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Application of the Life Cycle Assessment (LCA) Method in Assessing the Environmental Impact of New Materials Derived from Waste Polymers in Terms of Sustainability

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Abstract: Sustainable socioeconomic development should provide humans with a suitable environment for safe living. It can be debated whether the term "environment" should be used due to the significant anthropogenic transformation of the environment. Therefore, an essential part of solving environmental problems is innovation. Climate, resource conservation, and environmental protection are recognized worldwide as common challenges. Thus, it is necessary to implement solutions that simultaneously protect the environment and the climate with sustainable and rational use of resources. Related to this issue is the principle of a loop/closed-loop economy. Among other things, it refers to using waste to prepare materials that can be used for other purposes. The use of tools such as LCA (life cycle analysis) contributes to supporting environmental protection. With the LCA method, it is possible to analyze environmental risks and compare new technological alternatives. LCA is a methodology that has been used around the world with great success, especially for studying individual stages of the entire product life cycle. The results of studies that have been conducted in various research centers confirm the possibility of also using the LCA technique for the environmental assessment of new technologies or existing modernized technological processes. The purpose of this study was to assess the feasibility of using the LCA method to determine the environmental impact that the potential production and use of new materials will have.

Keywords: sustainability; technological innovation; polymer waste; flocculants; wastewater; LCA

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1. Introduction

Sustainable socio-economic development is all about taking care of a climate and environment that is favorable to humans. The common challenges around the world are climate and environmental protection. In December 2015, representatives of 195 countries and the European Union signed the Climate Agreement in Paris. The basic principles of the agreement are [1]:

- Global warming should be limited to well below two degrees Celsius;
- Greenhouse gas emissions should be reduced to zero from the middle of the 21st century;
- Developing countries should be helped financially in their efforts to protect the climate and adapt to the consequences of climate change;
- Climate change;
- National climate protection plans should be established and implemented.

Therefore, tools are needed to study the environmental impact of technologies. One method that estimates the environmental burden caused by a product, production process, or activity by determining the energy and material consumption and pollutants released into the environment; assesses the environmental impacts associated with energy consumption, material consumption, and pollutant emissions; and finally assesses the potential for improving environmental impacts is LCA analysis. Unlike traditional environmental management methods, it allows for:

- A comparison of alternative products and production technologies;
- The identification of the sites throughout their life cycle that generate the greatest environmental impact;
- The establishment of criteria for eco-labeling to identify the most environmentally friendly products;
- The comparison of waste treatment alternatives

Uncontrolled waste management still poses a significant threat to the environment, and in recent years, despite all measures, the negative impact of polymer waste can be observed. Therefore, the use of waste as secondary raw materials is technologically and economically justified [2], especially polymer waste. Full life cycle assessment takes into account the acquisition of raw materials, production, transportation, distribution, use, maintenance, reuse, recycling, or disposal. From this perspective, it is possible to apply the technique to evaluate not only products but also, among other things, chemical risks in potential wastewater treatment processes using new flocculants, thereby shaping a safe environment. The use of LCA is a good example for identifying the sources and assessing the environmental impact of the potential production of new-generation flocculants synthesized from post-production phenol-formaldehyde resin waste and their application in industrial wastewater treatment.

In the development of new technologies, the environmental aspect should be taken into account due to the recent push for sustainable development. One of the sectors that significantly burdens the environment is the iron and steel industry, which sees high energy consumption and dust and gas emissions. Efforts are currently underway in steel mills to modernize production processes to reduce dust and gas emissions, especially CO_2 emissions, and post-production waste. The use of LCA analysis in the steel industry allows for the identification of the largest sources of environmental risks and the estimation of the environmental effects associated with the steel production technologies under study [3].

In recent years, two main fields of application of LCA have been identified in environmental engineering: the field of waste management and disposal [4–7] and water and wastewater treatment technologies [8–12]. At present, a lot of research in these areas is being carried out worldwide, while the Polish experience, especially in the field of wastewater treatment technologies, is still relatively underdeveloped. Research on waste management should be carried out from the point of view of protecting the environment against harmful effects caused by the collection, storage, transport, recovery, neutralization, reuse, and disposal of waste.

The main author of the article conducted the first study covering the scope of using the LCA technique in the study of flocculant production processes. Subsequently, the LCA methodology was applied by the Author to the study of the next stage of wastewater and industrial water treatment using flocculants synthesized from polymer waste [13–15]. This article presents the possibility of obtaining a flocculant—an amine derivative of the phenol–formaldehyde resin of SE novolac—through technological innovations related to the use of waste, as well as the results of a study of the effectiveness of the application of an exemplary new polyelectrolyte in the treatment of metallurgical wastewater, and environmental impact assessment, which was carried out using the Life Cycle Assessment (LCA) program.

2. Materials and Methods

2.1. Defining the Purpose and Scope of LCA

The publication is based on the results of original research conducted as part of the collaboration between the Czestochowa University of Technology and the Institute of Mineral and Energy Economy of the Polish Academy of Sciences in Krakow.

LCA is a technique often used to create scenarios, and in this study, it was used to present an environmental life cycle analysis of the flocculant obtained in the original research conducted by the first author. The flocculant was chosen for environmental studies based on analyses of metallurgical wastewater treated with chemical compounds derived from phenol–formaldehyde resin waste (novolac SE), synthesized by the main author. The phenol–formaldehyde resins used in the research had varying phenol content, and due to this, the resin manufacturing plant adopted the conventional name "novolac SE".

For the application of LCA analysis of the newly synthesized polyelectrolytes:

Amino derivatives of novolac SE from phenol-formaldehyde resin waste were synthesized [16].

The impact of potential polyelectrolytes (flocculants) synthesized from post-production phenol–formaldehyde resin waste on reducing selected pollutant indices in metallurgical wastewater was determined (considering the coagulation process using the flocculant), as part of the original research. The results are presented in Table 1 and its description. The table is located in the Results Section.

Table 1. Material and energy balance of production of 100 kg of amine derivative of novolac SE.

Inputs—Demand for Raw Materials and Energy Factors	Weight	Unit
Sulfuric acid	209.72	kg
Nitric acid	259.87	kg
Water	5.32	ton
Hydrochloric acid	481	kg
Tin chloride	396	kg
Novolac waste	151.97	kg
Electricity	49	kWh

Life cycle analysis of polymer flocculants included, among other things, calculation of the environmental footprint for polyelectrolytes (flocculants) derived from polymer waste and their use in both municipal and industrial wastewater treatment. The analysis of the products according to LCA covered the life cycle from the extraction of primary raw materials (cradle-to-cradle), through transportation and substrate preparation to the production of flocculants and their use in water and wastewater treatment. Calculations were carried out in accordance with ISO 14040 [17] and ISO 14044 [18], and the analysis was based on project data for the territorial extent of Poland. The production of flocculant (100 kg) or the treatment of a daily volume of wastewater (20,000 m^3) was taken as the functional unit.

EF 3.0 is a method assessing impact accepted by the European Commission. It takes into account normalizing coefficients and weights published in November 2019 by said Commission. Table 2 presents recommended characteristic models where, upon application, it is advised that impact modeling be carried out within the individual categories of impact. The results represented in Table 1 reflect the category set characterized by EF 3.0.

Table 2. Environmental trace impact categories with category indicators and assessment models for recommended levels for environmental trace impact for application needs for the study of environmental traces of products and organizations.

Assessment Model for Environmental Trace Impact	Category Indicator for Environmental Trace		Source [19]
Climate change	Bern Model—global warming coefficient, 100-year range	Equivalent ton of CO_2	IPCC 2013
Ozone depletion	*Environmental Design of Industrial Products*, (*EDIP*), based on potential Ozone destruction (OPD) over an unspecified period developed by the World Meteorological Organization)	Kilogram equivalent to CFC-11	WMO 2014 + integrated data

Table 2. *Cont.*

Assessment Model for Environmental Trace Impact	Category Indicator for Environmental Trace		Source [19]
Ionizing radiation HH	Human health impact model	Kilobecquerel equivalent to U^{235} (emission into the atmosphere)	Dreicer and others, 1995
Photochemical ozone formation	Model LOTOS-EUROS	Kilogram equivalent NMZO	Van Zelm and others, 2008, in accordance with and application of ReCiPe
Particulate matter	Model PM	Disease incidence	Fantke and others, 2016 in UNEP 2016
Human toxicity, non-cancer	Model USEtox 2.1	Comparative toxic unit for humans (CTU_h)	Fantke and others, 2017), in accordance with Saouter and others, 2018
Human toxicity, cancer	Model USEtox	Comparative toxic unit for humans, CTU_h)	Fantke and others. 2017), in accordance with Saouter and others, 2018
Acidification	Accumulated exceedance	Mol+ equivalent H+	Seppälä and others, 2006, Posch and others, 2008
Freshwater eutrophication	Model EUTREND	Kilogram equivalent P	Struijs and others, 2009, in accordance with application of ReCiPe
Marine eutrophication	Model EUTREND	Kilogram equivalent N	Struijs and others, 2009, in accordance with application of ReCiPe
Terrestrial eutrophication	Accumulated exceedance model	Equivalent N	Seppälä and others, 2006, Posch and others, 2008
Freshwater ecotoxicity	Model USEtox 2.1	Comparative toxic unit for ecosystems, CTUe	Fantke and others, 2017, in accordance with Saouter and others, 2018
Land use	Soil class indicator according to LANCA	Dimensionless (pt)	De Laurentiis et al. 2019 and LANCA CF version 2.5 (Horn and Maier, 2018)
Water resource depletion	Available Water Remaining Model	Equivalent water volume removed from use in m^3	Boulay and others, 2018; UNEP 2016
Resource use, fossils	Depleted abiotic reserves—fossil fuels (ADP—mined raw materials)	MJ	Van Oers and others, 2002, as in CML Model 2002, v.4.8
Resource use, minerals and metals	Depleted abiotic reserves (final zasoby ADP)	equivalent kg SB	Van Oers and others, 2002, as in CML Model 2002, v.4.8

Source: Explanations to guidelines of EU Commission 2021/2279 of 15 December 2021 pertaining to methods applied in establishing environmental traces for measuring environmental effectiveness in the life cycle of products and organizations and information thereof (*Official Journal of the European Union*, L 471 of 30 December 2021). *Official Journal of the European Union*, L 144/2 of 23 May 2022, pp. 29–30.

2.2. Assumptions, Value Choices, and Exclusions

Processes were modeled based on design data. Infrastructure and plant maintenance materials were not included in the analysis. The data, which concerned the production of electricity on average for Poland, were modeled using data from the Ecoinvent database in SimaPro software: Electricity, low voltage [PL] | market for | Cutoff, U, and Transport of purchased raw materials: distance 200 km; load 20 t, EURO5 standard [20].

2.3. Input–Output Collection Analysis (LCI)

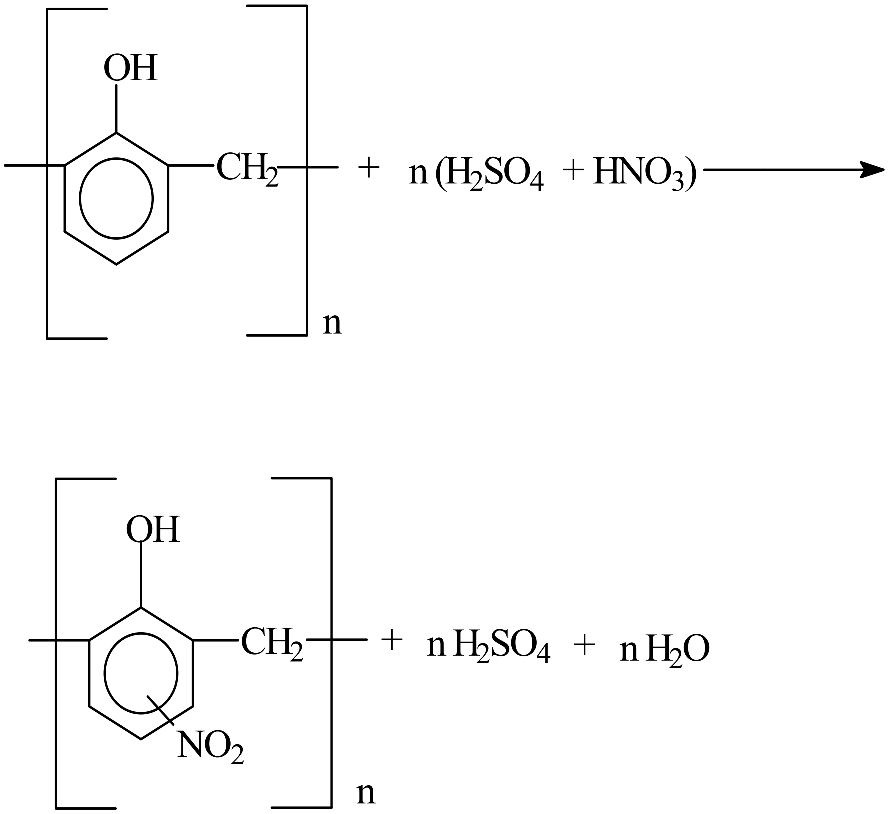
The subject of the LCA life cycle analysis of flocculants was a selected amine derivative of phenol-formaldehyde resin—novolac SE. The balance data and calculation results are presented below, which yielded the LCI (Life Cycle Inventory) indices necessary for the development of the final stage of the LCIA (Life Cycle Impact Assessment) analysis. The study used project data as well as IGSME PAN's own data and literature data.

The amine derivative of phenol-formaldehyde resin (novolac SE) was obtained in two stages—first, the nitro derivative of novolac was obtained. And then, as a result of the reduction of the nitro derivative, the amine derivative was obtained [21,22]. Idea diagrams of production were published in the author's monograph [16].

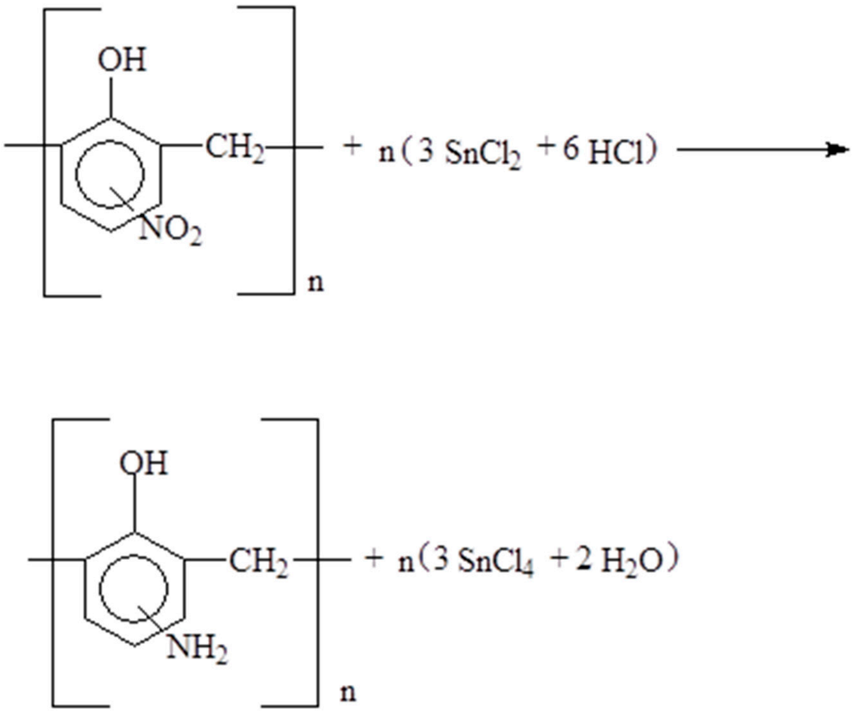
The production of 100 kg of flocculant (as the amount produced per month) was taken as the functional unit in the LCA analysis of the flocculant production stage. Based on the balance of inputs and outputs and the designed process line for the production of the new flocculant, which included chemical reactors, mixers, filters, pumps and dryers, the raw material and energy requirements for the production of 100 kg of flocculant were developed. After inputting data from inventory tables for the production process of potential flocculant based on post-production phenol-formaldehyde resin waste—SE novolac—a material balance was developed (Table 1).

The new synthetic polyelectrolyte (flocculant) was obtained from the post-production waste of phenol-formaldehyde resin (novolac SE). The amino derivative of novolac SE was produced by nitrating linear-structured novolac using a nitrating mixture (concentrated nitric acid (V) and concentrated sulfuric acid (VI)). Subsequently, to obtain the amino derivative, the reduction process of the nitro derivative of linear-structured novolac to its amino derivative was carried out using a mixture of tin (II) chloride, water, and concentrated hydrochloric acid.

The nitration reaction can be represented as:



The reduction reaction of the nitro derivative can be represented as:



As a result of the conducted studies on the coagulation process using the obtained flocculants, it was found that the most effective flocculants were the amino derivatives.

2.4. Life Cycle Impact Assessment—LCIA

The study was conducted using software, SimaPro Developer v. 9.4.0.2, characterization developed using the EF 3.0v.1.03 method, and weighting using a weighting factor of "1" for each impact category. After preparing the input–output (LCI) data set analysis, an environmental footprint assessment was performed to calculate the environmental footprint of the polyelectrolyte using all categories and environmental footprint impact models according to the selected method. The characterization models with which impact modeling is recommended within each impact category have been published in the authors' article, and the list presented here corresponds to the set of impact categories and characterization models of the EF 3.0 method with implemented databases—mainly Ecoinvent. The EF 3.0 method is an impact assessment method adopted by the European Commission (EC). It takes into account the normalization factors and weights published in November 2019 by the EC [23].

3. Results

In waste management, as well as in water treatment technologies, municipal and industrial wastewater treatment, and in the utilization of sludge, the use of the LCA (Life Cycle Assessment) method is of particular importance, especially the results of analyses that present various solutions considering the principles of sustainable development. In the conducted environmental impact analysis of a flocculant obtained from the modification of phenol–formaldehyde resin, on one hand, the utilization of hazardous waste containing phenol is observed, while on the other hand, the use of a by-product—an amine derivative of phenol–formaldehyde resin—novolac SE—in the process of treating wastewater and industrial waters. There are few scientific studies directly related to the LCA of synthesized flocculants based on waste and, at the same time, their application as agents supporting coagulation processes. Research over the last decade, for example, shows the potential for obtaining chemical agents with effective flocculating properties from tree bark waste, and their LCA studies mainly focus on the environmental impact of the production stage of these agents from waste [16]. In another exemplary publication, researchers in the first part presented the results of studies using chitosan, iron sulfate, and alum as coagulants, as well as Neochloris oleoabundans, which were tested to determine optimal conditions for removing algae from aquatic environments. In the second part of this study, a comparative life cycle assessment (LCA) of five different separation scenarios was presented, through which algae can potentially be recovered from a liquid medium on an industrial scale: flocculation with (1) chitosan, (2) iron sulfate, and (3) alum; (4) centrifugation; and (5) filter press separation. The energy and environmental implications of these different separation methods were examined to enable an effective and environmentally safe choice. The study appears comprehensive but is not related to waste recycling [12]. There are many such studies, some of which are cited in the introduction. However, the use of LCA for a comprehensive assessment of polymeric flocculants is mainly covered in the scientific works of Bajdur W.M. and co-authors [3,13–16,21]. The synthesis of a new generation of polyelectrolytes based on polymer waste and their application in wastewater treatment processes, along with a comparative analysis of the products in terms of environmental hazards using LCA, remains a relatively innovative approach to the problem of polymer waste management.

Both in waste management and in technologies for the treatment of municipal and industrial wastewater and the use of sludge, the use of the LCA method is of particular importance, especially the results of an analysis that presents different solutions taking into account sustainability principles [24–26].

Based on the results of the LCA analysis, an assessment of the impact of the production and use of an example polymer synthesized from post-production phenol–formaldehyde resin waste—novolac SE—was carried out. As intended, the scope of the study included the production process of phenol–formaldehyde resin waste to obtain the amine derivative of novolac SE. Figure 1 is the results after the characterisation step in the 16 impact categories for the flocculant, expressed in the unit mPt (mile Pt, Pt—point).

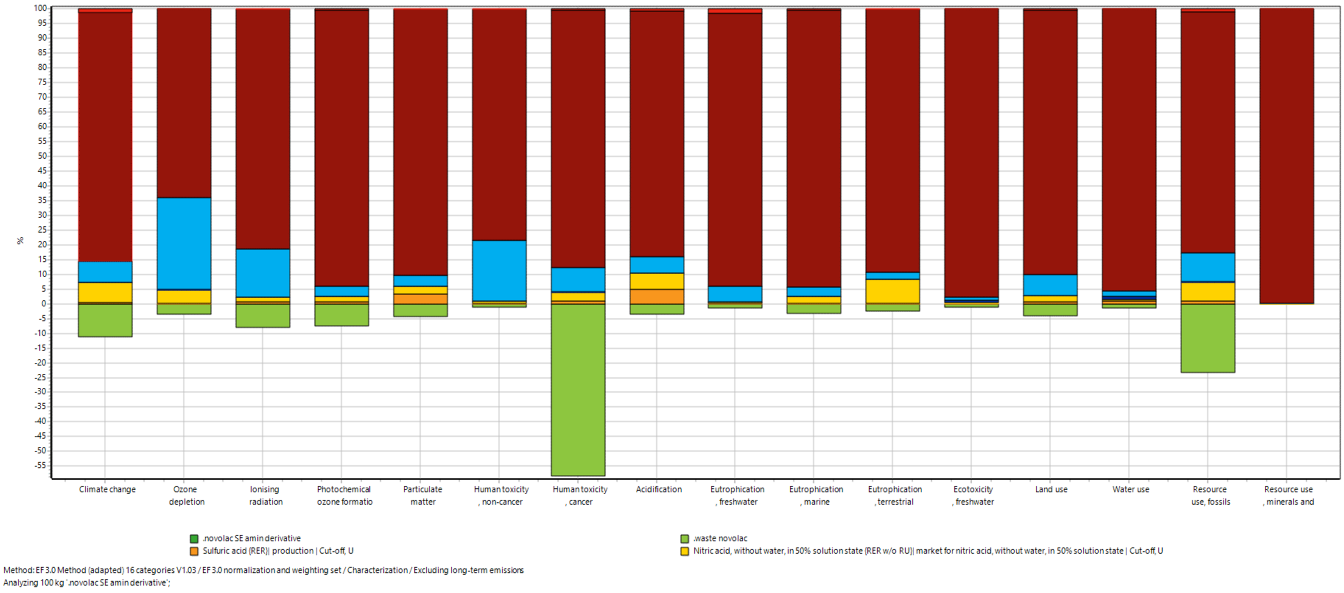


Figure 1. Results after the characterization step for the amine derivative of phenol–formaldehyde resin (novolac SE) concerning the functional unit.

From the data presented after the characterization stage, it can be seen that in all impact categories, the dominant and negative impact was the use of stannous (II) chloride to produce the amine derivative of novolac SE. The environmental benefit caused by the management of novolac waste is apparent, but in the no impact category, it offsets the potentially negative impact of $SnCl_2$ used. There is also a visible impact from the use of hydrochloric acid (blue), nitric acid (yellow), and sulfuric acid (orange). With such a large impact of the above reactants, the impact on the environmental footprint of electricity used during production is virtually invisible. The proportion of tin chloride in each category varies between 66 and 209%; hydrochloric acid—0.1–21%; nitric acid—0.06–8%; sulfuric acid—0.02 5%; and electricity—only 0.002–1.7%. For the production of the amine derivative of SE novolac, emissions were not modeled. If the potential environmental harms and benefits are given in one chart, then the score in a given category is their sum, which is in line with environmental benefits. If the potential environmental harms and benefits are given in one chart, the result in a given category is their sum understood as an environmental benefit. Analysis of the characteristics of the production process of the amine derivative of novolac post-production waste showed that the impact of the category of resource consumption through the use of resin waste is positive.

Weighted Results of Impact Category Indicators

Figure 2 shows the results after the weighting stage in 16 impact categories. The results in all impact categories are expressed in the unit of mPt (mile Pt, Pt—point).

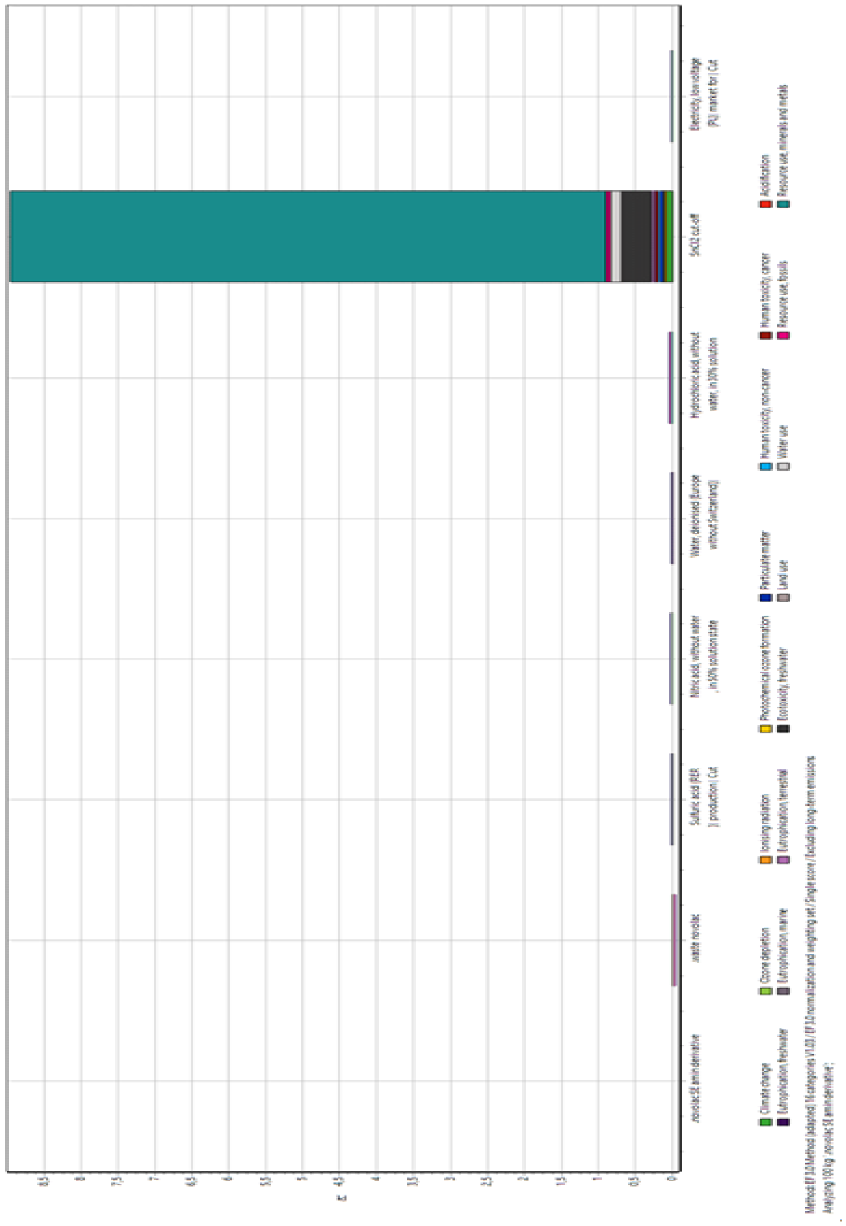


Figure 2. Results after the weighing step for the amine derivative of phenol–formaldehyde resin (novolac SE) concerning the functional unit.

The environmental footprint of the production of 100 kg of the amine derivative of novolac T is 8999.19 mPt. The main process affecting environmental quality is the production of used tin chloride (8961 mPt, 99.6%)—resulting from the depletion of raw material resources by tin; all other processes have an impact of less than 1%. The potential environmental benefit from the management of novolac waste is (-) 51.5 mPt, representing only (-)0.6% of the total impact. To the greatest extent, flocculant production affects the categories of resource use—minerals and metals (89.8%) and ecotoxicity to freshwater (4.6%). The environmental benefit of novolac waste management is not evident in any of the impact categories studied.

The results after the weighting stage can be presented in the form of similar histograms, as in the case of the characterization stage, or in a "process network" format (Figure 3). Figure 3 shows a process network as a single indicator. Process networks can be presented as a single indicator for a given impact category—for example, resource use—minerals and metals (Figure 4) or freshwater ecotoxicity (Figure 5).

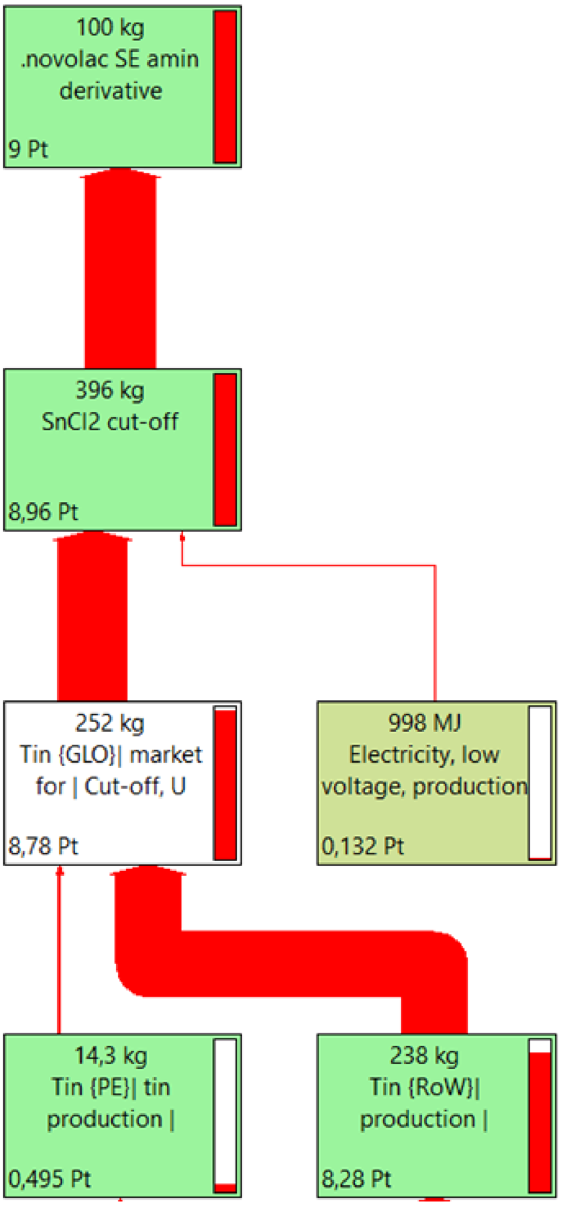


Figure 3. Environmental footprint for the production process of the amine derivative of the SE novolac-process network concerning the functional unit [Pt].

Figure 4. Environmental footprint for the production process of the amine derivative of the SE novolac-process network in the category of resource use—minerals and metals in relation to the functional unit.

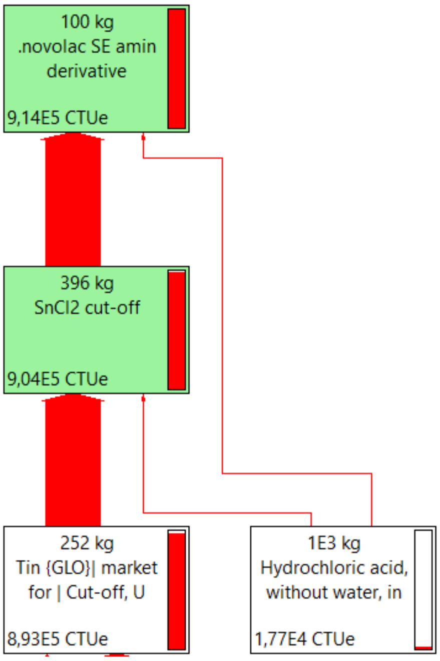


Figure 5. Environmental footprint for the production process of the amine derivative of the novolac SE-process network in the category of ecotoxicity for freshwater with respect to the functional unit.

The thickness of the arrows reflects the magnitude of the environmental impact, it follows that in the production of the amine derivative of SE novolac produced from the waste of this resin, the decisive factor that potentially burdens the environment is the use of stannous (II) chloride for its production. Furthermore, it follows from the developed raw material and process tree that in the assumed production of an amine derivative of phenol-formaldehyde resin, the decisive factor that potentially burdens the environment is the production of stannous (II) chloride. To evaluate the environmental impact of the stage of application of a potential flocculant in the treatment of metallurgical wastewater, the scope of the study was adopted, which included the process of modification of shredded SE novolac waste and subsequent use of the product to support the coagulation process of metallurgical wastewater. The analysis also included the calculation of the environmental footprint for the use of flocculants in metallurgical wastewater treatment. The life cycle of the product was analyzed from the extraction of primary raw materials (known as cradle-to-cradle), transportation of materials, manufacturing of flocculants, and their application. The calculations were carried out according to ISO 1404 and ISO 14044. The analysis was made based on design data, the functional unit of analysis was the treatment of 20,000 m^3 of polluted water (daily volume). Assumptions for the analysis were made as for flocculant production except for the functional unit. Table 3 includes the indicators in the metallurgical wastewater and the sulfide.

Table 3. Characteristic of metallurgical wastewater before the treatment process.

Emission to Water	Amount	Unit
2,4,6-trichlorofenol	4.9	mg
Cyanide	2.3	mg
Chemical Oxygen Demand COD	210	mgO_2/L
Ammonia as Nitrogen	315.3	mg
Sulfate	150.4	mg
Chloride	1556.5	mg
Suspended Substances, unspecified	36.6	mg

As a result of the wastewater treatment process using the flocculant—an amine derivative of Novolac SE—the indicators studied decreased significantly. Cyanides and phenols below 0.005 mg/dm^3. Oxidizability decreased to 21 mg O_2/L, chlorides decreased to 180 mg Cl/L, and sulfates decreased to 90 mg SO_4/L, with ammonia nitrogen below 20 mg/L. From the data presented after the characterization stage (Figure 6), it can be seen that in almost all impact categories, potentially negative impacts on environmental quality are caused by the use of the amine derivative of novolac SE for the treatment of metallurgical wastewater. Impacts related to the use of NaOH and electricity are also evident.

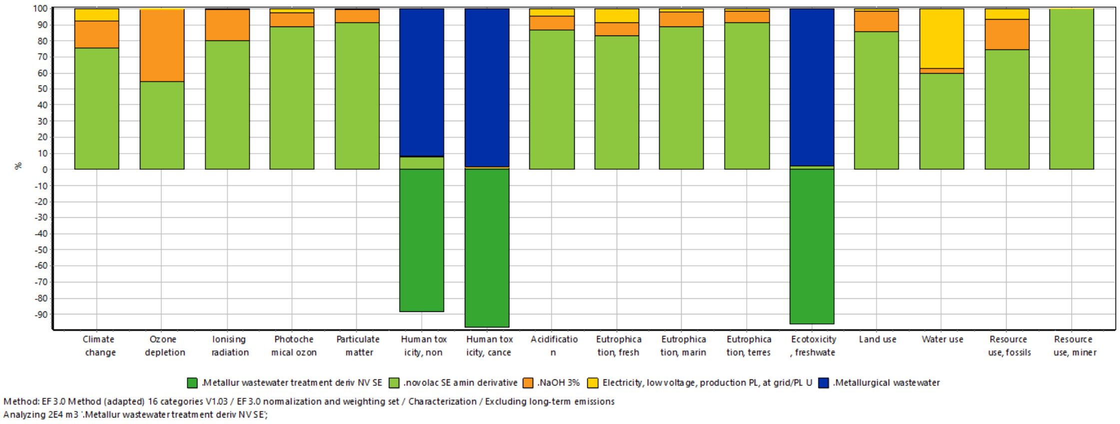


Figure 6. Results after the characterization stage for the treatment of metallurgical wastewater with the amine derivative of novolac SE in relation to the functional unit.

In the categories related to toxicity, one can see the negative impact on the environment of metallurgical wastewater before treatment, which is mostly offset by the beneficial impact of its treatment. The share of flocculant production in most of the impact categories varies between 70% and 91%, as well as electricity in each category—from about 0 to 37%—with the most frequent oscillation around 0–3%. This high potential environmental burden is due to the depletion of resources by tin, which is added to the production of flocculant (stannous (II) chloride). When potential environmental harms and benefits are given in one chart, the category score is their sum—the environmental benefit is included with a (-) sign.

Figure 7 shows the results after the weighting stage in 16 impact categories for metallurgical wastewater treatment. The results in all impact categories are expressed in the unit of mPt (Pt mile-point).

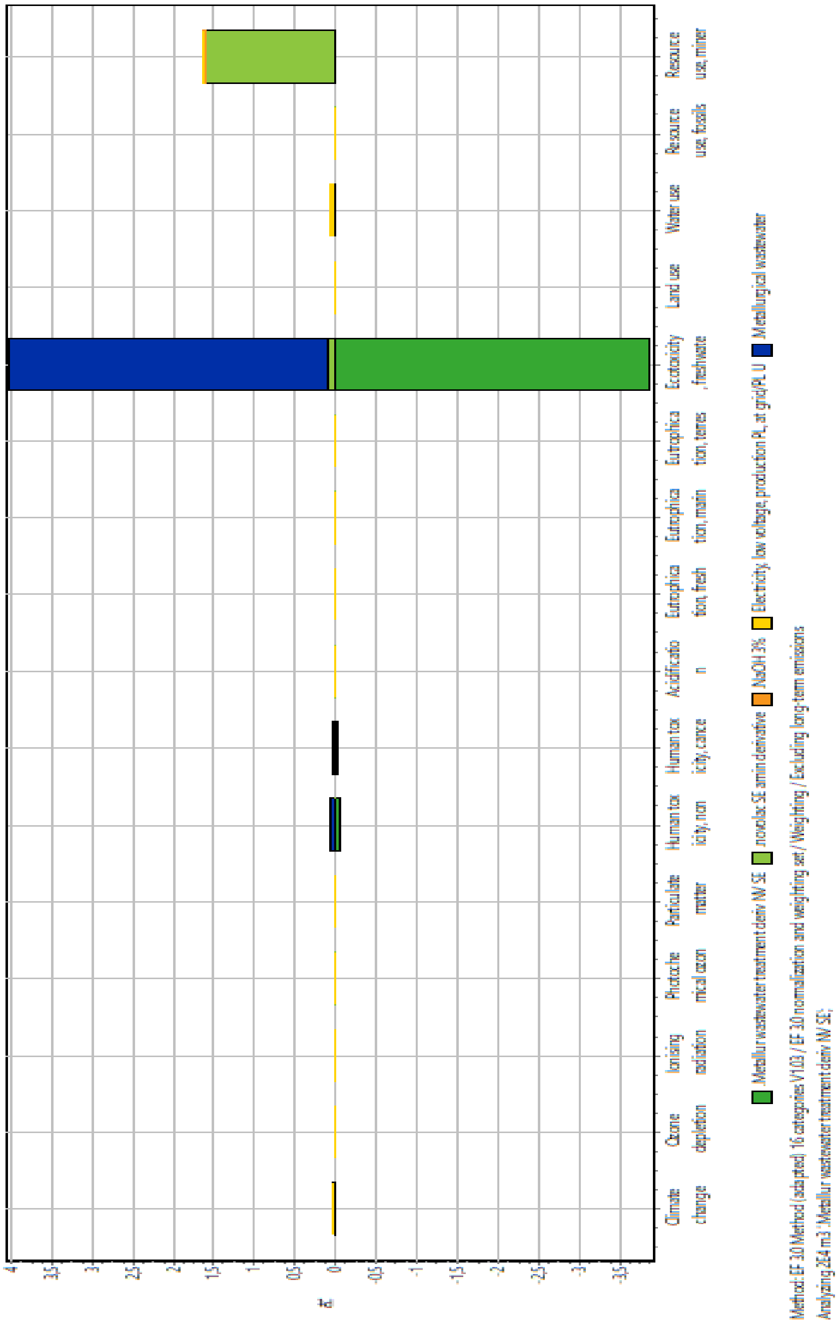


Figure 7. Post-weighting results for the treatment of metallurgical wastewater with the amine derivative of novolac SE with respect to the functional unit.

The environmental footprint of the treatment of 20,000 m^3 of metallurgical wastewater is 1910.8 mPt. The main components of the treatment process affecting the environment are contaminated metallurgical wastewater (4034.7 mPt, 211%), its treatment process (3964.3) mPt, (207%), flocculant production (1799.8 mPt, 94.2%), and electricity (23.7 mPt, 1.2%). To the greatest extent, the metallurgical wastewater treatment process potentially adversely affects categories of resource depletion—minerals and metals (84.7%), which is due to the depletion of resources by tin, and the category of ecotoxicity for freshwater (8%), which is affected by the incomplete removal of the chloride load from the metallurgical wastewater. There is also a noticeable impact in the water use category (2.8%). In the case of the production of the amine derivative of the SE novolac, even the minimum potentially beneficial environmental impact from the results after the weighing step cannot be represented in similar histograms as for the characterisation step or in a 'process network' format (Figure 7). The thickness of the arrows in the graphs is proportional to the magnitude of the impact of each component. Figure 8 shows the impact of metallurgical wastewater treatment concerning one indicator—it is the sum of all categories. They can be summed, because they have been normalized, and as a result, weighting is expressed in one unit (Pt).

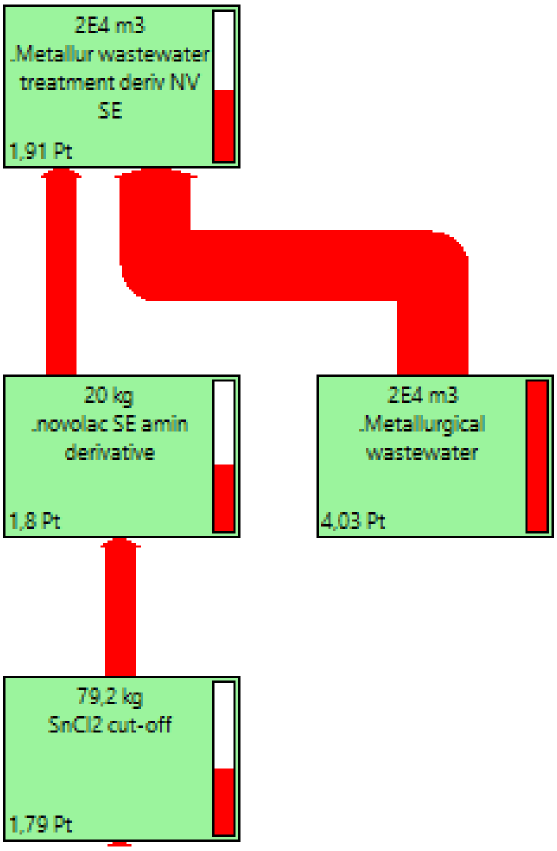


Figure 8. Environmental footprint for the process of treating metallurgical wastewater with an amine derivative of the SE novolac-process network in relation to the functional unit.

The thickness of the arrows is related to the magnitude of the environmental impact, so in the process of treating metallurgical wastewater, the decisive factor potentially burdening the environment is contaminated water, but in the results expressed in the unit Pt on the process tree, a reduction in the adverse environmental impact through the process of their treatment is evident—from 4 Pt to 0.1 Pt. Based on the analysis, it can be concluded that LCA is a good tool for studying the environmental impacts of technological processes and allows for assessment of the processing of polymer waste recycling especially in the era of sustainable development.

4. Conclusions

Nowadays, the application of LCA to the evaluation of new technological solutions in perspectives will allow for the maintenance of the principles of sustainable development concerning environmental safety. In many LCA publications, not only the safety aspect but also the socio-economic aspect is presented. This article presents the impact of the process of the potential production of a new generation of polymer—an amine derivative of phenol–formaldehyde resin. LCA analysis is not a substitute for the need to perform environmental impact assessments, but it is a good method that allows for reliable and credible study results in the histograms shown. The use of this technique makes it possible to forecast risks, as well as to reduce their environmental impact at the design stage of potential technologies, which is particularly important for the development of systemic solutions.

The research results provide a basis for further work on safety, specifically concerning processes such as production, in the context of so-called occupational health and safety. Presenting various scenarios would certainly be interesting from an economic and social perspective. This serves as a contribution to the development of other highly interesting research directions concerning polymer flocculants. Such research directions undoubtedly align with sustainable development efforts. LCA can also be utilized, as is particularly evident in the example of the United States, in the processes of creating and implementing environmental policies.

This work provides a basis for further research into the social and economic aspects of environmental safety. The potential market impact and economic benefits will allow a holistic view of the sustainable development of new wastewater treatment materials.

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