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Research Article

ASSESSING ENVIRONMENTAL HOTSPOTS OF TIRE CURING PRESS: A LIFE CYCLE PERSPECTIVE

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ABSTRACT

The machinery manufacturing sector is thought to be in a key position to achieve sustainable manufacturing because it uses large amounts of energy and raw materials. The aim of this study is to determine the environmental hotspots of manufacturing the tire curing press (hydraulic) through Life Cycle Assessment (LCA). The LCA methodology based on the ISO 14040 standard was conducted with SimaPro 8.0.4 software and the IMPACT 2002+ method. A "cradle-to-gate" approach was performed and functional unit was selected as manufacturing of one piece of product. In the scope of the sensitivity anaylsis, different impact assessment methods (ReCiPe Midpoint (H), TRACI, CML-IA, and ILCD 2011 Midpoint) were also performed to verify and compare the results. Results showed that the significant environmental impacts were respiratory inorganics, global warming, and non-renewable energy during the manufacturing of tire curing press. When the manufacturing stages were taken into account, it is important to state that raw material consumption has the highest adverse effect on environment. The study also reveals that the importance of the supply chain and lightweight design in LCA.
Keywords: Environmental impact, environmental hotspot, life cycle assessment, machinery manufacturing, tire curing press.

1. INTRODUCTION

The machinery manufacturing industry, which ensures a variety of materials and products for society, has become a pillar industry of the Turkey's economy. However, it is traditionally associated with high energy consumption, serious environmental contamination, and greenhouse gas (GHG) emissions (Du et al., 2015). Hence, the researchers have been focusing on finding the manufacturing methods that are more sustainable and greener (Goindi and Sarkar, 2017). The machinery manufacturing industry is also known to be resource intensive. The production of mechanical machinery contains about 13% of the entire world's steel production and a non-negligible amount of cast iron and aluminum (Strano et al., 2013).

Hydraulic presses are indispensable for metal forming because they can generate the necessary forming pressures, but in doing so, they consume large amounts of energy. Hydraulic press manufacturing is a primary contributor of carbon emissions (Gao et al., 2016). Aside from their use in metal working, presses with iron and/or steel frames are used to manufacture items

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such as ceramic tiles, plastic, or rubber. This contributes to the rapid worldwide growth of the machinery manufacturing sector. According to Eurostat, the machinery industry is the 6th-fastest growing of the 29 major industrial sectors. This indicates future increases in the number of presses manufactured along with the potential environmental impacts over their life cycles (manufacturing, use, and final disposal) (Strano et al., 2013). The major parameters adversely affecting the environment are cutting fluid use in machining, energy efficiency of machine tools, and process wastes (Akbari et al., 2001).

Sustainable manufacturing was developed from the sustainable development concept, and it aims to improve methods for converting raw materials into manufacturing products using fewer natural resources and less energy while minimizing wastes, environmental emissions, and health and safety risks (Rosen and Kishawy, 2012; Goindi and Sarkar, 2017). Life cycle assessment (LCA) is a significant tool used to accomplish sustainable manufacturing. It is a very useful methodology for estimating the environmental burden of a product or service over all life cycle stages: raw material production, manufacture, transportation, use, repair and maintenance, and disposal or recycling (Narita, 2012).

Numerous LCAs have been conducted to determine the environmental impacts of various machines and machine tools. While some of them compared the various manufacturing stages (e.g., machining, welding) (Lodhia, 2003; Fratila, 2010; Narita, 2012, Zendoia et al., 2014), others compared the entire product life cycles (use and end-of-life) (Song et al., 2010; Santos et al., 2011; Cao et al., 2012; Krautzer et al., 2015). Additionally, many studies have been performed about life cycle impact assessments (LCIAs) focusing on carbon emissions or energy efficiency (Song et al., 2010; Strano et al., 2013; Gao et al., 2016). However, because of the complexity of machine structures, few LCAs have been carried out for the manufacturing of presses (Santos et al., 2011; Zhang et al., 2016; Yu et al., 2013).

In this work, potential environmental impacts of manufacturing a hydraulic press were evaluated using LCA through the SimaPro 8.0.4 software. Environmental hotspots on the production stage of tire curing press were identified, and then the most significant environmental impacts were determined.

2. METHODOLOGY

A case-specific LCA was performed to evaluate the environmental hotspots of manufacturing a hydraulic press, and the 4 steps, according to the ISO 14040 standard, were applied: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation (ISO 2006a). In the first step, the goal of the study is clearly defined, and system boundaries are determined. In the second and most critical step of LCA, the process is defined, operation states are measured, data is collected, and consumption and waste are calculated for functional unit (Zendoia et al., 2014). In the third step, the environmental burdens associated with all inputs and outputs of the product or service are quantitatively determined using the mid-point and end-point impacts. In the final step, results are determined based on the system boundaries and inventories identified in the previous steps.

2.1. Goal, scope, and functional unit

The goal of this study was to determine the environmental hotspots of tire curing press (hydraulic) via a cradle-to-gate LCA. 2016 was selected as the target year to ensure reliable and available data. Tire curing press is serviceable product and it has a long lifetime (minimum 50 years). Because its use and end-of-life scenario is based on hypothesis almost completely, the scope of the study was limited only manufacturing stage. System boundary of the LCA includes supplying of raw materials, additives and auxiliary materials from supplier; transportation of all materials to the manufacturing plant; manufacturing processes in the plant (cutting, welding, chipping, etc.). It is shown in Figure 1.

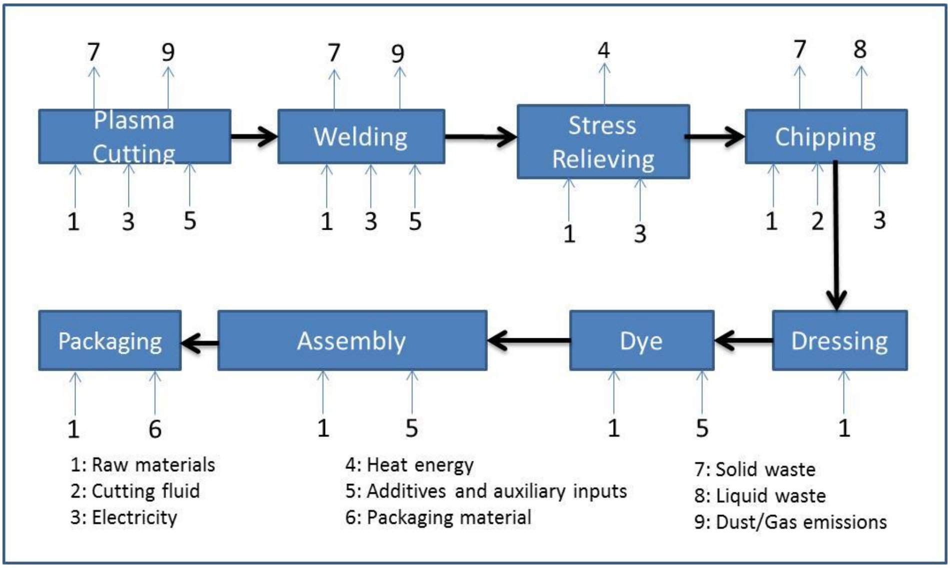

Figure 1. System boundary of the LCA

The primary material used to manufacture tire curing press is steel. Bronze is also used during assembly of the hydraulic press. Cutting fluids are important for the chipping process but have negative impact on the environment (Dahmus and Gutowski, 2004). The principal environmental and health impacts arise from water-based cutting fluids, which can have concentrated effects on ecological toxicity, water use, and fugitive emissions (Clarens et al., 2008). Oil-based cutting fluids can be improved by adding sulfur, phosphorus, chlorine, or boron (Brinksmeier et al. 2015). In our case, boron oil is used as a cutting fluid in the chipping processes. This fluid is typically 95% water and 5% boron oil (volumetric). Welding is also performed when making the hydraulic press. Electricity is consumed at nearly every manufacturing stage, except for dressing, dye, assembly, and packaging.

The weight of the hydraulic press produced in the selected plant is approximately 50 tones. Because the main focus of this study is to assess the environmental hotspots in manufacturing stage of the tire curing press, the functional unit was defined as the manufacturing one piece of tire curing press with a weight of 50 tones to achieve the meaningful results and comparing the literature.

2.2. Life cycle inventory

Inventory analysis is the most critical step in LCA studies because of data availability and quality (Çankaya and Pekey, 2015). The required information about inputs and outputs for various manufacturing stages, which is named as foreground data, was obtained from the manufacturing plant. Input data for the LCI includes the amounts of raw material (e.g., steel, aluminum), electricity consumption, water consumption, additives (cutting fluid, welding wire, dye, copper and/or shaped tubes, cables, etc.), and transport distance and vehicles. Output data consists of the quantities of emissions (to the air, water, and soil) and the product produced. Emission data were obtained from Annual Emission Report of the plant. Air emissions are generated during the welding (i.e., SO_2, NO_2, CO, NO, PMs) and dying (PMs and VOCs) processes in the plant. Additionally, waste steel, waste boron oil, and waste packaging paper were quantified from each manufacturing stage. Background data including Turkey's electricity mix, transport, and raw material production (e.g., steel, aluminum, cast iron) were obtained from SimaPro libraries (Ecoinvent, ELCD, and USLCI). Local data of energy production is the key factor for the environmental impacts. Therefore, electricity production mix for Turkey was used and obtained from Ecoinvent database. Electricity production is obtained from natural gas (28.5%), coal (36.4%), hydropower (22.4%), wind (6.3%), geothermal (2.3%), solar energy (2.4%) and other sources (1.6%) in Turkey (EMRA, 2018). All inputs and outputs per functional unit are shown in Table 1.

Table 1. Inputs and outputs for manufacturing the tire curing press per functional unit

Material name	**Amount**
Inputs:	
Raw material:	
Steel, hot rolled (t)	55.3
Copper alloy (kg)	58.8
Natural resource:	
Water (lt)	287
Electricity (kWh)	7361
Additives:	
Cutting fluid (kg)	345.2
Welding wire (m)	2450
Dye (kg)	34.1
Thinner (kg)	34.9
Copper tube (kg)	58.8
Shaped tube (m)	882.7
Structural steel tube (m)	109.8
Column shaft (t)	6.87
Material name	**Amount**
Spiral hose (m)	2542
Hydraulic unit (kg)	706
Control cable (m)	1970
Transport (tkm):	
Lorry	8875
Aircraft	51
Sea	12400
Outputs:	
Emissions (kg):	
Particulates	10.34
CO	0.61
SO_2	2.43
NO_2	0.35
VOC	0.685
Wastes (kg)	
Waste metal chips	20400
Waste cutting fluid	345
Waste packaging paper	0.785

Note: All values are given per functional unit of 1 piece

2.3. Life cycle impact assessment and interpretation

Potential human health and environmental impacts from environmental releases identified during the LCI were evaluated in this step, and it is described in ISO 14040. Selection of impact categories, category indicators, and characterization models is important for assessing and documenting potential environmental impacts. In practice, this selection is performed by choosing the impact assessment method (Carlson et al., 2003). IMPACT 2002+, which is a damage-oriented method, was used for impact assessment in this study. In this method, 15 mid-point and 4 end-point impacts were assessed and compared.

Interpretation occurs at every stage of LCA and consists of analyzing results from LCI and LCIA stages (Gürsel, 2014). The following steps to performing a life cycle interpretation are identified within the ISO 14044 standard: (1) Identify significant issues, (2) evaluate the completeness, sensitivity, and consistency of the data, and (3) conclusions, limitations, and recommendations (ISO 2006b).

In this study, contribution analysis was performed in order to identify the significance of environmental issues. The contributions of processes were compared to the total environmental burden by these analyses.

On the other hand, the second step of life cycle interpretation was accomplished by sensitivity check that assesses the influence of input parameter on impact assessment result and is conducted using sensitivity and/or uncertainty analysis. Although many LCIA methods have been applied in LCA studies, none of them have been internationally accepted according to the requirement of ISO and there is no guideline that helps the researcher for choosing between characterization models (Bueno et al. 2016). However, it is important to note that a meaningful comparison between impact assessment methods is difficult because impact categories, characterization indicators and characterization factors vary between them (Monteiro and Freire, 2012). Therefore, in order to verify the results and perform the reliable comparison, four different impact assessment methods (ReCiPe Midpoint (H), TRACI, CML-IA, and ILCD 2011 Midpoint) were used within the scope of the sensitivity analysis in this study.

Additionally, uncertainty analysis was performed to support the better understanding of the results and assess the robustness of the study. For this purpose, Monte Carlo Simulation (3000 iterations) was used to determine the parameter uncertainty.

3. RESULTS AND DISCUSSION

3.1. Life cycle impact assessment results for the tire curing press

Characterization results for manufacturing a hydraulic press is shown in Figure 2, wherein the greatest mid-point impact (66%-99%) across all categories is seen to be from raw material use, except for the aquatic eutrophication category. In that case, the greatest contributor was assembly, accounting for 51% of the overall impact. This result can be explained by the use of a hydraulic power unit in the press. Assembly also contributed to ionizing radiation, non-carcinogens, aquatic ecotoxicity, and terrestrial ecotoxicity. Electricity consumption also adversely affected respiratory inorganics (approximately 15%). Welding had no significant effect on the manufacturing of a tire curing press.

The positive environmental impacts of waste recycling on carcinogens, non-carcinogens, and ionizing radiation are also shown in Figure 2. Waste recycling reduced all three by about 42%, 15%, and 32%, respectively. The main reason of this positive environmental impact can be explained with recycling of waste steel during manufacturing of tire curing press according to the contribution analysis in SimaPro.

After normalization, the most important mid-point impacts of manufacturing tire curing press were respiratory inorganics, global warming, non-renewable energy, and terrestrial ecotoxicity.

Respiratory inorganics constituted about 44% of the overall environmental burden of manufacturing a hydraulic press. These values were 11%, 17%, and 7% for global warming, non-renewable energy, and terrestrial ecotoxicity, respectively. When the contribution analysis were taken into account, it was determined that respiratory inorganics mainly related to steel usage (78.5%) and electricity consumption (13.6%). On the other hand, the adverse effects of the machinery manufacturing industry on global warming are critical because the industry is energy- and resource-intensive. Zhang et al. (2016) used an LCA to evaluate GHG emissions during the manufacture of a hydraulic press slider, a 20-ton component typically found in forging machines. Results showed that the GWP was 60,560 kg CO_2-eq, and raw material acquisition was the largest contributor to GHG emissions (94.39%). These results are compatible with ours. The GWP of manufacturing a tire curing press (about 50-ton) was found to be 185 t CO_2-eq per unit, and the contribution of raw material (steel) use on global warming was 94.1%.

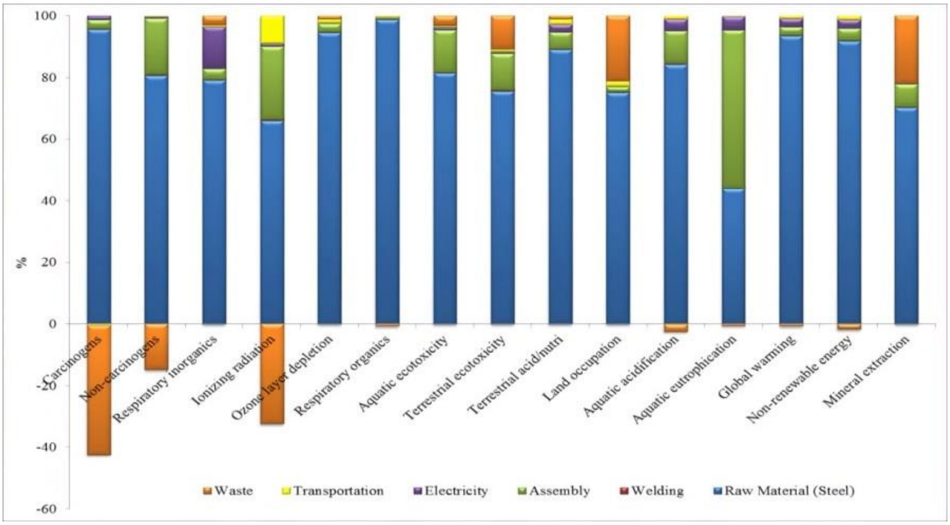

Figure 2. Process contributions on mid-point impact categories for 1 pcs hydraulic press

End-point impacts (as ecopoint, Pt) of manufacturing a hydraulic press, divided by process type, are presented in Figure 3. While overall environmental burden of manufacturing stage of the hydraulic press was found as 83 Pt, steel use constitutes 88% of the overall environmental burden following by electricity consumption (7%) and assembly (5%).

Welding and transportation made small contributions to the environmental burdens (approximately 1%) of the products assessed. Damage assessment showed that the most significant end-point impacts were on human health, climate change, and resources.

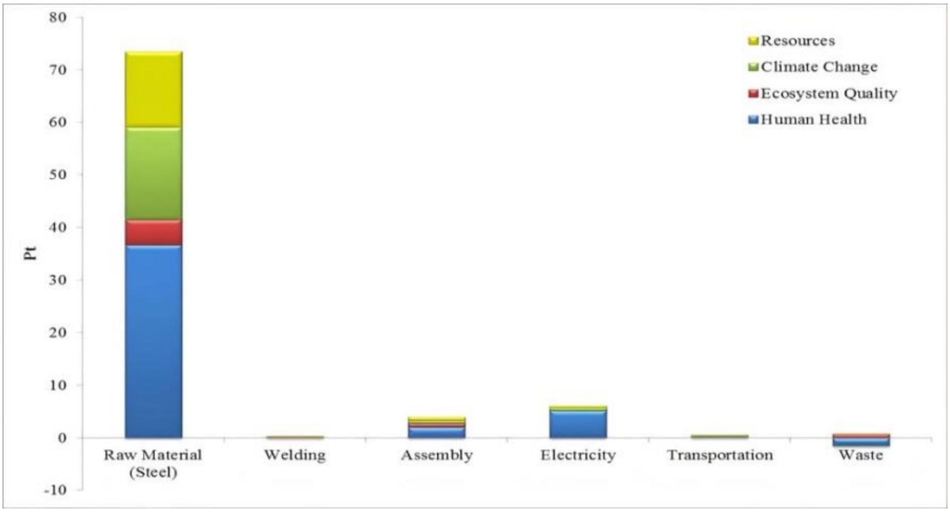

Figure 3. End-point impacts of tire curing press by process type (Pt: Point)

3.2. Sensitivity analysis

To verify the results and increase the reliability of this LCA, four different LCIA methods (ReCiPe-midpoint (H), CML IA, ILCD 2011 midpoint, and TRACI) were also used for comparison with IMPACT 2002+ and the results were given in the Table 2. The comparison was performed based on the mid-point impact categories. The main reason of the choice of these methods is that they are mostly used methods in the LCA studies (Bueno et al. 2016).

The Global warming impact category was found as same in four methods (ReCiPe, TRACI, CML IA, and ILCD 2011-midpoint) while IMPACT 2002+ was slightly lower than other methods. This result can be explained by usage of 500-year time horizon for global warming category in IMPACT 2002+ method to account for long term effects (Jolliet et al. 2003).

When ozone depletion potential of tire curing press was compared, the results using the IMPACT 2002+ method were similar to those of ReCiPe Midpoint (H), TRACI, CML IA, and ILCD 2011-midpoint. Acidification potential category is separated into aquatic acidification potential and terrestrial acid/nutri. potential in IMPACT 2002+ method (Mosteiro-Romero et al. 2014). However, CML and TRACI don't specifically define acidification as aquatic or terrestrial. Therefore, it is not practical to compare the CML and TRACI with IMPACT 2002+ in terms of terrestrial acidification potential (Landis and Theis 2008). On the other hand, aquatic acidification potential obtained from IMPACT 2002+ was almost similar with ReCiPe, TRACI, and CML-IA method.

Considering energy impact category, the results of ReCiPe method (change rate at 42.62 MJ/kg.oil eq.) were determined as approximately 2.14E+06 MJ to manufacturing 1 pcs of hydraulic press. The result obtained from ReCiPe and CML-IA methods are compatible with the results obtained from the IMPACT 2002+ method.

The impact assessment results using IMPACT 2002+ method were found as similar to those of TRACI methods in terms of respiratory effects which were unitized as kg $PM_{2.5}$ eq. On the other hand, respiratory effects derived from organic substances and/or photochemical oxidation was found as different in CML-IA method when compared with IMPACT 2002+. When all results were assessed comparatively, we have chosen the IMPACT 2002+ method because it proposed a feasible implementation of the combined midpoint/damage-oriented approach and linked all types of LCI results via 14 midpoint categories to damage categories including human health, ecosystem quality, climate change, and resources (Jolliet et al. 2003).

Table 2. Comparison of life cycle impact assessment results based on different impact assessment methods. (Adapted from Bueno et al. 2016).

Impact category	LCIA method	Characterization result
Global Warming ($kg\ CO_2$ eq.)	ReCiPe Midpoint (H), Climate change	1.92×10^5
	TRACI, Global warming	1.92×10^5
	CML IA, Global warming	1.92×10^5
	ILCD 2011 Midpoint, Climate change	1.92×10^5
	IMPACT 2002+, Global warming	1.85×10^5
Ozone Depletion (kg CFC-11 eq)	ReCiPe Midpoint (H), Ozone depletion	9.11×10^{-3}
	TRACI, Ozone depletion	1.03×10^{-2}
	CML IA, Ozone layer depletion	9.11×10^{-3}
	ILCD 2011 Midpoint, Ozone depletion	9.11×10^{-3}
	IMPACT 2002+, Ozone layer depletion	9.11×10^{-3}
Acidification ($kg\ SO_2$ eq.)	ReCiPe Midpoint (H), Terrestrial acidification	7.63×10^2
	TRACI, Acidification	8.45×10^2
	CML IA, Acidification	8.47×10^2
	IMPACT 2002+, Aquatic acidification	8.45×10^2
	IMPACT 2002+, Terrestrial acid./nutri.	3.16×10^3
Photochemical oxidation ($kg\ C_2H_4$ eq)	CML IA, Photochemical oxidation	2.53×10^2
	IMPACT 2002+, Respiratory organics	4.00×10^2
Respiratory effects ($kg\ PM_{2.5}$ eq.)	ReCiPe Midpoint (H), Particulate matter formation*	7.98×10^2*
	TRACI, Respiratory effects	3.83×10^2
	ILCD 2011 Midpoint, Particulate matter	1.94×10^2
	IMPACT 2002+, Respiratory inorganics	3.74×10^2
Non-renewable energy (MJ)	ReCiPe Midpoint (H), fossil depletion**	5.03×10^4 **
	CML IA, Abiotic depletion (fossil fuels)	2.62×10^6
	IMPACT 2002+, MJ	2.19×10^6

*: kg PM_{10} eq. per functional unit. ; **: kg oil eq. per functional unit (change rate 42.62 MJ/kg.oil).

3.3. Uncertainty analysis

The uncertainty analysis was performed with Monte Carlo simulation (3000 iterations) embedded in SimaPro 8.0.4 software in this study. The results were given in Table 3. When the results of uncertainty analysis were assessed, the highest uncertainty was identified in carcinogens impact category.

Although the least numbers of iterations have to be 1000 times in Monte Carlo simulation, the main criteria that govern the number of iterations is the standard error of mean (SEM). The standard error of mean indicates how much the mean is changed by the last Monte Carlo run. It is mean that the lower SEM, the more reliable results. Standard error of mean below 0.01 is quite acceptable (Al-Yaseri 2014; Goedkoop ve diğ., 2016). As can be seen from the Table 3, the SEM values of each impact categories are less than 0.01.

4. CONCLUSIONS

In this study, an LCA of a tire curing press was conducted. Raw material consumption was the process that had the most significant impact. It has constituted 88% of overall environmental burden of manufacturing the hydraulic press. A lightweight design would be important for conserving raw materials and energy in machinery manufacturing sector because metals accounted for the largest portion of the weight of a hydraulic press. On the contrary, recycling the waste metal chips and iron scraps has important positive environmental impact on carcinogens, non-carcinogens, and ionizing radiation. This result reveals the significance of recycling in machinery manufacturing sector.Considering differences in results obtained from various LCIA methods (ReCiPe Midpoint (H), TRACI, CML-IA, and ILCD 2011-Midpoint), global warming and ozone layer depletion potential obtained from the IMPACT 2002+ were almost same with the other four methods. The impact assessment results using IMPACT 2002+ method were similar to TRACI in terms of respiratory effects (derived from inorganics) and aquatic acidification. Considering the differences in energy impact, the similar results were obtained with ReCiPe Midpoint (H) and CML-IA methods. On the other hand, respiratory organics impact was found as different in CML-IA method comparing with IMPACT 2002+.

Table 3. Uncertainty analysis results for hydraulic press

Impact category	Unit	Mean	Median	SD*	CV *	2.5%	97.5%	SEM*
Mid-point impacts:								
Aquatic acidification	kg SO_2 eq	8.54×10^{2}	7.58×10^{2}	4.51×10^{2}	52.7%	2.92×10^{2}	2.00×10^{3}	9.63×10^{-3}
Aquatic ecotoxicity	kg TEG water	2.02×10^{7}	1.80×10^{7}	1.04×10^{7}	51.6%	7.07×10^{6}	4.71×10^{7}	9.43×10^{-3}
Aquatic eutrophication	kg PO4 P-lim	5.34×10^{1}	4.96×10^{1}	2.16×10^{1}	40.4%	2.26×10^{1}	1.07×10^{2}	7.38×10^{-3}
Carcinogens	kg C_2H_3Cl eq	7.38×10^{3}	6.16×10^{3}	5.81×10^{3}	78.7%	2.08×10^{2}	2.19×10^{4}	1.44×10^{-2}
Global warming	kg CO_2 eq	1.84×10^{5}	1.61×10^{5}	1.03×10^{5}	55.7%	5.82×10^{4}	4.48×10^{5}	1.02×10^{-2}
Ionizing radiation	Bq C-14 eq	-3.94×10^{5}	-3.30×10^{5}	2.52×10^{5}	-64%	-1.03×10^{6}	-1.03×10^{5}	-1.17×10^{-2}
Land occupation	m^2org.arable	7.10×10^{3}	6.23×10^{3}	3.86×10^{3}	54.4%	2.37×10^{3}	1.67×10^{4}	9.93×10^{-3}
Mineral extraction	MJ surplus	2.08×10^{5}	1.84×10^{5}	1.11×10^{5}	53.3%	7.21×10^{4}	4.87×10^{5}	9.73×10^{-3}
Non-carcinogens	kg C_2H_3Cl eq	6.84×10^{3}	6.08×10^{3}	3.61×10^{3}	52.8%	2.32×10^{3}	1.63×10^{4}	9.64×10^{-3}
Non-renewable energy	MJ primary	2.19×10^{6}	1.92×10^{6}	1.20×10^{6}	54.9%	7.06×10^{5}	5.30×10^{6}	1.00×10^{-2}
Ozone layer depletion	kg CFC-11 eq	9.10×10^{-3}	7.98×10^{-3}	5.04×10^{-3}	55.4%	2.91×10^{-3}	2.21×10^{-2}	1.01×10^{-2}
Respiratory inorganics	kg $PM_{2.5}$ eq	3.74×10^{2}	3.30×10^{2}	2.01×10^{2}	53.7%	1.23×10^{2}	8.89×10^{2}	9.80×10^{-3}
Respiratory organics	kg C_2H_4 eq	3.98×10^{2}	3.53×10^{2}	2.16×10^{2}	54.1%	1.31×10^{2}	9.54×10^{2}	9.88×10^{-3}
Terrestrial acid/nutri	kg SO_2 eq	3.16×10^{3}	2.79×10^{3}	1.71×10^{3}	54.1%	1.04×10^{3}	7.55×10^{3}	9.87×10^{-3}
Terrestrial ecotoxicity	kg TEG soil	9.72×10^{6}	8.63×10^{6}	5.02×10^{6}	51.6%	3.42×10^{6}	2.25×10^{7}	9.43×10^{-3}
Damage Assessment:								
Climate change	kg CO_2 eq	1.84×10^{5}	1.61×10^{5}	1.03×10^{5}	55.7%	5.82×10^{4}	4.48×10^{5}	1.02×10^{-2}
Ecosystem quality	PDF*m^2*yr	8.89×10^{4}	7.88×10^{4}	4.62×10^{4}	51.9%	3.10×10^{4}	2.06×10^{5}	9.48×10^{-3}
Human health	DALY	3.03×10^{-1}	2.66×10^{-1}	1.64×10^{-1}	54.2%	9.80×10^{-2}	7.23×10^{-1}	9.89×10^{-3}
Resources	MJ primary	2.39×10^{6}	2.11×10^{6}	1.31×10^{6}	54.6%	7.80×10^{5}	5.77×10^{6}	9.97×10^{-3}
Single score		8.35×10^{1}	7.36×10^{1}	4.54×10^{1}	54.3%	2.71×10^{1}	2.00×10^{2}	9.92×10^{-3}

*: SD refers to Standard Deviation, CV refers to Coefficient of Variation, SEM refers to Standard Error of the Mean.

The scope of this study was limited to a cradle-to-gate assessment, which includes raw material acquisition, transportation, the manufacturing stages, and waste treatment, in consideration of data availability. However, to determine the impact of manufacturing of these products in view of the machinery manufacturing sector, it is critical to perform a full LCA (cradle-to-grave) which includes product use and final disposal. Expansion of the boundary creates challenges, but it is important to develop low-emission product designs and evaluate the entire environmental impact. The other limitation of this study is deficiency of economic or social issues. This study does not include social and economic assessment. However, it is important to note that different approaches such as Social Life Cycle Assessment (S-LCA) and/or Life Cycle Costing (LCC) are needed to assess the all sustainability indicators (environmental, social, and economic) entirely and perform the life cycle sustainability assessment (LCSA) in the future. In general the results of this study can be used as manufacturing planning decision support by waste managers and decision makers when designing plant operations that reduce environmental impacts.

Conflicts of Interest

The authors declare they have no conflicts of interest.

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