

Environmental profile evaluations of piezoelectric polymers using life cycle assessment

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Abstract—Piezoelectric materials are indispensable to produce electricity, harvesting ambient mechanical energy through motion for sectors and products, from sensors, to biomedical systems, to tiny electronics. Nylon 66 and tetrafluoroethylene dominate the market among thousands of piezoelectric materials to provide an autonomous power supply. Emphasis has been given on investigating the environmental impacts of both materials due to the growing consciousness of the ecological and health risks of piezoelectric polymers. The fabrication steps of these polymers from raw materials are extremely hazardous to the environment in terms of toxicity and human health effects. However, no quantification of the possible environmental impacts for the manufacturing of nylon 66 and tetrafluoroethylene exists. This research paper addresses their comparative environmental effects, in terms of chemical constituents. Life cycle impact analysis has been carried out by ReCipe 2016 Endpoint, Ecopoints 97, Raw material flows and CML-IA baseline methods, using Australasian life cycle inventory database and SimaPro software. The impacts are considered in categories like global warming, eutrophication, terrestrial ecotoxicity, human carcinogenic toxicity, fine particulates, and marine ecotoxicity. The results show that there is a significant environmental impact caused by tetrafluoroethylene in comparison with nylon 66 polymer during the manufacturing process. These impacts occur due to the quantity of toxic chemical elements present as constituents of tetrafluoroethylene raw material and its fabrication periods. It can be anticipated that a better ecological performance can be attained through optimization, especially by cautiously picking substitute materials and machines, taking into account the toxicity aspects, and by minimizing the impacts related to designs, fabrication processes and usage.

1. Introduction

In recent times, there has been an increased demand for piezoelectric polymers to energize portable electronics, wearable sensors, biomedical tiny devices, and self-powered systems [1]. Nylon 66 and tetrafluoroethylene are better choices than lead-based piezoelectric materials for their smaller environmental impacts and health hazards [2]-[4]. The advancement of nature-friendly, viable piezoelectric polymer fabrication system is getting considerable interest because of its extensive usage and greenhouse gas (GHG) release reduction. However, taking the remarkable part that nylon 66 and tetrafluoroethylene material has to perform in fulfilling present power crisis, investigators need to assess their ecological impacts counting all the steps of the production method. The life-cycle assessment (LCA) is an orderly scientific way that provides an evaluation of the total ecological effects of a system for its whole lifetime using the comprehensive life-cycle input and output factors that act within the particular life-cycle inventory (LCI) [5]-[8].

All the piezoelectric polymer related LCA studies until now has stressed the assessment of the life-cycle GHG releases. None of the previous LCA research [9]-[10] assessed and compared the net environmental impacts by nylon 66 and tetrafluoroethylene polymer production technologies.



Moreover, no noteworthy study is stated which comprehensively highlights the ecological influences happened by the whole life cycle of these technologies. This work try to minimize this research gap by accomplishing a complete environmental LCA of nylon 66 and tetrafluoroethylene fabrication technologies. This research therefore is a first and inclusive life-cycle environmental impact assessment of nylon 66 and tetrafluoroethylene polymers through systematic life-cycle assessment approach considering their input materials, fabrication steps and associated machines. The LCI dataset is gathered from an Australasian life-cycle inventory (AusLCI) database and analysis is carried out using SimaPro software. LCA has been done by ReCipe 2016 Endpoint, Ecopoints 97, Raw material flows and CML-IA baseline methods. The impacts are addressed under 19 effect-assessing sets like global warming, acidification, eutrophication, terrestrial ecotoxicity, human toxicity, human carcinogenic toxicity, fine particulate matter formation, and marine ecotoxicity etc. The results indicate that nylon 66 has a better performance for most of the considered categories than tetrafluoroethylene. Moreover, the outcome by the Ecopoints 97 method shows that the emission rate of greenhouse gases (GHG) and CO₂ gas is much higher in tetrafluoroethylene than for nylon 66. In Section 2, an overview of the LCA methods is highlighted. Section 3 reveals the LCA outcomes using the ReCipe 2016 Endpoint, Ecopoints 97, Raw material flows and CML-IA baseline methods, thus advises environmental-impact diminution approaches for considered technologies.

2. Methodology

There are a few key steps involved in fabricating the nylon 66 and tetrafluoroethylene polymers at a plant. Nylon 66 polymer membrane is manufactured by polycondensation of adipic acid and hexamethylene-diamine. The key step for nylon 66 formation are the ammonium dinitramide (ADN) process, the Hexamethylene diamine (HMD) process and the adipic acid process which is highlighted in Figure 1. On the other hand, tetrafluoroethylene (TFE) is a chemical compound of fluorine and carbon. The major stages for TFE polymer production are casting, drying and salt crystalizing, sintering, cooling, and salt leaching (Figure 1). LCA is an effective approach to methodically calculate the environmental effects throughout the entire procedure of a system [11]-[12].

LCA is done by collection of the inputs and outputs at every production steps of the material, and environmental impacts are calculated using four main LCA steps [13] namely: (i) goal and scope definition, where the aim is described and the LCA boundaries are fixed; (ii) Life cycle inventory (LCI) analysis where the inputs and outputs at every steps of the manufacturing processes are assembled; (iii) life cycle impact assessment, where output emissions and input resources are clustered into their particular impact groups and transformed into same units for comparative assessment; (iv) the interpretation of the LCI and effect evaluation outcomes to realize the aims of this research.

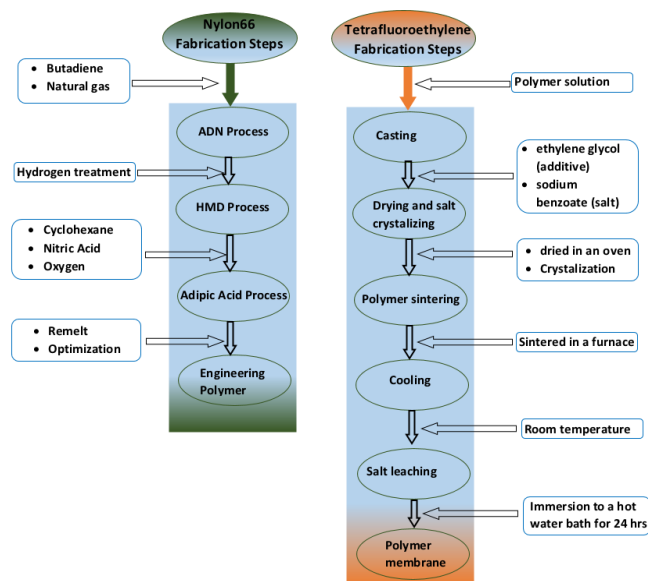


Figure 1. Nylon 66 and tetrafluoroethylene fabrication methods in plant.

To check the outcomes of every stage of both polymer production processes several sustainability metrics is considered into the inventory, and then LCA in this work is carried out by ReCiPe 2016 Endpoint, Ecopoints 97, Raw material flows and CML-IA baseline methods, using an Australasian life-cycle inventory database and SimaPro software. GHG emissions, abiotic depletion, acidification, eutrophication, marine aquatic ecotoxicity, human toxicity, and ionization radiation rates are obtained and compared for both cases based on the CML-IA baseline method [14]. Several metal and gas based endpoint indicators (Cd, Hg, Zn, Pb, Cu, Cr, P, N, NO_x, SO_x, NH₃, CO₂, Dust etc.) are calculated and compared utilizing Ecopoints 97 method. The total inputs from nature and outputs to air, water and land of both processes are also measured and compared by the Raw material flows method. Finally, the ReCiPe 2016 Endpoint method is used to get and compare 19 different environmental impact categories such as stratospheric ozone depletion, water consumption (human health, terrestrial ecosystem, aquatic ecosystems), global warming (human health, terrestrial ecosystem, aquatic ecosystems), fine particulate matter formation etc. for both cases.

3. Results and discussion

The effects are depicted at the effect calculation level. In the act of a comparative study, the results for each impact type for the system with the highest values are computed as 100% and the outcome for another arrangement is computed as the respective proportion.

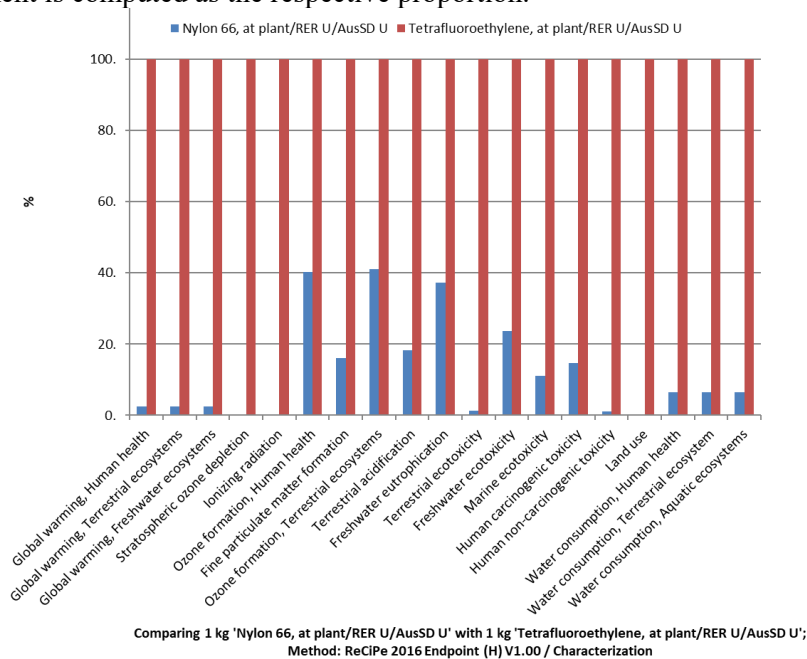


Figure 2. Impact comparison for 19 different impact categories of nylon 66 and tetrafluoroethylene fabrication processes in plant, by ReCiPe 2016 Endpoint method.

Figures 2 and 3 show the relative ecological impacts happened for each damage category of the nylon 66 and tetrafluoroethylene fabrication processes in plant. Figure 2 reveals the evaluation of net impacts, with the maximum effect set to 100, employing the ReCiPe 2016 Endpoint approach. It is evident that factories of the nylon 66 production process perform better environmentally than TFE fabrication process based plants. The endpoint comparison after weighing, using CML-IA baseline methodology is represented at Figure 3. The results indicate that the maximum impact happens at the eutrophication impact category, whilst the minimum is obtained in the abiotic depletion category and the marine aquatic ecotoxicity category by nylon 66 production process factories. It obtained because of the amount of toxic chemical elements available as constituents of TFE raw material and its fabrication stages.

The major impact categories such as global warming, ozone formation, acidification, eutrophication, ecotoxicity, human toxicity, water consumption, stratospheric ozone depletion, ionizing radiation, land

use, etc., which are found by ReCiPe 2016 Endpoint method and results are showed at Table 1. The overall results prove that greater environmental impact is caused by the TFE membrane polymer fabrication plant over the nylon 66 plant. Figure 4 shows the comparative metal and gas-based LCA outputs of nylon 66 and tetrafluoroethylene fabrication process in plant using Ecopoints 97 method. Among several categories CO₂, NO_x and SO_x emission rates are higher than others such as P, Hg, Cd, Cr, Zn, N, Pb etc. The comparative LCA inputs and outputs of the nylon 66 and tetrafluoroethylene fabrication processes in plant using the Raw material flows methodology is highlighted in Figure 5. Nylon 66 plant takes 95% smaller inputs from nature than TFE plant outputs to air is highest (39%). Overall, the effects obtained from this work highlight that a large amount of hazardous emission is occurred from both the nylon 66 and tetrafluoroethylene fabrication processes in plant, which can be reduced by optimization of raw materials and used devices at different fabrication steps. Thus emission of harmful radioactive particles and gases to the environment and ecosystems can be reduced. LCA results-ReCiPe 2016 endpoint method

TABLE 1: LCA RESULTS- RECIPE 2016 ENDPOINT METHOD

Impact Category	Nylon 66, at plant/RER U/AusSD U	Tetrafluoroethylene, at plant/RER U/AusSD U
Global warming, Human health	2.4061	100
Global warming, Terrestrial ecosystems	2.405	100
Global warming, Freshwater ecosystems	2.4054	100
Stratospheric ozone depletion	0.0959	100
Ionizing radiation	0.0062	100
Ozone formation, Human health	40.3002	100
Fine particulate matter formation	16.0143	100
Ozone formation, Terrestrial ecosystems	41.0914	100
Terrestrial acidification	18.357	100
Freshwater eutrophication	37.2802	100
Terrestrial ecotoxicity	1.3289	100
Freshwater ecotoxicity	23.5896	100
Marine ecotoxicity	11.1644	100
Human carcinogenic toxicity	14.692	100
Human non-carcinogenic toxicity	0.9986	100
Land use	0.1047	100
Water consumption, Human health	6.478	100
Water consumption, Terrestrial ecosystem	6.478	100
Water consumption, Aquatic ecosystems	6.478	100

The assessment outcome of human toxicity and ecotoxicity of the nylon 66 and tetrafluoroethylene fabrication processes in plant is highlighted in Figure 6, which is obtained by USEtox method. The cancer based human toxicity is doubled in TFE membrane polymer fabrication plant with respect to Nylon 66 manufacturing plant.

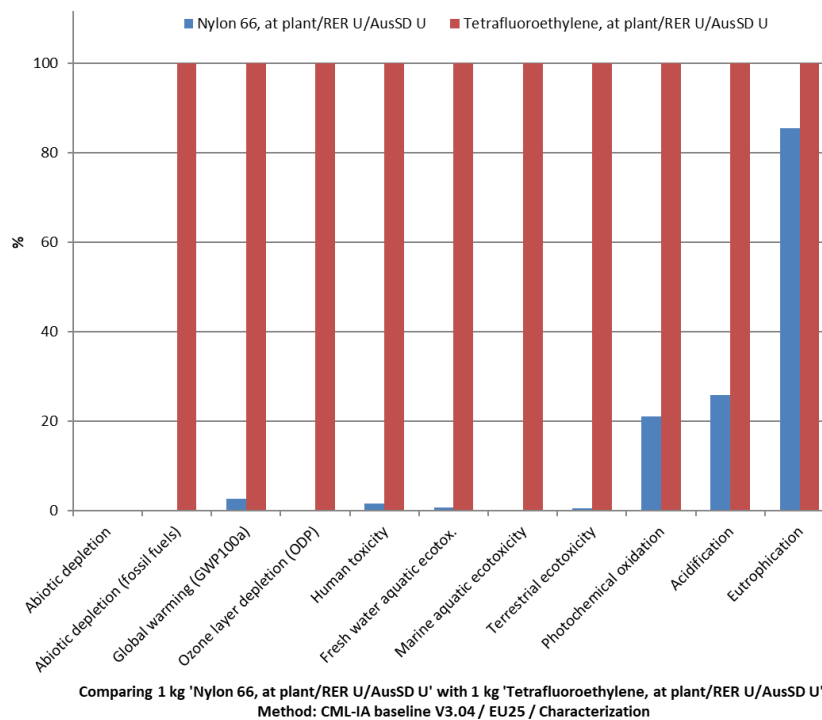


Figure 3. Comparative life-cycle impact assessment of the nylon 66 and tetrafluoroethylene fabrication processes in plant using the CML-IA baseline method.

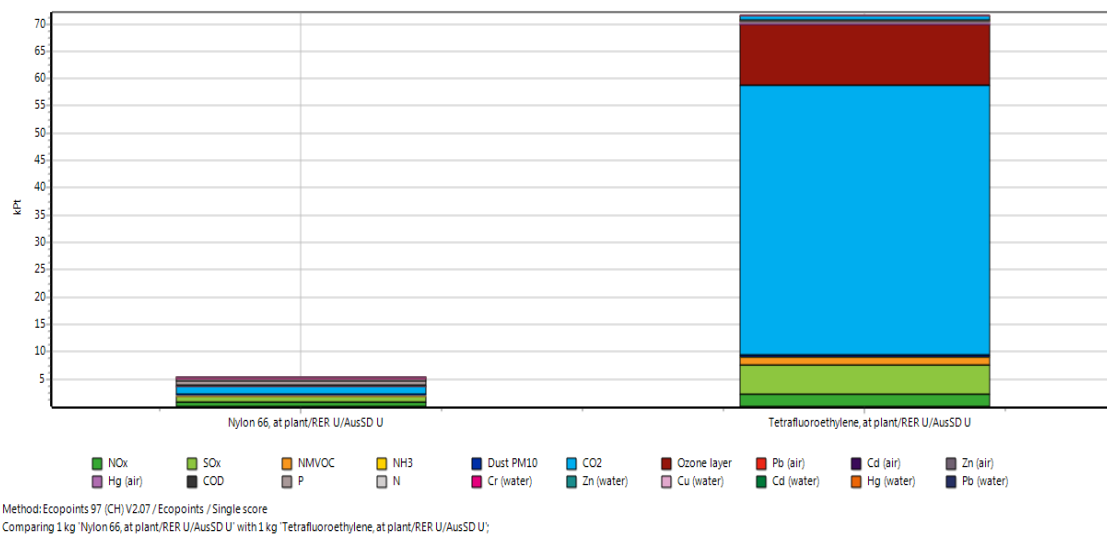


Figure 4. Comparative metal and gas-based LCA outputs of the nylon 66 and tetrafluoroethylene fabrication processes in plant using the Ecopoints 97 method.

Result indicates that the eco-toxicity occurred by Nylon 66 plant is one third of the amount in tetrafluoroethylene plant. It means that the production process of TFE polymer in plant is associated with more toxic element emissions compared to Nylon 66.

The relative effects of both polymer production plants on human health, ecosystem quality and resources, by Eco-indicator 99 method is represented at Figure 7. As shown, the TFE membrane polymer fabrication plant results in more damage compared to the nylon 66 plant in all three impact categories. This means that despite the potential application of tetrafluoroethylene there is still need for further improvement of its environmental profile through optimization during producing at plant.

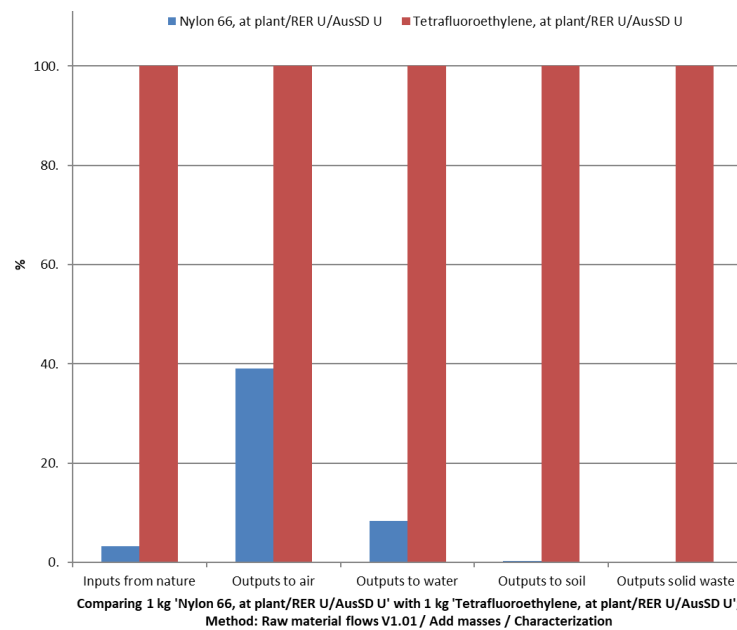


Figure 5. Comparative LCA inputs and outputs of the nylon 66 and tetrafluoroethylene fabrication processes in plant using the Raw material flows method.

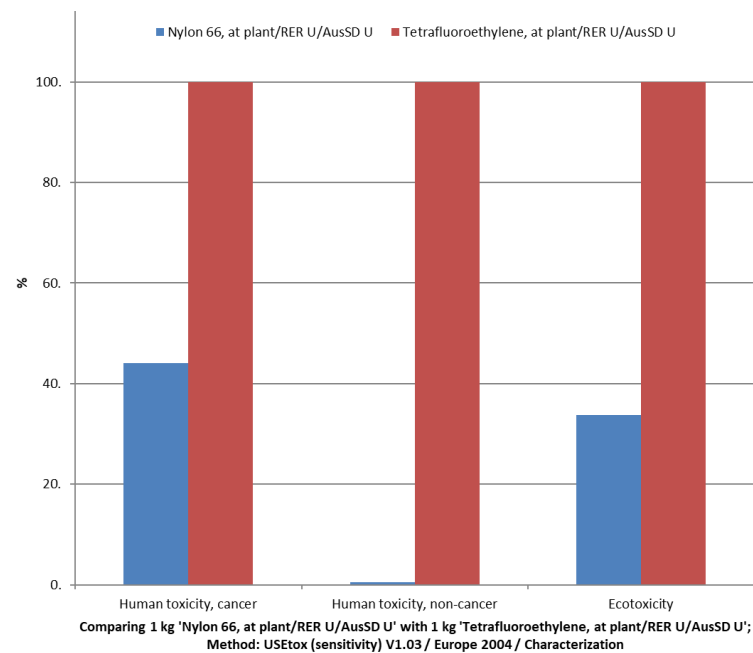


Figure 6. Comparative human toxicity and ecotoxicity of the nylon 66 and tetrafluoroethylene fabrication processes in plant using the USEtox method.

The comparative greenhouse gas emissions of the nylon 66 and tetrafluoroethylene fabrication processes in plant is depicted in Figure 8, which is obtained by the Greenhouse gas protocol methodology. We can conclude from this figure that a 96% reduction in GHG emissions is possible with Nylon 66 technologies and that plants score significantly better than the TFE membrane polymer production plants.

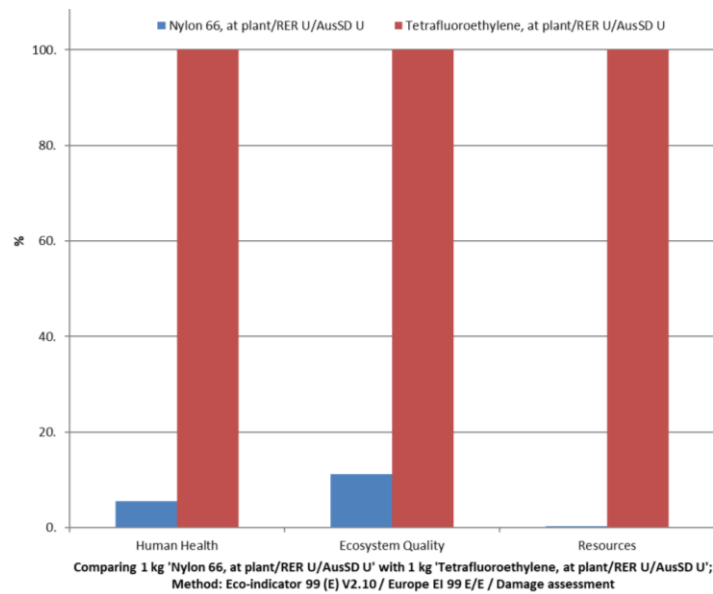


Figure 7. Relative effects of both polymer plants during production on human health, ecosystem quality and resources, by Eco-indicator 99 method.

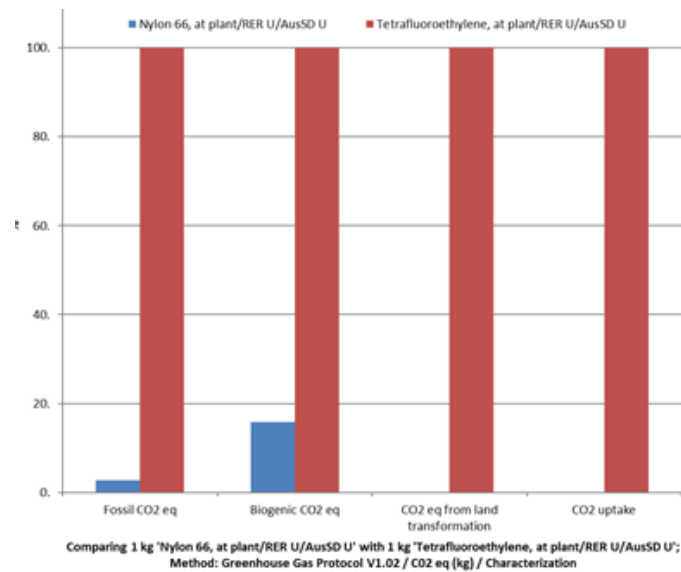


Figure 8. Comparative greenhouse gas emissions of the nylon 66 and tetrafluoroethylene fabrication processes in plant using the Greenhouse gas protocol method.

4. Conclusion

Piezoelectric materials like nylon 66 and tetrafluoroethylene are in great demand for self-powered electronics, biomedical devices and sensor production. The best choice of material depends on higher efficiency, lower fabrication cost, greater lifetime and better environmental performance. This research paper highlights the comparative environmental impacts of nylon 66 and tetrafluoroethylene through systematic LCA analysis by the ReCipe 2016 Endpoint, Ecopoints 97, Eco-indicator 99 (E), USEtox, Raw material flows and CML-IA baseline methods, using an Australasian life-cycle inventory database and SimaPro software. The results indicate that nylon 66 polymer fabrication plants emit lower GHGs, CO₂, NO_x and SO_x compared to TFE manufacturing plants. Moreover, global warming, ozone formation, acidification, eutrophication, ecotoxicity, human toxicity, water consumption, stratospheric ozone depletion and ionizing radiation rates are higher in tetrafluoroethylene polymer plants than for nylon 66. These impacts are occurred due to the amount of toxic chemical elements exist as

constituents of tetrafluoroethylene raw material and its manufacturing stages. Therefore, nylon 66 is indeed a better choice of piezoelectric material than TFE. It is suggested that cautious choice of machines and required ingredients can reduce toxic emissions and increase environmental performance by polymer production plants.

5. References

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