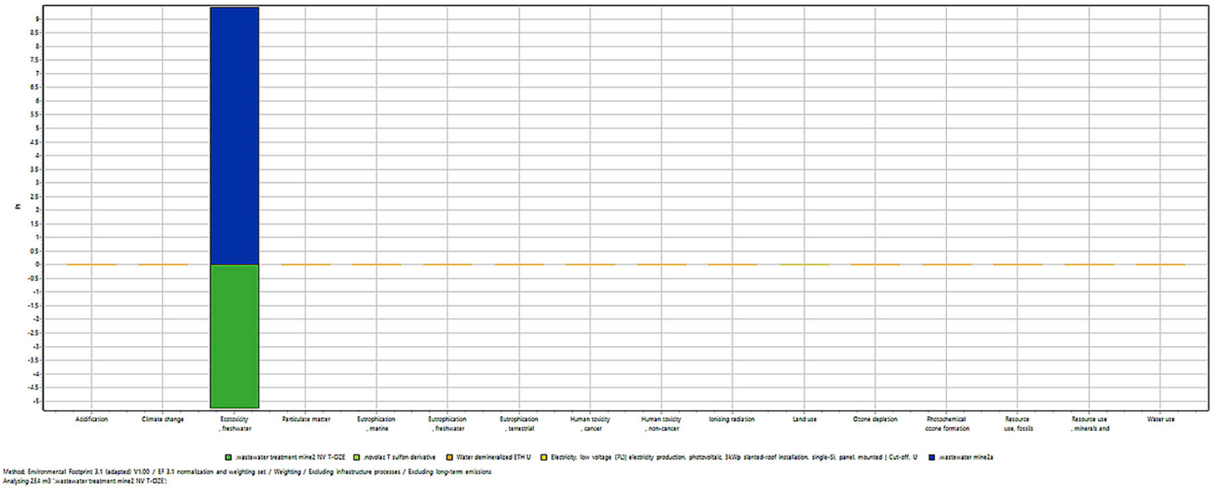

Figure 5. Post-weighting results for the KWK2 mine water treatment process with the sulfonated derivative of novolac T-OZE in relation to the functional unit

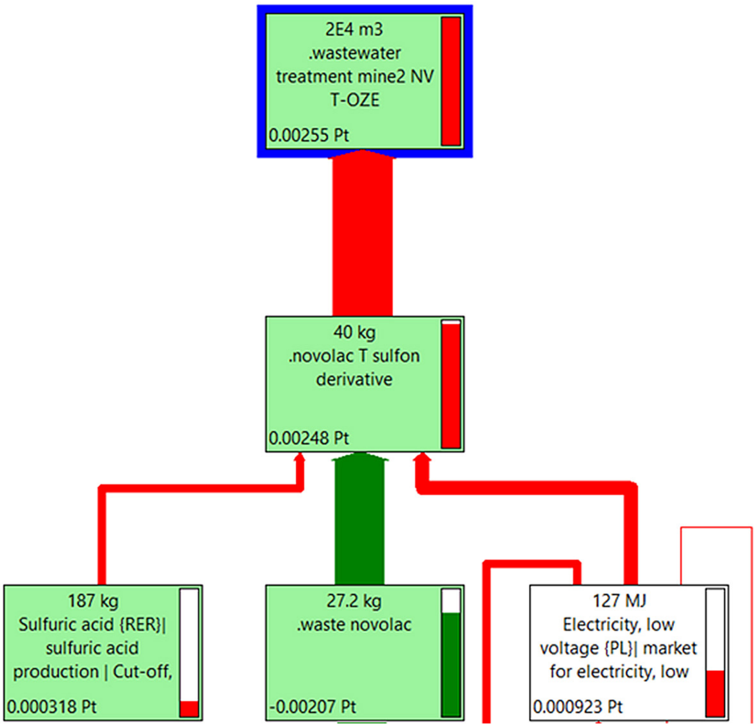

Figure 6. Environmental footprint for the wastewater treatment mine KWK2 with the sulfonated derivative of novolac T-OZE process network in relation to the functional unit

innovative methods of waste material management [1]. One of the key strategies in this area involves the chemical transformation of polymer waste into high value-added products, while simultaneously reducing their negative impact on the natural environment [2]. A notable example of such an approach is the use of expanded polystyrene and phenol–formaldehyde resin waste as raw materials for synthesizing a new generation of wastewater treatment aids – polyelectrolytes with flocculation properties [3–4]. Polymer-based flocculants are widely used in coagulation–flocculation processes to remove fine suspended solids from water and wastewater [5]. However, conventional production is associated with high energy consumption, reliance on non-renewable raw materials, and the emission of harmful chemical substances [3]. Moreover, synthetic flocculants are often poorly biodegradable, which can lead to secondary environmental pollution [6].

Consequently, increased attention is being directed towards the development of biodegradable and environmentally friendly alternatives that can be obtained from post-consumer or industrial waste, in line with the principles of a circular economy [7–8]. To provide a comprehensive evaluation of such solutions, life cycle assessment (LCA) is increasingly used to quantify environmental impacts across the full life cycle and to identify environmental "hotspots" [9]. In this work, the LCA framework follows ISO 14040 and ISO 14044 standards [10–11], enabling comparison of alternative production and application scenarios in terms of emissions, energy demand, and resource consumption. Recent LCA-related research indicates that integrating renewable energy sources into the flocculant synthesis process, as well as its subsequent application in wastewater treatment, can significantly reduce the overall environmental footprint [3]. In particular, replacing fossil fuel-based electricity with photovoltaic electricity resulted in a substantial decrease in the environmental impact associated with flocculant production and a noticeable reduction in the impact of the wastewater-treatment stage [3]. These findings highlight the role of renewable energy sources (RES) in mitigating the environmental impact of polymer waste management [12-14]. The synergy between material recovery and the use of clean energy can reduce the amount of waste sent to landfills and lower the energy intensity of the entire life cycle [15-16], while polyelectrolytes obtained in this way may retain high technological efficiency in water and wastewater treatment and exhibit a considerably lower environmental impact [17]. While numerous studies have addressed the efficiency and performance of polymer-based flocculants [18-20], fewer have investigated the environmental implications of producing such materials from hazardous phenol–formaldehyde resin waste, particularly when powered by renewable energy sources [13, 15, 17, 21]. Moreover, the integration of LCA methodology into comparative analyses of conventional versus RES-powered production of flocculants derived from industrial waste remains insufficiently explored in the literature [12,22]. In contrast to prior studies focusing on flocculant performance [18–20] and on renewable energy integration in wastewater treatment systems [12–17], the novelty of the present work lies in combining (i) the valorisation of hazardous phenol–formaldehyde resin waste (novolacT) into a sulfonated polymer flocculant, (ii) its application in two real mine-water treatment cases (KWK1 and KWK2), and (iii) a cradle-to-cradle LCA explicitly comparing photovoltaic versus conventional electricity supply using the EF 3.0 framework. This integrated perspective enables identification of life-cycle hotspots specific to waste-derived sulfonated flocculants (e.g., sulphuric-acid-related burdens) under the studied application conditions. Therefore, the purpose of this work was to assess the environmental performance of a polymer flocculant synthesised from phenol–formaldehyde resin waste (novolac T) and applied in industrial wastewater treatment, with particular focus on mine waters. A cradle-tocradle LCA model was developed covering raw-material supply, transport, chemical synthesis of the flocculant, and its application in two hard-coal mine case studies (KWK1 and KWK2), while explicitly considering both conventional electricity supply and photovoltaic-based electricity scenarios. The functional unit was defined as either the production of 100 kg of flocculant or the treatment of 20,000 m^3 of mine water per day, and the assessment used regional data representative for Poland [23,24].

CONCLUSIONS

On the basis of the LCA analysis of the production process of the sulphone resin derivative of novolac T using the chosen method, it was concluded that the results for the mine water treatment of KWK1 and KWK2 are comparable, and that the factor negatively affecting the environment is mainly sulphuric acid. This impact is caused by the use of sulphur for its production and electricity. Despite the use of photovoltaic panels in the electricity production process, the energy consumption generates little impact on environmental quality. The most important in the technological process of mine water treatment is the use of waste phenol-formaldehyde resins, which can pose a great danger through phenol given off by solar energy if stored. Therefore, a closed-loop economy may become very important in wastewater treatment processes, especially the use of polymer waste to produce flocculants and the use of alternative energy sources such as photovoltaic panels or other technological solutions to generate the necessary electricity. Such activities leading to waste management contribute to so-called ‘green technologies’ that protect the environment. They are also important in the responsible use of natural resources and are key in the fight against climate change by reducing environmental impact and saving energy. Such technologies are relevant to business through increased efficiency and access to government subsidies. They represent opportunities for economic development and innovation, which is in line with European Union policy.

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